Second best as a researcher, second to none as a populariser?

The atmospheric science of John Tyndall FRS (1820-1893)

By

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A dissertation submitted in fulfilment of the requirements for the degree of doctor of philosophy

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2012

I, Irena Maria McCabe confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

ABSTRACT

John Tyndall, FRS (1820-1893), the eminent scientist and mountaineer, the discoverer of the greenhouse gases, has been frequently presented as chiefly a populariser of science rather than a researcher. Although he regarded this education as an important function to fulfil, his researches and discoveries reported in the publications of the Royal Society, the Royal Institution and the British Association for the Advancement of Science, constitute a testimony to his standing as a scientist, hitherto neglected by his commentators. This thesis studies his contributions to the physics of the atmosphere and their subsequent impact on meteorology, research that is relevant to today's concerns about climate change. Tyndall, did however, also make discoveries in other branches of physics, chemistry and bacteriology.

Like many aspiring British scientists of the nineteenth century, Tyndall went to Germany as a mature student. He chose the University of Marburg to study chemistry, physics and mathematics under the renowned chemist, Robert Bunsen, the physicist Gerling and the mathematician Stegmann respectively, graduating with a PhD in applied mathematics.[1]

At this time Faraday's extraordinary discovery of diamagnetism in 1846 were causing a sensation in Germany, France and Britain. Scientists eagerly studied Faraday's research, replicating his experiments and interpreting his findings. Faraday's work apparently confirmed concomitant researches by Plücker on the magnetic properties of crystals. Tyndall's pioneering contributions to the study of diamagnetism[2] constituted his formative experiences as an experimentalist. He effectively challenged the opinions of the distinguished scientists, Faraday and Plücker.[3] The deportment of magnetism with respect to matter provided Tyndall with a comprehensive alternative to Faraday's views on the interaction of point forces with

[1] Tyndall (1870).

[2] Tyndall (1851), 2, (9), 165-188

[3] Plücker (1849), 5, 353-375; 376-382.

matter. Tyndall's analogous investigation of radiant heat and its transmission by the atmosphere enabled him to study matter in its gaseous phase, hitherto inaccessible to the experimental process, and to participate in the all-important shaping of meteorology as a scientific discipline. The analogous interactions of matter with the forces of light and heat prompted Tyndall's speculations on the role of the molecular structure in the modification and transmission of forces. The Tyndall Centre for the Study of Climate Change, thus named in his honour in the year 2000 by the Director of the Royal Institution, Professor Peter Day, testifies to the importance of Tyndall's contributions to the all pervading problems which today face mankind.

This thesis also addresses his role as a leading publicist for scientific naturalism and campaigner for science education, throwing a new light on his motives. On the death of his mentor and friend, Faraday, Tyndall succeeded him as Resident Professor in charge of the Royal Institution. In this historic laboratory Tyndall devised and perfected experimental methodology for the study of matter in its gaseous phase, thought, until then to not be amenable to scientific investigation. The importance of this contribution to science, underestimated over the years, is highlighted in the thesis. The thesis also looks at his pioneering researches on gases through their interaction with radiant heat and light. It examines how he used the forces of nature as tools to probe the nature of matter. It presents one consequence of Tyndall's work that led to the discovery of calorescence, from a new perspective.

The author of over 100 scientific papers, Tyndall is revealed as an inspiring research scientist, honoured by the Royal Society and numerous foreign academies. He was however castigated for an inadequate knowledge of mathematics, because he concentrated on imaginative physical interpretations of theoretical notions. At times, therefore, he was seriously underestimated as a scientist, despite admiration by some for the excellence of his work. This theme is also analysed in the thesis. Emerging from this study is an image of Tyndall's serious engagement with science, and his role as an eminent practitioner and spokesman, who viewed science as beneficial to mankind, and physics as a means of education.

ACKNOWLEDGEMENTS

I wish to thank my principal tutor Professor Hasok Chang and my subsidiary tutor Professor Steve Miller for an amazing academic experience due to their patient and inspiring guidance. My fellow students provided an essential friendly and supportive atmosphere – it is a privilege and a real pleasure to be a part of this vibrant academic community in the Department of the Science and Technology Studies. I wish to record my thanks to Professor Frank James of the Royal Institution of Great Britain for his encouragement and stimulating discussions. I am also grateful to Jane Harrison on his staff for her very efficient and cheerful assistance at all times. I would like to record my grateful thanks to Dr Catherine Jackson for her support and interest in the thesis.

I would like to put on record my thanks to the staff of the libraries of the UCL, Imperial College, the Science Museum, the University of London, the Royal Society, London Library and the British Library for their invaluable help at all times. Geoffrey Eastwood, Jim McGeever, Derek Randall, Margaret and Roger Woodall's reading of first drafts provided support for which I am grateful.

Brian and Marion Edwards and Margaret and Roger Woodall's friendly encouragement is much appreciated. My family's interest has meant a great deal to me: I thank Gavin, Fiona and Ian for their forbearance.

My thanks are also due to my examiners.

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CHRONOLOGY

1820	Birth
1839	Apprentice with the Irish Ordnance Survey
1842-1843	English Ordnance Survey at Preston- after dismissal, back in Ireland
1844-1847	Railway surveyor back in England
1847-1848	Mathematics master and secretary Queenwood College Hampshire
1848-1851	Bunsen's student at the university of Marburg; awarded a doctorate 1850 Knoblauch's physics student and a researcher in diamagnetism, Faraday's area of interest; meets Faraday at the Royal Institution in June 1850. After several months at the university of Berlin in Magnus's laboratory among budding German scientists, back in England meets Huxley and attends his first meeting at the British Association for the Advancement of Science, W. Thomson (later Lord Kelvin).
1852	Elected FRS
1853	Gives a Friday evening discourse at the Royal Institution; elected professor of natural philosophy.
1854	Lectures at the Royal Institution on physics and education alongside Faraday, Whewell and other eminent lecturers.
1855	Delivers his first Bakerian lecture at the Royal Society
1856	First visit to the Alps with Huxley to investigate glacier structure
1861	Inaugurates a pioneering programme of researches on radiant heat at his second Royal Society Bakerian lecture.
1864	Leading member of the X club; third Bakerian lecture

1867	On Faraday’s death, succeeds him as superintendent and resident professor at the Royal Institution
1868-1870	Discovery of new chemical reactions of light
1870-1880	Researches in microbiology, acknowledged by J. Lister
1872-1873	Lecture tour of the Unites States
1874	Belfast Address as President of the BAAS.
1876	Marriage to Lady Louisa Hamilton
1881	Fifth Bakerian lecture resuming researches on radiant heat
1887	Retirement from the Royal Institution
1893	Death

INTRODUCTION

John Tyndall (1820-1893), FRS, professor of natural philosophy at the Royal Institution of Great Britain (1853-1887), succeeded M. Faraday (1791-1867) as resident professor in charge of the Royal Institution in 1867.

He studied chemistry, physics and mathematics at the University of Marburg 1848-50 in the department of the famous chemist, R. Bunsen, graduating with a PhD in mechanics. His research skills were further developed in the department of physics investigating the pioneering discoveries of Julius Plücker of Bonn and Faraday in diamagnetism, continued at the University of Berlin. Tyndall returned to the UK in 1851, at first returning to occasional teaching at Queenwood School in Hampshire, and translating and reviewing science for the *Philosophical Magazine*. Elected Fellow of the Royal Society of London 1852, and appointed Professor of Natural Philosophy at the Royal Institution of Great Britain in 1853, he resumed his researches on diamagnetism and related subjects. At first Faraday's colleague, he became his successor as Resident Professor and Superintendent at the Royal Institution. He pursued a spectacular career in physics then in bacteriology collaborating with the foremost surgeon of the day, Joseph Lister.

In the early 1860s Tyndall identified greenhouse gases in the atmosphere, notably carbon dioxide and water vapour. He initiated a research programme into the interaction of radiant heat and matter in gaseous phase. The gaseous state was a desirable state of matter because the intermolecular forces of cohesion play a relatively negligible role. Due to the intrinsic difficulties of working with gases, the idea of experimenting on them, and the forces of nature such as radiant heat acting on them, had been thought impractical. Tyndall developed new experimental procedures for the purpose. The possibility of the scientific study of the interaction of radiant heat with gases became a reality when Tyndall experimented on coal gas and olefiant gas, revealing their very high absorptive power. Tyndall's apparatus was adapted from that of M. Melloni's (1798-1854), probably modelled on an optical bench. Its application to the study of climate contributed to the establishment of meteorology on a scientific basis. Tyndall's experimental procedures resulted in a novel approach whereby atmospheric phenomena could be studied in the laboratory. The controversial strategy of mimicking of nature at the laboratory bench yielded consistent results, providing quantitative data that enabled the formulation of new laws. These, in turn, fed further theoretical speculations. This thesis will examine Tyndall's experimental and theoretical researches using radiant heat to study the nature of matter, and hence his contributions to the composition of matter and to meteorology, and the presentation of his results to the professional scientists and the lay public, in the context of the science of his day. His innovative procedures played a part in the growth of meteorology as a scientific discipline that is still increasing in importance in today.

Chapter 1 considers the background to the dichotomy of Tyndall's reputations as a research scientist and populariser. Chapter 2 discusses the influences that shaped his science as an experimentalist. Chapters 3 and 4 investigate his progress as a professional scientist, as he initiated his research programme of the 1860s. They look at its consequences on experimental methodology, and Tyndall's view of the theoretical aspects of his discoveries. His contributions to meteorology are scrutinised in Chapter 5, followed by the concluding Chapter 6.

CHAPTER 1

John Tyndall FRS the Researcher and Populariser (1820-1893)

This chapter considers the background to Tyndall's reputation. Over the years Tyndall has been remembered as a populariser rather than a researcher. That is a misconception. The Tyndall Centre for the Study of Climate Change at the University of East Anglia, founded in 2000,[4] is a reminder of his lasting importance as a research scientist. Reactions to Tyndall from his death in 1893 to the present day reflect the polarised judgements in his lifetime. For example, D. Lindley commented in his 2004 biography of W. Thomson, later Lord Kelvin (1824-1907):

> He made a few modest experimental discoveries but was by no means a remarkable or original scientist, tending to throw out qualitative ideas on general grounds rather than work out fine details.[5]

In contrast to this unsubstantiated opinion, E. Bard of the College de France in Paris, also in 2004, assessed Tyndall's researches based on his publications:

> We are primarily indebted to the naturalists, physicists and chemists of 19th century, who carried out first scientific research on the greenhouse effect and glaciations. …The insatiable curiosity of these pioneers was accompanied by many different skills in disciplines as varied as physics, geology, chemistry, biology and astronomy. Thus John Tyndall contributed significantly not only to advances in thermodynamics, but also to the study of glaciers… These scientists lacked precise measurement techniques and had no large-scale information in meteorology, oceanography or geology. But, as Joseph Fourier pointed out, theory alone cannot be enough in these fields, because "mathematical analysis…can derive the expression of natural laws from general and simple phenomena; however, the application of these laws to highly composite effects requires a long series of exact observations."…the nineteenth

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[4]Anon. (2000), 11 and 18 April.

[5]Lindley (2004), p. 180.

> century pioneers often had prophetic and premonitory intuitions, although the observations at their disposal were…very fragmentary. The principal fundamental concepts that we use today were developed during the 19th-century.[6]

Tyndall's reputation as a populariser of science was a handicap to his recognition as a professional scientist by some of his peers. Lightman maintains that Huxley's and Tyndall's popularising constituted only a small part of that by the amateurs.[7] Nevertheless, the fame of Tyndall's lectures and publications for the non-specialist have tended to eclipse his contributions as a highly original research scientist. At the start of the professionalisation of science it became more acceptable for amateurs rather than specialists to popularise science. Popularisation can therefore be seen as a activity that separated the role of the amateur from that of the professional; a boundary that became increasingly important in the looming age of the Darwinian evolution and scientific naturalism. In the waning age of natural philosophy, an amateur could mix freely with professionals by virtue of his achievements. The mathematical physicists, J.C. Maxwell (1831-1879) and Thomson did occasionally ventured into popular science, but they lectured at the Royal Institution and the British Association, and never at the Royal School of Mines whose popular lectures were ardently supported by Huxley and Tyndall.

Maxwell and Thomson were among Tyndall's Royal Society referees and exerted a positive influence on his professional life. On the other hand in the Royal Society archives P.G. Tait (1831-1901) is not mentioned as a referee. His career was centred in Edinburgh and therefore around the Royal Society of Edinburgh. His exclusion from the Royal Society of London may be due to the influence that was allegedly exercised there by scientific naturalists such as Tyndall. Tait's hostility drew Tyndall into disputes that affected him deeply. Tyndall's ambitions as a researcher, Tait claimed, were tainted by his enthusiasm for popularising science, and his success in this area:

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[6]Bard (2004), p. 616.

[7]Lightman, ed. (1997), p. 187.

> I cordially recognise the services of Dr Tyndall in popularising certain parts of science. But his readers must be cautioned against accepting as correct great parts of what he has written. It is granted to very few men to do this useful work without thereby losing their claim to scientific authority. Dr Tyndall has, in fact martyred his scientific authority by deservedly winning distinction in the popular field. One learns too late that he cannot 'make the best of both worlds.[8]

Tait's position in 1877 echoes that of J.D. Forbes (1809-1868) Principal of United College, University of St. Andrews. T.B. Macauley (1800-1890), historian and politician, had championed the popularisation of science. Forbes' two Edinburgh lectures of 1849 formed an acrimonious response.[9] Tait ardently supported Forbes in his dispute with Tyndall, and he endeavoured in vain to undermine the campaign of the scientific naturalists at a time when the value of scientific education in schools and universities, and the importance of the national supremacy in science on the world stage was being recognised.[10] J. Gregory and S. Miller trace the process of the popularisation of science and they remark on its success on both sides of the Atlantic as interest gathered momentum during the second half of the nineteenth century.[11] The paradox of Tait's disdain for Tyndall, one of the most vociferous campaigners for professionalisation of science, confirmed the low status of the Victorian popularisers of science, referred to by B. Lightman.[12] Tait's hostility also suggests that the mathematical physicists, unlike the rising generation of the scientific naturalists such as Tyndall, had no status problem, and therefore did not support the campaign of the newly aspiring professionals. The highly respected scientific texts published by Tait, Maxwell or Thomson gave these authors a financial security that relieved them from dependence on a salaried university post for subsistence. In contrast, the scientific

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[8]Tait (1873), pp. 381-382.

[9]Forbes (1849).

[10]Knight (1989), pp. 137-138; 141-142.

[11]Gregory and Miller (1998), pp. 20-25.

[12]Lightman, ed. (1997), pp. 188-189.

naturalists had to establish their scientific credentials while searching for adequately rewarded permanent positions, which were not readily available.

R. Yeo and F. M. Turner have both examined the shift from natural theology being the dominant scientific attitude (as reflected in the Bridgewater Treatises), to the ascendancy of scientific naturalism. These were crucial years for Tyndall's professional development. The scientists' reaction to the controversial *Vestiges of the Natural History of Creation*[13] ranged from admiration to loathing and fear. Yeo sees the supporters of *the Vestiges* (such as Tyndall), as being keen to rival the church authorities for influence in the community at a time of increasing knowledge and clamour for democratic reforms.[14] Turner analyses this transition in the succeeding decades, assigning a crucial role in this enterprise to the new generation of professional scientists such as Tyndall.[15] Tyndall successfully lobbied the authorities of the Royal Society with eight like-minded friends, all members of the X Club that had been founded in 1864 by biologist T.H. Huxley (1825-1895).[16] The writings of Tyndall, Huxley and their associates, together with their speeches at the British Association and other venues, claimed a professional status for science that would put it on a par with the law, medicine and theology. As a consequence of their actions the Royal Commission looked into the place of science in the tertiary and subsequently secondary education, culminating in the briefs of the Devonshire Commission of 1871.[17]

1A. A Brief Introduction to Tyndall's Life

Tyndall's progress, from his humble beginnings to his post as director of one of the world's most prestigious scientific establishments, is covered in more detail in

[13]Anon. [Chambers] (1845).

[14]Yeo (1984), p. 6.

[15]Turner (1993), p. 78; Boas Hall (1984), p. 82.

[16]Harrison (1988), vol. 1, pp. 167-170.

[17]Barton (2003), volume 41, 73-119, 78.

Chapter 2. Below is a brief summary of his beginnings as a professional scientist that will be useful as a context for the rest of this chapter.

After being awarded a PhD in 1850 as a student of chemist Bunsen, in Marburg, Germany, Tyndall became a researcher in the department of physicist H. Knoblauch where they were investigating Faraday and Plücker's new discoveries in diamagnetism. Elected as a Fellow of the Royal Society in 1852, he was awarded the Royal Medal the following year, but since the award was not unanimously approved, Tyndall did not accept it. Among the members of the awarding committee there had been a few dissenting voices who claimed that the distinction came too soon, and that they may have been other more deserving candidates.

Tyndall's appointment as Professor of Natural Philosophy at the Royal Institution testifies to Faraday's recognition of Tyndall's talents as both lecturer and a researcher. At this time the RI was strengthening its research role, in addition to continuing to function as a centre for the diffusion of science to the public at large. Its founder, B. Thompson, Count Rumford (1753-1814) had proposed in 1799 "in the Metropolis of the British Empire a Public Institution for diffusing the knowledge and facilitating the general introduction of useful mechanical inventions and improvements, and for teaching by courses of philosophical lectures and experiments the application of science to the common purposes of life."[18] Tyndall's career at the Royal Institution spanned thirty-four years (1853-1887), and he succeeded Faraday as resident Professor in Charge in 1867.[19] Tyndall's modest start in life, served by his extraordinary intellect, judgement, industry, love of nature, and ability to communicate with others, impacted on the science of his day in two ways. Firstly, Tyndall exerted a strong influence on the establishment of science as an integral part of the educational process at a national scale. The age of reform provided him with opportunities to apply his strong convictions that nature should be studied in an independent manner, and that a scientific education to be accessible to all. As a

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[18]Rumford [1799], p. 1, reprinted in 1870-1873, volume 4, pp. 755-764, also in Bence Jones (1871), pp. 121-134.

[19]Eve, A.S. and C.H. Creasey (1945), pp. 43-58; Allen (1894), volume 9, pp. 21-26; Burchfield (1981), pp. 1-13. Crowther (1968), pp.157-185; Sawyer (1981), volume 360, pp 217-246.

research scientist he pioneered an experimental methodology backed by theoretical notions that was of benefit to succeeding generations of scientists across disciplines, in particular in the study of matter and meteorology.

Despite Tait's scurrilous utterances and some adverse comments from journals of a particular political outlook such as *Truth*, Tyndall by and large enjoyed acclaim from his contemporaries. On entering the scientific community, Tyndall rapidly developed a vast network of acquaintances, friends and colleagues both in Britain and abroad. From a slow beginning, he rose rapidly through the ranks to occupy a high position in Victorian society as a man of science, prone to controversial pronouncements and unpopular partisan causes, but always true to himself.[20] A prolific author of research papers, popular books and articles, and a renowned lecturer before audiences ranging from working-men at the School of Mines to the upper classes at the Royal Institution, Tyndall attracted the attention of the press and the public. A close friend and admirer of his mentor M. Faraday, he became also a popular dinner guest of aristocrats including the politician and scientist George John Douglas, the 8th Duke of Argyll MP (1823-1900).[21] Favoured by the historian and philosopher Thomas Carlyle (1795-1881),[22] he was also welcomed by the poet Laureate, A. Lord Tennyson ((1809-1892) at his home on the Isle of Wight. The eminent art critic and amateur geologist J. Ruskin (1819-1900) varied in his opinions of Tyndall. This was probably due to his attitude towards C. Darwin (1809-1882) whom Tyndall supported ardently, and also Tyndall's part in contemporary controversies on education, science, politics and religion. Friends and foes took sides and responded to the many roles fulfilled by Tyndall as a research scientist, but also as a populariser, educationalist, mountaineer and philosopher.

An exemplar of Ruth Barton's *man of science*, Tyndall was engaged in different fields of inquiry at different levels. Belonging to a new generation of men of science, Tyndall was imbued with a different outlook from that of a traditional British

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[20]Huxley (1894), volume 35 (203), pp. 1-11, 2, 5.

[21]Argyll to Tyndall 1866-1891 index, in James (2003), pp. 10-11, 54-55.

[22]Tyndall (1890].

man of science. He represents the diversity that impedes precise distinction between amateurs and professionals in Barton's investigation of the professionalisation of science.[23] His intensive university training in Germany, and subsequent dedicated research programme in London, contrasts with G.H. Lewes's meagre grasp of scientific understanding as rated in Huxley's critical review of Lewes's publications on science. Huxley approved of the polymath Lewes's study of Comte's philosophy, but took exception to factual scientific errors in the accounts of the contemporary science that Lewes gave to those outside the sphere of professional science.[24] In Huxley's opinion Lewes demonstrated an inadequate background in scientific literacy. Having acquired his knowledge of science exclusively from books; Lewes lacked the kind of in-depth comprehension built on actual scientific practice, which is necessary for the making of sound scientific pronouncements. According to Barton, Huxley thus attempts to impose boundaries that distinguish a man of science from an amateur to be excluded.

By contrast Barton cites the eminent scientist, President of the Royal Society William Spottiswoode (1825-1883) who describes himself as "one outside the sphere of professional science."[25] She appears to accept this surprising self-assessment and classes Spottiswoode as an amateur embraced by the community, despite his credentials as holder of a First Class mathematics degree from Cambridge, as respected author and lecturer in physical sciences,[26] and successful candidate for the Presidency of the Royal Society supported by the X Club in opposition to Stokes. I suggest that Spottiswoode saw himself outside the scientific community not because he was an amateur, but because, in addition to his professional scientific activities, he was preoccupied on the day-to-day basis with the family business matters. This was unusual among men of science at the time in Britain, but for exceptions such as Kelvin and H.C.F. Jenkin (1833-1885) in Scotland. Although other names with business connections come to mind, W. De La Rue (1815-1889), J. Lubbock (1834-

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[23]Barton (2003), volume 41, pp. 73-119.

[24]Ibid., Barton, p. 74.

[25]Ibid., Barton, p. 73.

[26]Crilly (2004-09) .

1913), J.P. Joule (1818-1899), among them; their business involvements, unlike those of Kelvin and Jenkin, were a part of their family inheritance and came early in life.

1B. Tyndall the Researcher

1B.1 Professional Dimension, especially his Fellowship of the Royal Society and his Decline of the Royal Medal.

In 1850 Tyndall, a student of chemistry, physics and mathematics in the department of the distinguished chemist R. Bunsen at the University of Marburg, was awarded a PhD degree, and became a researcher in the laboratory of the newly appointed Professor of Physics, H. Knoblauch. Because of his other commitments, Knoblauch asked Tyndall to take over work on the discoveries of Faraday and Plücker on diamagnetism, and replicate their experiments. Faraday's researches always generated a lot of interest among foreign scientists, particularly in Germany.

Knoblauch provided space and apparatus; Tyndall was given the responsibility for devising and carrying out the experiments. Both scientists discussed the progress of the work and jointly published two papers.[27] It was a prestigious undertaking for this recently qualified and ambitious researcher. Tyndall, unknowingly, was on the threshold of a remarkable career, one of the first generation of professional scientists to make his mark in the heart of London in the steps of his future friend and mentor, Faraday. Meanwhile Tyndall independently continued his research on the most recent developments in the science of electromagnetism at the prestigious University of Berlin in the department of the respected chemist and physicist G. M. Magnus. Magnus also supplied the space and apparatus required by Tyndall.[28] On completion of this research Tyndall returned to Britain, and joined other unemployed scientists, including Huxley, in seeking a position in Britain or the Empire, including Toronto. The secretary of the Royal Society E. Sabine (1788-1883) wrote:

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[27] Tyndall and Knoblauch (March 1850), vol. 36, pp. 178-1831; (July 1850), vol. 37, pp. 1-53.

[28] Tyndall (1851).

> I take it for granted that with such testimonials your prospect of obtaining the Professorship at Toronto is secure. I confess I do feel …a regret that the mother country is about to be deprived of two such persons as yourself and Mr Huxley – may this loss be compensated by the gain to yourselves and to the Colony…Would not the interests of all be advanced by your becoming a Fellow of the Royal Society before you go, and looking to that Society as the channel of your future communications? Should this appear to you as it does to me, I should be very happy to put matters in train for your election.[29]

Tyndall was elected Fellow of the Royal Society 3 June 1852. His biographical note at the Royal Society includes the statement that the history of climate science began with Tyndall when he established the concept of a greenhouse gas and that realised that by virtue of the fact that certain gases (water vapour and carbon dioxide in particular), possess the property of trapping infrared radiation from the sun, they protect the earth from excessive cold. His proposers to the Society included the most distinguished names in science, including Faraday, William Grove (1811-1896), and the Astronomer Royal, George Biddell Airy (1801-1892) amongst others.

Tyndall's biographers refer to the autumn of 1853 as being marked by the extraordinary controversy concerning the Royal Medal. This medal was awarded annually by the Royal Society "for distinguished work in the two great divisions of natural knowledge-biology and mathematics, physics and chemistry."[30] The Council decided that out of five candidates, Tyndall was to be the recipient. In a letter to the Council, Tyndall presented his case for declining the award. It came to his notice, that on reflection:

> Some members have reason to doubt the wisdom of the award. They are not convinced of the originality of my labours, nor perhaps of their worthiness even if original. On the former point the knowledge

[29] Sabine to Tyndall, 6 November 1851. RI MS JT/1/S/4.

[30] Eve and Creasey (1945), pp. 45-49

> I possess needs no ratification; but with regard to the latter, I am anxious, without a moment's delay, to put the Council in an unpledged position, and to restore to it that perfect freedom of action which it enjoyed before in a moment of precipitancy apparently, it made the Medal mine. I share to the fullest extent the convictions, evidently entertained by the Council that such awards ought not to be lightly made, and I should be doubly unworthy of any such distinction were I willing to accept it when coloured by a doubt.[31]

Tyndall had been appointed Professor of Natural Philosophy at the Royal Institution, only six months before the above episode, experiencing an extraordinary change in his fortunes, a meteoric rise in his status. He would have wished, particularly in those early days, to be seen to be reacting in a manner that maintained his dignity and scientific integrity. Declining the medal constituted the only response available to him in the circumstances, a gesture that would have met with the universal approval. He would need this kind of approval in the course of his problematic career.

1B.2 The Royal Society Referees

In this section I will discuss the Royal Society's acknowledgement of the excellence of Tyndall's research, and important indication of his success as a research scientist. Tyndall's first paper was published in the *Philosophical Transactions of the Royal Society*.[32] Three out of the ten papers by Tyndall on radiant heat (appearing in the *Philosophical Transactions of the Royal Society* between 1861 and 1870 and in 1882), were transcripts of the prestigious Bakerian lectures. The ten year interval between 1870-1880 was caused by Tyndall's preoccupation with his important work in microbiology in collaboration with Pasteur and Lister at the time of the cholera and plague epidemics.

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[31] Tyndall Journal vol. 5, 14 and 15 November, p. 279 (125) 636.

[32] Tyndall (1853), vol. 143, pp. 217-232.2222

The referees for Tyndall’s Royal Society papers were doyens of British science, Thomson, G.G. Stokes (1819-1903) and Maxwell among them. Their opinion of Tyndall’s research papers is particularly significant. One might assume that given their close association and friendship with Tait, who was a vehement critic of Tyndall the researcher, they would have had a low opinion of Tyndall's work. Despite Maxwell’s light-hearted lampooning of Tyndall as a populariser, this is not the case however.[33] Tyndall’s referees commented in detail and suggested occasional revisions to clarify certain points, but they were invariably impressed. The selected referees’ reports deal with important and controversial issues. Thomson’s appreciation of Tyndall’s work in the 1860s contrasts with his attitude in 1850. In 1850 Thomson, was critical of Tyndall’s and Knoblauch’s work on diamagnetism,[34] and requested that they perform the experiments as suggested in his paper[35] that had indicated a different interpretation of the phenomena:

> I should be extremely glad if the suggestion I have made should induce you, or Mr Knoblauch...to make some such experiments. There are several distinct arrangements I could indicate which I think might lead to a complete elucidation of the very remarkable experiments you have already made. If you wish it, I shall be glad to communicate all I could suggest.

He goes on suggesting references for Tyndall to read:

> Poisson’s[36] theory of induced magnetism briefly described in Lamé’s[37] *Cours de Physique* and probably in many other similar

[33]Maxwell (1871), which is the Presidential Address to the Physical and Mathematical Section, 15 September 1870; see also Garber, Brush and Everitt (1986), pp. 90-104; Maxwell (n.d.), in Campbell and Garnett (1884), 412-414.

[34]Tyndall and Knoblauch (1850a), s. 3, volume 36, pp. 177-183.

[35]Thomson (1850), 251-253; Thomson (1851), 184-185.

[36]Poisson, S.D. (1781-1840), French mathematician, professor of mechanics at the Sorbonne

[37]Lamé, G. (1795-1870), French mathematician and engineer, professor of physics at the École Polytechnique in Paris.

> treatises...the elementary mathematical treatment of the subject is given in Green's[38] essay and in Murphy's[39] treatise on electricity.

At this time when budding scientists such as himself were struggling for subsistence and faced an uncertain future, Tyndall felt particularly vulnerable to the criticism implied in the patronising tone of Thomson. Soon afterwards, however, Thomson wrote in a conciliatory mood that, "after discussing personally with Mr Tyndall the points of difference gave him reason for hoping that a complete agreement would be established."[40] Thomson also asked his student, the nineteen year-old Maxwell to prepare bismuth and other compounds for Tyndall and K. Knoblauch (1819-1903). Maxwell at home in Scotland, asked a friend for help and provides insight into an aspect of the contemporary research scene:

> Professor W. Thomson has asked me to make him some magne-crystallic preparations...bismuth is required which is not to be found...in Dumfries...Not that I am turned chemist. By no means, but common cook. My fingers are abominable with glue and chalk, gum and flour, wax and rosin, pitch and tallow, black oxide of iron, red ditto and vinegar. By combining these ingredients, I strive to please Prof Thomson, who intends to submit them to Tyndall and Knoblauch, who, by means of them, are to discover the secrets of nature, and the origin of magne-crystallic forces.[41]

A decade later Thomson read Tyndall's 1861 Bakerian lecture[42] "with much interest." Although he questioned the confident assertion that good conductors are bad radiators as too little was known of the phenomena, Thomson stated that he had no hesitation in advising its publication in the *Transactions.*

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[38]Green, G. (1793-1841), English mathematician and physicist, one of the pioneers of the Mathematical theory of magnetism.

[39]Murphy, R. (1807-1843), British mathematician and author of numerous works on electricity.

[40]Thomson (1851), p. 23.

[41]Maxwell to Campbell, 16 September 1850, in Harman (1990), 1, p. 205.

[42]Tyndall (1861a), pp. 1-36, 29.

> The results as to the great absorption of radiant heat by olefiant gas and the vapours experimented on, are (so far as I have the means of judging it) perfectly novel, and constitute a most important contribution to science. The illustration of Prevost's theory of exchanges by means of the experiments on radiation by heated gases and vapours, are striking and instructive. The only matter of primary importance of which I feel any doubt is the state of the case as to air and the other higher gases[43] and carbonic acid. The discrepancies between Professor Tyndall's results and those of Franz[44] did not appear to me sufficiently explained as stated by Professor Tyndall by the action of plate glass ends used by Franz. The general concluding remarks and theoretical statements seem in some particulars not satisfactory...[45]

Refereeing Tyndall's second memoir on the absorption and radiation of radiant heat by gases,[46] Thomson remarked:

> For the same reasons as I stated about a year ago with reference to his previous paper... the present one is entitled to appear in the Transactions. The subject is of extreme importance and the objection Magnus has raised, is to be met by every experimental argument Tyndall thinks necessary or desirable. As far as I was able to judge, he had made his case last year, but ten additional experiments described in the present paper were undoubtfully [sic] valuable. The decidedly novel form of the experiment described on p. 6 added was certainly what was desired.

Thomson, intrigued by Magnus's experiments, wrote to Stokes that although he wished to read them again, there was no doubt that Tyndall's second paper[47] was

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[43]The meaning of "higher gases" is not clear. Thomson may have referred to water vapour or compound gases in general. Tyndall does not appear to have used the term.

[44]Franz, R. (1827-1862), physicist at the Berlin gymnasium.

[45]Thomson (1861), Royal Society Referees Reports RR4, pp. 272-273.

[46]Tyndall (1863a for 1862), volume 152, pp. 59-98.

eminently worthy of being published in the *Transactions*. Even if Tyndall was not demonstrative in his answer to Magnus's objections, I think he wanted to have a right to speak and let the matter be judged by those who wished to study both sides.

Thomson indicated that he had a strong impression that:

> Tyndall is altogether in the right. He seems to answer G. Magnus's [1802-1870] objections to his own apparatus perfectly (although on this point I have been able only to read hastily), and Tyndall provided a satisfactory explanation of the very different results obtained by Magnus and himself. It seems to me quite impossible that Magnus can be right in anything approaching in his conclusion.[48]

Thomson questioned Tyndall's high values for the absorption of radiant heat by water vapour, considering the natural radiation from the ground through often nearly saturated air, affected by the presence of clouds at half to one mile above ground. Speculations were rife as to the cause of the irregular variations of the temperature of the atmosphere with height, and the variable density of water vapour in the atmosphere. Observations in four balloon ascents under the direction of the BAAS Kew Observatory Committee, challenged the hypothesis of uniform decrease of temperature with height.[49] Thomson therefore saw the need for a thorough analysis of radiant heat from obscure sources, which had not yet been accomplished. A prism may have been ineffective when working with long wavelengths since their refrangibilities would be almost the same. He argued:

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[47]Two volumes of the Philosophical Transactions were published in 1863: part I of volume 152 was published in 1863 for 1862, or in 1862; whereas part II volume 152 and volume 153 were published in 1863. I surmise that Thomson referring here to Tyndall's "second memoir" may mean third memoir, volume 153, 1863e, 1-12, but for Thomson it may have been only Tyndall's second memoir being reviewed by him. See Wilson (1990), volume 1, p. 307 note 8.

[48]Thomson to Stokes, 18 March 1863a, in the Royal Society Referees Reports RR 5, p. 273.

[49]Welsh (1853), volume 143, p. 335; Whewell [1857] 1976, volume 2, p. 486.

> An analysis by absorption might throw great light on the subject, and it is much to be desired that Tyndall would undertake it…John Tyndall's apparatus and skill is wanted.[50]

In his fourth Royal Society memoir, Tyndall did examine the effect of dispersive radiation.[51] Refereeing it, Thomson wrote:

> I have read carefully Professor Tyndall's paper and I am of the opinion that it ought to be published in the Transactions. It is chiefly a new part of the subject. The effect of the different lengths of path through the diathermanous medium … the necessity for the experimental examination of which was obvious from the results obtained in Dr Tyndall's first paper. The results of the present paper are quite in accordance with those; and tend to remove the difficulty of accepting some of those former results which their extraordinary character induced many readers to feel.[52]

As A. Harrison has argued in his PhD dissertation, Thomson's fairness is commendable at the time when the process of refereeing at the Royal Society was considered to be subject to personal animosity.[53] As a referee for Tyndall's third memoir,[54] Stokes wrote:

> The object of this paper is first, to describe some additional experiments (confirmatory) of the transferring of dry air and absorbing action of aqueous vapour for heat from sources at a low temperature, and secondly, to point out some applications of these principles to meteorology. The experiments are well described to remove any remaining doubt. They seem indeed to be almost superfluous after all that the author has already done. Still as long

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[50] Thomson, RR 5, p. 273.

[51] Tyndall (1864a), volume 154, pp. 201-225, 207-210, 225

[52] Thomson (1863), p. 274, in RS Referees Reports, RR5, p. 274.

[53] Harrison (1988), pp. 82 -149; Russell (1996), pp. 457- 460.

[54] Tyndall (1863e), volume 153, pp. 1-12.

> as any dispute remains on the subject, it is well the author's conclusions should be established by experiments designed to meet every conceivable objection. The applications to meteorology are presently the same, met merely by way of example not at all exhausting the subject. They tend to throw new light as the causes of (...?) phenomena. I recommend that this sequel to the author's other papers on the subject, be printed in the Philosophical Transactions[55]

In 1866 Maxwell and Stokes refereed Tyndall's paper on calorescence.[56] Approving of the study of the heating effect of light radiation, and advocating dispersive method of analysis to attain precision, Maxwell stated:

> This paper gives an account of experiments on invisible radiant heat, and shows that rays which are not capable in exciting in us the sense of sight, may be heating a body, [and] cause the body to emit luminous rays ... the heating effect of all such portions [parts of the spectrum] would furnish the most complete quantitative knowledge of the nature of the light ....[57]

Using coloured glass screens, Tyndall attempted the dispersive spectral analysis.[58] He wrote that when infrared rays are emitted by carbon filaments of an electric lamp on heating, their intensity may be augmented a thousand-fold by raising the carbons to the temperature necessary for the electric light. Here in fact the luminous and the non-luminous emission augment together, the maximum of brightness of the visible rays occurring simultaneously with the maximum calorific power of the invisible ones. He described an experiment to confirm the hypothesis.[59] Maxwell objected to the use of the word "maximum" despite the fact that this was confirmed by experiment. He misread and criticised Tyndall's statement as an assertion that the maximum thermal

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[55]Stokes 23 March 1863 in the Royal Society Referees Reports RR5, p. 275.

[56]Tyndall (1866a).

[57]Maxwell (1866), Referee's Report Royal Society MSS RR6, 1 January 1866, pp. 291-292.

[58]Tyndall (1866a), p. 23.

[59]Ibid., p. 2.

and luminous effects coincided in the spectrum, however this was not what Tyndall said. The maxima of the luminous and thermal effects were manifest simultaneously in time as demonstrated experimentally by Professor of Chemistry and President of the medical department at the University of New York, J.W. Draper (1811-1882).[60] They were not coincident in space; it was the time that was coincidental.[61] Expecting new fruitful fields of research to open in consequence of this paper, Maxwell concluded:

> I consider this paper …to be worthy of a place in the Philosophical Transactions as a step in the history of science.[62]

Stokes recommended Tyndall's paper for publication without reservation:

> There can be no question …as to the propriety of printing this paper in the Philosophical Transactions.[63]

In summary, most commentators have overlooked the favourable opinions of Tyndall's scientific contributions that were given by eminent referees who merit the highest approbation.

1B.3. Other Contemporary British Appraisals

This section will examine comment by other contemporary scientists, some better acquainted with Tyndall's researches than others, and the heated debates that ensued. In 1853 M. Faraday (1791-1867) recommended John Tyndall for the professorship of Natural Philosophy at the Royal Institution:

> He has been an original and successful investigator of different departments of physical science … he has written several papers of research highly acceptable to philosophers … his manner of expounding Nature by discourse and experiment was, according to

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[60]Draper (1847), s. 3, volume 30, pp. 345-360.

[61]Ibid., pp. 346, 351.

[62]Maxwell 1 January 1866, in the Royal Society Referees Report 6, p. 292.

[63]Stokes 18 January 1866, in the Royal Society Referees Report 6, p. 293.

> my judgement, excellent ... I believe that ... he would by his future researches, obtain honour, both to himself and to the Royal Institution.[64]

Tyndall and Faraday struck an enduring friendship starting from their first meeting at the Royal Institution in 1850 despite Tyndall's challenge to some of Faraday's conclusions concerning his discovery of diamagnetism.[65] Tyndall's friend, mathematician T. Hirst (1830-1892) commented: "it will be an interesting chapter in the history of Physics, which records the good understanding and friendship that exists between you and Faraday."[66]

The farewell dinner of June 1887 provided a suitable testimonial to Tyndall's scientific achievements witnessed by two hundred distinguished guests. Chaired by Stokes, President of the Royal Society, it was reported as an event unique in the history of science in Britain. *Nature* commented on the eminent gathering which included Presidents of the seven most important scientific societies, who acted as Vice-Chairmen. The sense of occasion was conveyed "doing honour to a life-work such as that of Professor Tyndall. In the promotion of the great scientific movement of the last fifty years he has played a part second to none." This celebration gathered togehter "scientists, politicians, and peers of the realm…a remarkable collection of intellect and talent...to praise the work and career of Tyndall". The *Nature* article stressed the overriding importance of the research laboratory as a domain where only a few possessed the talent to succeed and "were fully appreciated only by those who are intellectually competent to understand the difficulty and the success."

I contend that Tyndall accomplished this distinction on his own merit in the face of considerable disadvantages. From an impoverished background in Ireland, a country that commanded little respect in England where rank and wealth mattered, Tyndall rose to eminence as a scientist of versatility and distinction. He took on

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[64]Faraday to the Committee of the Managers of the Royal Institution 23 May 1853, in Greenaway, Berman, Forgan, and Chilton, Editors, volume 11, p. 14.

[65]Tyndall and Knoblauch (1850a), volume 36, pp. 177-183; (1850b), volume 37, pp. 1-33.

[66]Hirst to Tyndall 19 February 1854, in Eve and Creasey (1945), p. 57.

unpopular causes, unheeding the disapprobation from some members of the elite. *Nature's* editorial in praise of Tyndall continued:

> If a widespread knowledge of science was to be, as it is, an essential condition of national well-being, it was absolutely necessary that the people should know something of, and be in some sort in sympathy with, the methods and conditions of scientific thought. In supplying this need, Prof. Tyndall's greatest work has been done. Uniting scientific eminence of no ordinary kind with extraordinary gifts of exposition, he has by his lectures and his books, brought the democracy into touch with scientific research … He has done … more than any other living man to compel those who regard knowledge as valuable only in so far as it is immediately useful, to admit that the seed which is sown in the laboratory often produces the most abundant harvest ….[67]

"Nor was it only in clearness of verbal exposition that he [Tyndall] excelled." Stokes complimented him on his renowned manipulative skills in performing experiments initially in "the quiet of the laboratory" but also in front of an audience.[68] The chairman's speech was fully reported. I think the President of the Royal Society availed himself of an opportunity to emphasise Tyndall's eminent scientific and pedagogical contributions. He spoke from first-hand knowledge, paying tribute to Tyndall as a researcher of rare distinction as well as a talented teacher. For once here was an appropriate appreciation by a scientist fully able to judge Tyndall's achievements. Stokes paid tribute to Tyndall's original research on the relations of gases and vapours to radiant heat, drawing:

> … important inferences as to atmospheric temperature and climatological conditions … the results were established on so firm a basis, and the conclusions regarding the invisible radiations were so perfectly analogous to what we know to be true regarding the

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[67][Lockyer] (1887), volume 36, pp. 217-218.

[68]Stokes (1887), volume 36, pp. 222-223.

> visible ones, where the investigation is comparatively easy, that the work bore on it the stamp of truth.

Stokes went on to state that in addition to the original research, the cause of science was also advanced by the presentation of this research to a mixed audience in a clear manner.

According to Turner the prestigious occasion illustrated the dual aspect of the scientific profession: firstly scientists were perceived as an independent and distinguished professional group, embodying ‘power and knowledge’; secondly recognition and reward for this status by the state were seen as inadequate when compared to professionals in the church, medicine and the law.[69]

Apart from three publications as a co-author, Tyndall was the sole author of more than one hundred and forty publications, part of one of the last generations of scientists to work individually. Burchfield attributes the Royal Institution’s success in attracting audiences to its events in large part to Tyndall’s fame as a lecturer and public figure.[70]

Posthumous commentators may have had little empathy with Tyndall’s empirical approach to the almost total exclusion of mathematics. J. Meadows[71] considers this absence of mathematics, to be the reason that Tyndall was undervalued by the Cambridge-trained physicists of his generation. Their mathematical know-how accounts for the difference in approaches to studying physical phenomena. Tyndall’s interpretation was based on experimental results in contrast to a mathematical treatment by others. The Professor of Natural Philosophy at the Royal Institution J.W. Strutt, 3rd Lord Rayleigh’s (1842-1919) association with the Royal Institution under Tyndall’s directorship, however, would have provided him with greater appreciation of Tyndall’s contributions than the physicist graduate of University College London, O. Lodge (1851-1940) could muster. Lodge commented on Tyndall in both his

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[69]Turner (1981), pp. 169-180, 169-172.

[70]Burchfield (2002), pp. 165-166.

[71]Meadows. (1981), p. 90.

autobiography[72] and as a controversial anonymous contributor to the *Encyclopaedia Britannica.*[73]

Tyndall's widow vigorously objected to Lodge's lack of appreciation of Tyndall as a scientist, and in this she was supported by Tyndall's successor, Sir James Dewar (1842-1923) amongst others. Surprisingly, Tyndall’s five Bakerian lectures at the Royal Society, a sign of high esteem as a research scientist, were not mentioned either by Rayleigh or later by Lodge.

Inaugurating the posthumous tributes to Tyndall, the physician, treasurer and Vice-President of the Royal Institution, J. Crichton-Brown (1840-1938) chaired a special general meeting that had been ordered by the President, the Duke of Northumberland. Acknowledging Tyndall as an outstanding populariser, Crichton-Brown also called Tyndall an unrivalled experimentalist whose researches in the physical sciences were of permanent value, recorded in the Royal Society and the British Association publications, books and pamphlets. Crichton-Brown remarked:

> It was in the Royal Institution that his days were spent; it was in its laboratories that his well-devised, skilfully executed, and far reaching researches were carried out; it was in this theatre that in many fascinating chapters, the story of his work was told ... For over thirty three years he poured forth almost a continuous stream of lectures and discourses, marking the progress of those branches of science to which he devoted himself, and to the advancement of which he so largely contributed by his researches ....

Crichton-Brown did not see a sharp division between Tyndall's activities in scientific research and communication. This contrasts to the views of R. Cooter and S. Pumfrey,[74] who see the division becoming increasingly noticeable in this period. Amateur popularisers were being marginalised and replaced by professional scientists or writers. Frankland paid tribute to the number and importance of Tyndall’s original

[72]Lodge (1931).

[73]Lodge (1911).

[74]Cooter and Pumfrey, volume 32, (1994), pp. 237-267

investigations.[75] Rayleigh delivered the Tyndall eulogy three months later despite feeling inadequate to the task (others had known Tyndall better and for longer than he). Frankland acknowledged Tyndall's scientific contributions: "Even the strictest devotion of the time at my disposal to the survey of the scientific work of Tyndall, will not allow of more than a very imperfect and fragmentary treatment." Having demonstrated some of the early experiments relating to ice, Rayleigh concentrated on Tyndall's contributions to the science of heat, sound and "the behaviour of small particles…of living or dead matter".[76] He claimed that the earlier reports had mainly been published mainly in his popular book *Heat: a Mode of Motion*. It is surprising that Rayleigh ignored the numerous research papers which appeared from the early days in the *Philosophical Transactions of the Royal Society* dating back to 1853, the Bakerian lectures of 1855 on diamagnetism, on radiant heat of 1861, 1864, 1881 and articles in the *Philosophical Magazine* from 1852. No wonder the impression conveyed would be that of a populariser rather than serious researcher. Rayleigh conceded "The most important work that we owe…to Tyndall in connection with heat is the investigation of the absorption by gaseous bodies of invisible radiation." He granted that it was a very difficult problem to tackle and a controversial one in relation to the heat absorption by water vapour. "Having gone somewhat carefully into this question, I have been greatly impressed by the care and skill showed by Tyndall…He was at once sanguine and sceptical – a combination necessary for success in any branch of science." He was critical of Tyndall for failing to supply sufficient experimental details in his early papers, making the replication of the experiments difficult. He tentatively attributed the reason for this shortcoming to Tyndall's "literary instincts." One might feel sympathy for Tyndall who at the time performed experiments in Queenwood School outside London, since the Royal Institution laboratories were soon to undergo refurbishment to accommodate him. His heavy programme of experimental lectures at the Royal Institution and the Royal School of Mines, and his private accommodation in another part of London would have severely imposed on his timetable. In due course, and to the satisfaction of one

[75]Frankland (1894), volume 55, pp. xviii-xxxiv.

[76]Rayleigh (1896). RI discourse 16 March, 1894, volume 14, pp. 216-224.

of his referees, Thomson, Tyndall had remedied the problem of insufficient detail when faced with the challenge from Magnus and his followers. Rayleigh's address ended with a tribute:

> With more or less success I have laid before you the substance of some of Tyndall's contributions to knowledge…the brilliant and often poetic exposition by which his vivid imagination illumined the dry facts of science. Some reminiscences of this may still be recovered by the reader of his treatises and memoirs; but much survives only as an influence upon the minds of his contemporaries, and manifested in subsequent advances due to his inspiration.[77]

Rayleigh may well have been right in his assessment of himself as unable to do justice to Tyndall due to insufficient awareness of Tyndall's work.

1B.4 The Foreign Opinions

This section will investigate the reception of Tyndall's aptitude and enthusiasm for science by his hosts and colleagues abroad. Eminent scientists in continental Europe and America, supporters and opponents of his work, expressed their respect for Tyndall, the scientist. He was one of many British men of science educated in Germany in the mid-nineteenth century. The governments of the principalities composing the German nation were avid patrons of regional universities. Scholarship flourished in a liberal atmosphere for scientific and philosophical discourse. Post-revolutionary France with its reformed higher education and post-Laplacian scientific movement, provided Germans such as the renowned chemist J. von Liebig (1803-1873), with models for research schools.[78] This creation of methods and facilities for research for a new generation of students, delighted Tyndall.

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[77]Rayleigh (1896). RI discourse 16 March, 1894, volume 14, pp. 216-224.

[78]Olesko (1993), volume 8, pp.16-29.

Since his mentor Knoblauch at the University of Marburg was absorbed in his own research on radiant heat, he delegated to Tyndall the replication of the experiments on magneto-crystalline action, which had been announced in the late 1840s by the revered Faraday. Tyndall's standing in the eyes of Knoblauch must have been high to have been entrusted with such important work. Following publication in Britain Faraday's papers had been translated into German and French. His experiments elicited a great deal of interest and were replicated and vigorously debated. Having challenged some of Faraday's interpretations of the results,[79] Tyndall's own researches gained recognition in Berlin. The professor of the history of mathematics at the University of California, F. Cajori, described Tyndall as probably one of the most able physicists among Magnus's students. These had nonetheless included one of the pioneers of the kinetic theory of gases, R.J.E. Clausius (1822-1888), H.L.F. von Helmholtz (1821-1894) and the chemist, H. Debus (1834-1916).[80]

Tyndall, like other aspiring young scientists at the time, including Huxley, was unable to find employment back in Britain where few research positions were open to scientists. An obituary of Tyndall in the *Irish Times* quoted a letter from the early 1850s from Germany, written before Tyndall's R.I. appointment, probably from the well-known physiologist, E. Du Bois Reymond (1818-1896) to the secretary of the Royal Institution, Faraday's physician, H. Bence Jones (1813-1873):

> You English are the oddest people. Here to our laboratories comes a very young Irish schoolmaster called Tyndall with the quickest brain, the most honest capacity for research, I have ever seen. Would that our German youths were run from the same mould. This brilliant young fellow has never received the smallest recognition from Englishmen or institutions ... [81]

[79] Tyndall (1854), R.I. discourse 11 February 1853, volume 1, 254-259.

[80] Cajori (1929), p. 393.

[81] Jones Millicent Bence to Louisa Tyndall n.d. in volume 3 of the typed Tyndall Correspondence. RI MS JT/1/TYP 790. *The Irish Times* 5 December page 5, col. 7, 6 December 1893, p. 5,-7.

After studying physics and chemistry and gaining a PhD in applied mathematics from the German University, came two years of uncertainty and unsuccessful applications for the posts in the colonies. However, Tyndall abandoned his intentions of emigrating to America when his appointment to the chair of natural philosophy at the Royal Institution in the summer of 1853 came about. His inaugural discourse in February was very well received. Du Bois Reymond was informed and wrote to the honorary secretary of the Royal Institution, H. Bence Jones, of his delight at the news, “partly because of the share, however small, I have borne perhaps in procuring to Dr Tyndall this opportunity for displaying his talents, by repeatedly calling your attention upon him.”

Tyndall’s new status offered new opportunities. His nomination as a juror in the scientific section, and his position as secretary to the committee for magnetism and electricity at the Paris exhibition of 1855 gave Tyndall the occasion to meet French scientists. A French Jesuit writer on science and religion, became Tyndall’s supporter. The l’Abbé F. N. M. Moigno translated his writings, received enthusiastically in France, confirming Tyndall’s standing as a scientist on the continent.[82] His researches on radiant heat in the 1860s attracted the interest of Magnus in Berlin, and the professor of physics at Marseille, J. F. A. Morren (1804-1870). Magnus wrote to Tyndall about their overlapping research interests as the news of Tyndall’s Bakerian Lecture of 1861 and earlier publications, reached him:

> The only satisfaction I derive from this circumstance is, that I had to compete with the most eminent experimentalists, such as Regnault and yourself.[83]

It was a compliment indeed to be classed with the most eminent French physical chemist and physicist of the era. H. V. Regnault (1810-1878), was successor of Gay-Lussac to the chair of chemistry at the prestigious École Polytechnique in Paris, and subsequently Professor of Physics at the Collège de France, renowned for his

[82]Moigno to Tyndall 2 March 1871, in Eve and Creasey (1945), p. 153.

[83]Magnus to Tyndall 17 March 1861, in Tyndall (1872f), 60-61.

experimental researches on the physical properties of gases.[84] At the British Association 1869 meeting Morren reported on Tyndall's pioneering work in photochemistry.

> Mr Tyndall has published in several papers highly interesting researches on a particular species of luminous reactions, thus providing physicists and chemists with a new instrument, both of synthesis and analysis...[85]

Morren replicated the experiments and found them "all as rigorously exact as they are ably described." Stimulated by Tyndall's researches, using an apparatus very similar to that of Tyndall's, he worked with solar light where Tyndall had used electric light, and unlike Tyndall who worked mainly with organic substances, Morren used inorganic ones. Referring to Tyndall's researches reported in the last Bakerian lecture delivered in 1881, the American physicist and astronomer S. Langley (1834-1906) wrote that his own researches on radiant heat (performed outdoors with the apparatus of his own design) had confirmed Tyndall's laboratory results, and when published, will "put an end to any doubt as to the accuracy of the statements so long since made by you, as to the absorbent power of water-vapour over the greater part of the spectrum, and as to its predominant importance in modifying to us the solar energy."[86] Mme Wiedemann an avid German correspondent of Tyndall's wrote to his widow, Louisa:

> You must know, dear lady, how much pleasure and interest I have to make the works of your husband accessible to the German public, and what enjoyment I have experienced in working these through. It is most satisfying and rewarding that new editions of his work are demanded while time has left his opponents behind. The quality of

[84]Porter, R. and Ogilvie, M., Editors (2000), p. 799.

[85]Morren (1870), pp. 66-72.

[86]Langley to Tyndall 10 September 1882, in Tyndall (1882a), volume 173, pp. 340-358, 353-354.

> his lectures, their clear exposition, now finds the warmest recognition.[87]

She added, on another occasion:

> It is of great satisfaction to his friends and admirers that new editions of his works are constantly demanded…[88]

In conclusion I assign this approbation of Tyndall by his colleagues and acquaintances overseas to the integrity of his goals, an ability to establish his authority, and the convincing professionalism of his scientific endeavour.

1B.5. The Retrospect from the 20th Century Onwards

This section investigates reactions to Tyndall in succeeding generations over the last 100 years. These reflect the mixed reactions he faced in his lifetime. O. Lodge (1851-1940) wrote a critical and at times derogatory entry on Tyndall in the tenth edition of the *Encyclopedia Britannica*.[89] Tyndall's widow Louisa objected. J. Dewar (1842-1923), Tyndall's successor at the Royal Institution, found some of the pronouncements by Lodge, such as the characterisation of Tyndall as "physicist of the field ... derogatory untrue and objectionable", adding that Tyndall's contribution resulting in the award of the Royal Society Rumford medal to him "was far more original and meritorious than anything ever Lodge did ….”[90] Dewar alerted H. Debus FRS (1834-1916), the eminent German chemist, formerly Bunsen's assistant and later Tyndall's biographer.[91] Debus responded to Lodge's entry in a sixty-page document.[92]

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[87]Wiedemann to Louisa Tyndall, 19 March 1896, in RI Louisa Tyndall Papers 83/2

[88]Wiedemann to Louisa Tyndall, 13 June 1896 in RI MS Louisa Tyndall Papers 83/3.

[89]Lodge (1902), volume 33, pp. 517-521.

[90]Dewar to Louisa Tyndall 28 September 1908.

[91]Tyndall, L. to Debus 2 March 1903.

[92]This typescript is listed as Debus (1902-1904) in the list of manuscript material at the end of this dissertation.

Debus admits that it is by and large impossible to assess how far Lodge's statements were justified, as his claims were general and were not supported by evidence. Nevertheless he takes Lodge to task. Debus reacted to Lodge’s statement that Tyndall’s “knowledge of physics was picturesque and vivid rather than thorough and exact,” stating that:

> Anyone knowledgeable about Tyndall's work, would be aware of the fact that his knowledge of physics ... did not exceed what any highly educated man ... should aim at always took trouble to make his knowledge “thorough and exact”

Where Lodge ascertained that “His knowledge of physics ... did not exceed what any highly educated man of genuine all-round culture should aim at”, Debus asked “How has Sir Oliver measured Tyndall's knowledge of Physics?” Because, Debus recalled, Lodge did admit that with his ‘limited’ knowledge, Tyndall, had produced “most extraordinary results”.

Debus challenged Lodge's argument that the secret of Tyndall's success as a lecturer was due to his never undertaking anything “specially recondite.” When replicating experiments, Tyndall and Knoblauch exposed anomalies in both Faraday and Plücker's procedures. Further work showed that the “new” forces were the modifications of the existing diamagnetic and magnetic forces by the cleavage structure of crystals, not due to the optic axis and magne-crystallic forces. Debus stated that these results were of great importance at the time. I have covered only a fraction of Debus's response. It is important to stress that it was due to other commitments that Knoblauch had delegated to Tyndall the experimental part of their work, that they discussed it together, and that Tyndall did independent work on diamagnetism also in Berlin and in Britain, some of it at the Royal Institution.

A second version of the response by Debus was edited by J. Hooker (1817-1911), director of the Royal Botanic Gardens Kew,[93] together with Dewar. A third version remained unfinished. Debus pointed out scientific inaccuracies in Lodge’s article, due partly to misquoting or omitting Tyndall’s statements. Lodge claimed that

[93]Hooker to Louisa Tyndall 24 January 1904.

"to correct the exaggerated estimate common in the active part of his lifetime a certain amount of detraction naturally followed, and his memory came to be unduly depreciated." Lodge suggested that Tyndall's use of inappropriately simple language in the learned environment of the Royal Society had made any errors obvious, provoking harsh criticism. For Lodge, Tyndall's way of communicating science inspired in his audience the feeling of having learnt much, but Lodge argued this was no way of introducing a prospective scientist to a professional career. Lodge saw Tyndall as an educator, but also an explorer of nature, emotionally involved with it. Surprisingly he also criticised Tyndall's researches on diamagnetism at Marburg as lacking in direction and unproductive. Lodge could not have been acquainted with his research publications. Finally Lodge comments Tyndall's later research but this work is outside the scope of the time span of the thesis. Lodge rarely produces examples and references to his assertions.

Debus, Hooker, and Dewar corresponded with one another and Louisa Tyndall between 1903 and1910, and supported her when, in 1908, a new edition of the *Encyclopaedia* was considered. In response to Mrs Tyndall's inquiry regarding the publication of Debus's document, Hooker suggested three options to Mrs Tyndall: a periodical publication, a pamphlet for private distribution, or an appendix to Tyndall's biography. A new version of an article on Tyndall appeared in the 11th edition, but the author is not named. It was probably H. L. Callendar (1863-1930), Professor of Physics at University College London, coming to the rescue of Tyndall's reputation. This also replaced Lodge's article in the succeeding edition of the *Encyclopaedia Britannica*.[94] The 1953 edition, however, replicated the Lodge's tenth edition article. In conclusion, in death as in life, Tyndall's accomplishments have provoked a range of opinions.

Lodge's ill-judged article has been quoted uncritically by some authors, a habit that persists to this day even among experienced authors such as J.T. Lloyd,[95]

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[94]Anon. (1911), pp. 499-500.

[95]Lloyd (1970), volume 22, p. 211.

Lindley[96] and Rowlinson.[97]Half a century on, an American scientist, D. E. Williamson, comparing Tyndall's apparatus of 1859 and the infrared gas analyser of 1951, expressed astonishment at the similarity between them.[98] To him, in my view, Tyndall's design had evidently withstood the test of time. Nearly thirty years later P.S. Callahan was dismayed at the 1953 edition of the *Encyclopaedia Britannica* entry on Tyndall. Callahan considered Tyndall to be the father of infrared spectroscopy and inventor of the absorption and radiation spectrophotometers. He also credited Tyndall with being one of the founders of physical chemistry. For Callahan Tyndall crossed the boundaries of scientific disciplines, which he saw as an ideal path to scientific progress. As a mountaineer himself, the author also appreciated Tyndall as an accomplished, brave mountaineer, but "it is more to the point to consider him a giant among the scientists."[99] In addition to recognising Tyndall as the first to study the structure of ozone by means of radiant heat, he credited Tyndall for applying infra-red techniques to olfaction, pioneering research in optical acoustics, and also for his work in fibre optics.

J. C. D. Brand, the Canadian chemist and historian of dispersive spectroscopy assessed Tyndall's account of the diathermancy of symmetrical diatomic elemental molecules. Tyndall suggested that the shapes of atoms determined their movement through the aether[100] in the manner of the French philosopher and mathematician, P. Gassendi (1592-1655).[101] He envisaged the oscillating atoms as being connected by springs of different tensions that resulted in the atoms being pulled together or drawn apart when under the influence of the repellent or attractive forces governing the inter-atomic interactions.[102] That Tyndall thought the shapes of the atoms played a

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[96]Lindley (2004), p. 180.

[97]Rowlinson (1981), pp. 113-128, 113-115.

[98]Williamson (1951), volume 39, pp. 672-681.

[99]Callahan (1981), pp. 129-144.

[100]Tyndall [1861a] volume 151, 1-36, 35.

[101]Chang (2004), p. 162.

[102]Tyndall (1862c), RI discourse 7 June 1861, volume 3, pp. 387-396, 392-393

part in their interaction with the aether, indicated to Brand an awareness of the importance of the symmetry of the arrangement, “not unconnected” with the modern concept of dipoles.[103]

A member of the first generation of professional scientists in Britain, Tyndall conducted pioneering research of enduring value to mankind. He inspired new generations through his lectures and writings. T. H. Creasey, an engineering student and later a co-author of the biography of Tyndall paid him eloquent tribute :

> Many of us could attribute much of the inspiration of our student days to the work and writings of one man. In my case, that man was John Tyndall. Ill-clad, ill-fed, the desire to learn struggling amid unfavourable circumstances, I turned again and again to such books of his as were available...[104]

J. W. Gentry considers the aerosol scientists to be indebted to Tyndall, in particular his work on the scattering of light, radiant heat, origin of life and the environmental pollution. He considers that Tyndall provided “arguably, the first statement of the greenhouse effect.”[105]

1C. Tyndall the Populariser

Tyndall’s gift for inspiring interest in the natural world for people from various backgrounds is investigated in this section. In the first half of the 19th century the science was taking an increasingly important place in people’s daily lives. The preponderance of provincial societies including the Lunar Society of Birmingham, as well as the influence of various private lecturers, ensured the fostering of interest in science across all classes of society. In London the Royal Institution had played a crucial role as a place of research and the popularisation of science since its foundation in 1800. As Tyndall was reaching adulthood in the 1840s, steam power,

[103] Brand (1995), p. 82.

[104] Creasey (1933), in Eve and Creasey (1945), p. XV; Brock, McMillan and Mollan (1981), p. 151.

[105] Gentry (1997), volume 28, pp. 1365-1372.

railways and the cable telegraph were transforming society. His work as a railway surveyor brought him into contact with people from various developing professions and associations. The Mechanics' Institutes which he attended provided libraries and meetings where young people had the opportunity for self-improvement. The mechanisation of the paper production process and improved printing technology enabled the growth of published material on an unprecedented scale. Information became accessible as never before. The dissemination and acquisition of knowledge included acquaintance with new inventions and discoveries, promoting thought and lively debates on science education in general.[106]

Vestiges of the Natural History of Creation, a paradigm of popular and controversial science, was published anonymously in 1844 according to custom of authorship of popular science books and articles in particular.[107] Subsequently the book appeared in fourteen editions in forty years. The name of the author was speculated upon for years, and finally revealed in 1884 as that of the Edinburgh publisher, R. Chambers (1802-1871). This book, the writings of Carlyle, and the meeting with Emerson and his audience at Halifax, which included a nephew of William Paley, the author of *Natural Theology*, made an impression on Tyndall at the time.[108] Communicating his enthusiasm for the study of nature to his pupils at Queenwood School, and the awareness for the need to establish science as a profession in order to work in it, prompted Tyndall to embark on a life long campaign to promote the appreciation of science by the public everywhere. After qualifying at the University of Marburg, then only occasionally employed in Britain, Tyndall's appointment in 1853 to the professorship of Natural Philosophy at the Royal Institution provided him with the ideal forum for the communication of science to both young and old, professional scientists as well as non-specialists. Tyndall's reputation as a lecturer was established in his inaugural lecture of February 1853, the first lecture of this kind he had ever delivered.[109] In due course his authorship of

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[106]Cardwell [1957] 1972, pp. 44, 71-75.

[107]Secord (2000), pp.18-24.

[108]Ibid., pp. 338-339.

[109]Tyndall [1851-1854], RI discourse 11 February 1853, volume 1, pp. 254-259.

popular and research literature made his name familiar, and led to further engagements, particularly, but not exclusively, through the annual programme of British Association for the Advancement of Science.

Just as Tyndall's early research efforts placed him at the heart of the scientific endeavour in Europe with Faraday at the helm, so his foray into popularisation with its educational connotations and entertainment, placed him in competition with the most experienced and skilled communicators. Together with Faraday and, amongst others, the geologist and philosopher, Master of Trinity College Cambridge, W. Whewell (1794-1866), Tyndall participated in a conference on science education at the Royal Institution in 1854. Whilst the other speakers spoke of their subjects being established as branches of education, Tyndall lectured on physics as a means of education.[110] This insistence by Tyndall on imposing a cultural role for physics in the sphere of education, echoed Faraday's lecture "Observations on Mental Education", with its emphasis on the absolute value of appropriate judgement being inculcated in the educational process. Faraday regarded these observations as " … immediately connected in their nature and origin with my own experimental life, considered either as cause or consequence … ".[111]

Faraday's holistic approach included science as an integral part of the enlightening educational experience. He opposed the misuse of science for dubious practices such as spiritual séances, which exploited the ignorance of the public and duped people. Tyndall shared Faraday's concerns, and his contributions to the science education for all aimed at doing away with sophistry.

It is interesting to consider different styles of science popularisation. Tyndall's style was markedly different from Maxwell's vision as practised by Tait. Tyndall describes his motive as a compulsion to take science to the masses. The cultural pressures were favourable. His audiences included children as well as adults from a variety of cultural backgrounds and different locations. His manner of disseminating of science by word of mouth and in print earned him a mixed reaction. His network of

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[110]Tyndall [1854]1855, RI lecture 27 May 1854, pp. 171-211.

[111]Faraday [1854] 1855, RI lecture 6th May 1854, pp. 39-88.

friends and professional scientists played a part in this enterprise, not always to his advantage. In 1878 Maxwell, the reviewer of Tait's work on thermodynamics for the general audience, used the opportunity to voice his own and Tait's views on what constituted good, popular scientific literature:

> It is impossible to compare this book either with so-called popular treatises or with those of a more technical kind … [Professor Tait] serves up his strong meat for grown men…without thinking it necessary to employ either the language of the nursery or of the school… [the author] is at no pains… to smooth the obtrusive antinomies of a vigorous mind into the featureless consistency of a conventional philosopher… this sort of writing …unlike what we might expect from the conventional man of science, is the very thing to rouse the placid reader…[112]

Another view on popularisation can be gauged from comments on the President's annual address to the British Association. For example, A. Thomson's opening address at the 1877 meeting in Plymouth was considered by an anonymous reviewer in the *Saturday Review* "much too technical for the occasion and the audience", since the object of the BAAS at their annual meetings was to provide "a medium between the intimate scientific work of the Association and the diffused interest of the educated public." The Presidential addresses were important to the BAAS as the impression they left on the audience strongly influenced their support of the scientific community.

Among those who judged Tyndall the populariser, some misconstrued and ridiculed Tyndall's use of simple language, as Maxwell had done when referring to a conventional philosopher or a conventional man of science in the above extract. In their correspondence and publications, Tyndall's supporters and opponents revealed their approval or hostility to Tyndall's distinct and wholehearted commitment to communicating science in his particular style. Huxley's opinion was noted by Hirst:

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[112] Maxwell (1878), volume 17 (431), p.257.

> From Tyndall's lectures, one would not expect the man to be so governed by rigorous accuracy of thought as he is. The element of pleasing popularity he introduces would certainly mislead many as to his natural cast of severe thought. [113]

Huxley considered Tyndall's inaugural lecture to working men at the Dundee 1867 BAAS meeting, an exceptionally successful public engagement with science.[114] A commentary ten years on continued:

> The gift of interpreting results of highly specialised researches for the benefit of those who are not prepared beforehand by special knowledge is by no means a common one…it is itself a speciality which very few have mastered…people who are anxious to parade as amateurs in science are cheapening it. The notion that Professor Huxley and Professor Tyndall are mere popularisers - because… they expound as well as discover - has almost attained the rank of vulgar error…Those who imagine that such remarks give them a scientific air, may be assured that there is no more certain stamp of a narrow and superficial mind.[115]

Tyndall made skilful use of the new forums opened to him to take science to the masses. He felt that since in England, unlike abroad, science was not supported by the state, one was obliged to engage the support of the public at large. He attached, in his words "supreme importance" to informing the public about science, its achievements and its aims. He thought that although the practical consequences were obvious, they gave an incomplete image of science. For Tyndall it was not just a handicraft or an accumulation of facts, but an investigation of nature, how it worked. He called it the "glory and the responsibility of science" to explore and to make known.

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[113]Hirst 4 December 1859 journal in Eve and Creasey (1945), p. 330.

[114]Huxley to Tyndall 18 September 1867, in Howarth (1931), pp. 104-105.

[115]Anon (1877), volume 44, pp. 196-197.

Tyndall's most celebrated work of popular science were his lectures on heat to the public at the Royal Institution, later published as a volume entitled *Heat a Mode of Motion*, the first edition of which appeared in 1863. On the publication of his book, he wrote to Clausius:

> My course at the Royal Institution is just drawing to an end. I have treated heat from beginning to end according to the dynamical theory, and the audience has evinced an unflagging interest in the subject. I almost feared to risk the thing at first, but the experiment has been quite successful. I intend to publish the course, as something of the kind is very much needed in England.[116]

This book was a great success. It went through many editions, and was translated into Hungarian, French and German. Maxwell's recommendation of the book to students,[117] and Tait's description of it as designed specially for the non-scientific public, testifies to its versatility. "Probably no publication did more to establish a general kinetic view of matter and natural phenomena," commented J.T. Mertz.[118] Tyndall's Christmas lecture notes and publication in particular "Heat and Cold" of 1867-1868 exemplify the variety and the picturesque character of his demonstrations, and his technique of involving his public by posing questions. At a Friday Evening Discourse at the Royal Institution Thomson called it "a beautiful book"[119] He proposed to adapt the title for his own work on elasticity. The wife of an eminent banker, anthropologist and entomologist, John Lubbock MP (1834-1913), read the proofs of the second edition in 1865, and wrote that she delighted in the book. She thought that she would correct it better had she liked it less. The book became well known in both the United States and Europe. On the strength of this publication, an invitation was issued to Tyndall to lecture at the Lowell Institute in Boston for a fee of

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[116]Tyndall to Clausius, 5 April 1862 in RI MS JT/1/TYP/7 pp. 2238-2239.

[117]Maxwell (1872), p. vi

[118]Mertz [1894-1912] 1976, volume 2, p. 57.

[119]Thomson [1882] RI Discourse 4 March 1881, volume 9, pp. 520-521.

$1200. Although Tyndall declined, unwilling to leave a programme of research he was engaged on at the time, the invitation was renewed and accepted in 1872.

Tyndall remarked on his experience of writing *Heat: a Mode of Motion* "… awfully heavy work if done well. To forget one's self and to be simple is the highest quality of the scientific writer."[120] He "endeavoured to bring the rudiments of a new philosophy within the reach of a person of ordinary intelligence and culture… and to rise… from a basis so elementary, that a person possessing any imaginative faculty and power of concentration, might accompany me." By a new philosophy he meant the philosophy of heat, "without, however, restricting the term to the subject of heat. The fact is, it cannot be so restricted; for the connection of this agent with the general energies of the universe is such, that if we master it perfectly, we master all."[121] In this emotive statement Tyndall declared his vision of this all-embracing natural phenomenon. Although clearly based on his researches, there were numerous additional illustrations in the book, which had not appeared in his learned papers. Eager for the public to see the experimental demonstrations as effectively as possible, he developed or improved the existing techniques. Tyndall worked on effective ways to demonstrate science to large audiences. For example, he fixed a large convex lens above the galvanometer, the dial of which was lit by a beam of an electric lamp for an instant, the beam having been deprived of its heat by a passage through an alum solution, hence preventing the disturbing influence on the galvanometer of any convection effects. The magnified image of the needle was projected onto a screen by a mirror placed above the lens at an appropriate angle.[122] Tyndall may have adapted the procedures used in Germany by W. E. Weber (1804-1891). On one of his visits there he had written to Faraday on this subject, asking if money would be available to purchase some of the apparatus for the purpose.[123] J. D. Forbes used similar arrangement. Tyndall may have also adapted the newly invented mirror galvanometer by Thomson in 1857.

[120]Eve and Creasey (1945), p. 93.

[121]Tyndall (1863c), ix-x.

[122]Tyndall [1862a], RI discourse 10 June 1859, volume 3, 155-158.

[123]Tyndall to Faraday 24 July 1853, in James (1999), pp. 540-541.

Tyndall saw the study of heat as a means of promoting intellectual education at large, resulting in “greater and more beneficent revolutions… than its applications in the material world.” He was aware of opposite views of those who decried the influence of science and discouraged its advance, but he saw its aim as that of all education, “to improve the lot of mankind.”[124] He did not mix narrative and science, since he thought that the mind, once interested in the one, could not with satisfaction pass abruptly to the other.[125] He saw science as a logical enterprise. Significantly he stressed that other forms of culture have equal claim. It was not, he said, “intellectual all in all”. He did however, see the need for and claim for science the recognition that it deserved, and a more prominent place in public education than it had had hitherto.[126] J. Garnett wrote that Tyndall had provided a theatrical experience for his audience to stimulate interest: she referred to Tyndall’s creation of the illusion of the blue colour of the sky at the laboratory bench, very much in keeping with the prevailing culture of combining the oral, the visual and the literary.[127] Tyndall also popularised the work of Helmholtz on the sensation of tone.

Foreseeing the growth of science, his heuristic aim, directed at “the younger scientific teacher” in particular, was apparent: he advised acquisition of knowledge, patience, ordering the knowledge in one’s own mind, and conveying it with clearness and strength: simplicity and thoroughness could be matched. He felt that it would take a man, Milton and Helmholtz in one, to present the kind of guidance to satisfy the deeper needs of the audience. He felt that neither science alone nor religion, as the clergy was using it, were adequate. When presenting lectures to the public, it was necessary to build a connection between science and other contemporary knowledge.[128]

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[124]Tyndall (1863c), p. xii.

[125]Tyndall (1860c), p. v.

[126]Tyndall (1874a), volume 10 (251), pp. 308-319.

[127]Garnett (2000), pp. 195-227, 203.

[128]Tyndall (1871e), 3rd edition), pp. v-vii.

In 1867 the working-men of Dundee heard a lecture by Tyndall on matter and force.[129] It was the first lecture for outsiders delivered during a BA meeting. Huxley wrote to Tyndall:

> You have inaugurated the working men's lectures of the Association in a way that cannot be improved. And it was worth the trouble, for I suspect they will become a great and noble feature in the meetings.[130]

The formal establishment of these lectures took some time. From the very beginning of the BAAS, eminent lecturers faced a community which could not afford the membership of the BA. These gatherings took place outdoors with an audience of several thousand at times. After twenty years they were officially instated. Tyndall praised the audience for their obvious interest and enthusiasm. Tyndall also had additional agendas on some of those occasions. In 1868 at Norwich as President of the Mathematics and Physical Sciences section, and in 1870 at Liverpool, this was to protect science. He aimed to counteract the widespread opinion that science threatened to abolish the mystery of the place of mankind in nature, and the lectures served to combat attempts to prevent the scientific study of the origin of life.[131] In summary, Tyndall took up the task of disseminating science through various channels with remarkable success, appealing to the audiences of varied ages and backgrounds.

As with his scientific research, Tyndall's work in popular science elicited a wealth and variety of responses. Numerous records concerning Tyndall appear in the recent Science in the Nineteenth Century Periodicals Project, which enables an electronic search in non-scientific journals. A simple search on Tyndall returns entries in a wide variety of periodicals on miscellaneous topics. The sheer number and variety of references to Tyndall testify to his eminence as a Victorian scientist with popular appeal. [132] The press reacted, as one would expect, in a variety of ways. The

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[129]Tyndall lecture 5 September 1867, in Tyndall (1871b), pp. 71-94.

[130]Huxley to Tyndall 18 September 1867, in Howarth (1931), pp. 104-105.

[131]Tyndall (1870b) Explanatory Note following the title page.

[132]Knight (2005), pp. 618-625; http://www.sciper.org..

Times felt that Tyndall's 1870 address was an example of an imaginative use of science rather than a scientific use of the imagination. They felt there was a danger in using the imagination too freely, considering the amazing scientific discoveries.[133] In America in 1872-1873 Tyndall delivered 35 lectures in seven cities. He used his $13,000 profit to institute a bursary (a judicious investment, according to C. Sopka, more than doubled the amount within several years). His religious views did not endear him to the American audience, but the crowds were huge. Tyndall recorded that both a Church of England representative and a dissenter proposed a vote of thanks, but he was also warned that he would be punished for his irreligious views. According to Sopka, prayer meetings were held for him in Philadelphia and Boston, and their letters to him expressed their worries "about the future prospects of his soul".[134] The American press commented on Tyndall in a variety of ways, but the reactions were generally enthusiastic. One commentator described him as "the very beau-ideal of a scientific lecturer…His voice is pleasant and his enunciation clear, but he has none of the graces of oratory… [his manner] is so pleasant, so colloquial, so free of arrogance, so full of personal enthusiasm…"[135] Back in Britain, too, the reception of Tyndall's work as a populariser of science was generally very positive. Two typical responses are worth quoting. The eminent geologist, Adam Sedgwick (1785-1873) wrote to Tyndall from Cambridge:

> I write to thank you for the little book upon the *Glaciers of the Alps* you had the kindness to send me, and for the instruction and delight its perusal gave me. It is in fact a concise, a very luminous synopsis of your enormous Alpine labours and discoveries; and it is of its kind the most perfect work I ever read. Every page marks the most singular power you possess of putting your works in the bright colours of daylight before the reader's eye and make him feel as if he were your happy companion and fellow labourer.[136]

[133]*The Times* 17 September 1870, p. 7, columns c-f, in Tyndall 1870b, 1-3.

[134]Sopka, in Brock, McMillan and Mollan, eds. (1981), pp. 193-203, 198,

[135]Ibid., pp. 195-196.

[136]Sedgwick to Tyndall 29 January 1872, in Eve and Creasey 1945, p. 156.

Sir Frederick Pollock, a non-scientist, recalled the effect of Tyndall's writings on him long before they met: "those…have been to me, from a very early period of my life, companions so cherished that I learnt to look upon their writer as a dear personal friend and benefactor…"[137] Generally there is no doubt that Tyndall inspired new generations through his popular lectures and writings.

1D. Conclusion

This chapter has traced perception of Tyndall's roles as a research scientist and a populariser; in his own opinion, the eyes of his contemporaries and those of succeeding generations. What this brief survey already reveals is the widespread and long-standing misconception of a Tyndall whose achievements as a populariser far exceeded his research contributions. It is instructive to conclude with two assessments of Tyndall's work from two eminent nineteenth-century intellectuals, both of whom saw Tyndall's true abilities as cutting across the popular-professional boundary. The philosopher and sociologist, H. Spencer (1820-1903) commented:

> This constructive imagination, here resulting in the creation of the poet and there in the discoveries of the man of science, is the highest of the human faculties. With this faculty Professor Tyndall was largely endowed. He displayed it in forming true conceptions of physical processes previously misinterpreted or uninterpreted.[138]

Helmholtz, contributing to a series on contemporary scientists in *Nature*, and considering the importance and the difficulty of communicating science, commented:

> Professor Tyndall is held in … high esteem … on account of his talent for popular expositions of scientific subjects … it would be an erroneous conception to think of him merely as the able, popular lecturer; … the greater part of his activity has always been given to scientific investigation, and we owe to him a series of (in part) highly original and remarkable researches and discoveries in physics and physical chemistry … Mr Tyndall is *par excellence* an

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[137]Pollock, 29 June 1887, in Brock, McMillan and Mollan 1981, p. 151.

[138]Spencer (March 1894), pp. 401-408.

experimenter; he forms his generalisations from extensive observations … It is … a mistake to consider what he calls imagination as mere fancy… It is exactly the opposite that is meant – full sensuous contemplation. To this mode of working is … to be attributed the clearness of his lectures on physical phenomena, as is … his success as a popular lecturer.[139]

[139] Helmholtz (1874), volume 10, p. 302.

CHAPTER 2

Tyndall as an Experimentalist

2A. Introduction

Since the thesis aims at taking a fresh look at Tyndall as a research scientist, it is important to examine his early career, in order to elucidate how Tyndall became the exceptional experimentalist that he was. In this chapter I will therefore concentrate on period between 1848-1855, that encompasses his scientific training at the University of Marburg in the chemist Robert W. Bunsen's department, followed by his first steps in research with the newly appointed professor of physics, H. Knoblauch, independent work in the laboratory of Gustav Magnus in Berlin in 1851, and finally his work in Britain occasionally again at Queenwood College in the early 1850s, and at the Royal Institution late 1853.[140]

Influences in Tyndall's early life of significance to his future career will be identified in sections 2B and 2C. 2C describes the formative period in Tyndall's career as an experimentalist in Germany. The work on diamagnetism that he began in Germany, he continued in Britain partly in Queenwood and partly at the Royal Institution. This will be examined in section 2D. Section 2E looks at the relationship between Faraday and Tyndall. In section 2F the Royal Institution's tradition in research and Tyndall's place in it will be considered, followed by the conclusion in 2G. In view of the scarcity of the recent secondary literature on Tyndall especially as a researcher, the decision had to be made to include the most appropriate references from among the sources available, irrespective of their age, provided the discourse in the references was valid, and that it contributed to a scholarly debate.

2B. Early Influences: Ireland and England

Tyndall's progress from an apprentice railway surveyor to science master, from a mature student in Germany to the Fellow of the Royal Society of London, then

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[140] It should be noted that full laboratory facilities were not available to Tyndall at the Royal Institution till 1861, when Faraday's laboratory was enlarged to accommodate both experimenters. By then Faraday was unwell, living in the grace and favour house in Richmond with only occasional visits to the R.I.

to the professorship of natural philosophy at the Royal Institution at Faraday's side, had begun in Ireland. Until the age of nineteen Tyndall lived in County Carlow. His father was from a family of cloth-makers in Gloucestershire. He was a worker in leather and a police sergeant and he sent John to the local National School. The Catholic headmaster of this school, a teacher of surveying, science and mathematics, J. Conwill enjoyed an excellent reputation. When admonished by his local priest for entrusting his son to a Catholic master, Tyndall senior, an Orangeman Protestant, expressed his confidence that Mr Conwill would provide for his son "a sound secular education that will fit him for life."[141] Tyndall discussed theological schisms and politics with his father. His mother was from the local farming community, and had been a schoolroom companion to the aunt of an eminent Irish historian, W. Lecky (1838-1903). Because of John's love of outdoor life, dangerous pranks and enjoyment of fights with his schoolmates, she often feared for his safety. She encouraged his love of poetry. He read S.T. Coleridge (1772-1834), J. Keats (1995-1821), and R. Browning (1812-1889). This later manifested in his relationship with the Poet Laureate, A. Tennyson (1809-1892), together they discussed the science of the day, and Tyndall recorded his reminiscences of Tennyson in a moving memoir.[142] Like Faraday in the previous generation, in his youth Tyndall was an avid reader of the *Encyclopaedia Britannica* on aerostatics, electricity and phlogiston.

In a lecture to the Arts Faculty at University College London,[143] in his middle age Tyndall remembered that in his boyhood, the theological discussions apart, English grammar, particularly when applied to "Paradise Lost," was "a discipline of the highest value, and…a source of unflagging delight."[144] His biographers, A. S. Eve and C. H. Creasey remarked that Tyndall's education:

> … contained in mathematics and language the two principal tools by which self-culture can be achieved. Moreover they were not merely

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[141]Eve and Creasey (1945), p. 3.

[142]Tyndall (1892c), Unfinished ms, in Tennyson 1897, II, pp. 469-478.

[143]Tyndall (1871a), Lecture 25 June 1869, pp. 95-106 and (1892a), vol.2, pp. 91-100.

[144]Ibid., pp. 95-106, 98-99

> academic accomplishments. They had been sharpened on the whetstone of experience – the mathematics on surveying, and language in discussions on politics and religion.[145]

To summarise, in his early youth Tyndall received an eclectic education in the countryside, his family and his teacher providing a stimulating background of poetry and mathematics. Lively discussions, vibrant politics and religious issues were a part of daily life. When away, Tyndall corresponded with his friends in the local community, testifying to the significant role they played in Tyndall's early life. These sources constitute important historical documents in retrieving the early influences on Tyndall's perspective, although historians' opinions may vary on this point.

From the lectures he gave to the Birkbeck Institution in his sixties Tyndall also provides glimpses of his early life. Eager to become a civil engineer, he trained as a draughtsman, then as a 'calculator and computer,' (applied to humans, trained in calculations prior to the mechanical inventions). At the age of nineteen he joined the Irish Ordnance Survey, providing him with a chance to work in the field. The survey served the planning of railway routes in Ireland. Tyndall acquired most of the skills needed for the work. He seized an opportune moment, volunteering to replace the missing workforce. Having gained a good knowledge of trigonometry and geometry at school, to his relief a theodolite was entrusted to him - an experience that was still vivid in his mind many years later. He shared with his audience his difficulties at the start. His pay was low, less than twenty shillings a week, but he was surprised at the "amount of genuine happiness which a young fellow of regular habits, not caring for either pipe or mug, may extract even from pay like this."[146] Tyndall acknowledged the importance of Birkbeck's Mechanical Institute movement with its base in London and branches throughout Britain and abroad. He recalled the importance of the Preston Mechanics Institution to his early years; its library and its lectures in mechanics, astronomy, physics, chemistry, botany and physiology. The sensational *Vestiges of the Natural History of Creation,* published anonymously,[147] was debated at the

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[145]Eve and Creasey (1945), p. 5

[146]Tyndall (1892b) lecture 22 October 1884, pp. 224-247, 225-229.

[147]Anon (Chambers), 1844.

Mechanics Institutes and elsewhere, and fascinated Tyndall who produced copious notes on it.

The mechanisation of paper production, a crucial factor in the growth of published material on an unprecedented scale, made the information accessible as never before. The dissemination and acquisition of knowledge included learning about new inventions and discoveries. Witnessing an experiment on respiration at the Halifax Mechanics Institution, made a strong impression on Tyndall: .".. what went in as free oxygen, came out bound up in carbonic acid."[148] In turn, the acid reacted with lime solution – the resulting insoluble carbonate of lime was precipitated. The process taking place as predicted delighted him. He valued the experience: "the instruction entered into the texture of my mind, and influenced me in after-life."[149] He first heard one of his heroes, the American poet and philosopher R.W. Emerson (1803-1882) lecture at the Mechanics Institution in Halifax in 1847. There he argued against the design concept of the universe with the grandson of the eminent theologian W. Paley (1743-1805).[150]

During the railway mania he laboured in Staffordshire, Cheshire, Lancashire, Yorkshire, whence he was "in the thick of the fray. It was a time of terrible toil." The work was carried out round the clock as the deadline for the depositing of plans for the railways approached, causing him agony. "The atmosphere seemed filled with mocking demons, laughing at the vanity of my efforts to get the work done… Close at hand was the vicarage of Mr Brontë, where the genius was nursed which soon afterwards burst forth and astonished the world."[151]

He and his colleagues presented their work before a committee of the House of Lords. He heard of fortunes made and lost. It was "a time of mad unrest." Reporting on surveys to Parliament, enabled him to witness the vociferous arguments

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[148]Tyndall (1892b), pp. 224-228, 228.

[149]Ibid., pp. 224-228, 228.

[150]Secord (2000), p. 338.

[151]Tyndall (1892b), pp. 224-228, 226.

of the politicians, surveyors and businessmen on the proposed railway routes, and they left their mark. He mixed with the established civil engineers, G. Stephenson 1781-1848) and I.K. Brunel (1806-1859) among them, men from the legal profession, arguing on the planned lines, the experience which "broke strong men" on occasions. He recalled the "refreshment… derived from five minutes' sleep on a deal table, with the computer pioneer and mathematician, C. Babbage (1791-1871) and Callet's *Logarithms* under my head for a pillow." He interjected a welcome interlude: "then as now I loved the blue span of heaven."[152] Like many other people across all classes, he gambled with railway shares, which brought him several weeks of misery, haunted by the Stock Exchange. His impassioned recollections indicate that the experience made a life-long impression on Tyndall, who up to the age of almost twenty had led a sheltered life in the Irish countryside.

As the railway mania diminished, in 1847 Tyndall became a teacher and a secretary at the Quaker Queenwood College in Hampshire with one of the first science teaching laboratories in Britain on its premises.[153] There he learned the rudiments of chemistry from Edward Frankland (1825-1899), also a master at Queenwood, whom he taught mathematics. In years to come, Frankland became Tyndall's colleague at the Royal Institution, and a life long friend. From his experience at Queenwood, Tyndall concluded that the two essential qualities required of a good teacher were "mastery in one's subject and the ability to lift, exercise, and strengthen the growing minds committed to his care." This precept served him well in the future ahead.[154] The following year Tyndall and Frankland left Queenwood for Germany to study science at the University of Marburg. In conclusion I view Tyndall's early training as a preparation for the way his remarkable future career unexpectedly took shape. I contend that Tyndall's railway surveying experience made him a natural student of the new sciences of energy and thermodynamics, engendered by the new technologies,[155] which during the rapid industrialisation, provided

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[152]Tyndall (1892b), pp. 229-231.

[153]Brock (1996), part 3, pp. 1-23.

[154]Tyndall (1892b), pp. 229-231.

[155]Hobsbawm ([1962] 2003), pp. 208-209.

opportunities suited to his intellect. His experiences at Queenwood College brought the awareness of the different roles of teacher and student of science. His colleague at Queenwood, chemist Edward Frankland, on a brief visit the previous year to Bunsen's chemistry department in Marburg, communicated to Tyndall his enthusiasm for the German academic life. The following year in 1948 the two friends resolved to join the German scientific academic community as students, an experience that was denied to them at the time in Britain as young men without sufficient financial backing.

2C. Germany

The German chemist Robert W. Bunsen's (1811-1899) fame as a teacher induced Tyndall and his friend and colleague Frankland to choose his department at the University of Marburg as their place of study. Established in 1529, it was the first Protestant university in Germany. Marburg is a historic town where Tyndall's alleged ancestor William Tyndale (d.1536), the translator of the Bible from Latin into vernacular English, had lived before his martyrdom in Flanders.

Apart from Bunsen's presence there, it suited Tyndall's "mood and means."[156] This was his first experience of a formal scientific education, and hence the influence of Bunsen on Tyndall's future career as an experimentalist was particularly significant in view of Bunsen's qualities. Lockemann and Oesper provide a synopsis of Bunsen's own life.[157] Educated at Gottingen, on the death of the professor of chemistry Friedrich Stromeyer (1776-1835), Bunsen was appointed to a temporary post as a lecturer and head of the laboratory there at the age of 24. Although his researches were not extensive at that time, he discovered an effective antidote to arsenic poisoning still in use today. His course in theoretical chemistry included experiments, but two years later the permanent post was given to Friedrich Wöhler (1800-82). Bunsen then replaced Wöhler at the high technical school at Cassell. His referee Housmann testified to Bunsen's excellent knowledge of natural sciences, especially in chemistry and physics, emphasising his "ability to transmit it" and his practical and mechanical skills. Wöhler referred to his suitability as a chemistry teacher, also

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[156]Tyndall (1892a).

[157]Lockemann and Oesper (1955)

competent in mineralogy and mathematics. “Bunsen seeemed content to explore subjects of interest in his lab, but remained outside the fray that surrounded the often ‘violent’ discussions of theoretical subjects.”[158] Russell considers him to have been an inspiring teacher and an accomplished experimentalist, but a most reluctant theorist.[159] He sees Bunsen as being of the opinion that “one new chemical fact, even an unimportant one, accurately determined, was worth a whole congress of discussion of matters of theory.”[160] He therefore mostly eschewed research in organic chemistry, a subject bounded by theoretical disputes.

Bunsen's appointment at Marburg in 1839 as an associate professor occurred in the midst of a controversy between the political and the academic authorities involved. He proved himself worthy of his supporters' confidence in him; by 1841 he was given full professorship in the chemistry department. This department flourished during the twelve years of his tenure, attracting many able students, including Frankland and Tyndall. Russell favourably compared the new research school at Marburg under Bunsen with that at Giessen under Liebig.[161] He spent his time with his students emphasising the importance of experimental training. He demonstrated his lectures with well-planned experiments, which students replicated. They were encouraged to rely on their own observations and exercise their initiative. He introduced improvements in the existing analytical procedures devising new apparatus for his pioneering gas analysis, employing a method that was well suited to Lyon Playfair's (1818-1898) investigations of fire damp explosions in coalmines in his capacity as chemist to the British Geological Survey.[162]

Colin Russell notes how the European chemical community honoured Bunsen on many occasions. In 1860 he was awarded the Copley medal of the Royal Society for various researches including gaseous analysis with hitherto unattained accuracy

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[158]“Robert Wilhelm Bunsen (1811-1899), http://www.woodrow.org/teachers/ci/1992/Bunsen.html

[159]Russell (1999), pp. 321-326

[160]Ibid., p. 322

[161]Russell (1996), p. 31.

[162]Russell (1996), p. 24

and precision, and his investigations into the volcanic phenomena of Iceland with contributions to mineral chemistry applying physics and chemistry to geological phenomena. His research on cacodyl compounds provided the first example of a compound radical, with remarkable consequences for the progress of chemistry, such as the radical theory, the study of organometallic compounds, Frankland and Kolbe's work on the valency of the elements, Kekule's discovery of the tetra-valency of carbon, and the modern structure theory.[163]

Unusually severe volcanic eruptions in Iceland in 1845 prompted the study of the volcanic phenomena in Iceland sponsored by the Danish Government. With his wide ranging interests in the physical sciences and a love of geology, Robert Bunsen became one of the chief investigators, confirming theories about the internal heat of the geysers, the work which even a century later provided a satisfactory explanation of the geyser phenomena.[164] When Tyndall chose Bunsen's visit in 1846 to Iceland as the subject of his second discourse at the Royal Institution, he publicly endowed Bunsen's work with distinction and due recognition.[165] Where the causes of certain changes were being traced, Tyndall the experimentalist remarked: “In seeking insight here, experiment is our only safe guide.”[166] Two years after Tyndall’s departure from Germany Bunsen was appointed to the chair of chemistry at the University of Heidelberg where his researches in spectroscopy together with the physicist Gustav R. Kirchhoff (1824-1887) brought him international fame.

Tyndall’s German academic experience as a mature student and the development of his professional and social network of philosophers and scientists from across the disciplines provided him with an academic background which served him well in his future career at the Royal Institution as Faraday’s successor and Resident Professor of natural philosophy.

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[163]Lockemann and Oesper (1955), pp. 456-460, 456-57; Sabine (1860), vol. 11, pp. 14-16.

[164]Oesper and Freudenberg (1941), pp. 253-260;

[165]Tyndall (1853), vol. 6, pp. 150-156.

[166]Ibid., p. 151.

Tyndall used his savings from the shares purchased during the railway mania to study at Marburg. He attributed a large part of the greatness of Germany to its universities, for Tyndall they shared the nation's particular character, but "superposed upon it the informed and disciplined mind." Three decades later, in language unexpected of a scientific naturalist, he wanted Britain to emulate Germany: "We need muscle…brains, character and resolution as well as expertness of intellect…"[167]

In his speech of 1892, having set the scene of his arrival in Germany, Tyndall concentrated on describing his aspirations and experiences there. Mathematics, physics and chemistry were his choice of study. He provided a portrait of Bunsen as "a master of the language of experiment…reaching the mind through the eye as well as through the ear…the nearest approach to my ideal of a university teacher."[168] At his daily lectures Tyndall also absorbed the German language. His verdict on the Marburg University laboratory tells of his appreciation and of a keen sense of belonging there:

> Our University is not grand, it is broken into parts and presents no imposing front. Our laboratory presents rather a scoundrel-like appearance, but don't conclude hastily against it--it holds a man [Bunsen] whose superior as a chemist is not to be found within a radius of 8000 miles from the Piece Hall of Halifax. There, however, right over against me on the summit of a hill, with the sun shining upon its white walls, and its tower piercing the air, is a fine building–an astronomical observatory and physical institute, its interior furnished with costly apparatus; on the other hand I can lead you into a little room with hacked rickety benches, perhaps the whole not worth five and sixpence, where a man of genius makes his hearers forget the poorness of his furniture, as he crushes the crust of a mathematical calculation between his fingers.[169]

[167] Tyndall (1892b), pp. 234-235; 237-238.

[168] Ibid., p. 238.

[169] Tyndall [c. 1848-1850], in Gardner and Wilson (1993), p. 532.

In Germany, “a land of universities”, Tyndall was in his element. There in a mountainous landscape, he was surrounded by academics from various disciplines, including sociologists, philosophers, chemists and physicists who provided an intellectual background, which appealed to him. He recorded the walks and the vibrant atmosphere. He imbibed the habit of discussions. The outward neglected appearance of the university concealed the well-equipped laboratory and the excellent teaching by Bunsen – a training that left its mark on Tyndall when the German education was also becoming a model for the reform of science education in Britain.[170]

A German influence on the educational and scientific institutions in Britain began replacing the Scottish influence from the 1840s according to G. Haines. He suggest that Albert, the Prince Consort (1819-1861) played a role in the resulting changes which included the establishment of the Royal College of Chemistry and the School of Mines, the first technical school in England to train mining engineers. This attracted staff from various disciplines, including the physicist Stokes, the surgeon and physiologist Huxley, and the physicist Tyndall.[171] The establishment of the Royal College of Chemistry in London in 1845 under the German chemist August Wilhelm von Hofmann (1818-1892), one of Justus von Liebig’s (1803-1873) students, led to the creation of the synthetic dye industry in Britain under Hofmann’s British student William H. Perkin (1838-1907). David Knight referred to Germany as an intellectual centre of Europe at the time.[172] As it was the superiority of German education in science that was credited for the spectacularly successful military campaigns later in the century, reforms in science education in Britain began to be made. Meanwhile Britons availed themselves of the excellent facilities of the German science education. The German-educated British scientific luminaries numbered among them Henry Bence Jones (1813-1873), Lyon Playfair (1818-1898), Henry Enfield Roscoe (1833-1915), Thomas Archer Hirst (1830-1892), and Edward Frankland (1825-1899). Tyndall’s praise of the German intellectual climate caused resentment among some of

[170]Haines (1957), pp. 43-60.

[171]Haines (1957), pp. 43-60, 43-45; 49-52; 55-57.

[172]Knight [1986]1989, p. 140.

his peers.[173] On leaving Marburg University in 1850, he noted: "Here my pilgrimage in Germany ends. I believe I spent my money well. I am a poor man, but have no fear of poverty…I feel no anxiety about the future…"[174]

Tyndall's experiences this far exemplified a vital trend in the first attempts at the professionalisation of science including the broadening of the educational horizons of the population at large. Later Tyndall was to play a vital part in this effort not least because of his personal experiences, the vital record of which he has left to posterity in his notebooks, journals and correspondence. To summarise, Tyndall's impassioned recollections later in life indicate that his early experiences made a life-long impression on him. Study of the autobiographical writings of Tyndall acquaints us with the complex personality of a remarkable, original research scientist and educationalist whose life in the nineteenth century and his legacy has impacted through to the twenty first century.

2D. Researches in Diamagnetism

It was Faraday's momentous discoveries about the magnetic properties of matter that prompted Tyndall's forays into scientific research. Before discussing Tyndall's researches on diamagnetism, I will briefly outline what diamagnetism is, and the significance of its discovery.

In 1845 Faraday demonstrated a new phenomenon that all matter is affected by magnetism, manifested either by an attraction or repulsion. In recognising the importance of this event as an extension of the frontiers of knowledge in physical science, Tyndall and Knoblauch reflected the opinion of eminent European physicists some of whom participated in further investigations, notably Reich, Oersted, Weber, and Plücker in particular.[175]

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[173] Tait (1873), 382.

[174] Tyndall Journal vol. 2, 21.1. 1853, pp. 181 and 184 [sic], 596-597; quoted in Eve and Creasey (1945), p. 31.

[175] Tyndall and Knoblauch (1870 [1851]), p. 1 *Philosophical Magazine* July 1850

Tyndall considered Plücker and Faraday's discoveries on magne-crystallic action to be so remarkable that he focused on a thorough investigation of their experiments, which enunciated the laws of magnetic action. In particular he was interested in deviations from them.[176] He aimed to achieve the thorough understanding of the electromagnetic attractions necessary to the study of diamagnetism. As Tyndall stated, the laws of magnetic action had been established at distances at which the thickness of the magnet was negligible, by physicist/theologian Heinrich F.E. Lenz (1804-65) and physicist Moritz H. Jacobi (1801-74). There were however at distances at which the size of the magnet played a part, and here the law of magnetic action hitherto had been a matter of puzzling conjecture. Now for the first time they had been confirmed experimentally.[177]

Tyndall first heard of Faraday's discovery of diamagnetism from Bunsen at a lecture on electrochemistry very shortly after his arrival in Marburg in 1848. Tyndall's diary conveys the intensive training he was undergoing in Bunsen's department at that point:

> -At electricity compared effects of decomposition and the deflection of the magnetic needle, found them to agree beautifully.[178]
>
> -During the day, made experiments with magnets, & c; At physics, chemistry and maths. I have hardly time to observe any thing and less time still to note down my observations[179]
>
> -Studied and made apparatus[180]
>
> -Learned the use of Weber's travelling magnetometer[181]

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[176] Tyndall (April 1851), 1265-295, 294-5.

[177] Ibid.

[178] Tyndall Journal 28 March 1849

[179] Tyndall Journal 26 April 1849, p. 399.

[180] Tyndall Journal May 1849, p. 423, 431.

[181] Tyndall Journal 8 June 1849, p. 438.

This historic entry in his diary below marked a new era in Tyndall's life, its significance not suspected at the time:

> Amid all the light of Faraday's and Plücker's researches…. the papers now before me were objects of daily and nightly study…Every circumstance connected with the subject; every shade of department; every variation in the energy of the action; almost every application …to bring out in detail the character of this new force is minutely described...hardly anything experimental is left for the gleaner… Plücker's experiments with Knoblauch with a beautiful apparatus from Berlin to repeat and follow out the investigations of Faraday on the magnetic and diamagnetic properties of bodies. He has now no time, and the job has fallen to me. He has got a cosy little room ready for me, and here I experiment during the day…[182] and Faraday's investigations filled all minds at the time… and towards the end of 1849 Professor Knoblauch and I commenced a joint investigation of the entire question…[183]

Julius Plücker had continued researching the magnetic properties of crystals and claimed discovery of a new force. In response to the mathematician and physicist Julius Plücker's (1801-1868) paper on the magnetic properties of crystals, Tyndall and the newly appointed professor of physics H. Knoblauch embarked on the investigation of the subject in November 1849. As he was preoccupied with research on radiant heat, Knoblauch passed to his student the task of tackling the problems raised by Faraday's researches on diamagnetism and paramagnetism. This action shows Knoblauch's approbation of the budding scientist, Tyndall, who took up the challenge with alacrity. I have not come across any evidence of the deliberate scheming by Tyndall as alleged by some commentators.[184] Tyndall followed this research over the following years. Having completed his doctorate, he returned briefly to London before his stay at the University of Berlin under Magnus. It was a new area

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[182] Tyndall Journal 28 November 1849.

[183] Tyndall, unfinished ms, in Tennyson (1897), II, pp. 469-478.

[184] Smith (1998).

of research and Tyndall's involvement testified to his enterprising intellect ready to challenge the conclusions of the well-established and experienced scientists of the day by using the experimental evidence. It was a decisive step that determined Tyndall's future career. The controversy surrounding Faraday's discoveries and Tyndall's different interpretation of the results from those of the established authority of Plücker, Faraday as well as of the physicist William Thomson later Lord Kelvin, attracted the attention of the scientific community. In the following years, apart from the first two joint publications with Knoblauch,[185] other papers followed by Tyndall himself. Tyndall's researches on diamagnetism were reported by him in the early 1850s BAAS annual meetings at Edinburgh and Ipswich, in the *Philosophical Magazine* papers, in the Royal Institution Friday Evening Discourse, and in the 1855 Royal Society Bakerian Lecture[186] and in further communication to the Royal Society the following year.[187]

A discussion of Plücker's and Faraday's research[188] took place at the BAAS meeting in Edinburgh in 1850 where the chairman Edward Forbes introduced the novice speaker John Tyndall; "Here we have a memoir which tends directly to invalidate the views of Faraday and Plücker. If any gentleman has a remark to make or an objection to urge we shall be happy to hear him."[189] Tyndall recorded details of that event in his journal. [190] Distinguished attendees were in close proximity, such as William Thomson (future Lord Kelvin), George Gabriel Stokes, and Sir David Brewster. He took an early opportunity to discuss the subject with Thomson, and prepared to demolish his argument.

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[185] Tyndall and Knoblauch (1850a), s. 3, volume 36, pp. 178-183; (1850b), s. 3, volume 37, pp. 1-33.

[186]Tyndall (1855), 145, 1-52

[187]Tyndall (1856, part 1), 146, 237-259

[188] Tyndall (1851), RBA (1851), Powell, B. (1850), BAAS Report

[189]Tyndall (1850), pp. 504-5.

[190]Tyndall 7 August 1850 Journal pp. 504-505.

After Thomson completed a defence of Faraday's views, speaking, "for a considerable time," Tyndall was invited to defend himself. He did so in a style of his own, recalling a recent meeting with Faraday in London: "I told him that we felt compelled to differ from him. "No matter" he replied "you differ, not as a partisan, but because your convictions compel you." Tyndall continued:

> Thus encouraged by Mr Faraday himself, I feel rather inclined to stick to my old notion, notwithstanding all that has been urged by Professor Thomson. With regard to the three lines of equilibrium, the hypothesis is unfortunately against facts; for take a disc of calcareous spar cut perpendicular to the optic axis, and hang it horizontally between the poles. Thus hanging such a disc has three lines of equilibrium, not at right angles to each other, but in the same plane. The optic axis is also a line of equilibrium in this case, therefore we have four such lines instead of three.

Tyndall was challenged by Thomson who found it "very extraordinary and directly contradicts my notions of the matter." Tyndall retaliated. Brewster intervened and supported Tyndall. Tyndall described it as "a hand to hand fight" terminated by the chairman Edward Forbes's intervention. The discussion continued temporarily in Queenwood, and at the Royal Institution,[191] culminating in a Friday Evening Discourse in February 1853 at which Tyndall boldly announced his disagreement with Faraday's conclusions.[192]

As Plücker's and Faraday's researches on diamagnetism and magne-crystallic action in 1849 had produced inconsistent results, Tyndall and Knoblauch's first steps had been to attempt to replicate these experiments at the University of Marburg. Plücker's assertions regarding the magnetic properties of crystals followed his announcement of the existence of a new magne-crystallic force or optical axis force, independent of the magnetic or the diamagnetic forces.[193] In response to Faraday's researches on

[191]Tyndall (1856), 146 (1), 237-259.

[192]Tyndall (1851-1854), 1, 254-259.

[193]Faraday (1849), vol. 139, pp. 19-41, p. 32.

diamagnetism,[194] Plücker, on the basis of new observations, claimed to have discovered a new empirical law:

> When a crystal with a single optic axis is placed between the two poles of a magnet, the optic axis is repelled by each of the two poles. In a crystal with two optic axes, each of the axes is repelled by each of the two poles with the same force. The force exerting this repulsion is independent of the magnetic or the diamagnetic properties of the crystal; this new force is distinguished from them by the fact that it diminishes less with the increasing distance from the poles than the magnetic or the diamagnetic forces produced by the poles acting on the crystal.[195]

He therefore embarked on an experimental proof to explain an anomaly concerning certain substances which demonstrated dual behaviours, that of the diamagnetic behaviour, being repelled in the proximity of one pole, but also a magnetic behaviour in its alignment in the presence of two poles. This new force, according to him, was distinct from the existing magnetic and diamagnetic forces, since it diminished more rapidly with distance, than the other two forces.[196] He claimed that this force did not display the repulsive and attractive properties characterising the magnetic and diamagnetic forces. Plücker concluded that the distance between the poles determined the properties be they diamagnetic or magnetic in character.

Faraday disproved the hypothesis that diamagnetism was another form of magnetism, by demonstrating experimentally that the magnetic body was attracted by the two poles, whereas the diamagnetic body was repelled, and that a mixture of these two types of bodies, depending on the proportion of each, was characterised by the intermediate properties of the two substances, tending to the production of a neutral

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[194]Plūcker ([1847] 1849),. 5, 376-382.

[195] Tyndall, "Note", in Tyndall and Francis, eds. (1853), pp. 358-359.

[196]Plücker to Faraday 3 November 1847, in James, ed. (1996), pp. 648-9.

substance, bearing in mind that the magnetic bodies were considerably stronger, than the diamagnetic ones.

Having examined both Faraday and Plücker, Tyndall and Knoblauch described their approach in their first joint paper.[197] In order to study the controversial experimental results, Tyndall identified the importance of the investigation of the mutual relationship of magnetism to diamagnetism, essential for the thorough understanding of the new force of diamagnetism.[198] From initial investigations they had decided that it was essential to isolate the forces to be studied one by one to ensure that the effect of other influences to which the crystals might be subject, did not interfere with the results.

Plücker's law stated that the optical axes of negative crystals were repelled. The cubes were cut from tourmaline so that the optical axis of the cube ran parallel to four sides of the cube. When suspended between the poles of a magnet, the optical axis set equatorially as expected according to Plücker's law. When hanging the cube with the optical axes vertical, its effect was abolished; instead one of the diagonals to a horizontal side of the cube experienced repulsion, an effect not predicted by the law. To investigate the effect of the optical axis on magnetism further, thin rhombs were ground, from which discs were constructed. The line dissecting the acute angles of the rhomb set axial if the optical axis was repelled, but it set equatorially if it was attracted.

The anomalous results became evident when Tyndall substituted the carbonate of lime in the original crystal of Iceland spar for the carbonate of iron, isomorphous with the carbonate of lime. The optical properties and the physical form remained unaltered, only the chemical character of the crystal underwent change. When Tyndall and Knoblauch experimented with many other crystals used by Plücker and Faraday, they frequently obtained inconsistent results. They also used the discordant results of Plücker and Faraday to analyse the chemical composition of crystals. Tyndall and Knoblauch identified the impurities interfering with the results, making the crystals

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[197]Tyndall and Knoblauch (1850), s.3, 36, 178-183.

[198] Tyndall [1850] 1870,

unsuitable for the precise reproducible experimental conditions required. They then resorted to an elaborate regime of removing the impurities by an arduous process until they reached the stage of consistently reliable results.[199] They, themselves, also determined the optical properties of crystals from various sources, employing the well established procedures of an eminent German physicist and meteorologist, H.W. Dove (1803-1879)), ensuring the correct classification of positive and negative crystals. The crystals originating from mineralogists were frequently contaminated.

Tyndall and Knoblauch obtained consistent results when experimenting with gutta percha. Circular discs were cut exhibiting fibrous structure, the direction of the fibres being axial. Complex magnetic properties of crystals manifested themselves. An attempt at the experiments with discs at various angles confirmed Plücker’s law; if the optical axis was repelled, the line bisecting the acute angle of the rhomboid, set axial; if the optical axis was attracted, the bisecting line set equatorial. The aim of the experimental trials was to decide whether the experimental substance was magnetic or diamagnetic. Hanging the experimental bars vertically rather than horizontally gave a clearer picture whether the bars were attracted or repelled. Tyndall and Knoblauch selected two very pure and transparent crystals of each class for comparison, having performed chemical analysis on them first: although there were no visible differences between them, the analysis detected the presence of an iron compound in the crystals, the optical axes of which were attracted, but if iron was absent in the crystals, the optical axes were repelled. Tyndall and Knoblauch posited the shape of an egg, with the magnetic force acting preferentially in the direction of the fibres represented by the longer diameter of the egg. The lines through the centre of an ellipse represented a hypothetical magnetic or diamagnetic action of the crystal.

According to Plücker, the two forces acting on the tree bark were distinguished by the fact that the magnetic behaviour decreased with distance more slowly than the diamagnetic one. When a battery of four cells was used to excite the source of magnetism, an attraction was observed, whereas with the battery of twice as many cells a repulsion was noted. Tyndall considered Plücker’s information on the

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[199]Tyndall and Knoblauch (1850b).

power of the battery in terms of the number of cells unsatisfactory. He was fully aware that the power of the battery could not be determined from the number of cells, unless the shape of the circuit was also considered. Plücker therefore drew his conclusions on the wrong premises, invalidating his explanation. Subsequently Tyndall ensured that the strength of the current was accurately controlled and measured.

In January 1850 Tyndall recorded in his diary:

> For the last week I have worked constantly at my magnetic researches. A few days ago a light dawned in upon me. I had a cube of Iceland spar with the optical axis drawn on one of its faces, and parallel to one of the edges; this set itself equatorial when placed between the poles. When the cube was hung from another face, however, although the optical axis still remained horizontal, it stood diagonally. This roused various conjectures, and at length the thought of examining the cleavage occurred to me. Found it sufficient to account for all that Professor Plücker referred to the optical axis. Following up this thread, we have accounted for every discrepancy which heretofore puzzled us. This ("so" crossed out) much is now certain, that the theory of Plücker is False; for we have found in three different cases, with three different crystals, that the optical axis sets itself always axial.[200]

Six months later, Tyndall wrote in his journal:

> Brooded over the chaos and reduced it by degrees to order. New thoughts, new and more convincing methods of proof occurred during the writing of the memoir. And establish these methods by experiment took time. Patient thinking can enlighten the subject, impossible without it to get properly at the root of any thing. This is the best result which my investigation has delivered. It has convinced me of the power of endurance to beat down difficulty. How many blank experiments have I made; weeks, months passed...

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[200] Tyndall Journal (January 1850), RI MS JT/2/13b.

> It has convinced me of the power of endurance to beat down difficulty. How many blank experiments have I made; weeks, months passed without a single safe result. Now all is clear and the foundation stone of the matter laid bare.[201]

Both Tyndall's journal and his arguments in support of his views show his awareness of the complexity of the process of experimentation. This strength was acknowledged by William Thomson future Lord Kelvin, and J.C. Maxwell, who were later instrumental as the referees of Tyndall's early papers.

Tyndall's first independent experimental researches took place in the University of Berlin in the laboratory of G.H. Magnus in early 1851.[202] There, Tyndall met a chemist who gave him a sample of a crystal of bismuth and explained the procedure of purifying it. The extraordinary precision of this method must have surprised Tyndall because he recorded his experiences at the time in Berlin in a paper published in the *Philosophical Magazine* of September 1851.[203] Finding Plücker's torsion balance ill suited to the measurement of the weak forces involved, Tyndall also designed and constructed an apparatus expressly suited to the study involving weak forces. The campaign for the measurement of the earth's magnetic field earlier in the nineteenth century inaugurated by Wilhelm Weber (1804-1891) and Karl F. Gauss (1777-1855) in Germany and by Edward Sabine (17880-1883) in Britain, had led to a standardised torsion balance with improved sensitivity of its main components, the galvanometer and the magnetometer. The French engineer Charles-Augustin Coulomb (1736-1806) designed a torsion balance suited to measure the electric and magnetic forces, evolved from a range of instruments to measure the friction and rigidity of ropes. A needle suspended by a silk wire twisted in response to even the minimal changes in the magnetic force. The angle of the twisted thread was proportional to the elastic force with which it strained to unwind itself against the magnetic force. It received a mixed reception in Europe. Coulomb published several

[201] Tyndall Journal (2 June 1850), RI MS JT/2/13b.

[202] Tyndall (1851).

[203] Tyndall [1851], S.4, 2, 165-188; reprinted in Tyndall (1870), pp. 38-72.

memoirs on electricity and magnetism for the French Academy of Sciences. Coulomb provided an elaborate outline of its construction, but eventually Tyndall commissioned a torsion balance from a respected German instrument maker, C.A. Becker. Using these increasingly precise experimental setups Tyndall aimed to cover "in one investigation the whole of a subject whose separate details have occupied the attention of many experiments."[204]

Tyndall compared the effect of an electromagnet on the solid crystal of bismuth with pronounced diamagnetic properties with the effect the electromagnet exerted on fused iron in which the molecules, just like their atoms, were free to move or vibrate. He devised experiments which enabled him to study the relation between the power of an electromagnet and the attraction it exerted also on a soft iron sphere under specified conditions. In this way he established the antithesis between the magnetic and the diamagnetic forces. Could this magnetic power, exercising its force on the fixed molecules of a crystal, influence their arrangement in their free state in the fused bismuth? Tyndall expected the magnetic influence to manifest itself, although Faraday, like Tyndall, failed to detect it; Plücker had claimed to demonstrate it. An article that appeared in April 1851 "On the Laws of Magnetism" illuminates Tyndall's thinking. [205] Tyndall defined four fundamental events to assess the experiments performed by Faraday and Plücker. "An exact acquaintance with electro-magnetic attractions appeared to be a necessary discipline for the successful investigation of diamagnetic phenomena," mused Tyndall.[206] He decided it was necessary to find the relation between the strength of an electromagnet and the attraction of the magnet and a mass of soft iron in the shape of a sphere in contact with each other; when separated by a known distance; when separated by a varying distance, and finally to find the relation between the force and distance which governs the decrease of the magnetic attraction with increased distance.[207] He considered the outcome of these investigations very remarkable: a ball of soft iron separated from the

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[204] Tyndall (1851), 1, (4), 265-295), 294.

[205] Tyndall (1851), S. 4, 1, (4), 265-295,

[206] Tyndall (1851), S. 4, 2, (10), 167.

[207] Tyndall (1851), S. 4, 1, (4),p. 265.

pole of an electromagnet by a small fixed distance was attracted by a force proportional to the square of the exciting current, while the magnetism of the ball increased in the simple ratio of the current. Moreover the law of increase for a diamagnetic body was identical with that for a magnetic body. He established the equivalence of the repulsion of the diamagnetic body and the attraction of the magnetic one. The strongest attraction occurred when the attracting force acted in the direction of the axial position of the magnetic substance when suspended in the magnetic field. The diamagnetic substance was most strongly repulsed when the repulsive force acted in the direction of the equatorial position taken up by the diamagnetic body suspended in the magnetic field. He accounted for the maximum attraction and repulsion in the particular circumstances by the close positioning of the particles of matter in the preferred direction.[208] He successfully demonstrated the antithesis of the magnetic and the diamagnetic forces, both of which increased as the square of the exciting current,[209]

Tyndall's results were the same as those published simultaneously in France by physicist Alexander E. Becquerel (1820-91), who had been working over the preceding year. Like Tyndall, Becquerel confirmed the identity of the laws governing magnetic attraction and diamagnetic repulsion, exposing Plücker's assertions regarding the nature of the optic axis force as named by Faraday, to be incorrect.[210] "We have both been guided… by the same fundamental thought, though our modes of carrying out the thought are different,"[211] concluded Tyndall.

2E. Tyndall and Faraday at work

Faraday's persistent challenging of received opinions and his search for truth which put experiment as the ultimate arbiter, also defined Tyndall's philosophy. In Faraday's words: "All this is a dream... Still examine it by a few experiments.."[212]

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[208]Tyndall (1870), p. 66.

[209]Tyndall ([1851] 1870), pp. 38-66, 40-47.

[210]Becquerel (1853), 301, p. 301.

[211]Tyndall (1870), p. 47.

[212]Faraday Diary, vol. 5, 19 March 1948.

Darrigol comments on the popularity of experimenting and theorising amongst nineteenth century researchers, Faraday, Ampère, Weber, Thomson and Maxwell, Helmholtz and Hertz among them. Francis Bacon foresaw that from the combination of "the experimental and the rational...much may be hoped."[213] Like Faraday, Tyndall belongs to the list. In his biography of Faraday he commented on the absurdity of defining Faraday as an inductive philosopher. He instinctively looked for the theory underlying his experiments. Tyndall also took pride in experimentation as a hallmark of science. On the other hand he attached importance to theorising as an essential activity of "the scientific mode of thought." Tyndall, in the words of Cantor "revered Faraday as an experimentalist."[214] He succeeded his mentor and colleague as Resident Professor and Superintendent of the Royal Institution. His debt to Faraday, the scientist, will be assessed by attempting to identify Tyndall's experimental methodology along that of Faraday, to see when there are factors in common, and whether they are conscious of their influence on each other or not.

James considers the relationship between Faraday and Tyndall a "highly curious one."[215] Tyndall publicly disagreed with Faraday's friends such as Plücker. However James also notes Tyndall's readiness to quote the Bible in his efforts to please Faraday. Both were involved in controversies over the years. Faraday's and Tyndall's love of scientific research, their sharing some of the contemporary tenets of natural philosophy, the imperative of extracting information about the working of nature, seeking the truth when they differed in scientific views, prevented ill feeling between them if their opinions differed. One such occasion is referred to by Tyndall in his dispute with William Thomson at the BAAS meeting in Edinburgh, and recorded in Tyndall's journal. [216] Faraday commented: "No matter-you differ, not as a partisan, but because your convictions impel you." They appear to have appreciated these qualities in each other. Faraday's letters indicate a high regard for Tyndall as a scientist:

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[213]Bacon (1620), in Darrigol (1999), p. 307.

[214]Geoffrey Cantor, private communication, March 2010.

[215] James (1999), vol. 4, p. xxxiv.

[216]Tyndall Diary 7 August 1850, in James (1999), vol. 4, p. 166, n. 3.

> I am fully able to appreciate the results you have arrived at …they are exceedingly well established and of very great consequence. These elementary laws of action are of so much consequence in the development of the nature of a force which, like magnetism is as yet new to us.[217]

Faraday and Tyndall as experimentalists reached their respective positions from different backgrounds. Steeped in a geological environment as a surveyor for the Irish and then English rail network, reporting to Parliamentary committees against the clock, followed by an innovative Quaker school laboratory experience of teaching science, by his late twenties Tyndall had elected to enter the formal German academic scientific tradition. Acquaintance with the members of the thriving interdisciplinary academic community in Marburg and Berlin was an experience that Tyndall relished. As the translator of papers by Clausius on the mechanical theory of heat, and of the seminal paper by Helmholtz on the correlation of forces, as well those of Angström and Plücker among others, Tyndall was well informed on the scientific matters of his day. His name was known as reviewer and co-editor for contemporary science at the *Philosophical Magazine* in the early 1850s and he had personal knowledge of scientific developments in the UK and the interaction between the British scientific enterprise and the French, Swiss and German scientific scenes. His subsequent acquaintance with Faraday and involvement with Faraday's researches further advanced his grasp of contemporary science.

Faraday, on the other hand, was thirty years older. In his late teens, he had been influenced by the dissenting minister, hymn writer and author Isaac Watts' (1674-1748) philosophy in the tradition of the self-improvement in education, and therefore trained as a bookbinder. The freewheeling discussions at the London City Philosophical Society, which Faraday co-founded, and his attendance at Mr Tatum's evening classes in electricity, brought Faraday to the portals of the Royal Institution, where he attended a course of Humphry Davy's famous chemistry lectures. Subsequent travels in post Napoleonic Europe, acquiring skills as Davy's assistant, gave Faraday the extraordinary experience of meeting famous French, Swiss and

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[217]Faraday to Tyndall 19 April, 1851, in James, ed. (1999), pp. 280-1. R.I. MS JT/1/J/51

Italian scientists at a moment when contemporary science was taking shape amidst turbulent disputes.[218] Regarded by Gooding and James as mainly self-taught,[219] Faraday could not rely on any guidance from a particular school, but had to work out his own method for dealing with uncertainty. Gooding wondered, “How did Faraday turn tentative and private results into public, collectively witnessed and self-evidently natural facts?” Gooding asserts that Faraday won cooperation from nature by getting his experiments to work. The information was used “to modify and clarify his conception about the experiment…”[220] Gooding and James maintain that it was to Faraday’s advantage not to have had formal procedures for problem solving instilled in him; it left him to his own devices and judgement, motivating him to develop these faculties to a high degree. Even in his early twenties, without much experience of the world, while touring Europe with Davy, he had the confidence not to accept prevailing notions without replicating the work of the scientists himself.[221]

Tyndall saw Faraday’s publication of 1833[222] on electricity from various sources as a particularly fitting illustration of Faraday’s “strength as an experimenter.”[223] In his Faraday Memorial Lecture in 1868, Tyndall expounded on this theme. Using Faraday’s synthesis of water while studying its decomposition, Faraday noted the power of the positive platinum electrode to bring about the recombination of oxygen and hydrogen and assigned it to “the perfect cleanness of the positive plate.” Oxygen liberated against it with its properties of the nascent condition, absorbed all the impurities from the surface against which it was liberated. In these circumstances the bubbles of the liberated gas were always much smaller and rose more rapidly than from any other electrode. Since oxygen is sixteen times heavier than hydrogen, Tyndall wrongly concluded that these small bubbles must

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[218] Bowers and Symons, eds. (1991).

[219] Gooding and James [1985] 1989, p. 11

[220] Ibid.

[221]Gooding and James, eds., [1985] 1989, p. 12.

[222]Faraday (1833), 123,

[223]Tyndall [1854-58, 2, 132-135 ([1868] 1970, 2, 50-123, 72), Faraday (1833), 123, 23-54.

have been those of hydrogen. The hydrogen at the other electrode swells into large bubbles rising slower than Oxygen. “He has taught me that the fact here is the direct reverse of what I supposed it to be…”[224] recorded Tyndall. On reversing the current the hydrogen was liberated at the cleaned plate promoting the production of small bubbles of hydrogen. Tyndall made obvious deductions leading him into erroneous judgement. He recalled that Faraday would never be satisfied by deductions unless reduced into facts.

Faraday recorded his procedures and thoughts in detail in the experimental notebooks, learned publications and correspondence, leaving an extraordinarily fertile legacy for the historians, philosophers, cognitive and social scientists to examine the sources and learn from this creative and successful scientist his ways of studying nature:

> [F]acts were important to me and saved me. I could trust a fact, but always cross-examined an assertion. When I questioned Mrs Marcet’s book by such little experiments as I could find means to perform, and found it true to the facts as I could understand them, I felt that I had got hold of an anchor in chemical knowledge and clung fast to it.[225]

Meadows notes Tyndall's commitment to experiment, but as Tyndall explains, experiment was acceptable if within the context of a theoretical framework: “I hate writing facts and this is what kept me so long,”[226] wrote Tyndall. He sought an explanation for the results. Faraday did also, but in a non-mathematical style, claims Meadows who sees Tyndall's mathematical training as responsible for the difference between his approach and Faraday’s in the interpretation of results. The mixed mathematical abilities that characterised Davy’s disputes with Biot, Ampere and others could be seen to characterise the diamagnetic disputes of the following

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[224]Tyndall [1868] 1970, 2, 50-123, 72.

[225]Faraday to De La Rive 2 October 1, in James (2008), volume 5, 453-454.

[226]Tyndall R.I.MS journal 5 February 1851.

generations between Faraday, Tyndall and Thomson, who also exploited mathematics to different extents.

In his brief review of Faraday’s collected papers in electricity published in 1855,[227] Tyndall provided his view on Faraday as an experimentalist. By then as Professor of natural philosophy at the Royal Institution by Faraday's side, Tyndall was well briefed to review Faraday’s researches. Commenting on this work, Tyndall praised his mentor’s investigations. He remarked that Faraday’s lack of conventional scientific education caused him to communicate his researches in an unexpected turn of phrase, not always readily comprehensible to his audience.[228] Tyndall’s brief review was more of a tribute to Faraday’s “scientific mode of thought,” than a critical appraisal of Faraday’s publication.

Twelve years on, in a posthumous appraisal of Faraday as a discoverer,[229] Tyndall’s views on Faraday’s researches embrace Faraday’s achievements in depth. His assessment of the significance of Faraday’s discovery of diamagnetism and researches on magne-crystallic action testifies to Tyndall’s appreciation of Faraday’s contributions: “he never accepted a negative answer to an experiment.” This statement reflects Tyndall’s methodology in his investigations of the magne-crystallic phenomena and ultimately to the thermal properties of gases. Faraday’s “exhaustive researches” exposing the phenomenon of a new pervading force, impressed Tyndall. His intensive training under Bunsen provided the discipline also detectable in Faraday’s dedication to the task in hand in “nature’s school.”[230] Tyndall’s researches, contradicting the conclusions of Faraday and Plücker, must have been a disconcerting experience, of the heuristic kind, instructive in the broadening of his appreciation of the empirical input into the formulation of a correct theoretical framework. Faraday’s mimicking of nature in the laboratory within the boundaries of “what happens in nature” also appealed to Tyndall. (He used this argument in his confrontation with

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[227]Tyndall (1870 [1855]).

[228]Tyndall (1855), s. 3, volume 10.

[229]Tyndall (1870), pp. 109FF.

[230]Gooding, in Gooding and James, eds. (1989[1985]), pp. 105-135.

Challis who questioned Laplace's determination of the speed of sound in the air, based on the data obtained at the bench)[231].

In a discovery, leading ultimately to the researches on diamagnetism, using his heavy glass, Faraday demonstrated the existence of the magnetic repulsion which he proceeded to examine by subjecting a wide variety of substances of different kinds to the action of the magnet,[232] showing a universal effect that nearly all the wide variety of substances experimented upon, were affected by the magnet. "Faraday's thoughts ran intuitively into experimental combinations," commented Tyndall.[233] Tyndall's meaning encompassed Faraday's ability to view the context of the experiment from various relevant points of view to which the subject under investigation could be submitted. In the case of diamagnetic phenomena, Tyndall provided Faraday's application of the Archimedes's principle, whereby the strength of the magnetisation was analogous to the specific density of the medium by which the investigated object was surrounded. The relative densities of the two entities determined the result of the experiment, and therefore the theoretical interpretation. The magnetic induction led him to the concept on the reversed polarity. For a reason that Tyndall found inexplicable, Faraday left that path of research unexplored, favouring a non-polar characterisation of the diamagnetic force. One that was at odds with the interpretations of Tyndall and Weber. Tyndall's appreciation of this procedure in Faraday's methodology made a profound impression on him, as exemplified in his own methods of experimentation on diamagnetism. Referring to Faraday's work more than twenty years later, Tyndall recalled that they were:

> … objects of daily and nightly studies with me… and even now they astonish me. Every circumstance connected with the subject; every shade of deportment; every variation in the energy of the action; almost every application which could possibly be made of magnetism to bring out in detail the character of this new force, is minutely described. He assigns the law of action parallel to or at a

[231] Tyndall (1863), vol. 26, pp. 384-387; vol. 27, p. 41.

[232] Tyndall (1870), p. 111.

[233] Tyndall (1870), p. xii

> tangent to the magnetic curve or line of magnetic force passing through the place where the crystal is.[234]

Tyndall's memories are vivid, attesting to Faraday's "unique way of doing science."[235]

In his studies of Faraday as an experimentalist,[236] Gooding has examined his experimental processes and concludes that Faraday was good at learning from nature how to do experiments. According to Gooding an experiment is shaped by the technical and observational processes and reworked till anyone can perform it. At this point, what had been a personal, tentative experience is transformed in the public domain into an indisputable fact, independent of the location and the people involved. Gooding points out the skills of observation and techniques essential in the process of experimentation, the presentation and the communication of new information gained about nature that are demonstrated by Faraday in his efforts to improve his experimental skills and win nature as his collaborator.[237]

The leading exponents of the new philosophical concerns with experimentation include the editors and the contributors to the reassessment of Faraday as a discoverer, among them D. Gooding, T. Pinch and S. Schaffer.[238] They maintain that there is a consensus that **"**experiment is one of the hallmarks of science" and, that while the results of experiments are important, the process of experimentation is presumed to be unimportant and uninteresting, hence the meaning of it is missed. They maintain that despite the fact that the experimental results, observations, and data are accepted by historians and philosophers as representing nature, study of the practice that makes them so, has been neglected. An account of scientists' engagement with the world is absent; hence no link is evident between

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[234]Tyndall (1870a), pp. 109-120.

[235]Tweney (1990).

[236]Gooding ([1985] 1989), in Gooding and James, eds., (pp. 105-136) Gooding (1990)..

[237]Ibid., pp. 105-6.

[238]Gooding, Pinch and Schaffer (1989).

results and experimental practice. Gooding equates this neglect of the experimental process with the denigration of manual procedures, in favour of cerebral activity, evident in speech, which is respected. Yet an understanding of what scientists do is found in their practical procedures, testifying to their engagement with the social, natural and material world including the use of instruments and manipulation. This practical aspect exposes the real value of what the scientists do, how they interpret their laboratory work for those outside. According to Gooding, an experiment should be seen as an active process of argument and persuasion, focusing on the discovery of the natural world.[239] The philosophical view that the knowledge of natural laws emerges as a result of scientists' observations, theorising and experimenting, Gooding considers too be too limited. It excludes the scientists' interaction with each other and with nature, two activities essential in their endeavour to describe nature. As a consequence of taking this view the natural world is split into two domains that do not interact with each other, an empirical one of "immediate, direct, but unarticulated experience", and another one of the intellect, manifest in "the talk, thought and discourse" that is accepted as representing nature.[240] The experimental repertoire is therefore limited to the testing of theories, thus restricting scientific speculations, and hiding its empirical content. Gooding rejects existing descriptions of empirical access, because they exclude the practice, the inventiveness, the procedures and informal aspects of science, elements made visible in Tyndall's practice as demonstrated in Chapter 3 of this thesis.

Gooding sees the need for a convincing theory of observation to enable an empirical access to the representation of nature. To achieve it, Gooding resorts to a scientific process ignored by modern analytical philosophy, namely the observation of nature through the interaction of observers with each other and their instruments as well as the material world. Treating empirical access as a cognitive and a social process enables an understanding of the experience of new phenomena and how they are communicated to others. This is achieved, he suggests, by the scientists' interaction with, an often, uncooperative nature, as well as with uncooperative

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[239]Ibid., p. xiii.

[240]Ibid., p. xi.

people.[241] In the absence of an acceptable theory of observation, Gooding argues in favour of an alternative view based on those elements of scientific work that have been ignored by modern analytical philosophy. The new experience of the phenomena under investigation needs to be represented and communicated. These actions depend on an awareness that promotes the training of the sensory responses and is improved by interaction with other observers and the natural world.[242]

Gooding is concerned with the process of legitimising the empirical accomplishment of experimentation in the private world of laboratory and the skills needed to transform that experience into a shared environment via a semantic ascent to a world of discourse, generalisation and argument. The plasticity, or what I would call the flexibility of a new experience, is important to artists as well as scientists, argues Gooding in the name of Wittgenstein, especially if working on their own. To summarise, Faraday's work demonstrates the available empirical practice.

2F. Rayleigh's v. Tyndall's and Faraday's Mathematics

Another important aspect of Tyndall's style and method of science is the way in which he used mathematics. It is informative to note the differences in the uses of mathematics by the Cambridge-educated physicists such as Rayleigh and by those from other backgrounds, such as Faraday or Tyndall.

2F.1. Mathematisation of physics

The mathematisation of physics was one of the most important enterprises of the nineteenth century science according to Harman.[243] There has been a consensus among historians that whereas the French mathematics flourished at the turn of the nineteenth century, in contrast British physics was in the doldrums; as a result concept formation and methodological innovation that relied on a harmonious blend of the relation between theoretical and experimental practice, lagged behind in Britain.

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[241]Gooding (1990).

[242]Gooding (1990), p. xii.

[243]Harman (1985), p. 1

To ameliorate this situation, motivated by the work of the French mathematicians, Joseph Louis Lagrange, Comte (1736-1813), Pierre-Simon Laplace (1749-1827) and Sylvestre Delacroix, the Cambridge-trained mathematicians, George Peacock (1791-1858), John F. W. Herschel (1792-1871), William Whewell (1794-1866), Charles Babbage (1792-1871), and George B. Airy (1801-1892) among them, established the Analytical Society in 1812 dedicated to the revival of the application of mathematics to the solution of physical problems. This activity was thriving in France, and exemplified in the researches of A. J. Fresnel (1788-1827) into optics and in J. B. J. Fourier's (1768-1830) study of the propagation of heat.[244] There are no records of any formal activities of the Society beyond 1813. The names of the founders and active members, however, were also associated with the establishment of the Cambridge Philosophical Society in 1819, the Astronomical Society of London in 1820 and the British Association of the Advancement of Science in 1831, indicative of their crucial influence in the development of British science and in particular the role of mathematics in it.[245]

In Britain in the early nineteenth century, optics, electricity and magnetism were subjected to a rapid mathematisation, making them inaccessible to the non-mathematically trained men of science. Professional mathematicians educated in Cambridge and Trinity College Dublin dominated the study of theoretical physics. Mathematics and physical science underwent a change in the first half of the 19th century to include new relations between mathematics and scientific theory, based on an analytical relationship between mathematics and physics.[246] Mathematics itself also altered, with the introduction of an infinitesimal analytical calculus introduced from France by Peacock, Herschel, Babbage, Airy and Whewell. The new mathematics from France provided better problem-solving methods, more appropriate to physical analysis than Newton's fluxional calculus. The infinitesimal calculus became a part of the competitive tripos examination in Cambridge, enabling theories

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[244]Darrigol (1994), pp. 113; Harman (1985) p. 6, 95-113.

[245]Ashworth (2004-2011), in Oxford DNB article: Analytical Society 2011-5

[246]Cantor (1983), pp. 147-50; Kuhn, T. (1976), pp. 7, 1-31.

to produce numerical predictions that could be compared to experimental results.[247] Calculus became closely associated with the solution of physical problems through the use of just a small number of differential equations. Physical problems almost became identified with the mathematical techniques employed to solve them. Fourier's mathematisation of heat propagation was established through using calculus. Working on the historiography of light theories, Geoffrey Cantor notes although they had mostly been previously formulated by analogy the 19th century saw the introduction of mathematically based light theories. That by Fresnel for example, demonstrates the shift towards mathematics, representing the new physics.[248] It was also used by Ohm to solve problems in electricity.

2F.2. Rayleigh's mathematics

The future third Baron Rayleigh, John William Strutt (1842-1919) started his undergraduate training "less advanced in mathematical reading than the best of his contemporaries,"[249] despite a good education in arithmetic and geometry by the age of ten. The experience of academic training and interaction between the processes of research and examination, and the relationship between students and tutors in Cambridge have been investigated by Andrew Warwick.[250] Rayleigh, after spending five years at public schools, including Eton and Harrow, and a continuous mathematical training at home, in 1857 at the age of fifteen, entered the Rev. George Townsend Warner's School at Highstead, Torquay. Here he took mathematics lessons from the tutor, Lewis Hensley. After competing unsuccessfully for a Trinity College scholarship, Rayleigh returned home in early 1861 to be coached in mathematics by a Trinity College scholar, Frederick Thompson. Public school pupils aiming for Cambridge in the 1860s would study dynamics, statistics, hydrodynamics and

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[247] Cantor (1983), pp. 147-150.

[248] Ibid., pp. 15-19

[249] Strutt (1924). In Rayleigh scientific papers vol. 1, p. 24.

[250] Warwick (2003).

differential calculus in addition to arithmetic, algebra and geometry.[251] It has been argued that Rayleigh's background was not typical, since Cambridge students came from a variety of backgrounds, but they were all subsequently subjected to a rigorous and systematic programme of training. [252] The custom of examination questions providing clues to future research produced a vast number of results and techniques which Rayleigh and his contemporaries appeared to have "found it extremely difficult to keep track of…"[253] Evidently the questions that yielded such a preponderance of useful consequences were well thought out, but the level of knowledge required of students to make use of them was deficient. The author of Rayleigh's obituary, the physicist Arthur Schuster (1851-1932) provided a succinct comment on Rayleigh's procedures to overcome "accessory complications" in a mathematical discussion:

> The problem is always concisely stated, and the mathematical discussion is reduced to its simplest form by the omission of all that is not important. If we were called upon to define the quality of Rayleigh, the work, which forms its characteristic feature and marks his individuality, we should, I think, agree that it lay in his unfailing sense of what is essential in each problem, while he courageously left accessory complications to take care of themselves.

The first paragraph of his paper on " Some Electromagnetic Phenomena considered in connection with the Dynamical Theory" deserves quotation in full, because it is probably the only example in the history of science in which the first few lines, written by a young man for publication, are so typical of the procedure to which he adhered throughout his life:

It is now some time since the general equations applicable to the conditions of most electrical problems have been given, and attempts, more or less complete, have been made to establish an analogy between electrical

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[251]Opitz (2008), vol. , pp. 547-550.

[252]Harman, ed. (1985), p. 1-2.

[253]Warwick (2003), pp. 158-59.

phenomena and those of ordinary mechanics. In particular Maxwell has given a general dynamical theory of the electromagnetic field, according to which he shows the mutual interdependence of the various branches of the science, and lays down equations sufficient for the theoretical solutions of any electrical problem. He has also, in scattered papers, illustrated the solution of special problems by reference to those which correspond with them (at least, in their mathematical conditions) in ordinary mechanics. There can be no doubt, I think, of the value of such illustrations, both as helping the mind to a more vivid conception of what takes place, and to a rough quantitative result, which is often of more value, from a physical point of view, than the most elaborate mathematical analysis. It is because the dynamical theory seems to be far less generally understood than its importance requires, that I have thought that some more examples of electrical problems with their mechanical analogues, might not be superfluous.[254]

Rayleigh resumed his researches in optics at the time that Tyndall published his investigations on the cause of the blue colour of the sky. [255] Rayleigh assumed the medium conveying light was supposed to possess the properties of an elastic solid. According to Stokes, there was a fundamental unresolved question: was the direction of the vibration in a polarized ray parallel or at right angles to the plane of polarization? Tyndall's experiments had shown that the blue light scattered from small particles was polarized in a direction perpendicular to that of the incident beam. Rayleigh explained that, when the particles were small compared with the wavelength of the incident light, the intensity of the scattered beam varied inversely as the fourth power of the wavelength. Before working out this theory, the prismatic composition of the blue of the sky, as compared with sunlight, was examined experimentally, and had been found to be in good agreement with the theoretical laws.

In conclusion, Rayleigh’s training enabled him to employ the mathematics with confidence, expressing the physical results of his researches in a universally

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[254]Rayleigh (Scientific papers, vol. 1, 1924, pp. iv-v)

[255]Tyndall (1868-69), 17, 223-233.

recognisable form by other mathematicians without the ambiguities of the particular meaning attached to it. In contrast in the next two sections Faraday's and Tyndall's methodologies will be examined, methods that, yielded spectacular contributions to physics despite their limited knowledge of mathematics.

2F.3. Faraday's mathematics

Faraday was aware of the shortcomings of his mathematical knowledge, as limiting "his comprehension of the work of others."[256] Nonetheless Agassi marvelled at Faraday's mathematical intuition; without even basic understanding of the new potential theory and no mathematical training, he was able to make use of it to increase the explanatory power and the precision of the field theory.[257] Maxwell in a letter to Faraday expressed his appreciation for this work and mentioned the theory's application to gravitation.[258]

Faraday's lack of mathematical knowledge caused him an embarrassment on another occasion when he remarked:

> I am unfortunate in a want of mathematical knowledge and the power of entering with facility into abstract reasoning. I am obliged to feel my way by facts closely placed together...the habit I got into of attending too closely to experiment has somewhat fettered my powers of reasoning and chains me.[259]

Over the years varied opinions have been subsequently expressed on Faraday's mathematics. When Maxwell realised how well Faraday's ideas lent themselves to his mathematisation by means of the differential equations, he declared Faraday a magnificent "intuitive mathematician.[260] Tweney considers Faraday to be a

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[256]Gooding (1982), pp. 243-259, 246.

[257]Agassi (1971), pp. 92-3.

[258]Maxwell to Faraday 9 November 1857, in James, ed. (2008), vol. 5, pp. 301-3.

[259] Faraday to Ampère 3 September 1822, in James (1991), vol. 1, p. 287.

[260] Maxwell (1855), 10, 27-83.

visual thinker, hence a geometrician.[261] Darrigol concluded that Faraday knew no mathematics; instead he enhanced experimental procedures, improving his apparatus.[262]

Gooding studied mathematics and methods in Faraday's experiments, [263] concluding, "One of the most striking aspects of Faraday's scientific work was his near total neglect …of mathematical analyses of physical phenomena". Gooding discerns a "qualitative and geometrical reasoning in the development of some of Faraday's experimental arguments" but also posited that Faraday "seldom recorded and manipulated quantitative measurements or used equations." Gooding attributes Faraday's apparent lack of interest in mathematics to his aversion to the use of mathematics in the interpretation of nature as shared by followers of revealed religion, including the Sandemanians in the eighteenth century. They recommended that scientists should study the book of revelations first, followed by the book of nature. Mathematics as a human construct had no place. Mathematicians' language to describe nature was said to be unnatural. Faraday regarded the mathematician's attitude to nature less trustworthy than the experimentalist's, since the former anticipated nature, "treating hypotheses as necessities or…as certainties, rather than as mere possibilities." Faraday's irritation with "the high mathematicians" anticipation nature without submitting it to experiment provoked him to entitle a series of electrical investigations his "experimental researches." In a letter to Mary Somerville, Faraday doubted the predictive ability of mathematics with very few exceptions.[264] He remarked that it might be possible to compare the convertibility of electricity, gravity, cohesion, and chemical affinity… and from their effects deduce their relative equivalents.[265] According to Cantor, although Faraday avoided quantitative conclusions, he used the ratio of the products of decomposition as a constant, a useful

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[261] Tweney (1989), in Gholson, Shadiish, Jr, Neirmeyer, Houts, pp. 342-366, 352.

[262] Darrigol (2000), p. 39.

[263] Gooding (1992).

[264]Faraday to Mary Somerville, in Patterson (1983), p. 135.

[265]Faraday (1849), vol. 1, second edition, pp. 537, par. 1686.

and a familiar concept for his purpose. Many measurements were made and many calculations performed, but he did not endeavour to produce abstract representations of the quantities involved. [266]

There appears to have been a tension underlying his resistance to mathematics however. In Gooding's view, Faraday's hostility to quantification prevented him from producing effective arguments regarding the constancy of electro-chemical decomposition. Also, thinking that Joule's 1856 paper aimed at establishing mathematical foundations of the nature of the electro-magnetic forces[267] would be too mathematical for him, Faraday declined to act as his referee.[268] Reluctant to accept mathematical solutions unless adduced by experimental evidence, with his "rough geometrical mode of looking at things…[and] having no mathematical knowledge," Faraday did not feel competent to judge whether "Joule's data were adequate for the aim of the paper." In due course Tyndall,[269] W. Thomson and W. Miller[270] acted as the referees.

In examining the qualitative and geometrical reasoning in some of Faraday's experimental arguments, Gooding describes his mathematical method as the geometry of fast processes, consisting of patterns that represented the variables. These patterns were brought momentarily to a halt by means of techniques developed by Faraday for the investigation of optical deceptions and acoustical figures.[271] When converted into dynamic models, they illustrated the interaction of electricity, magnetism and motion before his discovery of the electromagnetic induction in 1831 to which I discuss in this thesis, Chapter 3. Gooding also noted Faraday's use of curves as representations

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[266] Cantor (1991), p. 218.

[267] Joule (1856), 146, 287-295.

[268] Faraday to Weld, 6 July 1855, in James, ed. (1999), vol. 4, p. 881.

[269] Tyndall, 25 July 1855 RS MS RR 3.155.

[270] Thomson and Miller RS MSS RR.2.252-253

[271] Faraday (1831a), Faraday (1831b).

in his research publications. Faraday's public pronouncements on mathematics were thought to be more discreet, than those expressed in private.[272]

2F.4. Tyndall and mathematics

In a Presidential address to the Mathematical and Physical Sciences Section of the British Association for the Advancement of Science in 1868, Tyndall expounded his views on the place of mathematics in science and in particular its link to physics:

> Mathematics and Physics have been long accustomed to coalesce…While mathematics as a product of the human mind, is self-sustaining and nobly self–rewarding, while the pure mathematician may never trouble his mind with considerations regarding the phenomena of the material universe, … the mode of reasoning which he employs, the power which that organisation of that reasoning confers, the applicability of the abstract conceptions to actual phenomena, render his science one of the most potent instruments in the solution of natural problems…without mathematics …our knowledge of physical science would be friable in the extreme.[273]

The question Faraday puts to Maxwell, however, suggests that communication could be improved between experimentalists and mathematicians:

> When a mathematician …has arrived at his own conclusions, may they not be expressed in common language as fully, clearly and definitely as in arithmetical formulae? … would it not be a great boon to such as I to express them so? … translating them out of their hieroglyphics, that we also might work upon them by experiment.[274]

According to Olesko, the widespread quantification in Germany in the 19th century in various walks of life, but the sciences in particular, was the consequence of

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[272]Ibid.

[273]Tyndall (1869), in RBA pp. 1-6.

[274]Faraday to Maxwell (13 November 1857), in James, ed., pp. 305-6

gradual improvements to the precision of experimental procedures.[275] Unlike experimental demonstrations, mathematical proof was accessible to very few people.[276] However, according to Gauss, in a German university, candidature for the professorship of physics required a very good knowledge of mathematics, but they should also be able to address a mixed audience, be a keen and skilful experimenter, be well informed in all branches of science and produce publications of the high standard expected by the Göttingen Society of Sciences. The candidate would also be involved in research in mathematical physics, in electromagnetism in particular.

Tyndall first received training in mathematics from his headmaster in Ireland. In his work as a surveyor he would have performed measurements with the theodolite. One of his tasks at Queenwood College was teaching mathematics in an English village. His first encounter with higher education in Germany included the experience of formal teaching by the mathematician Stegmann, who in addition to the teaching as part of the university syllabus, gave Tyndall free private lessons on calculus, in particular infinitesimal calculus that had been instrumental in the development of mathematical physics from the eighteenth century. Tyndall's PhD degree was in mechanics or applied mathematics, on screw surfaces. Frankland credited him with a high level of mathematical ability, and was not surprised when Tyndall turned from chemistry to physics. In the results of his researches, Tyndall drew an occasional graph, tabulated his results and employed arithmetical calculations.

2G. Tyndall's Role in the research tradition at the Royal Institution

William Spottiswoode (1825-1883), the treasurer of the Royal Society and the Royal Institution in 1873 reviewed "the past history and scientific results and the future prospects of the laboratory" at the Royal Institution.[277] The goals of the R.I. at the time of its establishment in 1799 were, "to diffuse the knowledge, and facilitate the introduction of useful inventions and improvements; and to teach by courses of lectures and experiments, the application of science to the common purposes of

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[275]Olesko (1995), in Wise,ed., pp. 103-134, 103.

[276]Warwick (2003), pp. 1-48, 29-30.

[277]Spottiswood (1873), 263-265.

life."[278] The Royal Institution was conceived in the proposals of Benjamin Thompson Count Rumford in 1798. In a letter to his friend, Colonel Baldwin, he referred to an undertaking of very great importance that would prevent him from visiting America just then. He wrote with conviction that "the success of the undertaking will be productive of so much good, and it will place me in so distinguished a situation in the eyes of the world and of posterity" that he was unable to refuse assistance.[279] The undertaking referred to was the establishment of the Royal Institution. The outline of the institution appeared first in the Rumford's essay of 1796.[280] Reflecting on what could be done "to diffuse the knowledge and facilitate the general introduction of such improvements" that may lead to useful results for the benefit of the poor, a report was submitted to the Society for the Improvement of the Condition and Increasing the Comforts of the Poor. The response of the founder member of the Society, Thomas Bernard included the recommendation that the plan be immediately put into effect in London.[281] Rumford envisaged stimulating "the spirit of inquiry and of improvements amongst all ranks of society", and recommended seeking the governmental approval of the plans. The committee, appointed to discuss the matter with Rumford, concluded that the proposed institution would be "extremely beneficial and interesting to the community."[282] An ambitious laboratory was planned: "This laboratory will be equal, or indeed superior, to any in this country, and probably to any on the Continent."[283] The appointments of the first professors of natural philosophy, Thomas Garnett (1766-1802) and his successor Thomas Young (1773-1829), were of short duration. Best known as lecturers at the Royal Institution, they appear to have had little impact on the establishment of the R.I. Bence Jones attributes this to the presence of Rumford. Garnet left the Institution in 1801. Young's remarkable researches that led to his discovery of the interference of light and the establishment of the wave theory

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[278]Spottiswood (1873), 7, 223-225,

[279]Rumford to Baldwin 14 March 1799, in Bence Jones, vol. 1, p. 65.

[280]Rumford (1796), essay number 2.

[281]Bence Jones (1870), p. 114.

[282]Ibid., pp. 116-137.

[283]Spottiswood (1873), 223-224, 263-265.

of light were enunciated in his Bakerian lecture of 1801 at the Royal Society, and first published in the syllabus of the lectures he delivered at the R.I. This took the form of two volumes in 1807 of *The Elements of Natural Philosophy* and constituted a milestone in the literature of the progress of science. The appointment of Humphry Davy early in 1801 heralded the development of the R.I. into a unique organisation where numerous great scientific discoveries of the nineteenth century took place. Many of them sprang from the momentous researches of Michael Faraday at the R.I., who having forsaken his career as a bookbinder's apprentice became the greatest scientific discoverer of his age with Davy as his mentor. Humphry Davy (1779-1829) appointed by Rumford as an assistant to Garnett in 1801, at first best known as a popular demonstration lecturer, was also making use of the laboratory for the analysis of minerals and soils. By 1806-7 Davy had turned the laboratory into a centre for fundamental research, isolating potassium, sodium and the alkaline earth metals, barium strontium, calcium, and magnesium.[284] He also offered to accept several pupils and instruct them in the running of the laboratory where various tests could be performed on demand. "Such a plan would gratify many persons."[285]

Sophie Forgan indicates the uncertainty of the goals of the Royal Institution regarding the work in the laboratory.[286] Was it to be scientific research or instruction, exact science or useful knowledge? Scientific research was not mentioned as one of its aims either in the original charter, or in the 1810 Act of Parliament when the membership status changed from proprietors to members subscribing at regular intervals. In the 1840s its educational and research functions were competing for facilities. Although the institution had always embraced an educational aim, the formal plans of instruction were abandoned[287] when school of chemistry planned since 1843, did not come about. Sir Benjamin Collins Brodie, (1783-1862) who was responsible for these plans, had reservations about the dual character of the laboratory. William Thomas Brande (1788-1866) also expressed concerns about the

[284]Knight, in James, ed. (2002), pp. -117; Harold Hartley ([1972] 1978), pp. 60-1.

[285]Bence Jones (1871), p. 269.

[286]Forgan (1977), pp. 122-169

[287]Ibid., p. 169

plans, urging the abandonment of the teaching function of the laboratory where research was conducted.

Thus research activities came to be recognised as the main goal of the institution. It was during the 1850s that research was however first named as the institution's main objective. A revised Prospectus of 1851, the first since 1830, updating the R.I.'s original objectives, included for the first time a reference to research functions. Forgan regards it as a significant change, in particular, since it headed the list of objectives.[288] Only a year later in 1852, however, this was amended to the promotion of scientific and literary research. Forgan sees it as a return to the older tradition describing the R.I. "as a cultural society covering the whole field of learning."[289] The presence of the qualified young physicist Tyndall who had shown his aptitude and enthusiasm for research and the diffusion of scientific knowledge would have coincided well with the Royal Institution's aim of promoting research at that time.

William Thomson had acted as referee when Tyndall's seminal paper was chosen as the Royal Society Bakerian Lecture for 1855. His report on this paper provided just the right sort of document to promote Tyndall as candidate to bring the Institution fame. W. Thomson wrote to Stokes and W.H. Miller about the paper: the letter is reproduced almost in its entirety as it conveys the turmoil among the scientists concerning the new force of diamagnetism:

> Theoretical conclusions derived from another experiment constitute in my opinion a longer and a very important addition to the knowledge of diamagnetism previously existing and very well deserving of a place in the Transactions of the Royal Society. I enclose another piece of paper notes of some trivial changes by which it appeared to me some points might be rendered rather clearer with some leaves of memoranda hastily put down in reading it. As regards the publication of it in the Transactions I think there

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[288] Forgan (1977), p. 149.

[289]Ibid., p. 150.

is so much of important and curious experimental investigation in it, for instance the directional and absolute effects and words as experiments on compressed powder of bismuth described in the appendix the numerical results [illegible] as ever since done, the relative forces of repulsion on the same mass held in different position. The investigation in which Mr Tyndall first showed what I think no other experimenter has ever since done) a case of magne-crystallic action depending on three principal axes at right angles to one another with 3 different inductive capacities and so much of interesting illustrations and reactions experienced by and produced by diamagnetism.

Still I think that (especially with reference to the title of the paper) Mr Tyndall is frequently contending a [illegible] an imaginary adversary. In fact except for Feilitzsch whose “theory” is founded on a mistake most obvious from the beginning and in my opinion not worthy of more notice than very shortly to point out that mistake. All Mr Tyndall's experiments and views are in perfect accordance with those indicated by Faraday from the beginning and advocated by myself as early as 1846 in the ? by myself uniformly on many different occasions of which short Reports have been published in the British Association volumes, the Philosophical Magazine and in the Comtes Rendus. The real question is “are the phenomena presented by diamagnetics to be explained by contrary magnetization to that of soft iron, or by a less magnetization than that of the medium (air or luminous ether) surrounding them. Which ever be the true result, the resultant action is undoubtedly the same as that which would be experienced by a small magnet with its axis reversed and therefore Mr Tyndall's experiments which amply confirm the view forced on us by Faraday… that the resultant action is such as that which does not at all contribute to a foundation of any theory in which one or the other alternative is essentially involved. Impressed with this belief I could wish much modification to be made in the controversial part of the communication, but should Mr Tyndall be

> disposed to making no change, I should advise its publication as it stands...[290]

The year 1852 was momentous in Tyndall's life. With the resignation of Professor Brande, and the encouragement by Bence Jones and Faraday, Tyndall became a candidate for the vacant professorship.

Burchfield views Tyndall's public career in science, as having been established on firm foundations laid by Faraday. Faraday, who saw Tyndall as his successor, was also dedicated to original research as a "primary function of the institution."[291] I. R. Morus comments on the complexity of procedures that allowed Faraday's experimental work in the basement to be recognised as a place where knowledge was produced. Public activities in the lecture theatre and the library on the first floor and the enthusiasm of the crowds attending the functions were essential to the appreciation of the experimental work in the laboratory, as the discoveries made there were the source of scientific advancements made for the benefit of the attending public. Faraday's so called 'private space' and the public space complimented each other.[292]

At a Friday evening discourse on the 11 February 1853 delivered by invitation, Tyndall addressed the distinguished audience at the Royal Institution for the first time.[293] Tyndall's future was at stake, his talents were on trial. To the concern of the R.I.'s future secretary Henry Bence Jones, Tyndall spoke without notes. He regaled the R.I. members and their guests with a controversial theme that had exercised humanity over generations. In Tyndall's world this was "the system of the universe", a subject embracing matter and force, the two most familiar words in the language. His first discourse presented Tyndall as a scientist differing from Faraday in a persuasive manner in the experimental results and their interpretation, partly due to

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[290]Thomson to Miller and Stokes 16 April 1855.

[291]Burchfield (2002), pp. 147-168.

[292]Morus (1998), p. 42.

[293]Tyndall (1851-1854), vol. 1, pp. 356-359, reprinted in Bragg and Porter, eds. (1970), vol. 1, pp. 78-83.

a different way of viewing the universe of matter and the agencies of forces in relation to it. He envisaged, for example, that heat conduction occurred due to motion among particles or atoms of matter that served as stepping-stones for its transmission. He appealed to the authority of an experiment by De la Rive and Candolle regarding the transmission of heat through wood along two axis at right angles to each other, the heat travelling at different velocities along each axis, the wood fibres of each possessing a different molecular structure. Tyndall recalled his own extension of this experiment when he discovered a third thermal axis along which heat travelled at a slower velocity than the other two. Similarly, magnetic phenomena displayed the composite character of conduction determined by the manner of aggregation of its molecules. It is interesting to note the inconsistent use of the words atoms and molecules, when applied at that time to particles of matter. In his demonstration experiment Tyndall compared the behaviour of two manufactured iron bars of the same size, but of different mechanical structure. In his view it was this structure that accounted for their different deportments with respect to magnetism. He broadened the significance of the experiment by varying the parameters, employing shale and a crystal of nickel sulphate “where nature herself has imposed the conditions of material aggregation.” He then analysed Plücker's experiments.

Faraday’s testimonial to the Committee of Managers at the Royal Institution indicated his high opinion of Tyndall’s researches on diamagnetism although they contradicted some of Faraday’s own conclusions on the subject.[294]

> In consequence of a recommendation from Mr Faraday the managers are desirous of proposing you for election as Professor of Natural Philosophy…We had a very full meeting and all were for you. Mr Gassiot spoke highly of you…Your lecture of Saturday was highly approved.[295]

He wrote to the editor of the *Philosophical Magazine* the day after Tyndall’s first discourse:

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[294]Archives of the R.I. MM vol. 13 pp. 13-15 ?

[295]Bence Jones to Tyndall 23 May 1853, p. 682.

> Tyndall gave us an excellent discourse last night delivered in an admirable manner.[296]

Tyndall's experimental virtuosity and his first discourse in February 1853 at the Royal Institution led to his appointment to the chair of Natural Philosophy. This marked the beginning of his association with the R.I. that continued for the next thirty-four years as professor of natural philosophy, and on Faraday's death in 1867, his successor as Resident Professor, superintendent of the house and the Director of the Laboratories. As a physicist, it would have been unrealistic to expect Tyndall to also inherit Faraday’s mantle as the Fullerian Professor of chemistry, a prestigious position to which Odling, Professor of chemistry at Oxford, was appointed. Tyndall’s role in the R.I.'s research tradition is evident in his programme of research into diamagnetism, an area of interest that he shared with Faraday.

Tyndall's first Bakerian Lecture to the Royal Society in 1855 reflects Tyndall's attributes as a researcher. He now was accorded a supportive environment and allegedly the best-equipped laboratory in Britain. Space, however, was limited and moves were afoot to improve the conditions. Faraday, Feitzlich and Matteucci contended the polarity of the diamagnetic force suggested by Tyndall. Tyndall, convinced of the polar nature of the diamagnetic force, continued to devise methods designed to invalidate the opposition. In 1856 Tyndall decided to adapt Weber's method of demonstrating polarity, suggesting an adjustment of Weber's apparatus to make it more versatile. Weber consented, confirming that astatic magnets, evidently suggested by Tyndall, would improve the performance of the instrument, which was promptly constructed under Weber's supervision. Tyndall evidently having read with care Faraday's comments on the deficiency of the apparatus used by himself do detect the diamagnetic polarity, was struck by the qualities of the new apparatus overcoming the previous disadvantages. Tyndall was assured that

> ... we have seen the objections raised against the diamagnetic polarity fall away...and a body of evidence accumulated in its favour, which places it among the most firmly established truths of

[296]Ibid., p. 486.

> science mainly to be attributed to the bold and sincere questioning of the principle when it seemed questionable.[297]

The following year Faraday wrote to Tyndall, by then Professor of Natural Philosophy at the Royal Institution:

> I have left its science in very good keeping and am glad to hear that you are at Experiment…as for the fruits I am sure they will be good, for though I despond of myself I do not for you…our subjects are so glorious that to work at them rejoices and encourages the feeblest delights and enchants the strongest…[298]

2H. Conclusion

Tyndall's first independent research publication on diamagnetism was based on the work he carried out in Berlin in the department of G.H. Magnus.[299] He was provided with experimental facilities and a lively intellectual environment in the company of the most eminent physicists in Germany. By then he had gained a PhD degree under the tutelage of Bunsen, Gerlich, and Stegmann, and had accumulated research experience in Knoblauch's laboratory at Marburg. Knoblauch had delegated the replication of Plücker and Faraday's work to Tyndall. Tyndall recalls their frequent discussions, and they published two papers together.

Through conducting a meticulous examination of the work of Faraday and Plücker, the most eminent workers in diamagnetism, Tyndall was able to establish his scientific authority and expertise, and attracted the interest of Weber, Thomson and Maxwell in a fecund debate that was so underestimated by Burchfield. Tyndall compelled attention to his research through the sheer excellence of his experimental work. Tyndall's approbation of Faraday's experimental approach is expressed in his comment, "he never accepted a negative answer to an experiment." He was also impressed by the extent of Faraday's "exhaustive researches" that exposed the

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[297]Tyndall (1870).

[298]Faraday to Tyndall 28 June 1854, in James, ed. (1996), vol. 3, 705.

[299]Tyndall (1851).

phenomenon of a new pervading force. His intensive training under Bunsen provided a discipline similar to that detectable in Faraday's dedication to the task in hand in "nature's school."[300] Tyndall's researches, must have been disconcerting to him because they contradicted the conclusions of Faraday and Plücker, but would have been a very instructive inquiry. The research required a heuristic approach, and would have been useful in broadening of Tyndall's appreciation of the role of empirical input in the formulation of theoretical frameworks. Faraday's view of the laboratory as a site to mimic nature within the boundaries of "what happens in nature" also appealed to Tyndall. As the result of engaging with the research on diamagnetism, using the approach outlined above, Tyndall published his first independent paper in September 1851. His first independent communication on diamagnetism submitted to the Royal Society was honoured as a choice for the Bakerian lecture of the year,[301] despite the fact that in it Tyndall argued against the theoretical findings of the established scientists, Plücker and Faraday.

When Tyndall was being considered for the Royal Medal award, Tyndall's official placements in Knoblauch's and then Magnus's laboratories were wrongly interpreted by some Fellows of the Royal Society. They assumed that the work had been carried out jointly by Tyndall, first with Knoblauch, then Magnus. Yet this was not the case. Knoblauch delegated the work to Tyndall, Magnus simply supplied apparatus at Tyndall's request as the need arose. When informed by Faraday and Gassiot of the lack of unanimity in the council after the formal nomination, encouraged by his two mentors, Tyndall declined the medal.[302]

Nonetheless, as an experimentalist, Tyndall became one of the distinguished researchers of nineteenth century. According to Burchfield, Tyndall succeeded in fulfilling Faraday's ambition to establish the primacy of research within the Royal Institution. He accomplished this "through his own considerable scientific achievements, which earned him a deserved place in the upper ranks of his

[300]Gooding, in Gooding and James, eds. (1989 [1985]), pp. 105-135.

[301]Tyndall (1855), pp. 1-52.

[302]Tyndall (1851), 1 (4), 265-295.

contemporaries."[303] Burchfield attributes the reputation of the Royal Institution under Tyndall as a centre for research, to the interests and reputation of its Resident Professor, as with Davy and Faraday before.[304] This was not recognised by all of his peers. P. G. Tait taunted that Tyndall had forsaken his authority as a research scientist through his extraordinary success as a populariser. This is reiterated in Burchfield's mixed assessment because he also asserts, "Tyndall's research did not open important new fields of inquiry."[305] Burchfield here betrays his unfamiliarity with Tyndall's research publications. I contend that Tyndall's publications in research journals of the day reveal that every paper contains contributions to scientific knowledge, broadening its scope, clarifying confusion, and building on existing knowledge. During the early years of his research Tyndall consolidated the knowledge he acquired as a student at Marburg. In Berlin as an independent researcher, engaged on a prestigious project examining the work of Faraday and Plücker, he exercised the critical faculties and the judgement for which he would later be so respected. From very early Tyndall worked among the elite of scientists as their equal, at ease with their way of thinking and familiar with their style of scientific attitude.

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[303]Burchfield, in James, ed. (2002), p. 148.

[304]Ibid., p. 167.

[305]Burchfield (2004), in Lightman, ed. (2004), pp. 2053-2058.

CHAPTER 3

The Experimental Researches of John Tyndall

This chapter will identify Tyndall's original experimental innovations, and distinguish them from replication of his predecessors' experimental methods. On occasion he acknowledged debt to these predecessors. Among those he referred to were: W. Herschel (1738-1822), the Hanoverian musician who settled in Britain and became an astronomer famed for the discovery of Uranus; physicist Count Rumford Benjamin Thomson (1753-1814), founder of the Royal Institution; J. Leslie (1766-1832), the Scottish natural philosopher; Baron J.B.J. Fourier (1768-1830), a French mathematician with interest in the nature of heat; C. Pouillet (1791-1868), the French physicist; W. Hopkins (1793-1866), the British geologist and mathematician; and M. Melloni (1798-1854), the Italian physicist.[306] In section 3A I will discuss the experimental procedures of Tyndall's predecessors that held epistemological value for Tyndall. Tyndall's own experimental methods will be evaluated in section 3B. Section 3C will trace the controversy between Tyndall and the German chemist and physicist G. Magnus (1802-1870).

3A. Experimental Procedures of Herschel, Leslie and Melloni

The most tenacious ideas and experimental methods that shaped the science of radiant heat in the first half of the nineteenth century are found in the experimental research of Herschel, Leslie and Melloni. Others did make contributions to elucidating the nature and properties of radiant heat phenomena, however their research will be viewed in the context of chapters two and four. The relationship between radiant heat and light came to dominate the debate on their properties and experimental results were used in arguments supporting at times a unified, at other times a pluralistic theory as has been analysed by H. Chang and S. Leonelli.[307] The work of these three researchers, and that of others, has already been studied by historians and philosophers of science over the years, hence this section will refer mainly to the secondary literature.

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[306]Tyndall (1861a), 151, pp. 1-36, 1.

[307]Chang and Leonelli (2005), 36, pp. 477-508.

3A.1. William Herschel, Accidental Pioneer of the Science of Radiant Heat

Through the discovery of the variety of heating effects in different colours of the light spectrum and the presence of these effects beyond the visible red region, Herschel unintentionally inaugurated the experimental study of radiant heat and its relation to light. This section will investigate this research that was particularly significant for Tyndall. R. McRae credits Herschel with having done more for the science of radiant heat and light than any of his predecessors. Moreover his contemporaries took up his work with alacrity.[308] An original experimental investigator of this elusive subject, Herschel played a pivotal role in attracting the interest of the eminent natural philosophers both in Britain and notably in France.[309] His extensive publications in the *Philosophical Transactions* of 1800 were widely read and led to more experimental investigations. After 1800, however, Herschel never again participated in radiant heat research.

Herschel structured his experimental procedure using questions which defined the issues of the character of radiant heat. These were dictated by Herschel's concerns as a natural philosopher and teacher from whom his successors, including Tyndall, had much to learn despite Leslie's onslaught. As McRae points out,[310] Herschel employed the existing apparatus routinely used in optical and heat investigations. However, he also extensively and productively used prisms and screens, items that had hitherto seen only limited applications. A prism was used by Herschel to demonstrate the existence of obscure heat rays from the sun.[311] Herschel's preliminary observation included a discovery of interest to other experimentalists: when glass prisms of different colours are used to observe the sun, they produce different degrees of heat and light intensities. Hilbert has reviewed Herschel's studies of radiant heat, particularly in reference to Herschel's early conclusion that the most

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[308]McRae (1969), p. 53

[309]Crosland (1967), pp. 274-275, 299, 353, 24.

[310]Note 3, McRae, p. 55.

[311]Ibid., McRae, p. 62-63.

intense light did not necessarily produce the most intense heat sensation.[312] According to Hilbert, every relevant historical study mentions Herschel's experiments. To twentieth century writers Herschel is the pioneer of infrared physics. The physicist, T. Preston published a work on the theory of heat in the 1890s that claimed "to treat the science of heat in a comprehensive manner, so as to produce a tolerably complete account of the whole subject in its experimental and theoretical aspect." Preston includes Herschel's name among the founders of the systematic study of heat.[313] Interest in Herschel's research waned after his death but was revived later in the nineteenth century, stimulated by Tyndall's experimental programme on the thermal properties of gases.

Herschel's investigations of radiant heat included interest in the phenomena of reflection, refraction, refrangibility, and scattering by rough surfaces and absorption, properties known in light phenomena.[314] In a pioneering experiment Herschel demonstrated the reflection of invisible solar rays using a metal concave mirror. An intense heat developed in the focus of the mirror, without the presence of luminous radiation. This demonstration was instrumental to Tyndall's separation of thermal and luminous radiation. Observing heat radiation from the coal fire, Herschel noted the internal reflection of heat rays at the hypotenuse surface of a glass prism, an indication that the rays were not all being absorbed by the glass. Heat radiation from any heat source could be focused through a lens. Although it was taken for granted by later generations of researchers, Herschel's discovery, that Snell's law of refraction and the sine law applicable to light also applied to heat radiation, was momentous. He then compared the propagation and scattering power of certain media, within the limits of his apparatus, of which he noted the shortcomings.[315] Subsequently, Herschel investigated the absorption of heat by certain substances for rays from different sources. As heat sources he used the sun, a candle flame, a coal fire, a stove, an incandescent, glowing or non-luminous poker, and an iron block heated to

[312]Hilbert (1999), 56, 357-378, 357.

[313]Preston [1894] 1919, pp. v, 7, 560.

[314]Note 3, McRae, pp. 66-67.

[315]Ibid., p. 72

redness.[316] This pioneering use of terrestrial heat sources[317] was a practice later adopted by both Melloni and Tyndall. The use of screens, also pioneered by Herschel, became an essential feature of radiant heat research by Melloni and Tyndall. In conclusion, Tyndall's generation of radiant heat researchers constructed their research programmes on the basis of discoveries resulting from the fecund ideas and experimental procedures of Herschel and his contemporaries. Although Herschel's work was rarely acknowledged, his successors' progress is clearly indebted to the impact of his research.

3A.2. John Leslie

John Leslie (1766-1832) was known to Carlyle by hearsay as 'the mathematical Leslie' and described by Cardwell as a member of the great Scottish school of science. He was also one of the pioneers of the experimental studies of radiant heat that provided Fourier with the evidence necessary for its mathematisation. Tyndall himself considered Leslie and Rumford's work as having been the most significant for the progress of the science of radiant heat.[318] Leslie's work was recognised in 1804 by the award of both Royal Society Rumford Medals, one for his contributions to the science of heat and a separate one for his contributions to the science of light (despite an early scepticism that had delayed publication in the *Philosophical Transactions*). This section examines the work of Leslie that was valued by Tyndall. As Rumford's rival, Leslie had to contend against a popular figure, the founder of the Royal Institution. Luckily for Leslie however, by 1804 Rumford had severed his connections with Britain, and settled permanently in France [319] In Olson's investigations into the history of the nature and propagation of heat at the turn of the nineteenth century, he describes a strong competitive element, "an intense personal rivalry ... for more than a quarter of a century" that played out between these two contemporary protagonists. Benjamin Thomson, Count Rumford

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[316]Ibid., pp. 67, 72-74, 78.

[317]Ibid., p. 66.

[318]Tyndall (1882a), 173, pp. 291-354, 291.

[319]Knight, in James, ed. (2002), pp. 97-113, 97-108.

(1753-1814) was a supporter of the dynamic theory of heat as a mode of motion. His rival and adversary, John Leslie (1766-1832) Professor of Mathematics (1805-1819), then Professor of Natural Philosophy (1819-1832) at the University of Edinburgh, supported material theories of radiant heat.[320] McRae reports Leslie's criticism of Herschel's experimental work,[321] and this is also relevant to Tyndall's research since the subject continued to attract disputes over experimental issues among men of science. Leslie's condemnation of Herschel's experiments may have acted as a stimulus to his own work on radiant heat. Criticism was also likely to attract the attention of the scientifically minded to a particular field of interest, thereby encouraging further research.

Through a programme of experiments, Leslie intended to discover the nature and properties of radiant heat, remarking that, "... no part of physical science appeared so dark, so dubious and neglected." Thomas Wedgwood's encouragement and a habitual independence of thought led Leslie to the study of natural philosophy. His remarks indicate his incentives: "the human condition [is] improved by acquaintance with the laws of nature .… The promise of a new world …" Here he possibly referred to the new millennium, as well as a prospect of peace with France; his visit to America may have also been a factor, while his discovery of "a few connecting principles" also encouraged him in these endeavours.[322]

In order to examine the propagation of heat in detail, Leslie aimed at isolating and identifying the influence of each element in this complex process. Through the use of the photometer he concluded that the air between insulated bodies played a part in the heat transfer between them. The important role he assigned to air led to his investigation of the influence of the densities of the permanent gases (including hydrogen, carbon dioxide and nitrogen) in the propagation of heat. Rarefying air increased its heat capacity, the temperature of dry air fell, the heat capacity of water

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[320]Olson (1970), 26, (4), pp. 273-204, 274.

[321]Both references are interesting: McRae (1969), pp. 85-88, is the author of a highly regarded PhD thesis; Oxford Dictionary of National Biography (2004-2012) provides up to date reference.

[322]Leslie (1804), pp. iii-xv.

was lower than that of its vapour. The properties of matter could be studied from the thermal properties of its surface. Radiant heat was distinguished from the other thermal phenomena by its heterogeneity.[323]

One can discern Leslie's influence in Melloni and Tyndall's experimental procedures. Leslie created powerful reflectors made of large tin plates, their surfaces bright, smooth and regular as concave as possible, focusing sunlight best when their diameter did not exceed half an inch, were used in a vertical position. To minimise any aberration in the focus due to reflection, parabolic shapes of different sizes were preferable to the segments of hollow spheres. He worked with models made of mahogany, favouring replication of experiments on a large scale. He advocated heat sources of a large mass to avoid rapid cooling before their regular effect could be determined. He thought hot water an excellent heat source, because its large heat capacity allowed its temperature to be measured accurately. In 1804 Leslie invented a new instrument in the shape of a cube. This served the generations of experimenters as a steady heat source for nearly a century. The symmetry of the cube meant that all sides were at the same angle to the reflector.[324] Identical sides were covered with different materials that enabled a comparison of the respective thermal properties of these materials, their emissivity and absorptive powers in particular. The temperature of the heat source varied between 100-200 degrees Centigrade, according to whether the cube contained water or oil. Leslie looked for the cause of the effects of these different surfaces on "the energy" of emission, and how they influenced the temperature. He demonstrated that the anterior surface of the focusing agent played a part. The nature of the surface of the reflector was also important; mirrors produced different effects from those of the tin reflectors. Paper and cloth caught fire when heat was focused efficiently. He showed a relationship of the same order between absorption and emission.[325] The foundation of the scientific basis of meteorology, hence the study of the solar heat and its distribution over the earth, as well as of the

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[323]Ibid., pp. vii-xv.

[324]Olson (1969), 25 (3), pp. 203-208.

[325]Ibid., pp. 1-17.

interaction of air and moisture, were important to Leslie.[326] He also used other gases for the purpose including hydrogen, carbon dioxide and nitrogen.[327]

Leslie's stated intentions and his contributions to the knowledge and understanding of the phenomenon of radiant heat also played a crucial part in Tyndall's experimental and theoretical development. For Leslie observations fulfilled an essential function since they acted as correctives of theories. At the time he thought that considering the state of physics, precision and accuracy determined the usefulness of experiments. In the discussion of precision and accuracy in connection with experiment, the design, construction and deployment of instruments becomes paramount. The experimenters' awareness of the usefulness of experiment and its limitations is important. According to Hilbert, Herschel's experiments encouraged the study of the nature of radiant heat and its relation to light.[328] Leslie also attached importance to the studies of artificial heat as it had application to "comforts or elegant luxuries of life." He produced the first effect of refrigeration using dry air.[329] Although superseded by the thermopile, Leslie's differential thermometer to record small temperature increments may have suggested to Tyndall the use of the thermopile in the differential mode. Leslie also noticed that the inverse square law applied to the relation connecting the distance from the heat source and the intensity of heat radiation. Like Rumford, Leslie identified the different means for the propagation of heat by convection, conduction and radiation, a distinction essential to a successful prosecution of the science of radiant heat.[330] In his 1818 paper he remarked on the dependence of the heat propagation on the constitution of the bodies: "The progress of heat through different bodies depends on their peculiar constitution, and varies… in its rate."[331]

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[326]Leslie (1813), pp. iii-iv; 1-8, 17-18, 37, 103.

[327]Ibid., p. 31; Leslie (1818), 8, pp. 470-473.

[328]Hilbert (1999), 56, pp. 357-378, 358.

[329]Leslie (1813), p. 176.

[330]Olson (1970), 26, pp. 273-304.

[331]Note 22, Leslie (1818), p. 468.

McRae considers Leslie's experimental contributions to radiant heat phenomena "significant and pioneering."[332] Hilbert[333] sums up Leslie's experimental work as significant, and includes in it Leslie's demonstration of the power of the blackened surfaces to absorb radiant heat faster than of the polished ones. This work by Leslie, essential to the correct understanding of the study of the mechanism of thermal absorption and radiation, was replicated and taken further by Melloni who also looked for a theoretical backing for Leslie's results.[334] Tyndall's subsequent investigations of the nature of matter included further studies of the role of the different surfaces in the process of the polarisation of radiant heat as well as its emission and absorption by matter. In summary Leslie's influence was profound. Some apparatus devised by him is still in use. Melloni and then Tyndall embraced Leslie's observations and discoveries; Melloni applied them to propel the science of radiant heat; Tyndall advanced the science of the nature of matter by the use of radiant heat as an analytical tool on a bigger scale than had been done hitherto.

3A.3. Macedonio Melloni

Another model of a research physicist for Tyndall was the Italian physicist Melloni. Melloni pioneered a programme of research to study the propagation of radiant heat through liquids and solids, concentrating on the nature of the luminous and obscure thermal radiation. During a crucial time for his work in the 1830s, he was obliged to seek political refuge in France and Switzerland, he later returned to Italy in 1839 as the Head of the Observatory in Naples and director of instruments, only to be stripped of his official posts in 1849 because of the resurgent unstable political situation in continental Europe.

Chang and Leonelli have investigated Melloni's experiments of 1833 that led to important findings on the interaction of radiant heat with liquids and solids.[335] They trace his work on the different refrangibilities of radiant heat as analogous to different

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[332]McRae (1969), p. 86.

[333]Hilbert (1999), 56, pp. 357-78

[334]Melloni to Jacques Binet 2 February 1845, in Schettino (1994), pp. 343-351.

[335]Chang and Leonelli (2005), 36 (1), pp. 477-508, 487.

colours of the light spectrum.[336] Although Herschel had previously demonstrated this concept of the nature of radiant heat, Melloni's work, in my view, imposed a coherent character on the phenomenon of radiant heat, and subsequently enabled Tyndall to apply radiant heat as an analytical tool to study the nature of matter.

Until the invention of the thermocouple by L. Nobili (1784-1835),[337] Melloni had been handicapped by a lack of suitable apparatus to study radiant heat. Melloni adapted the thermocouple to detect the distant thermal radiation from very weak heat sources, while remaining insensitive to the temperature variations of the surrounding air. The instrument could detect the heat radiated from a human twenty five to thirty feet away. To improve its efficiency, the thermopile was covered with lampblack. Melloni recorded his own contribution to Nobili's invention in a letter to the Academy of Sciences in Paris, February 1833, suggesting its use in conjunction with an astatic galvanometer.[338] Melloni also increased the number of the bismuth/antimony bars. The length of the circuit, however, was maintained by shortening the individual elements of it as suggested by Fourier and Oersted. Melloni found that up to thirty degrees, the deflection of the galvanometer needle corresponded to the difference in temperature between the adjacent faces of the thermocouple; for large deflections he devised a conversion table calibrating the galvanometer to ensure the correct recording of the quantity of heat.[339] His mathematical rigour enabled him to interpret the readings of the needle in terms of the true heat radiation occurring on the basis of the experimental evidence, equating back to the corresponding deflections lower down the scale. Tyndall made extensive use of Melloni's thermo-pile, adapting it to his purpose. Melloni's joint paper with Nobili[340] marked the end of the initial exploration of the possibilities that the new instrument provided. Melloni followed this with a pioneering research programme, the

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[336]Ibid., pp. 487-489.

[337]Melloni (1850), pp. xii-xiii.

[338]Melloni (4 February 1833), in Schettino (1994), pp. 108-111.

[339]Melloni (1850), pp. 32-34.

[340]Melloni and Nobili (1831), 48, pp. 198-218.

importance of which has not diminished with time, which also ushered in the era of the analytical infrared spectroscopy according to Barr.[341] Some experiments confirmed previous findings, others were examining phenomena which had not been looked at. The arrangement of Melloni's apparatus was probably adapted from an optical bench. Tyndall used the same system, introducing the changes essential to inaugurate his entirely new scientific enterprise, the study of the interaction of radiant heat with matter in its gaseous phase.

Melloni aimed at systematising the interaction of radiant heat and matter in the liquid and solid state. At the Paris Observatory, before an audience including D.J.F. Arago (1786-1853), A. von Humboldt (1769-1859) and P.L. Dulong (1785-1835), he and L. Nobili (1784-1835) demonstrated the passage of radiant heat through optically transparent liquids. They concluded that in addition to their diathermancy, a more dominant influence was their power to refract the rays of radiant heat. These unambiguous experimental findings were fundamental to Tyndall's experimental work in relation to the structure of matter. According to Melloni no absorption was detected by the passage of radiant heat through the vacuum or the air.[342] Replication of these experiments led Tyndall to improved procedures and consistent results.

Melloni, aware of the conflicting opinions on the effect of different heat sources on the absorptive power of bodies including air, devised an experiment using a Locatelli lamp and an incandescent platinum spiral as luminous heat sources, and a copper sheet heated by an alcohol flame and hydrogen or oxyhydrogen flame as obscure sources. They influenced heat absorption by glass screens. Tyndall in his preliminary experiments made use of the same heat sources as Melloni[343] who also discussed with P. Prévost (1751-1839) the absorptive power of water,[344] concluding that the heat from the obscure sources was absorbed by a layer of water only two or three mm deep, whilst the heat from a luminous source was transmitted. F. Delaroche

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[341]Barr, (1962), 2, pp. 62-74, 68.

[342]Melloni (1850), p. 136.

[343]Melloni (1837b), 1, p. 41.

[344]Melloni to Prévost 9 April 1831, in Schettino (1994), pp. 96-101, 98.

(1781-1813) reported similar results for glass. Tyndall also pursued this method of studying the difference in heat absorption and radiation according to the amount of liquid present. In his 1833 paper, Melloni embarked on the study of the propagation of thermal radiation through liquids and solids, aware that not enough attention had been paid to the influence of the internal structure of bodies on their thermal properties.[345] Tyndall, the first to plan an experimental programme on the subject, discovered the diathermancy of the elementary and the athermancy of compounds bodies. This had crucial significance for science, meteorology in particular.

Melloni also examined the influence of identical transparent screens, increasing their thickness in an arithmetical progression from 0.5 mm to 10 cm. In passing through layers of a homogeneous medium, the radiant heat diminished according to the distance from the surface at which it entered, but the heat by conduction remained constant.[346]. Melloni's investigations of the absorptive powers of liquid media had an impact on Tyndall's discovery of the relation between the thermal properties of liquids and their vapours. Tyndall also studied the relationship between radiation and absorption independently since, unlike Melloni, Tyndall adopted the dynamic heating and cooling phenomena for that purpose. Melloni's finding that rock salt was diathermic for obscure heat radiation became important to Tyndall.[347] According to Barr, Melloni's experiments with rock salt and its use by him for prisms and lenses with different heat sources meant that some of his experimental measurements were those of roughly dispersed radiation. This comment also applies to Tyndall despite the unjustified criticism that he worked only with undispersed radiation. Of particular interest to Tyndall was the universal adoption of Melloni's thermopile for radiant heat experiments as an instrument of unparalleled excellence. This vast accumulation of data enabled Melloni to discern patterns, and establish systematic procedures in this difficult area of research. In conclusion the importance of Melloni's work has not diminished with time. Some experiments confirmed previous findings; others examined phenomena that had been overlooked

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[345]Note 331, pp. 142-146, 154-162.

[346]Melloni (25.3 and 29.4.1833), in Schettino (1994), pp. 109-114.

[347]Barr (1962), 2, pp. 62-74, 68; Tyndall (1865a), pp. 2, .99-300.

in the past. Tyndall's sound judgement in recognising the importance of Melloni's contributions was unappreciated by his mathematically minded peers.

3B. Tyndall's Experimental work on Radiant Heat and Gases

Tyndall studied the interaction of radiant heat with gases, prodding the structure of matter using radiant heat as an analytical tool. This section examines the experimental techniques he employed in order to establish his innovative original contributions, as distinct from replicating the work of his predecessors. His innovations, resulting from his controversy with Magnus, are studied in Section C.

Tyndall's work elicited approval from Faraday, derision from Tait, and a challenge by Magnus. Tutored in the German University of Marburg by first Bunsen then Knoblauch, (both admired in Britain), Tyndall aimed to gain recognition as a serious scientist through his experimental procedures in an age when Faraday stated; "Nothing is too wonderful to be true if it is consistent with the laws of nature and in such things ... experiment is the best test of such consistency."[348]

Tyndall modelled himself on Melloni[349] and Faraday.[350] Jungnickel and McCormmach assert that the trend in Germany in the first half of the nineteenth century was to confirm and extend research done elsewhere.[351] This included work done by Melloni and Faraday, admired, reported and elaborated there. Tyndall's method can therefore be seen as part of the German tradition within which he received his university education. Tyndall embarked on his work on radiant heat, convinced that aside from examination by Franz and Melloni of the effect of gases on radiant heat, a consensus had been established that gases were inaccessible to experimental methods. Tyndall acknowledged Rumford and Leslie's contributions. With hindsight he remarked that there must have been attempts by other experimenters to examine the absorption of radiant heat by air for this consensus to be

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[348]Faraday Diary for 19 March 1849, in Martin (1932), volume 5, p. 152.

[349]Tyndall (1861a), 151, p. 2.

[350]Tyndall (1970), 3, pp. 50-123, 122, first published 1868.

[351]Jungnickel and McCormmach (1986), pp. 42-43.

so widespread.[352] He hoped to achieve for gases what Melloni had done for liquids and solids. His work led to protracted disagreements with some of his peers. At the heart of his programme of investigations lay his interest in the nature of matter. This also paved the way for a better understanding of the role of the atmosphere in terrestrial climate and the study of the temperature of the intergalactic space.

3B.1. Infra-red Absorption and Radiation by Gases

This section examines Tyndall's pioneering experiments with matter in gaseous phase. As discussed above, the study of the absorption and radiation of radiant heat by various substances was an accepted way of investigating its nature and had been employed by Herschel, Leslie and Melloni among others. Tyndall's predecessors had however, made limited use of gases. Tyndall ascribed this to the difficulty of handling gaseous media. Particular experimental conditions were required to forestall the liability to error. In a brief preliminary announcement to the Royal Society in 1859,[353] Tyndall identified some essential requirements for procedures if the thermal properties of gases were to be investigated: the sensitivity of the galvanometer, the identification and removal of impurities, the use of powerful heat sources, the study of the effect of the temperature of heat sources on the thermal absorption of liquids and their vapours, and the investigation of the thermal absorption and radiation of a large number of gases and vapours in order to gain insight into the nature of matter.

Tyndall's second Bakerian Lecture to the Royal Society in 1861 (the first was in 1855 on diamagnetism) inaugurated a period of publications on this intensive research that lasted for nearly a decade.[354] This was followed by a Friday Evening Discourse at the Royal Institution, chaired by Albert, the Prince Consort (1819-1861).[355] Here, Tyndall introduced this subject to the public, stressing the importance of experimental investigation of the propagation of radiant heat through air and other

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[352]Tyndall (1872f), note p. 8.

[353]Tyndall (1860b), 10, pp. 37-39.

[354]Tyndall (1861a), 151, pp. 1-36.

[355]Tyndall (1862a), 3, pp. 155-158.

gases as “desirable on purely scientific grounds, and also on account of certain speculations … based upon the supposed deportment of the atmosphere as regards radiant heat.” In the discourse, Tyndall also reported speculations originating from J.B.J. Fourier (1768-1830), developed by C.S.M. Pouillet (1791-1868) and W. Hopkins (1793-1866).[356] In an analysis, that preceded an 1872 reprint of his 1861 Bakerian lecture, Tyndall recalled: “... following the methods of observation introduced by Melloni, experiments on air and other gases were executed and recorded.”[357] He adapted Melloni’s expensive thermopile. He also adapted the popular Leslie cube containing either boiling water or oil.[358] This was the most reliable contemporary source for obscure heat with a temperature range of 0-200 degrees that could provide stability, flexibility, consistent results, and was suited to a variety of investigations.[359]

Using Leslie’s cube with water boiling at 100 degrees, Tyndall compared the effect on radiant heat when passed through a vacuum, through air, and through hydrogen gas. Hardly any absorption was detectable in either case. He reasoned that when this feeble heat source was employed, a fraction of the already small amount of heat present would not be detectable. The galvanometer needle would only move through the lower degrees of the scale, covering an infinitesimal, hardly perceptible distance. Using a more powerful heat source at 300 degrees, he successfully demonstrated in the lecture theatre the diathermancy of hydrogen, the powers of absorption of radiant heat, though weak, by the air and a far greater absorption by dry coal gas. Vapours of ether and carbon bisulphide similarly exhibited different powers of absorption, but many times more powerful than those of the elementary gases or air. This pioneering discovery of the very different absorptive powers by elements and compounds preoccupied Tyndall for over a decade. His search for the theoretical explanation of the phenomenon is studied in Chapter 4.

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[356]Ibid., Tyndall, 3, (1862a), pp. 155-156.

[357]Tyndall (1872g), pp. 2-5, 2.

[358]Eve and Creasey (1945), pp. 308-311.

[359]Olson (1969), pp. 203-208, 203, 205-206.

To demonstrate this effect to a large audience, Tyndall fixed a large convex lens above the galvanometer and lit it with the beam of an electric lamp. This beam had been deprived of its heat by passing it through an alum solution, which prevented the disturbing influence of convection. This magnified image of the needle was projected onto a screen by a mirror above the lens.[360] Tyndall may have adapted these procedures from the work of the German physicist W.E. Weber (1804-1891). When away in Germany, he had written to Faraday on the subject.[361] In the 1830s J.D. Forbes (1809-1868) had recorded the use of a telescope in a similar manner to render experimental effects. By 1861, Thomson's mirror galvanometer of 1857 may have also been known to Tyndall and used in preference to a telescope.[362] Tyndall had already lectured on radiant heat in 1856 at the London Institution,[363] but from the notes in his journal,[364] one can surmise that these demonstrations of his research, a part of his planned programme, were performed in public for the first time in February 1861.

[360]Note 343, pp.306-307.

[361]Tyndall to Faraday 24 July 1853, in James (1999), volume 4, p. 540-541.

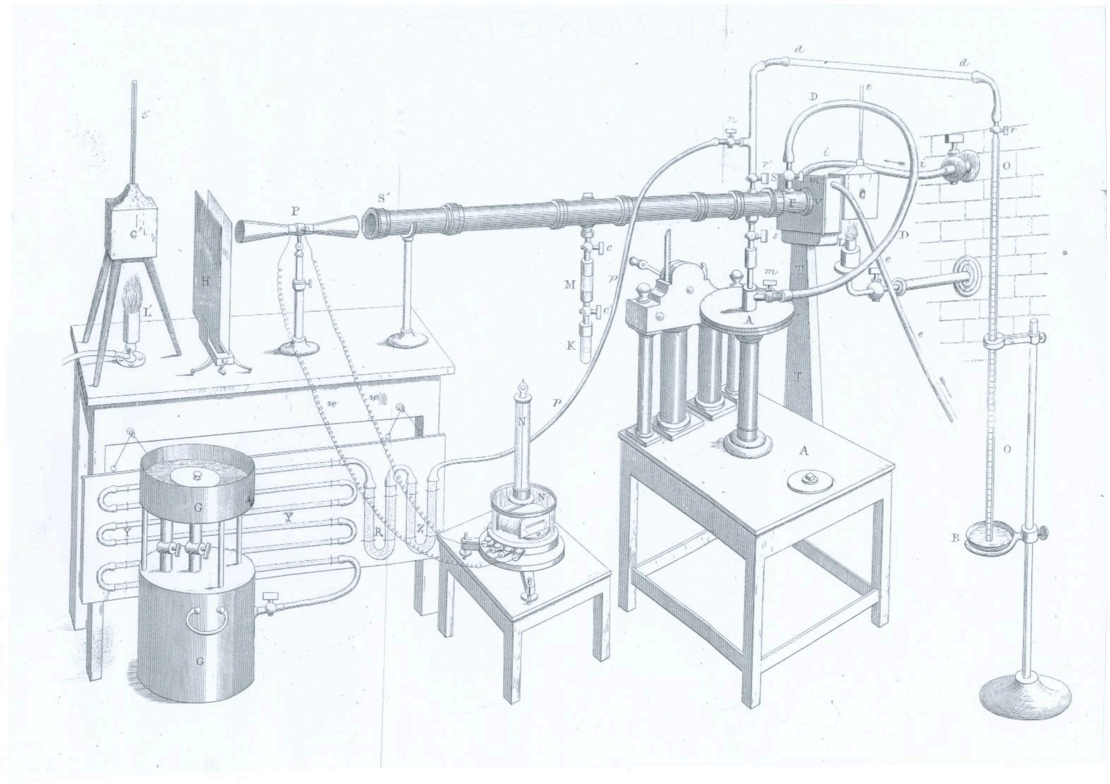
[362]Thompson (1910), volume 1, pp. 347-348.

[363]Eve and Creasey (1945), p. 62.

[364]Tyndall journal 2 November, 1860, in Eve and Creasey (1945), p. 86.

Tyndall's basic apparatus

"A tube … its ends stopped airtight by polished plates of rock-salt … the tube could be attached to an air pump and exhausted, and any … gas or vapour could be admitted into it. A thermo-electric pile … at one end of the tube … a source of heat at the other."



C: copper cube containing boiling water with one face blackened constituting the source of radiant heat

SS': experimental brass or glass tube 4 feet long, 2.4 inches in diameter to contain gases or vapours, each end stopped air tight by a plate of rock-salt and connected to an air pump to be evacuated as required

F: front chamber between source C and the right hand end of the experimental tube connected with the air pump capable of being evacuated independently of the experimental tube

L: gas lamp heating the cube C

P: thermoelectric pile at the opposite end of the experimental tube with two conical reflectors attached to it, serving as a differential instrument

C’: compensating cube neutralising the radiation of the substance passing through the experimental tube

H: double screen with finely adjustable mechanism to move it through small space

NN: galvanometer with astatic needles and non-magnetic coil, connected to pile P, and calibrated according to Melloni’s instructions

YY: six U- tubes contain calcium chloride to remove moisture

R: U-tube containing pumice stone moistened with potassium hydroxide to remove carbon dioxide

Z: U-tube containing pumice stone moistened with sulphuric acid to remove moisture

The first public demonstration of the reciprocity of radiation and absorption by Tyndall happened at a Friday evening discourse in the summer of 1861.[365] Tyndall introduced the subject of heat radiation by gases and vapours in a series of the Royal Institution public lectures, saying “to use the common language, having learnt something of the power of different gases as absorbers of radiant heat, we have now to inquire into their capacities as radiators.”[366] Melloni had remarked in 1847 that heat

[365]Tyndall (1862c), 3, pp. 387-396; in Bragg and Porter (1970), 1, pp. 381-389,.

[366]Tyndall (1861a), 151, pp. 1-36, 29-33.

radiation by transparent gases had not yet been demonstrated.[367] Tyndall began as usual by demonstrating the instrumental arrangement, "by means of which we can test the general principle." He planned to refine the procedure with "more far reaching combinations." Here he revealed the deliberate planning of his experimental programme, at its core the discovery of the thermal properties of gases when exposed to sunlight. He emphasised the importance of experimenting with gases and vapours since they "probe the question of atomic constitution to a depth quite unattainable with solids and liquids".[368]

Tyndall demonstrated the radiation of heat by pure air, adapting Melloni's method to increase the radiation from the alcohol flame by plunging a platinum spiral into it. Melloni had also attempted to record radiation from hot air rising from an Argand lamp by placing a bundle of wire in it, but on removing the wire, there had been no deflection.[369] Using terrestrial sources of heat emitted by a candle, or a gas or alcohol flame, Tyndall obtained a large deflection due to heat radiation by air that had not subjected to drying procedures. He did this by placing a hot iron spatula behind a polished tin screen that separated the heat source and spatula from the pile. The radiation of the air was then neutralised by positioning Leslie's cube so that the needle pointed to zero. Tyndall placed various experimental gases in the ball 'A' noting their deflections.[370] To summarise, he demonstrated a correspondence between the order of absorption and radiation such that substances capable of absorption also acted as radiators of radiant heat. He announced their "correlative properties."[371]

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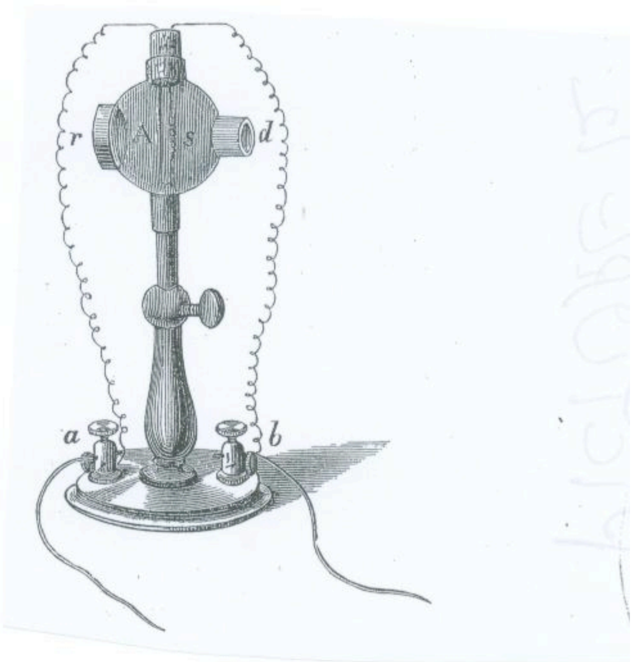
[367]Melloni (1850), pp. 94-95; Tyndall (1872g), pp, 2-5, 4.

[368]Tyndall (1865a), pp. 350-351.

[369]Tyndall (1860b), 10, p. 37-39, 39.

[370]Tyndall (1898), p. 343.

[371]Ibid., p. 344.



Tyndall detected a feeble absorption of heat by elementary gases, and a much more powerful one by compound gases. Although Leslie (p.84 of this chapter) had assigned an important role to air in the propagation of heat between insulated bodies, he was non-committal as to its character. Leslie's opinion on the importance of the water vapour content of the air noted by Tyndall is discussed later in Chapter 5 of this dissertation.[372]

3B.2. Tyndall's Improvements on Experimental Apparatus

(a) The Use of Powerful Heat Sources

Tyndall reasoned that because of the rarefied character of gases, in order to study their absorption of heat, one had to render even a minute change large enough to be registered by the galvanometer linked to the thermocouple. Since a large deflection of the galvanometer would deviate significantly from the true measurement

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[372]See pp. 195-222

of the thermo-electric current, Melloni's method for calibrating the galvanometer, (routinely adopted by Tyndall) allowed for the necessary adjustment of the data. Like Melloni, Tyndall used four luminous and obscure heat sources, ranging from 100-300 degrees Centigrade. Investigations by Herschel and Leslie had employed solar and terrestrial heat sources to explore the similarities and difference between luminous and thermal radiations.

According to Melloni, one essential condition for success was a source with a steady temperature. To increase the sensitivity of his apparatus, Tyndall devised a compensation method. He used two sources of radiant heat on opposite faces of the thermopile. The screens placed in the front of the sources cancelled the effect of thermal radiation on the galvanometer and its needle pointed to zero. Tyndall tried other powerful sources of obscure heat such as copper balls containing fusible metals or oil at high temperature. These unstable heat sources did not produce consistent results on replication. Tyndall described this period as 'an incessant struggle with experimental difficulties'. Since he aimed at 'exact measurements,' he looked for a steady supply of powerful heat. He therefore employed a specially constructed lamp. This produced a constant flame and was controlled by a gas regulator made for the purpose. A sheet of this constant gas flame heating a copper plate resulted in an appreciable deflection that would require significant absorption to produce the comparable diminution in the current. However this arrangement was also rejected in favour of the constancy of boiling water. He concluded that a source of lower temperature, apart from a few exceptions, was acceptable or even preferable for most gases and all the vapours.[373] A powerful heat source was essential only in certain circumstances. One such instance was when the brass tubes were replaced by glass to combat the corrosive effects of chlorine. A powerful heat source required three conditions: an increase in the sensitivity of the galvanometer in the presence of strong currents, and the elimination of convection and conduction.[374] Since glass was less reflective than brass, a weak heat source was not good enough at times to reveal variations in absorptive powers of different gases. Since Tyndall wanted to observe

[373]Tyndall (1861a), 151, pp. 5-6.

[374]Ibid., p. 24.

what was taking place at all times, a transparent tube was preferable for experiments with hydrochloric or hydrobromic acids, as these were liable to form dense fumes in the presence of water vapour. The state of knowledge on this subject of research warranted a trial and error approach. Exploration of the appropriate experimental procedures, and isolating and identifying the essential conditions to obtain a steady heat supply would ensure a consistency in replication. With this settled Tyndall could testify to the consistency of the natural phenomenon under investigation. As Faraday wrote: "Nothing is too wonderful to be true if it is consistent with the laws of nature ...experiment is the best test of such consistency." [375]

(b) Eliminating the Effects of Conduction and Convection

Tyndall protected the apparatus from disturbances due to convection and conduction, to ensure a steady supply of heat from a powerful heat source. Melloni had already attempted this. Melloni had understood that the immediate propagation of radiant heat and the corresponding response of the instrument, forestalled the delayed effects of conducted heat. Tyndall took another tactic however by taking steps to minimise the effect of the conducted heat on the pile. He avoided direct contact between the gas (or vapour), the heat source or thermopile, and immersed the front chamber F, in a vessel V, through which cold water circulated. This vessel intercepted any heat due to conduction, which might otherwise have reached the experimental tube. To improve protection against conduction and convection, Tyndall planned to abolish the air space between the heat source and the anterior end of the experimental tube in the original arrangement, but this procedure risked lowering the temperature of the source through the processes of conduction and convection. Instead, a second tube or front chamber of the same diameter, but shorter than the experimental tube, became a link between the heat source and the anterior end of the experimental tube. This link could be evacuated independently and was also protected by a copper hood. These adaptations meant that radiation from the heat source could enter the experimental tube almost unaffected by its passage through the link. A copper plate was heated to nearly 300 degrees using a lamp that provided a flame produced by the

[375]Faraday (19 March 1849), in Martin, ed (1932-36), vol. 4, p

ignition of a mixture of gas and air. To ensure steadiness and prevent flickering of the flame, the lamp was surrounded by pasteboard, towels and screens of wire gauze. The compensating cube, the double screen and the thermopile were protected by hoarding.[376] Although Melloni had taken steps to protect his apparatus, fewer details are available in his publications, and this appreciation of the need to control or eliminate extraneous effects is characteristic of Tyndall's meticulous approach. This care is not evident to such an extent in the work of his predecessors or contemporaries.

(c) Galvanometer

In his description of the instruments required for his programme of research, Tyndall gave priority to the need for a 'first class' galvanometer. These were constructed for him by a well-known Berlin-based technician, Sauerwald. Its needles were suspended in such a way to prevent interference with the enclosing glass shade, even when this was reduced to a minute area to avoid aerial currents. The glass cover was placed close to the needles to ensure a precise reading of the deflection by either the naked eye or a magnifying lens. To improve the sensitivity of the galvanometer, Tyndall adopted the so-called 'compensating method'. First he converted the galvanometer into a differential instrument by connecting each of the two wires wound round the needle to two separate thermopiles, so that the currents generated by the powerful heat source were flowing in opposite directions. The position of the piles was adjusted so that the currents of the two piles balanced each other when the needle pointed to zero. The use of strong heat source ensured that even a small absorption could be detected when the experimental gas radiated heat on to the face of the thermopile, with the needle at its most sensitive position. Equilibrium was destroyed when heat was radiated through the evacuated experimental tube, causing the needle to deflect. When the gas filled the tube, absorption lessened the deflection of the needle.

In 1852, as co-editor and reviewer for the *Philosophical Magazine*, Tyndall had reviewed the work of Magnus. Here he showed interest in thermo-electric

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[376]Tyndall (1863a for 1862), 152, pp. 59-98, 59-61.

currents and speculated on the potential and drawbacks of contemporary apparatus and the problems of the magnetic effects in the construction of the galvanometer that might distort experimental results.[377] In his 1862 series of lectures Tyndall described Melloni's use of Nobili's astatic galvanometer to prevent interference from the earth's magnetic field on the deflection of the galvanometer needle of the thermopile. He endeavoured to make further refinements of the thermopile in an entirely original way. The coil supplied by a Berlin factory for Magnus[378] and Melloni, was made of copper that had been purified to remove traces of magnetic impurities such as iron. Tyndall thought this method too laborious. Instead he tested samples of copper for their diamagnetic properties, revealing the presence of the magnetic impurities. He commissioned the German technician Becker to provide him with the purest copper wire of the type used by the electrophysiologist Du Bois Raymond, thereby reducing impurities from thirty percent to three percent. This copper then satisfied the sensitive diamagnetic test devised by Tyndall, and he could identify the green dye of the insulating tape as another source of the magnetic contamination. Once this was replaced by white tape, and he had ensured the components were handled with clean hands he had solved the problem. In his appendix to the lecture inaugurating an afternoon course of the 1862 Royal Institution lectures on heat, Tyndall provided notes for students on the construction of an astatic galvanometer adapted to the study of radiant heat.[379] Tyndall's notes were an extended version of those that Melloni and Nobili had made to serve professionals. Both Tyndall's and Melloni's versions appeared in a single volume edition 'for the use of younger students'.[380] Using the underlying geometry of the galvanometer, Tyndall accounted for the absence of correspondence between the amount of heat falling on the thermopile, and the action of the needle beyond a 30-degree reflection. Melloni had described how this could be corrected using a small circuit to divert the current, but Tyndall used a conversion

[377]Tyndall (1852), S. 4, 3, pp. 81-92, 82-86.

[378]Tyndall (1865c), p. 29.

[379]Tyndall (1865a), pp. 19-22; Melloni (1850), pp. 30-48.

[380]Tyndall (1872f), pp. 51-55.

table that Melloni had compiled[381] to calibrate the galvanometer and correctly interpret the quantities of heat that caused large deflections.[382]

Tyndall replaced the use of the galvanometer with the thermo-electric pile as a differential instrument. In the nineteenth century the compensator or null method was probably modelled on the best-known example, that of Wheatstone's Bridge. In Tyndall's case a second heat source was placed in front of the opposite face to that already exposed, and an adjustable screen separated the second face from its facing heat source. The position of the screen was adjusted until the heat falling on the posterior face of the pile equalled that received by the anterior face nearest to the experimental tube. When point the needle pointed to zero, it indicated equilibrium had been achieved. No current was flowing through the pile, as there was no difference in temperature between the two exposed surfaces. Evacuating the experimental tube then introducing a gas to it destroyed the equilibrium; a deflection of the thermopile recorded the thermal absorption of the gas.[383] In conclusion this pioneering procedure of adapting the existing components of the setup as differential instruments, provided the necessary flexibility to achieve the most favourable experimental conditions.

(d) Preparation of Gases by Chemical and Electrolytic Methods

Unlike Melloni, Tyndall detected weak absorptive powers of the elementary gases as compared with those of the compound gases. The preparation of the gases exposed the importance of maintaining very high standards of care to ensure that the results were not affected by the presence of any impurities, even in very small quantities that were undetectable by chemical means. Tyndall's social and professional network played a part in the different sources of the chemicals available to him, including the presence of Frankland at the Royal Institution since Faraday had partly retired.

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[381]Ibid., pp. 56-58.

[382]Melloni (1850a), pp. 54-63.

[383]Note 367, Tyndall, 152, pp. 59-98, 60.

Elementary gases, including oxygen, were prepared according to instructions in chemistry textbooks. Compound gases were obtained from the substances provided by some of the most eminent chemists of the day, including Frankland, Williamson and others. Tyndall mentioned disadvantages, but did not specify them; however in a note he indicated that the disparate results of absorption by the two samples of methyl alcohol provided by two different ‘chemical friends’ were probably due to the presence of impurities. The absorption by the two samples differed by 250%; the one subjected to purification displayed a far lower power of absorption.[384] When Oxygen was prepared by chemical method from potassium chlorate and manganese peroxide was virtually diathermic producing a deflection of one degree.[385] When it was obtained by the electrolysis of water and passed through eight tubes of potassium iodide, it produced the same results, but when it was not freed of its small quantity of ozone, the absorption was three times greater. Powerful heat sources produced still greater differences of absorption of oxygen both alone and in the presence of ozone which was produced in greater quantities than before.[386] Tyndall employed two methods to produce oxygen electrolytically. In the presence of a large platinum electrodes facilitating the passage of electric current by the reduction of resistance through the acidified water, hardly any ozone was produced. If the procedure was repeated in the presence of small electrodes it produced oxygen accompanied by greater quantities of ozone, this considerably increased the absorbing power of the elementary oxygen. Tyndall speculated that the amount of ozone produced during electrolysis depended on the current density at the electrode where oxygen was evolved. Tyndall was gratified that another researcher mentioned by A. de La Rive, M. Meidinger had arrived at the same conclusions through different procedures. The presence of ozone, too small to detect by chemical means, made a vast difference to the power of absorption of oxygen, quadrupling the results. The experiments on ozone carried out at first in a brass tube, were then repeated in a glass tube with identical

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[384] Note 365, Melloni to Prevost 9 April 1833, in Schettino (1994), pp. 96-101, 98.

[385] Ibid., p. 7.

[386] Ibid., p. 8.

results. The speculations on its composition are discussed in Chapter 4 Section C.5. pp. 163-166.

Hydrogen, whether prepared chemically from zinc and sulphuric acid or by electrolysis of water displayed a negligible power of absorption. Despite several hundred experiments performed by Tyndall, the very small deflection indicating negligible absorption prevented Tyndall from arranging the elementary gases in any preferential order of absorption, as he could detect no clear difference between them. Traces of impurities made a significant impact on the results. He nevertheless ventured to consider hydrogen on the basis of his experiments as the most diathermic of all.[387]

In contrast to the elementary gases, olefiant gas displayer the very high absorptive power of 80% prompting Tyndall to ensure that there were no extraneous factors interfering with the result. He submitted the gas to optical examination in case any cloudy effect indicated the presence of water vapour, but the results were negative. He removed the hygroscopic rock-salt stoppers to verify they were not responsible for the effect, but the absorptive power of the olefiant gas remained the same. Moreover when atmospheric air was sent through the same path as the olefiant gas and, and also reached the temperature of the cold water present, its absorptive power remained very low.[388] When atmospheric air was being used, one had to ensure that any moisture or carbon dioxide had been removed. In view of the controversy with Magnus, Tyndall devised improved ways of removing these impurities. These improvements will be referred to in the next section. In the reports of other researchers in this field the presence of the extraneous constituents as being potentially undesirable, is not discussed. Tyndall's originality as an experimenter sets him out from among his peers.

(e) The Dynamic Heating of Gases and Vapours

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[387]Ibid., Tyndall, p. 85.

[388]Note 375, Tyndall, pp. 9-10.

In his first significant paper delivered at the Royal Society, his second Bakerian lecture on radiant heat in 1861, Tyndall observed that the expansion of the dry air into the evacuated tube was capable of provoking considerable heat radiation by any vapour present in the tube.[389] Evidently the adiabatic phenomenon was occurring, serving as a natural heat source, enabling the vapour to absorb the heat generated, and radiate it in turn. Tyndall determined the difference in temperature between when the air was allowed to expand into an experimental tube containing alcohol vapour, and when it was pumped out. He realised that this phenomena represented an opportunity to replace an external heat source with a naturally occurring one. Tyndall used this method to establish the relationship between radiation and absorption.[390] Adiabatic heating and cooling phenomena had been recognised for some time. To confirm the phenomenon at the lecture, Tyndall performed an experiment whereby the thermocouple was soldered directly to the exterior of the experimental tube, which was evacuated. When air entered the tube, the galvanometer needle recorded a temperature increase; on evacuation the deflection of the needle indicated a fall in temperature. Tyndall also repeated the experiment with thermometers fitted into a perforated experimental tube. The temperature rise and fall was recorded as expected, giving the difference between the maximum heating and cooling of 5 degrees Fahrenheit. The intermediate effects registered by the deflection of the galvanometer needle were fully accounted for by the subsequent steps in which radiation rapidly followed absorption; the cooling was due to radiation by the vapour as it expanded into the tube, replacing the withdrawn air; absorption occurred as air entered the tube, compressing the vapour. Tyndall demonstrated the absorption and radiation of the alcohol and ether vapours by dynamic expansion and compression of the air.[391] His theoretical conclusions will be discussed in Chapter 4.

Tyndall justifiably referred to the application of this technique without an external heat source as novel and it produced very accurate results in the study of the

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[389]Ibid., pp. 32-33.

[390]Note 379, Tyndall, pp. 74-80.

[391]Ibid., Tyndall, 72, pp. 76-80.

relationship between absorption and radiation. From experiments on about twelve alcohol and ether vapours without an external heat source, Tyndall observed a correspondence in their order of absorption and radiation. He obtained the same results in experiments with these vapours using an external heat source. The same order of absorption by vapours at 0.5 inches pressure was recorded in both cases. This fecund technique, applying dynamic gas phenomena to the study of the interaction of radiant heat with gaseous bodies, yielded reliable results.

3B.3. Different Absorbing Powers of Different Gases and Vapours

Experimenting with a variety of gases and vapours, Tyndall concluded that heat absorption took place to different extents and that the absorptive power of gases and vapours varied as much as those of liquids and solids, over a large range. This was a significant statement in view of the initial studies of the diathermancy of the elementary gases found in the atmosphere. The order of the absorptive power of the vapours corresponded to those of their liquids. When the mass of matter in the liquid was the same as that in the vapour, the numerical results were identical. Tyndall attached great importance to this experimental result, drawing important theoretical conclusions discussed in chapter 4 p. 159 of the dissertation.

Tyndall was guided by Melloni's methodical investigations of liquids, but in devising new conditions for the investigation of gases and vapours with respect to radiant heat, displayed a profound knowledge of the physics underlying their behaviour, and a considerable ingenuity, perseverance, and dexterity. Tyndall was capable of working with trial and error or rule of thumb; he hinted at the elaboration of a consistent method in his remarks to Hirst at the early stages of his research.[392] As Tyndall himself asserted, the disdain which some of Tyndall's peers showed with regard to his experiments may have been partly due to their lack of awareness of the difficulties to be overcome.

Melloni at first confirmed the results of F. Delaroche that absorption of heat increased with a rise in temperature of the heat source. The absorption by pure rock salt, however, was the same irrespective of the temperature of the heat source. His

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[392]Tyndall (1861a), volume 151, 1-36, p. 5-6.

experiments in conjunction with Forbes, however, had convinced him that the absorption of prepared rock salt increased with the decreased temperature of the source. Melloni subsequently changed his mind about the results that apparently confirming those of Delaroche, since the heat transmitted was not purely of the radiant kind. Because of these contradictory results, Knoblauch re-investigated the subject and concluded that any variations in the power of absorption were only due to the structure of the substances under investigation, not the quality or temperature of the source.[393] To in order to further test the effect of different heat intensities, Tyndall adopted the method of the American chemist J.W. Draper (1811-1882)[394] whereby a platinum spiral was heated in stages. Through these stages it produced first obscure heat, then redness, then incandescence that generated luminous heat. By preserving the same substance as a heat source, Tyndall was able to gauge the influence of one single variable, the intensity of heat exercised on the absorptive power of the experimental substance. Using the platinum spiral heated to different temperatures, Tyndall concluded that differing heat qualities of the source made a difference to the order of the absorptive power of some liquids and their vapours. He concluded that the absorptive power of substances *decreased,* since the vibrations of their atoms did not synchronise with the vibrations of the heat waves emanating from a luminous heat source.[395]

[393]Knoblauch (1852), pp. 193-203, 433.

[394]Draper (1847), s. 3, volume 30, pp. 345-359.

[395]Tyndall (1864b), 154, pp. 327-368, 346-347.

Absorption of heat through vapours

(Heat source: platinum spiral)

Vapour	*Barely visible*	*Bright Red*	*White hot*	*Near fusion*
Carbon bisulphide	6.5	4.7	2.9	2.5
Chloroform	9.1	6.3	5.6	3.9
Methyl iodide	12.5	9.6	7.8	
Ethyl iodide	21	17.7	12.8	
Benzol	26.3	20.6	16.5	
Amylene	T	27.5	22.7	
Sulphuric ether	43.4	31.4	25.9	23.7
Formic ether	45.2	31.9	25.1	21.3
Acetic ether	49.6	34.6	27.2	

The order of absorption of sulphuric ether and formic ether vapours were reversed for the two hottest sources.[396]

In studying the diathermancy of chlorine and of bromine and their respective acids, Tyndall observed that despite the colour and the density of elementary gases, their transparent acids showed much higher absorptive power.[397] He determined that the power of absorption of olefiant gas was nearly a thousand times that of dry air at atmospheric pressure, at a very reduced pressure (one thirtieth of an atmosphere) it was possibly eight thousand times as absorbent as dry air. Ammonia gas displayed still greater power of absorption. Tyndall then found that the vapours of some volatile liquids displayed greater powers of absorption than the gases. This was a pioneering investigation. He designed an apparatus that enabled him to study liquids and their

[396]Tyndall (1872), p. 92.

[397]Tyndall (1898), pp. 321-357.

vapours in a variety of thicknesses from 0.001 inch to 49 inches.[398] Anomalies in the results were ascribed to differing modes of preparation of the experimental gases and vapours. Carbonic acid was generated in three ways: from marble and hydrochloric acid, from chalk and sulphuric acid or from sodium bicarbonate and sulphuric acid. Some olefiant gas was prepared under E. Frankland's (1825-1899) supervision by the "continuous process" whereby alcohol vapour was passed through dilute sulphuric acid. However the samples of olefiant gas generated by heating liquid alcohol with sulphuric acid, generated results that indicated 10% higher absorption. The quantity of gas required for the duration of the experiments was too large to produce at one time. Tyndall concluded that variable conditions at the different times the gas was prepared would also have contributed to the inconsistency of the results.[399] The lengths of the experimental tube also affected results, the greatest absorption occurred at the first step, provided the quantity and the character of the gas was capable of absorbing most of the radiant heat of the kind produced by a source at 250 degrees Celsius.

From these experiments Tyndall identified water vapour and carbonic acid gas as the main constituents responsible for the absorption of heat in the atmosphere. These important findings, exposed by exhaustive experimental procedures, are Tyndall's own achievements. Some of his predecessors, notably Leslie among them, had noted that events in the atmosphere suggested an interrelationship between the air, humidity and heat, clearly a field for an experimental programme to be pursued. In the historical chapter of his book, Melloni was struck by the work of Herschel and Leslie on this subject, and his own interest encompassed the natural occurrences that pointed to the legitimacy of serious study. However although he was involved in the radiant heat investigations, Melloni showed no sign of being able to think meteorologically to the extent that Tyndall was doing, through his first hand experience while mountaineering and meteorological studies discussed in Chapter 5.

In his most important work belonging to this chapter, Tyndall studied the radiation of aqueous vapour using a flame from hydrogen as a source, whereas the

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[398] Tyndall (1898), p. 313.

[399] Tyndall (1864a), volume 154, p. 208.

radiation of carbonic acid was investigated by the use of a flame provided by the ignition of carbonic oxide. He probably wanted the most energetic possible demonstration of radiation by these two gaseous states, bearing in mind that the absorption occurred most energetically from heat generated by similar substances.[400] Tyndall found that the heat generated by the hydrogen flame was absorbed by water vapour three times or more powerfully than heat from the platinum spiral. Carbonic acid gas was shown to be a powerful absorber of heat generated from a carbonic acid flame, although if the heat was generated from a heated solid, it was remarkable for its low absorptive power.[401]

Tyndall's discovery of the high heat absorption of water vapour and carbon dioxide constitute a milestone in atmospheric physics with the momentous consequences for meteorology. Magnus' initial challenge to Tyndall's results on the diathermancy of air led Tyndall to repeat his experiments of February 7th 1861. He looked for the causes of the anomalous results that showed high heat absorbency of apparently dry air from which moisture and carbonic acid were supposed to have been removed. He found that his procedure to remove these substances had been at fault. He therefore adjusted his method discussed in section C. Melloni and Herschel had both pronounced on the high thermal heat absorption by water. Leslie effected refrigeration by the desiccation of air, and was speculating on the content of water vapour and its important role in meteorology as a constituent of the atmosphere. Leslie and Melloni also demonstrated high heat absorption by lampblack (high content of carbon), with implications for the thermal properties of carbon dioxide.

The interference of impurities in experimental gases, including moisture, occurred to Tyndall, when he noted that an air-filled experimental tube possessed increased thermal absorption when evacuated. A cloud formed in the tube, due to the precipitation of the water vapour in the laboratory air. As evacuation continued, however, the needle was seen to move back to zero, and then to the other side and settled permanently at a deflection. This effect was avoided when the laboratory air

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[400]Siegel (1976) 67, pp. 565-600, 576-577.

[401]Tyndall (1864b), pp. 154, 327-368, 356

was first dried by passing it over calcium chloride or over pumice stone soaked in sulphuric acid.[402] The refinement of this procedure is discussed in section C. Tyndall found that the laboratory air displayed fifteen times the absorption of air that had been deprived of its water vapour content in this way. Carbon dioxide was removed by passing the air over potassium hydroxide.[403] The need to dry gases was recognised by Tyndall in early stages of his research. When Tyndall compared his results on the absorptive power of the air with those obtained by Franz, he found several ways to account for the latter's high results. Firstly, Franz's three-foot long tube was blackened within; Tyndall's four-foot long tube was polished. In addition, Franz's apparatus used a Locatelli lamp as a source of heat whereas Tyndall used an obscure heat source. Finally, the stoppers of his experimental tube were of glass, so they had a high absorptive power of radiant heat and radiated it in turn, Tyndall used rock salt stoppers.

Writing about water vapour, Tyndall recalled: "I quite neglected this substance for a time, and could hardly credit my first result, which made the action of the aqueous vapour of our laboratory fifteen times that of the air in which it was diffused.…"[404] On another occasion he wrote: "I first neglected atmospheric vapour and carbonic acid altogether; concluding, as others afterwards did, that the quantities of these substances being so small, their effect on radiant heat must be quite inappreciable; after a time, however, I found this assumption leading me quite astray."[405] In performing experiments with very pure substances, Tyndall obtained absorption by an undried air over seventy times that of dry air. Contamination from just traces of microscopic organic matter augmented the absorption of dry air by fifty times. As the solution of rock salt was known to be highly athermic, the use of rock salt in radiant heat studies raised the question whether the deposition of a film of the solution was responsible for what was apparently absorbed by the water vapour itself. To resolve this question Tyndall set the apparatus up, part of it filled with fused

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[402]Tyndall (1863a for 1862), 152, 59-98, 61-62.

[403]Ibid., pp. 62-63.

[404]Tyndall (1862f), S. 4, 23, pp. 252-266..

[405]Tyndall (1865a), p. 337.

calcium chloride to ensure that water vapour could not settle on the instruments being used. The apparatus was subjected to an examination for traces of condensation. After one hundred replications the experiment confirmed the initial experiment (presumably meaning that the solid rock-salt was diathermic to most of the obscure radiation). However the controversy discussed in the next section led to yet further refinements to this experiment.

3B.4. The Effect of Various Physical Conditions on Absorptive Power

Having performed hundreds of experiments to confirm a very high absorptive power from olefiant gas, Tyndall examined the effect of the density of a gas on its thermal absorption. He subjected compound gases to a pressure of one inch and above. The pressure was measured by a mercury gauge, and exerted by water. This showed a gradual, irregular and diminishing increase in the thermal absorption of gas. However when the experiment was repeated with the smaller increments in pressure, steps of 0.02–0.03 inches, thermal absorption appeared proportional to the density of the gas. Vapours of some volatile liquids showed more thermal absorption than olefiant gas. Tyndall reasoned that since the thermal absorption of a gas is limited, most of it will be utilised at the beginning of the experiment provided the concentration of the gas is high enough; subsequent absorptions would increase at a smaller rate. Working at a more gradual pace, revealed the phenomenon. The object of the experiment was accomplished; he had shown that each vapour displayed its own characteristic thermal absorption according to its density. The calculated absorption corresponded to the experimental results. Vapours of volatile liquids exceeded the gases in their absorptive power, sulphuric ether being the most, and carbon bisulphide the least powerful absorber. Unlike with liquids and solids, the quantity of gases could be adjusted while investigating the effect of pressure. Tyndall reported an experiment with olefiant gas under pressure varying from 1 to 10 inches. He concluded that olefiant gas at the pressure of one thirtieth of an atmosphere exercised ninety times the absorption of air at atmospheric pressure. As pressure was increased inch by inch a smaller proportion of the heat was being absorbed.[406] Having assumed that for small amounts of gas, absorption was proportional to quantity, he

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[406]Tyndall (1863a), pp. 67-74.

confirmed his calculations experimentally. He then proceeded to compare the absorption of ten compound gases and two elements, chlorine and bromine, at atmospheric pressure and at a pressure of 1 inch. At low pressures the absorption of radiant heat by compound gases increased by several hundred percent.[407]

Modelling his setup on Melloni's investigations of the absorptive power of liquids and solids at different thicknesses, Tyndall examined the effect of vapours on radiant heat by noting their absorptive power at different thicknesses. As on previous occasions, he aimed to bring out any differences between elementary gases, compound gases and vapours. For that purpose he adjusted his basic apparatus to compare different gaseous substances at different thicknesses. By means of what he called a piston apparatus, he could vary the thickness of the experimental gas or vapour from 0.01 to 2 inches. To avoid any strain on the rock-salt plates, and the risk of the experimental gas leaking into the experimental part too early, he replaced the vacuum with dry air. Apart from the permanent compound gases, he tested only one vapour with this apparatus, sulphuric ether, which he obtained by passing dry air through a u-tube filled with moistened glass fragments. When only a small amount of the vapour was present it displayed weaker absorption than the gas, but with an increased thickness vapour overtook the gas in its thermal absorption.[408] To check results that were obtained from experiments performed by his assistants, Tyndall divided the experimental tube into two chambers by means of a movable plate of rock salt. Since the tube was originally constructed from individual components, that allowed the flexibility of varying its length from 2.8 to 46.4 inches, it was possible to compare the effect on radiant heat of the quantity of different gases over a large range. Moreover the absorption of the sum of two parts of the tube was always greater than the absorption of the entire tube[409] volatile liquids to the boil,[410] a standard procedure that had been worked out by L. Playfair (1819-1898). The liquid was enclosed in a flask and attached to an evacuated experimental tube. The space above

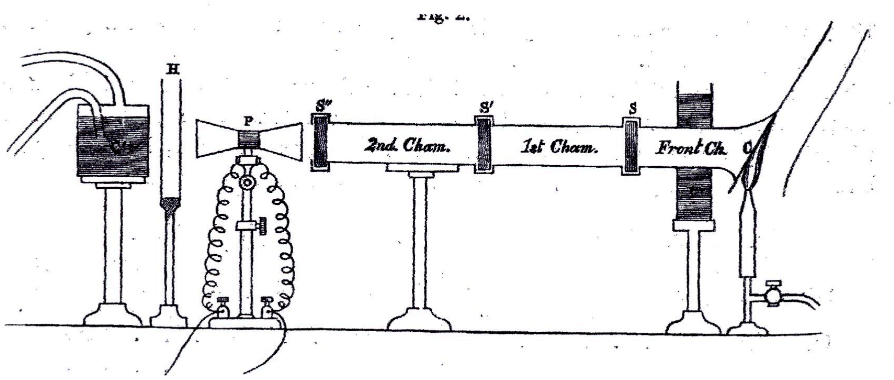
[407]Tyndall (1861a), volume 151, pp. 10-29.

[408]Tyndall (1864a) volume 154, pp. 201-225, 208-210.

[409]Ibid., p. 207.

[410]Tyndall (1864), 154, p. 211.

the liquid level in the flask was also evacuated. The liquid vapour was slowly let into the tube, and measurements of absorption were made at five intervals at increments of a pressure of one inch each time. The deflection of the needle indicated the extent of infrared absorption. Tyndall repeated the experiment with twelve other vapours, concluding that large variations in thermal absorptions existed between different vapours. The1864 action of aqueous vapour, in particular, was at the heart of Tyndall's dispute with Magnus, which will be studied in Section C of this chapter. The importance of the role of this result in meteorology is discussed in Chapter 5.



3B.5. Physical Interpretation of Thermal Absorption and Radiation Phenomena

In his investigations of the thermal phenomena of liquids and their vapours, Tyndall resolved a perplexing question concerning the site of action of thermal absorption and radiation. He found that in both phases the order of absorption and radiation was usually the same. When the quantity of matter in each state corresponded, the extent of absorption and radiation was very close. He therefore demonstrated that thermal absorption and emission phenomena were intra-molecular, that is occurring inside the molecules. He repeated the experiments on different days, and used different thicknesses of liquid substances enclosed in carefully constructed cells of rock salt crystal. The experimental tube was closed with rock salt plates. He used a thermo-multiplier with two galvanometers of different sensitivities.[411]

It appears surprising that Melloni used glass rather than rock salt in his work on the diathermancy of liquids. The most likely explanation is that rock salt plates of the right size and quality were hard to find. Even Tyndall remarked on this problem despite the presence of deposits in Cheshire, and an extensive network of researchers and acquaintances that had responded to his advertisement for rock-salt plates in the *Philosophical Magazine*, 1862. Unlike Melloni, Tyndall aimed to modify the heat emanating from the source as little as possible. He chose well-polished and precisely ground rock salt for his experimental cells that were crafted to his specifications by a skilful technician, Becker.

Tyndall also constructed a lamp with a platinum spiral heated to incandescence by an electric current from a Grove battery in order to ensure a steady and powerful heat source. Platinum wire was used to connect the spiral instead of copper. Copper had a tendency to oxidise that caused undesirable variations to the current. To guarantee a reliable, steady performance, a tangent galvanometer and a rheostat were inserted into the circuit, and the spiral was enclosed in a glass globe. A

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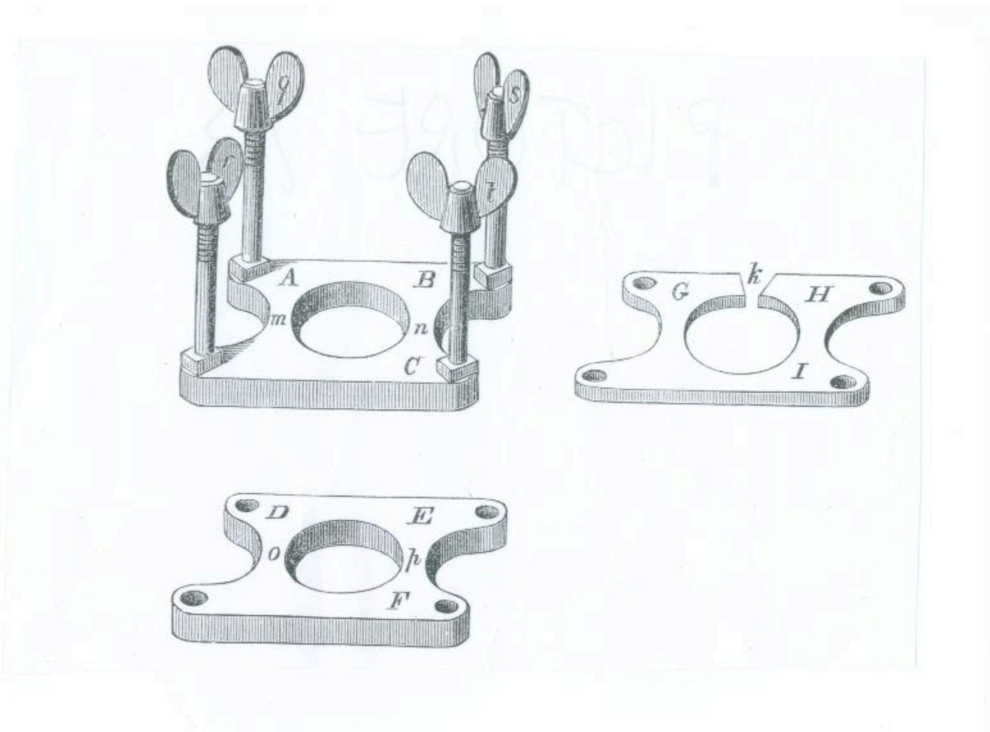
[411]Tyndall (1864b), pp. 154, 327-368, 328.

tube with a polished interior increased the quantity of heat to reach the experimental cell. This cell was attached to a screen, after passing through a hole in this screen the heat radiation fell on to the near end of a pile. The pile was placed at a distance that would ensure no heat from the screen affected it. The pile and the compensating cube were protected from convection generated air currents. The other end of the thermopile faced a screen controlling the heat emanated from a compensating cube containing boiling water. The rock salt receptacle was empty and protected against heat radiating from the platinum spiral by a silver screen not in the diagram. A double screen controlled heat from the spiral. When the galvanometer was at zero, heat from the cube was being compensated. The position of this screen remained fixed throughout the experiment. Any small variation from the platinum heat source was adjusted by means of a rheostat. The experiment then proceeded by filling the rock-salt cell with the liquid under investigation. Deflection was recorded and the reading converted into the percentage of absorption that had occurred. Melloni's galvanometer calibration tables served Tyndall well. After each use, the cell was dismantled, washed thoroughly and reused within two or three minutes. The thickness of the liquids was adjusted between 0.02 and 0.27 inches. Tyndall followed the advice of his continental friends and in his report he included details of both the deflection and the conversion[412] in order to demonstrate the precision of his apparatus. W. Thomson, one of Tyndall's referees, was also then in Germany, and also urged this in his correspondence with Stokes. Such details facilitated later replications of experiments. Each liquid showed a characteristic absorptive power, varying over a wide range.

Tyndall next examined the vapours of these liquids. The liquids were placed in elongated tubes, and attached to an experimental tube. The vapours of volatile liquids replaced air. The pressure of each vapour could be controlled by a barometer attached to the experimental tube. The reading of its finely divided column was read off by means of a magnifying lens. The vapours were first examined at a pressure of 5 inches. He observed that at this pressure absorption and radiation corresponded, giving the deflections of the galvanometer needle that are recorded in the chart below.

[412]This refers to the calibration of the galvanometer following Melloni's method

Air 0 degrees	A fraction of a degree
Oxygen 0 "	" " "
Nitrogen 0 "	" " "
Hydrogen 0 "	" " "
Carbonic Oxide 12 "	18
Carbonic Acid 18 "	25
Nitrous Oxide 29 "	44
Olefiant Gas 53	61



The order of absorption and radiation corresponded to one another. Refining the experimental conditions, he then replaced the cube of boiling water with a more powerful heat source, using a copper plate heated to 270 degrees C by a steady gas flame from a Bunsen burner.[413] The brass was also replaced by one of glass, however the principle of the apparatus remained the same. At a pressure of one atmosphere he then demonstrated the relative absorption of ammonia to be 1195, whereas those of hydrogen, nitrogen and air respectively, amounted to no more than 1. Moreover Tyndall suggested a way of exhibiting radiation and absorption by either varnishing the polished face of Leslie's cube, or passing a film of olefiant gas over it to increase the effect. Absorption increased when the cube was filled with cold water and the copper ball cooled only a few degrees below the surrounding air. Tyndall demonstrated that air was a mixture and not a compound by comparing the negligible radiation and absorption of nitrogen and oxygen at one-inch pressure, against that of nitrous oxide that showed an absorption of 1860. He also compared hydrogen and nitrogen at one-inch pressure to ammonia, which had a relative absorption of 5460. In Tyndall's words: "No fact in chemistry carries the same conviction … that air is a mixture and not a compound." Tyndall also demonstrated the absorption and radiation of vapours of alcohol and ether by dynamic expansion and compression of the air.[414] The weakest absorption was shown by carbon bisulphide, the strongest by the sulphuric ether vapour. Tyndall demonstrated a vast range of heat absorptions by vapours, and for small amounts the absorptive powers were proportional to the vapour densities.[415]

3B.6. Tyndall's Original Contributions

Tyndall's contributions, resulting from his primary experimental procedures in radiant heat, include the following: pioneering techniques to study the interaction of radiant heat with matter in gaseous phase, improving the sensitivity of the thermopile by the compensator method, thereby enabling the all important detection of weak

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[413] Tyndall (1865a), pp. 349-353, (1898, reprint of 1880), pp. 343-345.

[414] Tyndall (1861a), 151, pp. 31-34.

[415] Ibid., Tyndall, pp. 13-17.

absorption, identifying impurities as artefacts, and their effective detection and removal. These contributions have had an interdisciplinary impact on the progress of existing knowledge.

In Tyndall's time the purification of gases was a topical issue in the gas industries and their drying was problematic.[416] His awareness of the effect of impurities on results, and his recognition of the importance of refining their removal, ensured a successful programme of research that yielded precise and consistent results.

Having discovered the different thermal properties of the elementary and the compound gases, Tyndall succeeded in determining the chemical composition of ozone. He pioneered investigations of vapours, identifying their thermal properties and correspondence to those of their liquids.

As one of the pioneers of the experimental dispersive spectroscopic techniques, Tyndall contributed to the launch of the new discipline of infrared spectroscopy. He applied the previously known phenomena of dynamic heating and cooling to radiant heat studies, particularly in the investigation of the mutual relation of absorption and radiation phenomena, and provided the necessary precision. He confirmed a relationship between gas densities and their power to absorb radiant heat. By the investigation of the absorptive powers of gases exhaled by humans after subjecting individuals (including himself), to a variety of food and drink such as brandy, he paved the way for the breathalyser. The interpretation of his discovery of calorescence lent itself to a variety of opinions.[417] As will be seen in Chapter Four, unlike his predecessors, Tyndall used the results of his experiments for theoretical speculation regarding the structure of matter. He speculated on the causes of the strong absorptive power of compound gases and ozone and the weaker power of elementary gases.

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[416]Wilson to Faraday 29 March 1850, in James (1999), pp. 136-137.

[417]See p. 170-172 of this dissertation

3C. The Magnus Challenge

3C.1. Magnus, the Doyen of German Science

H.G. Magnus (1802-1870) was born and died in Berlin where he also spent most of his professional life. Tyndall was deeply affected by his dispute with Magnus, his former mentor, over experimental procedures and results. His involvement in this controversy resulted in improvements of Tyndall's procedures. Magnus was educated at the Cauer Private Institute where more emphasis was put on science than at the gymnasium. He continued to study natural science at the University of Berlin where he remained all his life, except for a period between 1827 and 1829 when he gained experience in the laboratory of Berzelius in Stockholm and with Dulong, Gay-Lussac and Thenard in Paris. He qualified in technology and physics. Appointed associate professor at Berlin University in 1833, and elected member of the Berlin Academy of Sciences in 1840, he taught physics at the Artillery and Engineering School from 1832 until 1840, and chemical technology from 1850-1856 at the Gewerbe Institute. Magnus also served on various government commissions with a particular interest in chemical aspects of agriculture, and was the rector of the University between 1861-1862. He discovered what is known as Magnus's green salt (an ammonium compound of platinum), and other acids and salts. His research on projectiles led to the theory of the "Magnus effect" concerning rotations in air currents. In a biographical article G.B. Kaufmann assessed Magnus's experimental skills: "Neither a theoretician nor an original thinker, Magnus was, however, an acute, conscientious, and diligent experimenter. …"[418] Since the University of Berlin did not have a physical laboratory or a budget for the purchase of scientific instruments, Magnus also lectured at his home and provided his own instruments. These were described by Helmholtz in the Magnus Memorial lecture as constituting "the most splendid physical collection" in existence.[419] His innovative weekly colloquia became a feature of academic instruction in physics throughout the German university system, linking teaching and research, encouraging critical discussion and offering opportunities to lecture and

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[418]Kaufmann, in Gillispi (1974), volume 9, pp. 18-19, 19.

[419]Helmholtz, H. von (1900), p. 3

perform experiments.[420] Tyndall's publications in the1860s testify to the anxiety with which he regarded Magnus's criticism. The public character of this disagreement may have contributed to his overreaction to his encounters with Tait and Thomson.

There are few indicators of British scientific opinion of Magnus although publications by Magnus were translated into English, like writings of other eminent men of science. Faraday's flattering comments, as gathered from his letters, attest to his good opinion of Magnus. On several occasions he came to Britain for brief visits and occasionally met Faraday. In a letter to a Birmingham metallurgist, John Percy (1817-1889), Faraday asked him to inform The British Association of Magnus's expected attendance at a Birmingham meeting, as they were "always glad to know beforehand of any eminent philosopher. He is a very pleasant man and talks good English"[421] Corresponding with Du Bois-Reymond, Faraday referred to Magnus "whom I rejoice to call a friend."[422] Magnus was expected by Faraday at the Royal Institution in 1851.[423] He felt free to write to Faraday introducing Helmholtz.[424] In separate correspondence to Tyndall Faraday wrote: "I have not heard anything yet from Magnus – thoughts of him always delight me …."[425]

Tyndall also regarded Magnus with respect, despite their intense scientific disagreements. In a lecture Tyndall referred to an opportunity that had arisen in 1851 to work in the laboratory of Magnus of Berlin: "The last years of his life were ... occupied in a discussion with myself on one of the most difficult subjects of experimental physics-the interaction of radiant heat and matter in the gaseous state…."[426] Writing to Faraday from Berlin, Tyndall reported: "I have been working

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[420]Jungnickel and McCormmach, pp. 107-110

[421]Faraday to Percy, 7 September 1849, in James (1999), volume 4, p. 69.

[422]Faraday to Du Bois Reymond 15 January 1850, in James (1999), volume 4, pp. 116-117.

[423]Faraday to H. Rose, eminent German chemist, 23 August 1851, in James (1999), volume 4, p. 331.

[424]Magnus to Faraday 10 August 1853, in James (1999), volume 4, p. 555.

[425]Faraday to Tyndall 28 June 1854, in James (1999), volume 4, p. 705.

[426]Tyndall (1892a), p. 243

for the last five weeks at diamagnetism. Prof. Magnus has been kind enough to place the necessary space and apparatus at my disposal-indeed I cannot speak too highly of the kindness of the men of science of Berlin generally."[427] Tyndall asked Magnus for testimonials in support of his application to the University of Toronto as Professor of Natural Philosophy.[428] He recalled congenial walks in 1862 when Magnus was in London for the London Industrial Exhibition, and also noted Magnus's visit to the Royal Institution laboratory where he witnessed Tyndall's experiments.[429] Tyndall described Magnus as a good friend as well as a stalwart adversary. When their paths crossed as experimentalists, Magnus's presence shaped Tyndall's research programme on radiant heat, and probably the pattern of his popular lectures on the subject.

3C.2. Magnus's Experimental Challenge to Tyndall

Initially Magnus's main interest had been heat conduction by gases in reference to the work of Franz,[430] though not that of Melloni. This is not surprising in my view, since Melloni's interest was mainly heat radiation, and that of Magnus, heat conduction. Nevertheless in 1846 Magnus, among several other German scientists, was willing to supervise the translation of *La Thermochrose.* It was ready for publication that same year, and Melloni hoped to publish it in Germany, but conditions imposed by the publishers on foreign books were unfavourable, "barbaric jurisprudence … legally established literary piracy."[431]

Magnus regarded the investigation of heat propagation in gases important to theoretical study of the nature of heat.[432] In a letter to Tyndall in March 1861, he indicated that he was led to this area of research by the need to clarify results from his

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[427]Tyndall to Faraday 26 May 1851, in James (1999), volume 4, p. 296.

[428]Tyndall to Faraday, 30 July 1851, in James (1999), volume 4, pp. 323-325

[429]Tyndall (1872e), pp. 124-125; Tyndall (1863e), 153, pp. 1-12, 2;

[430]Magnus to Tyndall, 17 March 1861, in Tyndall (1872f), pp. 60-61.

[431]Dirichlet to Melloni, 16 August 1846, in Schettino (1994), pp. 397-398.

[432]Magnus (1861a), S. 4, 22, pp. 1- 12, 3.

earlier work on conduction.[433] Whereas Franz used an Argand lamp as a powerful source of heat, Magnus worked with boiling water throughout for consistency's sake, suspecting that "it was not merely possible, but …probable that the transmission of thermal rays would differ with the source whence they came."[434] The subject of heat propagation in gases and in liquids was a contentious one in which Davy, Rumford and Dalton, as well as Biot, Dulong and Petit, among others, had participated, and Magnus was aware of this. Initially Magnus took interest in Grove's experimental results that showed that platinum wire attained a lower temperature when heated by an electric current in an atmosphere of hydrogen, than it did in air or any other gas. On replicating and subsequently adapting Grove's experiments, Magnus challenged the prevalent explanation, which described the mobility of hydrogen particles as causing a cooling influence on the platinum wire, since even a very thin layer of hydrogen was effective in lowering its temperature. He attributed it instead mainly to a high conductivity, a phenomena unusual in gases.[435]

Magnus devised new experiments on the diathermancy of gases that dispensed with plates in the experimental tube, whether glass or even rock salt, in case the plates caused corrosion in the metal of the thermopile, thus interfering with the measurement the apparatus recorded.

His results were remarkably consistent. Since results were identical for oxygen and the air, he saw no need to repeat the experiments with nitrogen. Like Tyndall, he obtained a range of absorptions with different gases. He was conscious of the shortcomings of the results due to the presence of impurities, but there was no mention of any attempt to remove them. For a heat source at a higher temperature than 100 degrees he used plates. He attributed the greater absorption seen without plates to the reflection of radiation from the inner surface of the tube, even if its internal walls had been lined with black, rough matt paper. Three screens were used, one of them movable, the remaining two fixed on either side of the experimental tube

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[433] Tyndall (1872), pp. 60-63

[434] Magnus (1861b), S. 4, 22, pp. 85-106, 86.

[435] Tyndall (1872f), pp. 66-121, 105 - 106.

to protect the heat source and the pile respectively from undue influences. Results were recorded with the blackened as well as unblackened tube to indicate the wide variations due to the nature of its inner surface. Magnus experimented with air dried by passage through calcium chloride tubes, as well as air saturated with water vapour. He was convinced that the small amount of water vapour saturating the air at 16 degrees, unless precipitated as fog, would not have any effect on the propagation of radiant heat.[436] Tyndall's discovery of the vast absorptive power of the olefiant gas and ammonia obliged Magnus to repeat the above experiments, but his results remained the same, supporting in his eyes, assumptions regarding the low heat absorption of water vapour. He decided unequivocally that solar heat reaching the earth was equally affected irrespective whether the air was dry or laden with moisture.Re =re Referring to Melloni's results on the absorption of the obscure heat radiation by one millimetre of pure water, Magnus attributed the enormous heat absorption by water vapour in Tyndall's results to his use of rock-salt plates that precipitated and dripped salt solution at between 10 and 25 degrees, but not in Tyndall's experiments. Citing Melloni's findings, Magnus concluded that with an Argand lamp as the heat source, the saturated solution of rock salt was only 10% less absorbent than water. Here again Magnus made an assumption this time deciding that the rock salt solution was a powerful heat absorber, although he had no evidence from other experiments on this matter. In his attempts to reproduce Tyndall's experiments, he failed to obtain Tyndall's "remarkable results.

One year later Magnus showed reluctance to assign the cause to the hygroscopic properties of the rock salt plates "since I neither know sufficiently the quality of these plates, nor the precautions which Dr Tyndall took in his experiments. My only object is to call attention to the difficulties incidental to the use of plates of rock salt in such experiments."[437] Feeling that his research was being criticised, and also in response to his having witnessed Tyndall's demonstrations at the Royal Institution laboratory, he reluctantly resumed further tests, although in his opinion at this stage the subject did not warrant such attention. However, Magnus's figures for

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[436]Tyndall (1865a), pp. 114-117.

[437]Magnus (1862), S. 4, 23, pp. 249-252.

the passage of heat through dry air when compared with passage through a vacuum, showed greater heat absorption for air than Tyndall’s results. In Magnus’ data, the difference between moist air and dry air was small, whereas Tyndall’s showed a large difference. In Magnus’s eyes, Tyndall’s experiments without plates carried more conviction, but on his return to Berlin he could not recall whether the deflections of the galvanometer had been for dry or moist air, or what kind of heat source had been used. He thought the experiments and the results so extraordinary that he decided to repeat them in his own laboratory. His arrangement of the experimental apparatus was in part like that of Tyndall, but partly it differed. He increased the sensitivity of his galvanometer by introducing an additional magnet to counteract the possible effects of the earth’s magnetic field. He also took care to use the best available quality of copper wires. These were reputedly free of iron (Tyndall had obtained the copper from the same source, but in his judgement, it required further purification). Magnus employed calcium chloride although no indication was given if it was as freshly fused as Tyndall’s. Tyndall also specified the purity of the broken glass and sulphuric acid he used as a drying apparatus. Magnus had used broken glass, but did not comment on its purity. In his paper Magnus also lists his precautions to prevent the effects of convection and to ensure the stability of the flame among others.[438]

Some of his results were identical with those of Tyndall, but were not consistently so. Magnus was taken by surprise when he found that the deflection of the galvanometer was not due to the heat absorption by moist air (therefore he meant presumably that it was not less), but that the side of the thermopile facing the experimental tube was “most heated”. Having checked that there was no condensation of moisture on the inside of the tube, Magnus was satisfied that the deflection was not due to the absorption by the air, but to absorption at the face of the pile. He did not mention the possibility of dynamic heating and cooling effects. When the air saturated with water vapour was used, Magnus noted water condensing on the surface of the pile with the consequent heating; using dry air caused this moisture to evaporate with the consequent cooling, which accounted for the equilibrium position of the galvanometer needle. The cycle was resumed as the continuous current of the air

[438]Magnus (1863), S. 4, 26, pp. 21-30, 21-24.

persisted. This process, due to the evaporation and condensation of the water vapour, continued without a heat source. This occurred even with different substances lining the pile. This phenomenon convinced Magnus that air was unsuited to this type of experiments. I contend that Magnus may have missed the dynamic effects taking place.

Magnus persisted with a modified apparatus where compartments of the experimental tubes of various adjustable lengths were separated by means of rock salt. Hitherto Magnus used the thermopile inside the tube. Because of Tyndall's criticism on this point, Magnus left the thermopile outside the experimental tube, although he claimed this would make the apparatus less sensitive. Searching for the cause of the disparate results on moist air, Magnus stated firmly: "There seems to be no doubt that this cause is to be sought in the employment of the rock-salt plates." He also disapproved of Tyndall's use of the compensator method and felt it caused errors in Tyndall's determination of the absorptive powers of gases. [439]

The following year Tyndall enlisted Frankland's skills to replicate his experiments in order to eliminate the possibility of error. Magnus criticised this decision, feeling that further replications were superfluous. Magnus had simply indicated that his own results always differed from those of Tyndall, without meaning to imply any errors on Tyndall's part. Magnus concluded that a factor thus far unrecognised or at any rate not made known, had caused the pattern in Tyndall's results. Magnus, evidently offended, challenged Tyndall's right to account for their differences by a comparison of their work. Magnus used a metaphor of a balance weighing milligrams versus that of weighing pounds., symbolising the difference in the sophistication of the instrument used by Tyndall and Magnus respectively, hence representing the quality of their work.[440]

Although in 1863 Magnus had regarded the heat absorption by aqueous vapour to be unimportant, by 1867 his position had changed. At this time Magnus wrote that since Tyndall had drawn conclusions that were of considerable interest to

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[439]Ibid., Magnus, pp. 25-27; 29-30.

[440]Magnus (1864), s. 4, volume 27, pp. 241-250, 249-250.

meteorology, and that he had the support of other physicists in this respect, the thermal absorption was of importance after all, and that it was therefore necessary to find out whether the heat absorption by moist air was so very much greater than the dry air. Magnus also paid tribute to Tyndall's work, granting that both he and Tyndall worked with utmost diligence. The differences in their results therefore, Magnus inferred again, must be due to "circumstances hitherto unknown or disregarded … in our experiments". Whilst these factors remained unknown or unacknowledged both of them were repeatedly approaching their problem by means of new experiments, originating "from a different point of view."[441]

Magnus replicated Wild's experiments, the results of which supported Tyndall's and were at odds with those of his own previous work. He acknowledged the importance of Wild's provision of the accurate dimensions of his apparatus as "very much depended on these dimensions. "I soon found that the discrepancy between the present results and those I had formerly observed, depended on a circumstance which I had previously neglected."[442] Magnus was convinced that the inside of the tube determined the phenomena. Moreover water vapour, even though invisible, always condensed on the surfaces with which it came into contact. He also commented on the diameters of the experimental tubes he used which were narrower than those of Wild and Tyndall. He reiterated that had Wild and Tyndall adhered to his instructions and procedures, neither of them would have had difficulties in replicating his results. Magnus saw no need to employ wider tubes to study absorption and criticised their use as being deficient. With wider tubes he would have replicated Wild's results. With hindsight he regretted not having done so. He urged Tyndall and Wild to repeat his experiments with the lined tubes. He was certain that then they would share his opinion, that "aqueous vapours have no such great absorptive power. Professor Wild will then no longer adhere to the opinion that the science of meteorology may without hesitation utilize the great absorption of heat by aqueous vapour as a mode of explanation." According to Magnus the reflection produced by the invisible adhesion of the water vapour to the sides of the experimental tube

[441]Magnus (1867), volume 33, pp. 413-425.

[442]Ibid., Magnus, p. 414.

accounted for the difference of opinion between the three experimentalists. Magnus conceded that the issue of thermal absorption by aqueous vapour in the tubes was a complex one and thought that it was not possible to determine its role in heat absorption; though claimed to recognise "with certainty" that its heat absorption was not very great after all.[443]

3C.3. Tyndall's Refinements of Experimental Procedures

In 1861, in a letter to JWF Herschel Tyndall wrote of the difference between his results and those obtained by Magnus on the propagation of heat through the atmosphere. According to Tyndall dry air was virtually diathermous to radiant heat. When absorption was detected, it was due to the presence of water vapour which augmented the absorption of the air forty times on any particular day, whereas carbon dioxide and other pollutants increased the absorption by only twenty seven times from pure air to which Tyndall assigned the value one as an approximation of the relative absorption.[444]

Before addressing the specific reservations voiced by Magnus, in view of the different results obtained by his former mentor,[445] higher absorption for dry air, less for water vapour, Tyndall extended his experiments and modified his apparatus to reduce the risk of errors. To highlight the range of heat absorptions by gases, Tyndall replaced Leslie cube filled with boiling water at 100 degrees as a heat source by a plate of copper heated by a constant sheet of flame reaching 270 degrees. The sheet was protected from the irregular air currents by means of a copper hood, as the stability of the heat source was a prerequisite condition for the reliable outcome of the experiment. The flame was generated from a lamp constructed on the principles of Bunsen's burner. He also connected a second tube that could be independently evacuated, to the experimental tube of the same diameter to ensure the constancy of

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[443]Ibid,. Magnus, pp. 422-425.

[444]Tyndall to Herschel, 21 October 1861 in *Philosophical Magazine*, 22, pp. 377-378.

[445]Note 418, Tyndall, pp. 105-113.

the quality of the heat source. Further precautions had to be adopted if potentially corrosive gases were used: the brass tube was replaced by a glass tube which in turn required a stronger heat source because of the smaller reflective power of the inner walls of glass than that possessed by the brass. Tyndall related the volatility and the thermal properties of vapours when experimenting with them in the open air.[446]

He remarked that those who replicated his experiments with different results did not appreciate the care needed. He probably had Magnus's challenges about the inner surfaces of the tube in mind.[447] In his last and fourth Bakerian lecture of 1882 in the face of further criticism from Germany, Tyndall took up the subject of films again. He concluded that by replacing the brass tube with a glass tube, the risk of corrosion was avoided and there was no necessity for lampblack.

Tyndall was using more experimental substances consisting of elementary and compound gases and vapours. The constancy of the flame of the heat source presented the greatest problem. The flame was therefore surrounded by wire gauze as well as pasteboard. Further precautions to protect the apparatus from the factors extraneous to the actual experiment consisted of the refinements of Melloni's methods used in his researches on liquids and solids and their interaction with radiant heat.[448] Tyndall saw the athermancy of many gases in the results of Magnus's experiments on the conductivity of hydrogen and other gases. Even when Tyndall used a tube fifteen times the length of Magnus', his results for oxygen and for hydrogen indicated less than 0.1% heat absorption of the results obtained by Magnus. Even allowing for the different heat sources used by Magnus and Tyndall, this discrepancy was still large. Conversely for the gases that were powerful absorbers, Tyndall obtained higher figures than Magnus. On the other hand the lengths of the experimental tubes differed. The results approximated those of an earlier pioneer of the study of the thermal properties of gases, Franz (about 3%), whereas a bare tube produced an absorption about five times stronger. This, according to Magnus, was due to the change of

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[446]Tyndall [1865] 1898, pp. 345-347.,

[447]Ibid., Tyndall, p. 355

[448]Tyndall [1863a for 1862], pp. 59-98, 59-61.

refrangibility of the heat reflecting from the internal walls of the tube. Tyndall regretted that he lacked the time to repeat the experiment using the same heat source as Magnus. He also wished to investigate further the fact that in Magnus' experiments dry and moist air showed very little difference.[449] In his Memoir 3 Tyndall recalled again a visit to London by Magnus to the International Exhibition in London in 1862. This gave Tyndall the opportunity "due to him to pay strict attention to every objection he raised" and perform his experiments in Magnus's presence at the laboratory of the Royal Institution. The results obtained by Magnus also stimulated a lot of interest in the scientific London community, and this spurred Tyndall to account for the variations in their respective results. In response to the criticism by Magnus and the public interest, Tyndall devoted his next paper[450] to meeting objections to the use of rock salt and the influence of the polluted London air on his results.

Tyndall addressed concerns about impurities in the experimental gases. During a walk in London Magnus drew Tyndall's attention to "the sunbeams slanting through the dusty air of London" which could be a source of absorption in Tyndall's experiments. Tyndall then experimented with the air from rural locations including the Isle of Wight, Hyde Park, and Hampstead Heath, confirming his previous results. The experimental results were also confirmed when London air was purified and dried before being used as an experimental gas. When heavy smoke, thicker than generally found in London, was generated by smouldering paper in a receiver and passing air through it which was subsequently dried, the absorption by the smoke was still only a fraction of that of the water vapour.

3C.4. Tyndall's Responses to Magnus

Tyndall's first published response to Magnus appeared in the second Memoir: "my first care was to examine whether my published experiments on moist and dry air stood a test of repetition."[451] His initial experiments revealed that dry air absorbed only a fraction of the radiant heat that was absorbed by the moist air. On replicating

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[449]Ibid., Tyndall, pp. 86-89.

[450]Tyndall

[451]Tyndall (1863a for 1862), 152, p. 61.

the experiments, to his surprise, at first little difference was shown between the moist laboratory air and the air that had passed through drying apparatus (a U-tube containing pumice wetted with sulphuric acid, followed by a similar tube with the pumice stone wetted with caustic potash to remove carbonic acid). Perplexed by this unexpected result, Tyndall soon realised that in its passage through the second tube, the air lost its carbonic acid, but gained moisture. On reversing the order of the tubes Tyndall remedied the situation. The air containing moisture and carbonic acid was six times more powerful heat absorber than the dry and clean air. When Tyndall replaced the pumice stone with old calcium chloride, the “dry” air became a more powerful absorber than the moist air. Evidently the old calcium chloride had lost its efficiency as a drying agent. The moist air and the air after its exposure to the freshly fused pure calcium chloride, were then compared in their power of absorption of radiant heat: the moist air absorbed thirty times as much radiant heat as the dry air.

As a result of Magnus’s interventions in his research, Tyndall became aware of the adverse effects of impurities. He had already studied Faraday and Plücker’s inconsistent results in their diamagnetic researches, due to the presence of impurities.[452] He therefore elaborated his procedures to ensure that his results were untainted. He replaced the pumice stone with small pieces of very pure glass obtained from the interior of a large glass block; the glass fragments were washed with nitric acid, thoroughly rinsed with distilled water and dried, then moistened with pure sulphuric acid. A funnel was used to fill the U-tube with the glass in order to prevent even a slight contamination of the corks in the neck of the U- tube with the acid. Another potential source of contamination was dust from the cork stoppers or sealing wax. Filling the upper parts of the U-tube arms with the glass pieces ensured that the contaminants were trapped before they could reach the interior. Tyndall repeatedly confirmed his results with the air and elementary gases over four months, and obtained lower results for their power of absorption as “I became more and more master of my apparatus, and more acquainted with the precautions necessary in delicate cases...”[453]

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[452]Tyndall and Knoblauch (1850a), 36, pp. 178-183; (1850b), 37, pp. 1-53

[453]Tyndall (1863a), pp. 61-63.

Tyndall articulated the importance of experimental techniques in detecting a difference in the powers of absorption between the elementary gases.

> ... the most powerful and delicate tests which I have hitherto applied, have failed to establish a difference in a satisfactory manner. It is not improbable that the action of these gases may turn out to be less even than I have found it. For who can say that the best constructed drying apparatus is really perfect? ... if any further advance should be made in the purification of the gases, it will certainly only tend to augment the enormous differences exhibited ....[454]

He referred to Table I reproduced below, listing the absorption of gases at the pressure of one atmosphere, revealing the powers of absorption by compound gases to be many times the powers of absorption of the elementary gases. In table II he compiled a list of powers of absorption at one inch pressure: the ammonia gas displayed over 7000, olefiant gas nearly 8000 and sulphurous acid over 8000 times the power of absorption of the elementary gases.[455]

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[454]Ibid., pp. 67-8

[455]Ibid., Tyndall, pp. 67-68.

TABLE I		TABLE II	
Name	*Absorption*	*Name*	*Absorption*
Air	1	Air	1
Oxygen	1	Oxygen	1
Nitrogen	1	Nitrogen	1
Hydrogen	1	Hydrogen	1
Chlorine	39	Chlorine	60
Hydrochloric Acid	62	Bromine	160
Carbonic Oxide	90	Hydrobromic Acid	1005
Carbonic Acid	90	Carbonic Oxide	750
Nitrous Oxide	355	Nitric Oxide	1590
Sulphuretted Hydrogen	390	Nitrous Oxide	1850
Marsh-Gas	403	Sulphide of Hydrogen	2100
Sulphurous Acid	710	Ammonia	7260
Olefiant Gas	970	Olefiant Gas	7950
Ammonia	1195	Sulphurous Acid	8800

Using, like Magnus, a heat source at 100 degrees Centigrade, Tyndall found the absorption of air, oxygen and hydrogen to be 0.33%. Magnus claimed the results to be between thirty and forty times larger, and eventually 100 and 140 times respectively as large as Tyndall's who by further experimental refinements had reduced the absorption of these gases to less than 0.1%. Although Tyndall remarked that his results for compound gases indicated a "considerably stronger action" than Magnus's results, he granted that at least for one result this might be expected since they used the experimental tubes of different lengths. Tyndall referred to "the interesting question",[456] Magnus's assertion that the heat quality changed on reflection from the internal walls of the glass tube, and that this accounted for the

[456]Tyndall (1862 for 1863), 152, p. 89

difference in their results. Magnus had made this point when replicating Franz's experiment using a glass tube and a powerful luminous heat source. Whereas for air and oxygen the tube lined with black paper reproduced the Franz's results, the tube without the lining gave more than four or five times that result. When Tyndall replicated this experiment using a tube of the same length without the lining, but with an obscure heat source of 100 degrees centigrade, his results were only a fraction (140^{th} to 160^{th}) of those of Magnus. He implied that because the heat from a luminous source is known to pass through gases more readily than heat from an obscure heat, the results were more significant than appeared at first sight.[457] One can surmise that the readings were the deflections of the galvanometer needle.

In the Memoir Tyndall also took up the discussion of the main point of disagreement between him and Magnus, that of the effect of water vapour on the absorption of radiant heat. Using the luminous and the obscure heat sources, Magnus detected no difference between dry air and the air saturated with aqueous vapour. Tyndall found repeatedly a difference between dried air and moist laboratory air. The absorptive power of the moist air was found to be between fifty and sixty-five times that of dry air in the course of experiments that were conducted daily for more than a fortnight. Tyndall stated that "Differing as I did from so cautious an experimenter, I deemed it due to Professor Magnus and myself to spare no pains in securing myself against error."[458] Tyndall used various means of moistening the air, including Magnus's- passing small bubbles of it through water. For moist air Tyndall recorded an absorption of sixty to eighty times that of dry air. He concluded: "The action of aqueous vapour is exactly such as might be expected from the vapour of a liquid which Melloni found to be the most powerful absorber of radiant heat of all he had examined."[459] Tyndall however, eventually attributed the difference his results and those of Magnus to defects in Magnus's apparatus. Tyndall stated that at the very beginning of his programme in 1859 he had been about to commit the same mistake and do away with the plates between the source and the thermopile that would bring

[457]Ibid., Tyndall (1862-3), 152, pp. 86-89.

[458]Ibid., Tyndall, p. 89.

[459]Ibid., p. 90

the gas into contact with the heat source. However, because his preliminary experiments had revealed results many times greater than what he had expected Tyndall had made additional innovation in the arrangement, that of inserting another tube between the experimental tube and the heat source. This tube served as the front chamber, only quarter of the length of the experimental tube and firmly attached to it. The air sent through the drying apparatus, that showed absorption of one, when it was sent through the front chamber, (in direct contact with the source), showed absorption fifty times greater, despite the fact that the chamber was a tube of only one quarter length of the original experimental tube. These results were confirmed on replication.

Tyndall thought that this subject merited additional confirmation by studying radiation through open air. A brass cylinder was filled with quartz moistened by distilled water. A burner was placed underneath and all these then placed between a heat source of 100 degrees (presumably centigrade) and the thermopile. The burner was connected to an air bag from which air was pumped, circulated through the quartz to imbibe it with vapour, and finally allowed to rise between the heat source and the pile. Screens controlled the amount of heat from the compensating source falling on the pile. It was important to protect the apparatus from outside influences that might cause convection currents. This was achieved by means of tin screens separating the space occupied by the apparatus into compartments filled with paper or horsehair. The whole area was then surrounded with boards, with a tin roof to protect the thermopile. The needle was deflected indicating an increase in heat absorption due to the presence of the water vapour. The wet quartz in the brass cylinder was replaced with calcium chloride through which the air circulated; the dry air then rose as before between the pile and the heat source. The greater deflection of the galvanometer needle indicated the greater transparency of the dry air to radiant heat. On repeating the experiment the moist air always showed the greater opacity to radiant heat; the dry air demonstrated diathermancy.

In response to criticism that precipitation on the polished walls was confounding the results, Tyndall argued that this was unlikely, since on the days of his experiments the ambient air was hardly saturated enough to cause the precipitation on heated metal surfaces. He performed experiments on vapours as well as humid air in a specially designed tube of a wide diameter and this procedure ensured that the experimental vapours and gases did not touch the walls of the tube. The experiments with the air between 1 inch and 30 inches pressure showed that the power of absorption varied as expected with the density of the vapour according to calculations. The fact that the results were consistent within experimental error testified against the possibility of random precipitation.[460] Having done away with the experimental tube, Tyndall could still demonstrate the same effects, though because these tests were on a smaller scale, they needed further repetition.

By experimenting with various quantities of moist air Tyndall demonstrated that the absorption of radiant heat was proportional to the quantity of the vapour present, and hence refuted Magnus's assertions that the reflectivity of the inner walls of the experimental tube was reduced by the supposed condensation of moisture on them.[461] Tyndall used a galvanometer deflection as the measure of the heat available; beyond certain deflection the galvanometer was calibrated according to Melloni's instructions.[462] He could dispense with specifying the units, since he worked with ratios such as percentages; the figures were not expressing absolute, but relative results. Tyndall concluded that a slow diffusion of the water vapour through the dry air was witnessed as the needle gradually reached zero. When the dry air was allowed to flow through the tube, the reflection remained stable. When the air was saturated with water vapour before being replaced by air more saturated with water vapour than the ambient air. At the suggestion of eminent men, presumably witnesses, Tyndall repeated the experiment hundreds of times and under different conditions, but his results remained consistent, the ambient air absorbing 4.2%, the saturated air 5.5% of radiant heat. With satisfaction he announced that no experiments performed on liquids and vapours so far had displayed consistency. Considering the different methods pursued by Magnus and himself, Tyndall found a remarkable agreement between them on many issues. He emphasised the differences, "for the benefit of the researchers wishing in the future to participate in these investigations."[463] Tyndall

[460]Tyndall (1882a), 173, pp. 291-354, 316-319.

[461]Tyndall [1863e], 153, pp. 1-12, 5-6.

[462]Tyndall (1872f), pp. 56-59.

[463]Tyndall (1863a), 152, pp. 59-98, 86-87.

expressed his great reluctance, "to dissent from so excellent a worker as Professor Magnus. Hitherto, however, our differences have only led to the shedding of light upon the subject; and as long as this is the result, such differences are not to be deprecated."[464] In his last pronouncement on the subject in 1882, Tyndall, recalling Magnus's challenge, remarked that this discord was due to their different approaches. Whereas Magnus ascertained that "... it could be foreseen with certainty that the small amount of aqueous vapour taken up by air at ordinary temperatures could exert no influence on the transmission." Tyndall, although of the same opinion at the start of his programme, "until practically instructed to the contrary," reached the opposite conclusion. "Magnus tested his foregone conclusion, and found it verified; … I … justified mine." [465]

3C.5. Conclusion

Daniel Spiegel, in his study of the Balfour Stewart-Gustav Kirchhoff controversy, an event that took place in the same decade as that between Magnus and Tyndall, placed his protagonists' disagreement in the context of "substantial and explicit animosity between the British and German scientific communities."[466] Considering Tyndall's positive experience in Germany, Magnus's friendship with Faraday and his frequent visits to the UK, it is doubtful that one would apply the same reasoning.

Tyndall the physicist, close to Faraday and possibly in Faraday's shadow, strove to prove his virtuosity as an experimentalist. Caneva claims that Magnus, a chemist and recognised organiser would have been expected to establish himself as a teacher first, and as a researcher second, according to the German tradition of a professor. He neglected what appeared to Tyndall as obvious problems, and his ready assumptions point to a curious absence of concern for experimental details in this notoriously intricate field. This might be accounted for by a certain vanity, absent in Tyndall, but evident in Magnus, possibly partly due to his virtual confinement to

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[464]Tyndall (1872b), pp. 378-401, 388.

[465]Tyndall, pp. 291-354, 296.

[466]Siegel (1976), 67, pp. 565-600, p. 567.

Berlin where he reigned supreme. Magnus, eighteen years senior to Tyndall and in a position of authority two decades before Tyndall's appointment at the Royal Institution, had never been called to account. The challenge from Tyndall appeared to be a bitter experience. Tyndall had protested in his youth on behalf of starving surveyor apprentices in Preston, and his modest Irish background contrasted with that of Magnus who was placed firmly in the German bourgeoisie. As one of the leading scientists of the strong empirical tradition in Berlin, Magnus's interpretation of invisible experimental factors, preponderant in gas experiments, contrasts with those made by Tyndall who allowed also a role for his fine intuitive faculty (e.g. in such decisions as to the presence or absence of the convection currents), and who recognised the physical manifestations of dynamic thermal events that were missed by Magnus. Their respective experimental procedures seem to expose the chasm between their cognitive approaches; Magnus of a traditional and rigid vanishing school, Tyndall of the innovative and imaginative characteristics of a science that he helped to create.[467] Jungnickel and McCormmach discuss the role of experiment in the German approach to controversial research, and refer to the experimentalist Poggendorff's reductionist preferences with a strong mathematical emphasis. Müller has considered the theoretical background to controversies, and asserts with reference to the theory of galvanism: "The passion for controversy dies away once the theory is well grounded…"[468]

The concept of the water vapour as a strong heat absorber, and the explanatory power of this result for puzzling meteorological phenomena established Tyndall's experimental results as being key to the burgeoning science of meteorology discussed in Chapter 5. Since an experimental strategy was at stake, judging from the respective papers of Magnus and Tyndall, I see it as an empirically rather than an ontologically driven confrontation.

In this chapter I have followed Tyndall's experimental programme, announced in his first communication to the Royal Society in 1859. Soon after his first paper was

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[467]These thoughts occurred to me after a seminar by H. Chang at the LSE 26 April 2006.

[468]Jungnickel and McCormmach (1986), pp.121-122.

published in 1861 (chosen as a Bakerian lecture for the year), it was subjected to criticism by Magnus. Tyndall responded to the problems raised. The modified programme included additional experiments that confirmed or refuted his initial results. Tyndall was profoundly affected by the doubts expressed by his mentor and friend Magnus, and repeatedly returned to the theme in the following twenty years. His colleagues, Frankland and Wild after having been approached by Tyndall, independently confirmed his results. Magnus's involvement dominated Tyndall's experimental work throughout his professional life. Tyndall's excellence in precision, like that of his French contemporary H.V. Regnault's (1810-1878) discussed by Chang,[469] produced an empirical methodology with results of great significance for the future of mankind.

[469]Chang (2004), pp. 84-102.

CHAPTER 4

Tyndall the Physical Theoretician

With the 1861 Bakerian lecture Tyndall inaugurated a decade of research into the interaction of radiant heat and matter in gaseous state. Although he used radiant heat mostly as a tool to investigate the composition of matter, in his discovery of calorescence,[470] radiant heat became an active agent, revealing a new phenomenon in nature. Reputed for the excellence of his experiments since 1850, he has been unappreciated as a theoretician. His writings, however, declare his continuous interest in theoretical physics, radiant heat, and in particular the composition of matter.

In this chapter I explore the theoretical ideas that guided Tyndall's experimental programme investigating the diathermancy and athermancy of the elementary and compound bodies as a means to study the molecular constitution of matter. In turn the experimental investigations produced results suggestive of further theoretical developments or requiring an alteration of the initial hypothesis. In Section 4A relevant aspects of the physical theory in Germany and in Britain will be discussed, with emphasis on radiant heat, matter and the aether in British science. In Section 4B I examine Tyndall's adaptation of these theories. Since Tyndall the scientist derived inspiration from the work of his mentor and friend, M. Faraday (1791-1867),[471] I will refer to Tyndall's use of radiant heat as 'thermal mode of investigation' reminiscent of what Faraday called an 'optical mode of investigation,'[472] that is his use of light to probe the constitution of matter. This approach is prompted by James who discusses how Faraday's use of light, initially as an operational resource, together with matter, came to play an important role in his natural philosophy.[473] In a similar way in Section 4C, I will scrutinise Tyndall's theoretical notions to determine whether radiant heat played a part in his natural

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[470]Tyndall (1866a), 156, pp. 1-24.

[471]Hobsbawm [1962] 2003.

[472]Faraday (1844), S. 3, 24, pp. 136-144.

[473]James (1989), pp. 136-161.

philosophy.[474] Section 4D will investigate the perception of Tyndall's theoretical work by his contemporaries and following generations of historians.

4A. Physical Theory in Nineteenth-Century Germany and Britain

In this section I concentrate on Germany and Britain, the two countries where Tyndall studied and worked, and which therefore had a potent influence on his science. It was an era of fierce debates among natural philosophers concerning natural phenomena within the newly emerging, distinct scientific disciplines, including physics. The Italian Melloni, the American Draper and the Frenchman Ampère, in addition to Faraday and Helmholtz among others, also impacted on Tyndall's natural philosophy.

4A.1. Theoretical Physics in Germany

This section considers German theoretical physics for two reasons. The first is Tyndall's experience of German higher education in Marburg and Berlin, 1848-1851. This was a time when German liberal higher education embraced science as a cultural amenity, informing their citizens through translating foreign research, and welcoming foreign students.[475] Secondly, because the role of one of the discoverers of the energy principles, the eminent German physicist H. von Helmholtz (1821-1894) in the establishment of physics in Germany, and in its dissemination in Britain. Tyndall made an important contribution to this process through translations and popularisation of the works by the distinguished German physicists, K.H. Knoblauch (1820-1895), R.J.E. Clausius (1822-1888), and von Helmholtz.

F. Bevilacqua suggests that Helmholtz led the emergence of theoretical physics as distinct from mathematical physics. Rooted in the conservation of energy, with the concomitant potential and kinetic energy principles envisaged by Helmholtz, theoretical physics in its new discursive qualitative mode provided an alternative theoretical base to mathematics with a well-defined framework and guidelines. Hence he pioneered a research process based on the interplay of mathematically based theory

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[474] See this dissertation section 4 C.7 pp. 37-41; Tyndall (1866a), 156, 1-24.

[475] Jungnickel and McCormmach (1986), p. 120.

and experiment was replaced by the interplay between theory and principle. The new theoretical physics served as a unifying agent for different branches of physics and other disciplines that enabled the non-mathematical physicists to understand the role of the forces involved in natural processes, and their relation to the concept of energy in nature.[476] In this mode, theory had the task of revealing the causes of the phenomena behind visible effects. Here I see a probable source for Tyndall's thoughts on scientific imagination. Helmholtz also postulated that nature might not be entirely comprehensible, but instead unpredictable, spontaneous at times.[477] In translating some of the papers by Helmholtz, as well as ensuring the translations of other works, Tyndall was well informed of the scientific issues in German physics. His network of friends and colleagues in Germany also testifies to this.

Also relevant to Tyndall's German background is the historian K.L. Caneva's review of the two trends in German science. One was a concretizing science, where experiment preceded and served as a source for theory, the other an abstract science where mathematics determined the theory, and experiment served to confirm it. The adherents of concretising science maintained that by not explaining the essence of the physical phenomena in depth, mathematics misled the physicist. In time, what I see as a compromise, a new methodology of abstract science began to emerge, emphasising the importance of precision in experimental procedures. Theories became provisional unless confirmed by rigorous experiments. Although Caneva's work is based on electro-magnetic researches, he reserved judgement as to what extent this could apply to other branches of physics. In the era when energy principles were applicable across all the branches of physics, a further study of the new methodology may reveal that it also applies to light and radiant heat investigations. It was generally accepted that the experimental evidence provided a closer link to the investigated phenomena than abstruse, mathematically based theories. Consequently the exclusively mathematical interpretation was assigned a lower ontological status.[478]

[476]Bevilacqua (1996), pp. 1-155, 5-7, 22-30.

[477]Helmholtz [1847]1853, volume 5, pp. 114-162, 114-115.

[478]Caneva (1978), volume 9, pp. 63-159, 66, 78-83, 86.

The status of German mathematics is however, considered here because of its high profile in Britain.[479] This created problems for some, including Tyndall himself. German physicist G.S. Ohm (1789-1854) formulated his theory of electrical currents with the help of the, "the torch of mathematics," an expression prevalent in Germany at the turn of the century, which endured unchallenged till the 1830s.[480] Tyndall's syllabus at Marburg embraced differential calculus, which was timely as, "basic laws of physics that could be tested by experiment, had all been formulated as partial differential equations," including French mathematical physicist J.B.J. Fourier's (1768-1830) successful mathematisation of the theory of heat conduction.[481] By the late 1830s, the application of mathematics was considered insufficient to discover the laws of nature, and the roles of observation and experiment were gaining in importance.[482] This discouraging attitude to mathematics, coupled with his supervisor Knoblauch's reputation as an experimentalist, might have contributed to Tyndall being inclined to Faraday's ideas, discussed in more detail below. E. Frankland (1825-1899), chemist at the Royal Institution 1863-1868, later director of the Royal College of Chemistry, was Tyndall's colleague and held high opinion of Tyndall's mathematical skills. Frankland recalled that in Marburg Tyndall concentrated on physics in which "[he] found more scope for his mathematical knowledge."[483] An awareness of the shortcomings of mathematics in physical theory encouraged physicists like Tyndall towards creative thinking, enriching the abstract aspects of physical theory.

According to the historian of science J. Hendry the concept of polarity was used by the German philosopher I. Kant (1724-1804), to provide science with the dynamic foundation of forces. The co-founder of Naturphilosophie, F.W.J. von Schelling (1775-1854) elaborated Kant's ideas on the subject, and the poet S. L.

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[479]Warwick (2003).

[480]Jungnickel and McCormmach (1986), p. 1.

[481]Ibid., p. 178.

[482]Ibid., Jungnickel and McCormmack, pp. 44-45.

[483]Frankland (1893), in McCabe (1981), pp. 93-102, 93.

Coleridge (1772-1834) introduced the concept of polarity to Britain.[484] His biographer R. Holmes identifies in Coleridge a profound "philosophical transformation" at this time. Coleridge abandoned empiricism for a non-mechanical, creative dynamic view of human mental faculties, endowing consciousness with polarity: fancy represented the mechanical aspects of thought; the dynamic, creative features exemplified the power of imagination.[485] Tyndall acknowledged Coleridge whose writings taught him "how to look at nature."[486]

4A.2. Natural Philosophy and Theoretical Physics in Britain

In this section I consider the context of natural philosophy and theoretical physics in Britain where it was taking a different course. Discussing the contemporary controversial issues in natural philosophy and the interdisciplinary impact, D. Knight noted different attitudes to the meaning of theory in the middle of the nineteenth century Britain. The physicist, G.G. Stokes (1819-1903), like most other Cambridge physicists, saw the use of theory not only in connecting facts, but also in accounting for the "real operations of nature."[487] This attitude to theory is akin to that of D. Brewster (1781-1868), the Scottish physicist studied by Frank James. Brewster felt that if a theory included "some principle … inherent in and inseparable from the real producing cause of the phenomena … then it constitutes "an instrument of discovery."[488] I see it as a valuable concept, whether amenable to direct observations, or inferred through hypothesis. The fragmentation of science itself into distinct disciplines, contributed to a different reading of "the book of nature." Discussing the legitimacy of the use of analogies in nature, the mathematical physicist J.C. Maxwell (1831-1879) argued

> Perhaps the 'book' as it has been called, of nature is regularly paged; if so, …the introductory parts will explain those that

[484]Hendry (1986), pp. 18-19.

[485]Holmes (1998), pp. 393-394.

[486]Tyndall (1860c), pp. 38-39.

[487]Stokes (1849), in Stokes (1880-1905), volume 2, pp. 96-97.

[488]James (1984), pp. 47-60, 59.

> follow.... but if it is not a 'book' at all, but a magazine, nothing is more foolish than to suppose that one part can throw light on another.[489]

The Cambridge philosopher W. Whewell (1794-1866) argued that "the ideas at the basis of the Mathematical Truth are concerned with the formation of scientific truth in general;" in addition, he felt: "discussions concerning the nature "of matter, of forces, of atoms, of mediums, of kinds, of organization" had contributed to the progress of science.[490] Carnot's vision of the transformation and conservation of energy in the universe, contained in a manuscript of 1824-1832, was not published till 1878 in Paris when passed by Carnot's family to the French Academy of Sciences. However it was described by Tyndall as remarkable.[491] The manuscript prompted the historian G. Sarton to declare Carnot "the father of thermodynamics."[492] In these notes, Carnot posited a principle that the moving power in nature was a constant quantity which could be neither created nor destroyed, producing a quantity of heat proportional to the amount of the moving power destroyed in the process of being converted into heat. His calculation of the mechanical equivalent of heat approximated to that of Mayer.

The wide-ranging cultural curiosity about science highlights its emerging autonomy. I contend that the new generation of scientists participated in the creation of the new ontology of the study of nature with profound consequences for science. Colliding with the deeply held precepts of natural theology, scientific naturalists interacted and reacted against the background of personal beliefs[493] and in support of Darwin's theory of evolution.[494] F. Turner[495] and C. Smith,[496] see this new mental

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[489]Maxwell (1856), p. 243.

[490]Whewell [1857] 1976, volume 1, pp.viii-ix.

[491]Carnot (1878), quoted in Tyndall [1880]1898, pp. ix-xiii.

[492]Sarton (1929), volume 13 (1), pp. 18-44, 33-34.

[493]Schaffer (1986), volume 16, pp. 387-420.

[494]Bowler (1990), pp. 145-150.

[495]Turner (1981), pp. 169-180, 170-173.

outlook of independence of science from theology, as a hostile enterprise, "a challenge to the existing cultural authorities" which it would replace.

4A.3. Key Themes in the Theoretical Background to Tyndall's Work

(a) Radiant Heat

Before Tyndall's time, the theory of radiant heat had made a transition from the caloric theory to a wave theory. Tyndall's interest in radiant heat began early in his career. When reminiscing about his youth, he recalled aspiring to conduct research like the Geneva physicist and diplomat, M.A. Pictet (1752-1825), and the famous chemist in charge of the Royal Institution (1801-1813) H. Davy (1778-1829).[497] His early impressions of his stay in Marburg included a sketch that described the working of a stove in his room. Tyndall's interest in radiant heat was spurred on in 1850 by the Italian physicist M. Melloni's (1798-1854) incisive work on radiant heat and matter in liquid and solid state.[498] Several copies of this book, which enthralled Tyndall, were sent by Melloni to Faraday with instructions to keep one, and to send others on to the addressees.[499] In 1851 Tyndall also visited the University of Berlin, where he discussed the subject with the respected scientist in charge, G. Magnus (1802-1870) who in 1860s challenged some of Tyndall's theories. The ensuing controversy is examined in Chapter 3 Section E of this dissertation. Tyndall wrote biographical articles on the pioneers of experimental demonstrations of the nature of heat such as the founder of the Royal Institution in 1799, Count Rumford Benjamin Thompson (1753-1814) and the eminent natural philosopher in charge of the Royal Institution 1801-1803, T. Young (1773-1829). The excellence of Tyndall's former Marburg mentor, Knoblauch's work in this area, acknowledged in the 1854 Report to the British Association by the Savillian professor of Geometry at Oxford, B. Powell

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[496]Smith (1998), pp. 170-191, 171-172.

[497]Helmholtz (1874), volume 10, pp. 299-302, 299; Chang (2004), p. 164 n.9-165.

[498]Melloni (1850a).

[499]Melloni to Faraday 14 January 1850 in James [1999], volume 4, pp. 111-116.

(1796-1860).[500] This is likely to have strengthened Tyndall's resolve to contribute to the subject.

The acceptance of the identity of radiant heat with light as different manifestations of the same natural phenomenon resulted in the abandonment of the material theory of heat. Whewell remarked on the common properties identified in light and radiant heat: "recent discoveries of the refraction, polarisation and depolarisation of heat has … altered the theoretical aspect of the subject, and almost at a single blow, ruined the emission theory."[501] Young's wave theory of light and heat of 1802[502] had been ignored except for a few supporters including Rumford, Davy and Pictet. Whewell commented that at the time: "the condition of England was not…favourable to a fair appreciation of the value of the new opinion." Whewell also blamed Young's "affectation of simplicity" for an unsatisfactory presentation.[503] F. James clarifies this lack of support for Young: the French physicist A.J. Fresnel's (1788-1827) transverse wave theory of light was presented in mathematical terms and found ready recognition, whereas Young did not provide a mathematical framework for his theory, at that time still an essential condition for a physical theory to gain scientific credibility.[504]

Contributory factors in the acceptance of the new theory of heat as undulatory motion can be traced also, among others, to the French physicist A. -M. Ampère's (1775-1836) interpretation of radiant heat phenomena in terms of the vibrations of the atoms transmitted by the undulatory motion of the aether,[505] Fourier's analytical theory of radiant heat, independent of the nature of heat or matter.[506] The Swedish chemist J.J. Berzelius's (1779-1848) electro-chemical theory made the corpuscular

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[500]Powell (1855), pp. 337-355.

[501]Whewell [1857] 1976, volume 2, pp 344-345, 431-432.

[502]Young (1802), pp. 32-33, in Brush (1976), volume 2, pp. 309, 654.

[503]Whewell [1857] 1976, volume 2, p. 346-348; Preston [1894] 1919, p. 52.

[504]James (1984), volume 17, pp. 47-60, 47, 57, 60.

[505]Ampère (1835), s. 3, volume 7, pp. 342-349, 343, 345;

[506]Fourier [1822] 1878.

theory of heat less credible.[507] The caloric theory, moreover, failed to conform to the energy conservation principle.[508] According to Robert Fox the caloric theory was also failing to conform to the energy conservation principle. Furthermore the acceptance of a wave theory of light whereby it was propagated through transverse vibrations of the aether, in Fox's view, was particularly influential in the new approach to the nature of heat.[509] S.G. Brush analyses the process of the demise of caloric theory in favour of a wave theory of heat, modified to include the molecular or atomic vibrations as the source of heat phenomena. He considers the studies on radiant heat an important feature in the progress of modern physics, in particular this moment of transition from a caloric to a wave theory of heat, and the subsequent development of the mechanical theory of heat.[510] Clausius and Maxwell's kinetic theory of gases began to serve as an explanatory device for the interaction of particulate matter with radiant heat.[511]

In sum, Tyndall's interest in radiant heat began early in his career. He referred in his papers to the work of his predecessors, indicating his acquaintance with and enthusiasm for the subject.[512] The unravelling of these influences exposes physicists and chemists playing an active part in the emergence of new theories about the forces of nature.[513] As the wave theory of heat began its ascendancy, its allegiance to physics rather than chemistry became recognised.[514]

(b) Matter Theories

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[507] Fox (1971), p. 279

[508] Ibid., pp. 2-3

[509] Ibid., p. 3.

[510] Brush (1976), volume 2, pp. 303-334.

[511] Brush [and Hall, eds.] (2003), pp. 527-528.

[512] Tyndall (1882), lecture 24 November 1881, 173, pp. 291-354, 291.

[513] Fox (1971), p. 279

[514] Ibid.

In addition to theories of radiant heat, the chief theories of matter at the time were crucial to Tyndall's research. Maxwell's article on the atom in the Encyclopaedia Britannica,[515] his paper in Nature on the molecule,[516] and his article on Helmholtz,[517] broadly represented the prevalent schools of thought on the theory of matter. The particulate atomic composition of matter controlled by forces as separate entities, was rooted in Dalton's atomic theory. That of continuous matter, where the atoms were centres of forces and co-existent with them was based on O.F. Mossotti's (1791-1863) hypothesis,[518] and favoured by Faraday. They are considered by Knight as a compromise between the atomic theory and the view that matter is a continuum.[519] Considering the molecular constitution of bodies and the existence of atoms, Maxwell urged Rayleigh "if you can, give us the quantity of light scattered in a given direction…we might get a little more information about these little bodies."[520] Helmholtz's hydrodynamic research,[521] and W.J.M. Rankine's (1820-1872)[522] vortex theory of the atom, (further developed by W. Thomson),[523] began to lose favour by the turn of the new century, argues Knight, in view of the discovery of cathode rays.[524] However, Preston maintained that the vortex theory provided a basis for the development of the modern atomic theory.[525] This paragraph details the main opposing views on the nature of matter, as the context for Tyndall's research.

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[515]Maxwell (1875), volume 3, pp. 36-49.

[516]Maxwell (1873b), volume 8, pp. 137-141.

[517]Maxwell (1877a), volume 15, 8 March, pp. 389-391.

[518]Mossotti (1837), volume 1, pp. 448-469.

[519]Knight [1967] 1970, p. 73.

[520]Maxwell, in Pesic (2005), pp. 121-122.

[521]Helmholtz [1858]1867, s. 4, volume 34, pp. 485-512.

[522]Rankine (1851), s. 4, volume 2, pp. 509-542.

[523]Thomson [1867] 1869, pp. 94-105; Silliman (1963), volume 54 (178), pp. 461-474.

[524]Knight [1967]1970, p. 139-140.

[525]Preston [1894] 1919, pp. 75-76.

Contrasting views on matter were represented by J. Dalton (1766-1844) and Faraday. Tyndall adhered to Dalton's atomic theory, useful for the characterization of matter, as revealed in its interaction with radiant heat. Dalton argued for the essential aspects of the nature of matter: the weights and arrangements of the compound atoms composing the molecules, their number and weights, as "the only ones representing nature."[526] Presenting the Royal Medal to Dalton in 1826, the president of the Royal Society 1820-1826, H. Davy (1778-1829) compared Dalton's achievements to those of the astronomer, J. Kepler (1572-1630).[527] To illustrate the viability of Dalton's atomic theory, Tyndall also invoked Kepler; he compared Dalton's atomic theory to I. Newton's (1642-1727) gravitation theory, revealing further facts based on Kepler's research. For Tyndall the gravitation principle constituted an addition to the facts. Likewise Dalton's laws of definite proportions or equivalents derived from the observed facts. For Tyndall, this embodied the essence of all theory, "a backward guess from fact to principle; the conjecture, or divination regarding something, which lies behind the facts, and from which they flow…"[528] Another enthusiastic proponent of Dalton's atomic theory, W.A. Williamson (1824-1904) professor of chemistry at University College London, also favoured theorising from facts to principles as heuristically advantageous according to the historian of chemistry A.J. Rocke.[529] The historian of science D. Cressey, examining the reception of Dalton's atomic theory in the nineteenth century, echoes Williamson's appreciation of its heuristic advantage: Dalton's ideas, modified and adapted, proved their power as a pedagogical tool.[530] I contend that their adaptability explains their power of endurance.

Dalton's atomic theory had many supporters, but some detractors, including Faraday. Although scientific issues played a part in Faraday's rejection of the atomic theory, Cantor asserts: "they were coloured by his religious conception of nature." For

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[526]Thackray (1970), p. 266, n. 57 the phrase "representing nature" has not been confirmed; Dalton (1837), pp. xxix-xxxii, 77, 207.

[527]Davy [1827] 1840, pp. 92-99 in Davy (1840), 90-112.

[528]Tyndall [1868a], pp. 120-121.

[529]Rocke (2004).

[530]Cressey (2002-2003), pp. 53-56.

Faraday, matter endowed with power by God, was not compatible with inert matter, moving in a void, and constituted of atoms.[531] I contend that Tyndall was unaware of the theological issues that the atomic theory raised for Faraday. Theological considerations were unproblematic in gravitational theory, since in framing it, Newton had maintained a role for the divine. Faraday's research programme on gold enabled him to challenge the atomic theory, and offered an experimentally backed alternative.[532] Writing to the chemist and editor of the *Philosophical Magazine*, R. Phillips F.R.S. (1778-1851) two years later, Faraday reiterated his speculations on "the nature of matter which considers its ultimate atoms as centres of force … that which represents size … extending to any distance to which the lines of force of the particle extend: the particle … is supposed to exist only by these forces and where they are it is."[533] Faraday's matter, co-extensive with forces, was endowed with attractive and repulsive properties, in contrast to matter that Helmholtz described as neutral unless acted on by external forces.[534] Whewell respected Dalton's contributions, but reserved judgement on the arrangement of atoms in molecules, since there were still uncertainties to clarify. For Whewell, the theory, though accepted by the chemists, did not fulfil the criteria for "scientific truths…recognised by all competent judges." Dalton's theory, therefore, did not qualify for inclusion in Whewell's book on the history of science.[535]

W. Brock discusses the calculus of chemical operations as an alternative to atomic theory. This work was done by the president of the Chemical Society, professor of chemistry at Oxford, B.C. Brodie (1817-1880) and presented at a joint meeting of the Royal Society and the Chemical Society in 1867.[536] Chemists were equivocal in their reactions. Physicists attending included Maxwell, G.G. Stokes

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[531]Cantor (1991), pp. pp. 176-185.

[532]Faraday (1844), s. 3, volume 24, pp. 136-144; James (1989), pp. 137-161, 141-142, 144.

[533]Faraday [1846], s. 3, volume 28, pp. 345-350.

[534]Helmholtz [1847] 1853, pp. 114-162; 114-115.

[535]Whewell [1857] 1976, volume 3, pp. 127-134, 132.

[536]Brock (1967), pp. 91-152.

(1819-1903), professor of Physics at University College London, G.C. Foster (1835-1919), and Tyndall. They supported the atomic theory by and large, Foster with reservations. Faraday's alternative views are examined by James.[537] The kinetic theory of gases, Maxwell said, favoured the existence of the atom, but now and again one discerns doubts in his and other participants' pronouncements.[538] Tyndall expressed surprise that the people who accepted the concept of the aether and the wave theory of light, objected to the atomic theory.[539] He felt that the level of evidence was the same in each case. The Karlsruhe Conference put a seal on atomic theory through the persuasive powers of S. Cannizzarro (1826-1910).[540] E. Garber and colleagues date the involvement of physicists in the study of matter to post-1857, after the establishment of the kinetic theory of gases and the dynamic theory of heat, chiefly by Clausius, co-founder of the science of thermo-dynamics, and the two Scottish physicists and mathematicians, Maxwell and Thomson. While matter theories were within the discipline of chemistry, Garber posits the natural philosophers' preoccupations with philosophical and theological context, whereas "the microstructure of matter … was in no sense a recognised problem area in physics".[541] According to Garber, the work of Clausius, Maxwell and Thomson provided a stimulus for other physicists to participate; before 1857 it had been the prerogative of the chemists. Garber maintains that speculations on the internal structure of matter were unpopular as there was no evidence for it. Although the explanation of the physical phenomena on an experimental basis was acceptable, a mathematical confirmation was expected to follow.[542] In my view Brock reflects the prevalent uncertainty in the absence of firm evidence about the structure of matter.[543] I refute Garber's assumption that there was no interest among natural philosophers in the

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[537]James [1985]1989, pp. 136-161.

[538]Brodie (1867), volume 15, pp. 295-305, 303-305.

[539]Tyndall (1867), in Knight (1970), p. 121.

[540]Knight (!970), pp. 25, 77.

[541]Garber (1976b), pp. 265-297, 265-266.

[542]Garber, Brush and Everitt (1995), p.37.

[543]Brock (1967), pp. 22-23, 159-160.

structure of matter before 1857, their main preoccupation being philosophy and theology. Firstly, their interest in the structure of matter may not have been included in the domain of physics. This is possibly more a reflection on the status of physics at the time, not yet a fully developed speculative theoretical science and unable to accommodate some aspects of the wide-ranging debate within its framework. Secondly, there is evidence of considerable interest among natural philosophers in the structure of matter at the time: Dalton's early research into the physical properties of the gases of the atmosphere and the three states of matter,[544] Faraday's study of the propagation of gases through capillary tubes in 1817 heralding his almost continuous focus on the physical aspects of matter,[545] natural philosopher A.M. Ampère's 1775-1836) influential theoretical speculations in 1820s, Melloni's research between 1830-1854, Tyndall's preoccupation with matter from 1850. Moreover their concerns with philosophical and theological contexts did not prevent them from studying the physical aspects of the structure of matter, and their philosophy and theology had an influence on their science beyond 1857. Despite the absence of firm evidence, Tyndall and some of his contemporaries made significant contributions to theoretical issues of the nature of matter in terms of Dalton's atomic theory.

(c) The "Matter" of the Aether

The concept of the aether[546] was of particular importance to Tyndall. The interaction of heat and matter, at the heart of Tyndall's research, required the positing of the medium aether pervading all space. This Newtonian concept held sway over nineteenth century science as the imponderable matter of heat, light, electricity and magnetism of the previous century had been replaced by the concept of forces and their interaction with matter.[547]

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[544] Dalton [1808]1965, pp. 112-161.

[545] Notes 514 and 515, Faraday.

[546] The spelling 'aether' or 'ether' was acceptable. I choose the former spelling to distinguish it from 'ether', a substance or a class of substances in chemistry.

[547] Harman [1982]1983, p. 3-4.

Fresnel's vibrations of the aether at right angles to the direction of the propagation of light and therefore radiant heat, prompted mathematical physicist Stokes to impose the properties of solidity and elasticity on the aether.[548] This inconceivable combination of properties made Maxwell weary of the concept of aether, but he paid a lip service to it on occasions. At a Friday Evening Discourse at the Royal Institution, however, he made his opposition to the aether theory clear, since it duplicated light theory which fulfilled the same purpose.[549] For Preston, aether, since not directly detectable by the senses, had to remain a hypothetical notion. Its importance was however indisputable. Every molecule of matter vibrated, generating waves in the aether which was never at rest. In turn the aethereal waves were assumed to affect the material body producing a sensation according to the wavelengths that had been generated in the aether.[550] The mathematician L. Euler's (1707-1883) ideas on the synchronization of particulate vibrations of the body with those of the aether, provided nineteenth century researchers, including Tyndall, with an explanatory hypothesis for the mechanism of this interaction.[551] I conclude that the concept of the aether appealed to Tyndall as an explanatory device in his speculations on matter and natural phenomena; for the same reason he argued for the acceptance of Dalton's atomic theory.

(d) Energy Principles

Here I review the two energy principles in the context of contemporary natural philosophy. The concepts of the conservation and inter-conversion of energy were of crucial importance in Tyndall's work. The new physics raised scientific issues in Britain, tinted also with political overtones. An admirer of the theoretical aspects of the work of the German physiologist, J.R. Mayer (1814-1878), Tyndall acknowledged him as the pioneer of the mechanical theory of heat, and saw him on an equal footing

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[548]Stokes (1848), volume 32, pp. 343-349.

[549]Maxwell [1875], RI discourse 21 February 1873, pp. 44-54.

[550]Preston [1894]1919, pp. 54-56.

[551]Cantor (1983), pp. 118-122.

with the physicist, J. P. Joule (1818-1889), a pioneer of its experimental proof[552] (as also stated by Joule and Thomson).[553] T. Preston (1860-1900), Professor of Natural Philosophy at University College Dublin, also saw Joule and Mayer as playing an equal part in their respective fields of expertise as energy scientists.[554] The Scottish Professors of Natural Philosophy, namely Thomson at Glasgow and Tait (1831-1901) at Edinburgh, attacked Tyndall as biased in favour of the German scientist, and not paying sufficient tribute to Britain's Joule.[555] According to Joule, Mayer had published his hypothesis prematurely to claim priority, whereas he himself would publish only theories supported by experiments, abiding by J. Herschel's (1792-1871) canon that "hasty generalisation is the bane of science."[556] Maxwell criticised Mayer's calculation of the equivalent of heat as illegitimate, since it was based on a proposition, unproven at the time, that at constant temperature the heat developed on the compression of air equalled the thermal equivalent of the work done in compression.[557] Stokes sided with the detractors, and on the occasion of the award of Copley Medal to Mayer, a message was read from Stokes, maintaining that Mayer's results were obtained on a false premise, and may have been wide off the mark, if applying pressure to the air had required the consumption of heat.[558] Tyndall's German university background and friendships, evoked sympathy for Mayer's personal plight; his distinguished opponents' scientific arguments did not prevent the award of the Copley medal to Mayer, a prestigious recognition of his contributions. In T. Kuhn's (1922-1996) work as in that of Preston,[559] and Tait the previous century,[560]

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[552]Tyndall [1863c] 1898, p. 132.

[553]Smith (1998), pp. 73-74.

[554]Preston [1894] 1919, p. 86.

[555]Thomson and Tait (1862), p. 604

[556]Joule (1864), s. 4, volume 28, p. 151, in Preston (1919), p. 85, n.2.

[557]Maxwell (1872), pp. 196-197; Anon. (1883), p. 649.

[558]Stokes 30 November 1871, volume 20, (1871-1872), pp. 47-61, p. 55.

[559]Preston (1919), pp. 85-86.

[560]Knott (1911), pp. 208, 210-211.

other notable participants in the science of energy are also identified. Most important are L.A. Colding (1815-1888), and Helmholtz who between 1842-1847 each unaware of each other's work, announced the energy conservation principle in terms of general proposals and mathematical relationships. They also include French engineer, M. Séguin (1786-1875), Clausius, W.J.M. Rankine (1820-1872), and Thomson, the last three applying energy principles between 1849 and 1851. Four others wrote of forces as having a common origin, being able to be transformed from one form to another, but not being created or destroyed. The theory of energy conservation became more established, as experiments and concepts by early participants made way for the coherent discourse that eventually emerged.[561] As Kuhn noted in the late 20th century, the Victorian physicists Tait and Preston acknowledged several researchers' involvement in the simultaneous discovery of the energy principles. The ready acceptance of the principles in Britain as a unifying factor for science, in my view, replaced natural theology. C. Smith concentrates on the development of the British energy physics as understood by the contemporary scientists 1850-1875, with Thomson its chief exponent.[562] This is a useful way of viewing Tyndall's attitude to the mainstream of the science of his day.[563] Tyndall embraced the mechanical theory of heat, lectured on it at the Royal Institution in 1858, and on the basis of his lectures, published a book,[564] the first popular exposition of Clausius's mechanical theory of heat,[565] which appeared in many editions in English and translation. Whereas in Germany, according to Smith, the concept of energy did not feature prominently in its physics, Cambridge, Edinburgh, and London scientists enthusiastically incorporated the concept in their mechanical philosophy, natural philosophy or physics, according to their understanding of the existing discipline.[566] For the British physicists the energy served to give unity to physical science as it became a discipline of physics

[561]Kuhn [1959],1969, in Clagett (1969), 321—356.

[562]Smith (1978), volume 16, pp. 231-279.

[563]Heimann (1974), pp. 147-161.

[564]Tyndall (1863c).

[565]Clausius [1850] 1851, s. 4, volume 2, pp. 1-21, 102-121, in Yagi (2002), p. 42-49.

[566]Smith (1976), pp. 3-29.

related to dynamics. Tait defined physics as the study of energy and its transformations.[567] Smith suggests a multifaceted role for this new science, applicable to terrestrial and cosmic phenomena, their empirical as well as theoretical investigations, and technological applications, therefore characterising the Victorian idea of the study of nature at large, not only of physics. For Smith the advantages of the energy principles were summarised by Maxwell pointing the way to the discovery of laws in other branches of science.[568] Tyndall, like Maxwell, saw the application of the principles as a unifying factor.[569] Balfour Stewart, in view of the prevailing ignorance of the ultimate nature of matter, assigned the principles of the conservation of energy and of the dissipation of energy as the basis on which research into heat phenomena should be conducted.[570]

4B. Tyndall on Mathematics and Imagination

For Tyndall, nature was "an organic whole…changing…but without one …break of continuity, or a single interruption of fixed relation of cause and effect."[571] Addressing student teachers in 1861, Tyndall stated:

> A perfect theory gives dominion over natural facts; and even an assumption which can only partially stand the test of a comparison with facts, may be of eminent use in enabling us to connect and classify groups of phenomena.[572]

This flexible view of the relationship between theory and observed fact was modified when twenty years on Tyndall wrote: "By his observations and reflections in the domain of fact the scientific philosopher is led irresistibly into the domain of theory, his final repose depending on the establishment of absolute harmony between

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[567]Tait, in Smith (1978), pp. 231-279, 233-234.

[568]Maxwell (1877), volume 15, pp. 389-391, 390; also in Smith (1998), p. 126

[569]Tyndall (1865a), p. x.

[570]Stewart (1876), p. vi.

[571]Tyndall (1861b), p. 3.

[572]Ibid., pp. 7-8.

both domains."[573] By instating this rigid relationship between theory and fact, Tyndall aimed to establish for thermal phenomena as firm and precise a basis in the mechanical theory of heat, as the motions of the solar system found in the principle of gravitation or as the light phenomena did in terms of wave motion. He speculated on the nature of atoms in the manner of Ampère, and defended the acceptance of the atomic theory, arguing for its effective role as an explanatory device of the phenomena, irrespective whether the atoms had real existence, or not. To convey "the operations of the inquiring mind" as well as the results of the research process, Tyndall looked at the philosophers' endeavours since the dawn of history,

> To pass from the world of the senses to a world where vision becomes spiritual, where principles are elaborated, and from which the explorer emerges with conceptions and conclusions, to be approved or rejected according as they coincide, or refuse to coincide, with sensible things.[574]

Tyndall's views on physical theory in his natural philosophy are manifest in his assessment of Faraday's research:

> … this rebel against theory was incessantly theorising himself … Theoretic ideas were the very sap of his intellect – the source from which all his strength as an experimenter was derived … And so it must always be: the great experimentalist must ever be the habitual theorist, whether or not he gives to his theories formal enunciation.[575]

Tyndall investigated the application of the principle of the conservation of energy to optical phenomena, and light absorption theories by Stokes, Angström and Thomson.[576] While translating Angström's paper[577] Tyndall would have learned of L.

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[573]Tyndall [1880] 1898, p. viii.

[574]Ibid., viii.

[575]Tyndall [1868], pp. 79-80..

[576]James (1983a), volume 38 (1), 79-107, 92.

[577]Angström (1855), s. 4, volume 9, pp. 327-342.

Euler's (1707-1783) theory of resonance, and Angström's application of a modified version of the synchronisation principle.[578] On the strength of it, periods of vibrations not synchronising with the matter of the eye, would be invisible, since matter absorbed only the vibrations that it could emit.[579] Having discovered that transparent gases were diathermic to the visible spectrum, Tyndall concluded that they absorbed only the slower vibrations emanating from the obscure heat source that he had used in his experiments. This fact fitted with the hypothesis that the compound molecules would be expected to move through the aether at a slower pace than uncompounded atoms. To account for exceptions, he used an additional concept to enable molecules create *"points d'appui"*[580] for the aether. Tentatively he drew analogy with electricity but when discussing conduction, he decided that the speculations had gone far enough "and must now abide the judgement of those competent to decide whether they are the mere emanations of fancy, or a fair application of principles …."[581]

He drew profusely on the analogy of light and sound: "In the study of Nature the coarser phenomena, which come under the cognizance of the senses … suggest … the finer phenomena … under the cognizance of the mind." He recalled that the analogy of light with sound waves had suggested itself when sound became visible, for instance in the quivering of the flame, or vibrations of a string. The role of the luminiferous aether in the propagation of light and heat vibrations was analogous with that of air in the propagation of sound. Unlike Faraday and Maxwell, Tyndall embraced the concept of the aether completely: "To the philosopher [the] waves of the aether are almost as palpable and certain as the waves of the sea …."[582]

Tyndall's non-mathematical approach elicited hostile reactions from the mathematician Tait, who mistrusted Tyndall's results on radiant heat.[583] Maxwell

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[578]Tyndall to Herschel 21 October 1861, in s. 4, volume 22, pp. 377-378.

[579]Tyndall (1862c), R.I. discourse 7 June 1861, volume 3, 387-396.

[580]Tyndall (1861a), R.S. lecture 7 February volume 151, 1-36, p. 35.

[581]Ibid., Tyndall p.36.

[582]Tyndall (1860c), p. 228.

[583]Knott (1911), p. 92.

mildly ridiculed Tyndall's metaphysics in poetic stanzas.[584] However he did adopt Tyndall's reliance on indirect detection of effects that could lead to the measurement of phenomena undetectable by the senses. In Maxwell's study of Helmholtz's contributions to the conservation of energy principle and the new methods of observation, he acknowledged: "the great work for the men of science … is to extend our knowledge of the motion of matter from those instances in which we can see and measure … to those in which our senses are unable to trace."[585] In his letter to the philosopher and sociologist H. Spencer (1820-1903), Maxwell betrayed impatience with mathematicians: "by guiding their thoughts always along the same tracks, [they] have converted their field of thought into a kind of railway system and are apt to neglect cross-country speculations."[586]

In his elegiac biography of Faraday, one discerns Tyndall in difficulty, despite being well acquainted with Faraday's research: "to grasp him and his research as a whole; to seize upon the ideas which guided him, and connect them; to gain entrance into that strong and active brain and read from it the riddle of the world-this is a work not easy of performance…."[587] Tyndall then articulated his views on Faraday's use of hypothesis: "He incessantly employed them to gain experimental ends, but he incessantly took them down, as an architect removes the scaffolding when the edifice is complete." He quoted Faraday urging the distinction between assumptions, meaning theory and hypothesis, and, "the knowledge of facts and laws." Tyndall further commented that Faraday "always guessed by hypothesis … making theoretic divination the stepping-stone to his experimental results."[588] In my view, Tyndall looked for the correspondence between theory and fact. Faraday was more tentative in his theoretical speculations, putting trust unequivocally in experiment. Tyndall and Faraday, however, shared, an generally flexible approach to theory as Tyndall

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[584]Maxwell (after 20 August 1874), in Campbell and Garnett (1884), pp. 412-414.

[585]Maxwell, (1873b), volume 8, pp. 437-441. 389-391, 389.

[586]Maxwell to Spencer (1873), in Harman (1990), volume 2, p. 957.

[587]Note 167, Tyndall, p. 1.

[588]Tyndall [1868], p. 121.

recorded: “His [Faraday’s] theoretic notions were *fluent*: and when minds less plastic than his own attempted to render those fluxional images rigid, he rebelled.”[589] In his Presidential Address to section A at the British Association Annual Meeting in Liverpool, illustrating the use of scientific imagination in theories of light, he stated: “Far be it from me … to wish you to fix you immovably in this or any other theoretic conception. With all our belief of it, it will be well to keep the theory plastic and capable of change.”[590]

Apart from Faraday’s influence, Tyndall’s reluctance to include mathematics in his research may be traced to his higher education in Germany at the time of the reaction against the use of mathematics in physics, from fear that mathematicians would take over physics to the exclusion of a thorough understanding of the phenomena. He considered the use of imagination in formulating physical theories on a par with mathematics. Invoking his power of imagination, he drew theoretical conclusions from his experiments. In the change of the thermal properties of air when dynamically heated in the presence of a vapour, Tyndall discerned the relationship between the chemical and mechanical phenomena. Provided that “the theory of an aether be true,” he claimed that this conclusion was as fully justified as “any conclusion of mathematics, and which would hardly be rendered more certain if the physical vision were so sharpened as to be able to see the oscillating atom and the medium in which it swings.”[591] This newly acquired property of air in the presence of the vapour was analogous in Tyndall’s mind to a hot polished plate of metal, also converted to a radiator when covered with a coat of varnish.[592] Tyndall belonged to the last generation of physicists without a strong mathematical base. To some of his peers his theorising reflected a disadvantage, and coloured their attitude to him. His emphasis on the faculty of imagination earned disdain among some mathematicians as unacceptable metaphysics. Meadows attributed the under-estimation of Tyndall by his

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[589]Note 570, Tyndall, pp. 124.

[590]Tyndall (1871c), p. 134.

[591] Tyndall (1862), 152, p. 81

[592]Tyndall [1863a for 1862], volume 152, pp. 59-98, 80-81.

Cambridge educated peers to Tyndall having neglected the quantification of his experimental results.[593]

In addition to his preference for theorising using non-mathematical procedures, Tyndall's method of theorising was distinctive in his emphasis on the use of imagination as an effective replacement for mathematics in theoretical speculations**.**

Tyndall envisioned his task to be to find out "how … to pass from the world of the senses to a world where vision becomes spiritual, where principles are elaborated, and from which the explorer emerges with conceptions and conclusions, to be approved or rejected according as they coincide, or refuse to coincide, with sensible things."[594] In his lectures on light delivered in the United States, Tyndall included the subject of the "origin and scope of physical theories"[595]. They required "the exercise of the imagination … which seems to render many respectable people, both in the ranks of science and out of them, uncomfortable". He referred to imagination as a "great faculty" without which "we cannot take a step beyond the bourne (sic) of the animal world, perhaps not even to the edge of this one."[596] He provided a framework for its exercise:

> … not a riotous power which deals capriciously with facts, but a well-ordered and disciplined power, whose sole function is to form such conceptions as the intellect … demands. Imagination, thus exercised never severs itself from the world of fact … the magic of its art consists, not in creating things anew, but in so changing the magnitude, position, grouping, and other relations of sensible things, as to render them fit for the requirements of the intellect in the subsensible world."[597]

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[593]Note 574, Meadows, p. 91.

[594]Tyndall [1880]1898, p. viii.

[595]Tyndall [1873] 1915, pp. 41-44.

[596]Ibid., p. 42.

[597]Ibid., pp. 42-43.

In his deliberations on the art of imagination, Tyndall credited the Scottish mathematician, C. Maclaurin (1698-1746), Professor at Aberdeen and Edinburgh, and the first exponent of Newton's philosophy, as his source of inspiration.[598]

This section has illustrated Tyndall's ideas on theorising, which in my view, in due course enabled him to arrive at hypothesis on thermal absorption and radiation without mathematics, the themes to be treated in the next section.

4C. Tyndall's Thermal Modes of Investigation and their Fruits

Recognised as an experimenter *par excellence* after 1853, Tyndall also proved himself to be a theoretician, eager to exploit the results of his carefully designed experimental procedures, pioneering systematic investigation of matter in gaseous phase. Here he states his theoretical objectives:

> To come closer to the origin of the ethereal waves –to obtain if possible, some experimental hold of the oscillating atoms themselves–has been the main object of … research on the radiation and absorption of heat by gases and vapours.[599]

In 1861 in the presence of the Members of the Royal Institution, demonstrating for the first time in public the difference in the absorption and corresponding radiation between elements and compounds, Tyndall explained his thermal mode of investigating the nature of matter: "we look with the telescope of the intellect into atomic systems, and obtain a conception of processes which the eye of sense can never reach." Radiation, he explained, was due to the transference of motion from the vibrating body to the aether in which the body was immersed; absorption consisted of the conveyance of motion from the agitated aether to the particles of the absorbing body. There was a reciprocal relation between absorption and radiation always in proportion to each other, as firmly established as polarity in electricity and magnetism. This applied equally to luminous and thermal phenomena acting according to mechanical principles. The selective absorption and radiation was

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[598]Maclaurin, C. (1750 [1728]), pp. 18-19, quoted in Tyndall (1915), p. 43, n.1.

[599]Tyndall (1865a), p.409.

demonstrated by passing an electric spark through the gas, or applied to a vaporised metal. The spectrum characteristic of the gas or metallic vapour featured bright bands, their position in the spectrum always the same. Tyndall proceeded to "look with the mind's eye at the…oscillating atoms of the volatilised metal." He spoke of these atoms as connected by springs of a certain tension. The strengths of the springs, pushed or pulled, determined the rates of vibrations of the atoms. The imaginary springs were a visual representation of the inter-atomic forces. The terminology was not precise. From the concept of forces, he extrapolated to a concept of vibrating waves acting on the atoms, where the waves in synchronisation with the motions of vibrating atoms would be absorbed.[600] A decade later he clarified his use of radiant heat as a tool:

> I would ask it to be remembered that my object in these inquiries was not to follow the track of my eminent predecessors, who made radiant heat the primary object of their thoughts, but rather to employ radiant heat as an explorer of molecular condition. ... I wanted to show the *physical* significance of an atomic theory which had been founded on purely *chemical* considerations.[601]

In his pioneering experiments using radiant heat as an investigative tool, Tyndall discovered that the elements showed marked diathermancy or transparency to heat, whereas compounds displayed athermancy or opaqueness, trapping heat and becoming heated in the process. Revealed for the first time through Tyndall's innovative experimental techniques, this important result exposed a clear distinction between elements, mixtures and compounds in terms of their respective thermal properties, embodying important contributions to the physics of gases. Until then the gaseous state had been considered inaccessible to experiment. In the prestigious Royal Society Bakerian lecture of 1861 Tyndall referred to "*free* atoms both simple and compound" of gases hence not subject to the forces of cohesion operating in the liquid or solid states of matter. The term 'atom' was used imprecisely and included molecules. He suggested a rough surface of the atoms that would enable the aether "to

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[600]Tyndall (1862c), R.I. discourse 7 June 1861, volume 3, pp. 387-396.

[601]Tyndall (1872a), pp. 146-148, 148.

bite them" in the process of absorption, implying a corresponding radiation. He explained a wide range of thermal properties and the differences between elements, their mixtures and compounds, in terms of the atomic theory and the concept of the aether, reducing "the phenomena of radiation and absorption to the simplest mechanical principles."[602]

In March 1861 H.E. Roscoe (1833-1915), former student at University College London and at Heidelberg under R.W. Bunsen (1811-1899), delivered a Friday Evening Discourse at the Royal Institution on the pioneer spectroscopists, German physicist G.R. Kirchhoff (1824-1887) and chemist Bunsen.[603] Their research, stated Roscoe, enabled the identification of chemical elements on earth and in the sun's atmosphere.[604] Three months on, Tyndall, in his lecture, identified the metals by their spectra, paying tribute to Kirchhoff for introducing "the order of law amid a vast assemblage of empirical observations."[605]

Tyndall's discovery of the diathermancy and athermancy of gases by the study of the interaction of radiant heat with matter provided new understanding of various natural phenomena, to be considered in detail below. This remarkable discovery by Tyndall led to the mechanical interpretation of the phenomena of thermal absorption and radiation, the unique characterisation of matter in terms of its thermal properties, the realisation of the infra-red spectroscopy, the confirmation of the composition of the atmosphere, the understanding of its variable constituents in meteorology, and it provided an original method for the confirmation of the composition of ozone.

4C.1. The Physical Interpretation of Thermal Absorption and Radiation

In this section I scrutinise Tyndall's ideas on the phenomena of the thermal absorption and radiation by matter in nature. In Tyndall's philosophy, the physical meaning of thermal absorption and radiation resided in the vibrations of the

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[602]Tyndall (1861a), pp. 1-36, 33-36.

[603]Kirchhoff and Bunsen (1860), s. 4, volume 20, pp. 89-109.

[604]Roscoe (1862), R.I. discourse 1 March 1861, volume 3, pp. 323-328.

[605]Ibid., p. 396.

molecules, and eventually of the atoms of matter, propagated in waves through the aether, in a direction perpendicular to that of the direction in which the radiation travelled. He equated the phenomena of absorption and radiation with the communication of molecular motion from the radiating body to the aether, which in turn conveyed a vibratory motion to the molecules of matter under investigation. By considering the vibrations emanating from the heat source, Tyndall accepted a theory of the heat waves as analogous to sound waves, as enunciated by J.W. Draper (1811-1882), former student at University College London, and Professor of Chemistry (1839-1882) at New York University.[606] The aether mediated the interaction of force and matter. The molecules of a material were capable of accepting vibratory motion from the aether if a synchronisation existed to its existing molecular vibration. Aether accepted all vibrations. Tyndall adopted this concept in early 1860s to account for the different degrees of diathermancy and athermancy he had detected by experiment. The nature of the matter that composed the radiating body, as well as the nature of the matter receiving the aethereal vibrations, determined the extent of diathermancy or athermancy of the material under investigation. By demonstrating that the vibrations of elementary bodies differed from those of their compounds, Tyndall provided a strong argument in support of Dalton's atomic theory and the existence of the aether as a vehicle for atomic motion.[607] At an 1880 RI Discourse, (not published till 1883), Tyndall also endorsed the concept of heat generated in a body that wasn't the result of vibrations, but by virtue of the movement of translation of the molecules in space and the quivering of their atoms,[608] an idea current at the time. Tyndall did not produce a reference for this, but he may have been interpreting the ideas in Maxwell's definitions of molecular motion.[609]

At the beginning of his research, Tyndall expressed an interest in the propagation of solar and terrestrial heat through the earth's atmosphere[610] as also

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[606]Draper [1857], 1878, p. 100.

[607]Tyndall [1865c], pp. 12-14; 56-57.

[608]Tyndall (1883), R.I. discourse 19 March 1880, volume 9, 340-358.

[609]Maxwell in Campbell and Garnett (1882), pp. 956-961.

[610]Tyndall (1861a), lecture 7 February 1861, volume 151, pp. 1-36..

considered by H.B. De Saussure (1740-1799),[611] J.B.J. Fourier (1768-1830),[612] C.S.M. Pouillet (1791-1868),[613] and Cambridge geologist, W. Hopkins (1796-1866).[614] Tyndall looked for the 'atomic conditions' responsible for the extent of radiation, absorption and conduction of heat. He planned to discover why absorption and radiation corresponded, whereas good absorbers were bad conductors. Where absorption was manifested 'on theoretic grounds' Tyndall inferred radiation and vice versa, each being the measure of the other. In conclusion this section illustrates Tyndall's prolific knowledge and imaginative use of it to devise explanations for the observed phenomena.

4C.2. Locating Thermal Absorption and Radiation

In this section I trace Tyndall's attempts to discover whether these phenomena resided outside or inside the molecule. His pioneering experimental research on the athermancy of liquids and their vapours revealed that the absorption and radiation properties of liquids and their vapours corresponded in both phases. This confirmed their dependence on the synchronisation of atomic vibrations, and hence occurred inside the molecules.[615] Tyndall called this natural law the 'thermal continuity of liquids and vapours.' Thirty years earlier, Herschel regarded "the law of continuity" common in nature, "a fertile source of physical discovery," as it revealed unexpected analogies between phenomena.[616]

In 1881 Tyndall resumed his research on radiant heat, "for my own instruction and to the removal of uncertainty from other minds." He remarked in particular on research into the thermal continuity of liquids and vapours: "they had a weight and import greater than those of any other experiments published by me" but without the

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[611]De Saussure (1779-1796), in Pesic (2005), pp. 59-62.

[612]Fourier (1890), p. 54.

[613]Kidwell (1981), volume 38, pp. 457-476.

[614]Smith (2007), p. 2.

[615]Tyndall [1864a], volume 154, pp. 191-193; 224-225.

[616]Herschel [1830]1987, pp. 187-188.

appreciation of their significance by his peers.[617] Tyndall retested and confirmed his results, but to strengthen their scientific credibility, he varied his methods, using acoustical and manometric procedures.[618] In doing so he also confirmed the work of the German physicist and first Nobel Prize winner W.K. Röntgen (1845-1923) who had manometrically recorded the absorption of radiant heat by gases, including the controversial water vapour. Results obtained with a heat source that used an adiabatic compression of air, indicated that vapour molecules played a part in the phenomena of absorption and radiation, in a way that one would expect from the molecular mechanism implicated in these phenomena. [619]

4C.3. The Advent of Infra-red Spectroscopy

In this section I will trace Tyndall's thinking as it led to his anticipation of the application of radiant heat to a detailed study of the ultimate particles of matter in the gaseous phase. To account for the phenomena of diathermancy of elements in contrast to the athermancy of compounds, Tyndall speculated that single atoms of the elements were incapable of generating the degree of disturbance of the aether that groups of atoms forming systems of compound bodies could achieve.[620] Tyndall discovered wide variations in the diathermancy and athermancy of bodies in a gaseous state, just as Melloni had found for liquids and solids. The differences in the thermal properties of bodies, demonstrated to Tyndall

> … extraordinary differences in the constitution and character of the molecules of gases … With such results before us, we can hardly help trying, with the eye of intellect, to discern the physical qualities on which these vast differences depend. Is the hope unwarranted, that we may ultimately make radiant heat such a *feeler*

[617]Tyndall (1882a), RS lecture 24 November 1881, volume 173, pp. 291-354, 327.

[618]Ibid., p. 339.

[619]Ibid., pp. 298-300.

[620]Tyndall (1898), p. 297.

> of atomic constitution that we shall be able to infer from its action, the mechanism of the molecules themselves?"[621]

With this question Tyndall anticipated the advent of the infrared spectroscopy. Although other natural philosophers, including Melloni, also used heat as a means of exploring nature of matter, in my view, Tyndall methodically designed his experiments with the purpose of employing radiant heat as an analytical tool, like Faraday in his use of electricity, magnetism and ultimately light, scrutinised by James.[622] For Tyndall, as for Faraday, experimental results were suggestive of further theoretical speculations that in turn suggested innovative experimental procedures. The desirability of studying matter in its gaseous phase commended itself in particular, since the cohesive forces between molecules were negligible in the gaseous phase, and could be ignored. Tyndall's profound understanding of the likely behaviour of atoms and molecules allowed him to devise experiments that that suggested an activity in accordance with mechanical principles.

4C.4. The Composition of the Atmosphere

One of the first applications of Tyndall's discovery of the difference in thermal properties of elements and compounds was to confirm the composition of the atmosphere. By combining Dalton's atomic theory with the concept of the aether, Tyndall accounted for the high absorptive power of a compound as being due to the chemical combination of its elements, in contrast to elements combined as a mixture that exhibited diathermancy. He made experimental demonstrations of the high thermal absorptive power or athermancy of hydrogen and nitrogen when they combined chemically to form ammonia. Individually, he demonstrated these elements to be virtually diathermic. The same applied to hydrogen and oxygen in their chemical combination as water. Mixtures of the constituents in the same proportions, were diathermic. "No fact in chemistry carries the same conviction … that air is a mixture not a compound …." he pronounced. In support of his hypothesis that compounds were more powerful absorbers than the elements composing them, he also

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[621] Ibid., (1898), p. 348.

[622] James [1985] 1989, pp. 137-161.

cited the power of carbon dioxide as an absorber, when compared with its element, oxygen.

Having demonstrated that the variable constituents of the atmosphere such as water vapour and carbon dioxide, by virtue of being compound bodies, were characterised by high athermancy, Tyndall concluded that even a small variation in their amount would affect climate, "while an almost inappreciable admixture of any of the stronger hydrocarbon vapours would powerfully hold back the terrestrial rays and produce the corresponding climatic changes."[623]

To illustrate a mechanical explanation of the phenomenon of bodies radiating the same rays as they absorb, Tyndall used the action of white light on yellow sodium flame. The sodium vapour of the flame absorbed the yellow portion of the spectrum of white light, producing at first a dark band. He had been expecting a bright yellow band, however when he volatilised some sodium, in due course this bright band reappeared. He explained this event by surmising that initially there had been a production of cold sodium vapour encircling the hot sodium vapour that emanated from the flame. The absorption of the waves of the hot yellow by the cold vapour occurred, but by re-adjusting the electric circuit, the cold vapour was dispersed, allowing the reappearance of the original yellow part of the spectrum.[624]

Another discovery by Tyndall, which may have implications, in my view, on the absorption of the solar heat by the atmosphere, concerned the changes of the thermal properties of a substance, according to the type of the heat source to which it was exposed. Carbonic acid which was diathermous when hydrogen flame was the source, displayed a very high thermal absorption when carbonic oxide was the heat source. This increase of thermal power occurred when the heat source contained an element in common with the substance being tested. Tyndall explained the phenomenon in terms of a synchronisation of the vibrations of the atoms of the hot and the cold acid, that was promoting absorption. Tyndall asserted that his discoveries of the thermal properties of gases and vapours enabled the posing of fundamental

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[623]Ibid., Tyndall, p. 29.

[624]Note 590, Tyndall, volume 3, pp. 387-396.

questions on the interaction of radiant heat and matter, such as the origin of light and radiant heat. Tyndall posited their origin in the aether, generated from the vibrations of the "ultimate particles of bodies," located in the molecules, or their atomic constituents. This issue was subsequently resolved by Tyndall's investigation of the athermancy of liquids and their vapours, scrutinised in section 4C.2. Another fundamental issue, the cause of heating of the gas, was addressed in terms of dynamic theory, according to which gases and vapours consisted of "molecular or atomic projectiles darting to and fro, clashing and recoiling" due to a motion of translation, not of vibration as had been thought hitherto.[625] On collision with one another, or the wall of the container, the molecules became deformed by the temporary displacement of their atoms, endowed with a very rapid quivering motion. They demonstrated the existence of the world even beyond the range of the microscope, in Newton's words, representing "the more secret and noble works of Nature."[626] Using radiant heat, Tyndall proceeded to reveal this microscopic world and beyond, which, in his opinion, determined the interaction of radiant heat and matter.

Tyndall's use of radiant heat as an analytical tool confirmed the composition of the atmosphere mainly as a mixture of gases in a constant ratio; a very small proportion of the atmosphere consisted of compounds, water vapour and carbon dioxide in variable amount. This successful demonstration illustrated the capabilities of his procedures, and provided the occasion for the experimental improvements of the technique, hence innovations, another example of the iterative process in action. His use of different sources of heat influenced the degree of athermancy displayed by matter under investigation.[627]

4C.5. Research on Ozone

In this section I consider Tyndall's contributions to the study of the constitution of ozone by the thermal mode of investigation, a physical method established by Tyndall for gases. I also examine the contributions of his

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[625]Tyndall (1884) RI discourse 16 March 1883, volume 10, 253-265.

[626]Ibid., Tyndall, pp. 253-265,

[627]Note 614, Tyndall, pp. 387-396

contemporaries in this field to highlight Tyndall's innovative and unique approach. In the Bakerian lecture of 1861, inaugurating the publication of his research on radiant heat and its interaction with gases, Tyndall included a report on yet another pioneering investigation, the demonstration of a remarkably high thermal absorptive power in ozone, even when present only in small amount, not detectable by chemical means. Tyndall noted the presence of ozone during preparation of oxygen by the electrolysis of water. He identified it from an apparently high thermal absorption in oxygen. On the removal of ozone, the thermal absorption of oxygen, as expected, was negligible. At first he concluded: "this result is in harmony with the supposition that ozone, obtained in the manner described, is a compound body."[628] In this study, Tyndall again employed radiant heat as an analytical tool. He explored the thermal properties of ozone further in his second paper, confirming his previous findings of "that extraordinary substance, ozone," but adding, "I hold that ozone is produced by the packing of the atoms of elementary oxygen into oscillating groups" hence, like compounds, encountering resistance while moving through the aether. He rejected the proposal that it was a hydrogen compound, because no water vapour was detected when ozone was decomposed while heating.[629]

Tyndall published his research on ozone twenty years after its isolation in 1839 by professor of chemistry at the University of Basel, C.F. Schönbein (1799-1868). Schönbein's work engaged the interest of eminent researchers in Britain and abroad. Ozone's extraordinary reactivity, and uncertainty about its composition meant that it attracted attention.[630] Schönbein informed the scientific world of his work. In 1840, he announced his discovery in letters to Faraday at the Royal Institution,[631] and to D.F. Arago (1786-1853), director of the Paris Observatory, permanent secretary of the French Academy of Sciences.[632] He also reported on it at the British Association

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[628]Tyndall [1861a], volume 151, pp. 8, 35.

[629]Tyndall [1863a for 1862], volume 152, pp. 59-98, 84-86.

[630]Oesper (1929a), volume 6, (3), pp. 432-439.

[631]Schönbein (1840a), s. 3, volume 17, pp. 293-294.

[632]Schönbein (1840b), s. C, volume 10, pp. 706-710.

Meeting in Glasgow.[633] According to his biographer, R.E. Oesper, Schönbein, on arrival in London in 1839, worked with Faraday and the natural philosopher and judge W. Grove (1811-1896) at the Royal Institution.[634] At the Royal Society, Faraday read some of Schönbein's letters on ozone in 1844 and 1845,[635] and lectured on it at the Royal Institution in the 1850s on three occasions. Alluding to its presence in the atmosphere and its reactivity in the presence of sunlight, he predicted "the probable fertility and importance of the subject…"[636] Controversial work on ozone by the professor of physics at the École Polytechnique and director of the Museum of Natural History in Paris E. Frémy (1814-1894) and that of a respected French physicist, A.C. Becquerel (1788-1878)[637] was also commented upon by Faraday.[638] The Geneva physicist, A. De La Rive (1801-1873), studying the chemical effects of electric current, referred to an electrical discharge in air resulting in the production of ozone, which was of particular interest.[639] Clausius published a paper on it.[640] The different preparation methods spurred some to suspect the production of a different substance on each occasion. Others repudiated that suggestion. Rubin credits the Swiss scientist, J.L. Soret (1827-1890), with the determination of ozone's constitution of three oxygen atoms in a molecule.[641] H. Day (1814-1881), a Stafford physician and researcher, remarked that ozone was of interest to physicists, "in relation to the general phenomena of the universe," to the chemists on account of its novelty, yielding new compounds, providing "new views respecting molecular condition" and to the physicians who looked on it as a source, a remedy, or the means to prevention

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[633]Schönbein (1841), pp. 209-215.

[634]Oesper (1929b), volume 6 (4), pp. 677-685, 678.

[635]Schönbein (1851), volume 5, pp. 507, 508, 565.

[636]Faraday (1854a), RI discourse 13 June 1851, volume 1, pp. 94-97.

[637]Frémy and Becquerel (1852), volume 35, pp. 62-105.

[638]Faraday (1854b), RI discourse 10 June 1853, volume 1, pp. 337-339.

[639]De La Rive (1853-1858), volume 2, pp. 469-482.

[640]Clausius (1858), s. 4, volume 16, pp. 145-151.

[641]Soret (1863), s. C, volume 56, pp. 390-393; (1865), p. 941.

of disease. "It has been a subject of vast erudition; and yet … a subject of intense doubt."[642] Day urged the application of spectroscopy to unravel its secrets.

Tyndall's publications concerning ozone followed those by T. Andrews (1813-1885) of Belfast and Tait of Edinburgh, examining the conflicting evidence on its composition.[643] W. Odling (1829-1921), lecturer at Guy's and St Bartholomew's hospitals and the Fullerian Professor of Chemistry at the Royal Institution (1868-1873), then at Oxford, considered Andrews and Tait's results on ozone being "identical with oxygen … in a denser form", the most significant. He commended Tyndall's confirmation of their results "in a very interesting manner" whereby the thermal absorption of ozone prepared by the electrolysis of water, was a hundredfold of that of oxygen, pointing to a "more complex molecular constitution" than that of oxygen. Had the product included aqueous vapour as surmised by some researchers, the absorptive power on theoretical grounds, would have been greater.[644] L. Soret, the experimentalist who had detected the presence of water vapour, supporting the theory that ozone was a compound of hydrogen, later found that with the appropriate precautions no water vapour was detected.[645] His correspondence with Tyndall may reveal Tyndall's influence on Soret's methodology. As we have seen, Tyndall in the early 1860s recognised the importance of stringent experimental procedures that he greatly improved to avoid the interference of the contaminants, including moisture. Schönbein thought ozone, an allotrope of oxygen, but also a component of nitrogen.[646] R.W.E. Bunsen (1811-1899), eminent German chemist, participated in the debate. His lectures met with the approbation of his student, Tyndall. Bunsen later championed physical chemistry as an independent discipline.[647] Schönbein wrote to Faraday in 1853: "The question of the nature of ozone seems to have been settled in

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[642]Day (1868), volume 91 (2316), pp. 79-81; volume 91 (2317), pp. 124-126.

[643]Andrews and Tait (1860), volume 150, pp. 113-131.

[644]Odling [1872]), lecture 7 June, volume 6, pp.

[645]Soret (1853), s. C volume 38, pp. 445-448.

[646]Schönbein (1844), volume 5, p. 508.

[647]Jungnickel and McCormmach (1986), p. 302.

the laboratory of Mr Bunsen at Heidelberg. And it appears that both views … are correct."[648] B.C. Brodie (1817-1880), president of the Chemical Society 1859-1861, professor of chemistry at Oxford 1855-1872, over the years studied in depth the composition of ozone, and produced a review of its history in 1872.[649]

In this section I scrutinised the discovery and the study of the structure of ozone, a substance of interest to Tyndall's theoretical views and empirically framed by his work on radiant heat. Throughout his career Tyndall's use of radiant heat as an analytical tool demonstrated its effectiveness and its power to yield results in the most fundamental problems concerning the nature of matter in its elementary and compound states. Despite the controversial nature of the research on ozone, in Bunsen's manner, Tyndall remained aloof from the disputed areas. He was the only one to employ ozone's unusually high absorbency of heat to characterise its presence even in minute quantities not detectable by other means. His research was of an entirely original character, not impinging on the work of others, and therefore of little interest to them. Despite Tyndall's innovative approach to the detection of ozone and its composition, exposing its remarkable thermal properties, his name does not feature in otherwise comprehensive paper on the history of ozone by M.B. Rubin.[650]

4C.6. Mimicry of Nature

In this section I will investigate Tyndall's justification for mimicking nature in the laboratory, and his explanation of the transformation of the thermal property of air from that of diathermancy to athermancy in the process of the adiabatic compression of the air in the presence of vapour.

From his support of Stokes's position in the latter's dispute with Challis, concerning Laplace's correction of the velocity of sound in the air, Tyndall exposed the connection between chemical and the mechanical phenomena. He challenged Challis's view that Laplace's correction of sound was invalid, because the

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[648]Schönbein to Faraday, 11 July, 1853, in James (1999), volume 4, pp. 535-536.

[649]Brodie [1872] volume 162, pp. 435-484; (1874) volume 164, 83-103, 93.

[650]Rubin (2001), volume 26 (1), pp. 40-57.

experimental conditions in the laboratory could not be equated with the conditions in which natural phenomena occurred. According to Tyndall, the heat radiation in the experimental tube was as unlimited as in nature, and the variation or flux of this thermal radiation could be measured. Tyndall argued that the tube was mechanically closed by the relatively diathermic rock-salt plates, but thermally open in all directions. This fact, Tyndall maintained, was established by his empirical confirmation of the diathermancy of the air and elementary gases, as well as the diathermic characteristics of rock salt.[651] The validity of mimicking of nature in the laboratory was a contested issue at the time, as seen in Chapter 5 of this dissertation. Challis asserted that the heat of the air was always instantly dissipated in nature. Having justified the theoretical aspects of the principle of mimicking nature with rigorous empirical support, Tyndall argued that this did not hold when air was heated by an adiabatic process in the presence of vapour. He exposed this phenomenon of the atmosphere through an analogy with non-radiating polished metal, converted by a coat of varnish into a radiating body. Despite the fact that the atoms of the elements vibrated by virtue of heat motion, neither the atoms of the elementary air constituents without the presence of vapour, nor the metal elements without varnish, could communicate motion to the aether, irrespective of the heat source. In the fundamental alteration of the thermal properties of the air through the presence of a vapour, Tyndall saw a mechanical consequence of the chemical union revealed. He evidently assumed a chemical interaction was occurring, between the air and the vapour. The Scottish chemist J. Stenhouse's (1809-1880) lecture at the Royal Institution,[652] a part of his research on the adsorption of gases by matter in solid and liquid phase[653] may have been suggestive to Tyndall in pursuing this reasoning. He concluded that additional factors beyond synchronisation must play a part in the absorption and radiation of heat: "The form of the atom … or some other attribute than its period of

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[651]Tyndall [1863a for 1862], volume 152, pp. 58-98, 97-98.

[652]Stenhouse (1851-1854)), volume 2, p. 53-55.

[653]Partington (1964), volume 4, p. 740.

oscillation, must enter into the question of absorption."[654] This fecund statement by Tyndall, was considered by J.C.D. Brand as significant:

> [Tyndall] looked for a reason why the symmetrical diatomics were transparent [diathermic] and suggested that their shape allowed them, in ways undefined to glide through the aether without disturbing it ... Nowadays we think of dipoles rather than shape, but the two are not unconnected and Tyndall's suggestion has the germ of a correlation between shape, or symmetry and spectral activity.[655]

The shape of atoms had also been considered by the French philosopher, tutor of the playwright, J.B. Poquelin alias Molière (1622-1673), P. Gassendi (1592-1655)[656] to whom Tyndall referred in the Belfast address.[657]

Tyndall used the velocity of sound controversy to advance his hypothesis on the different thermal properties of elements and compounds, and to legitimise the extrapolation of his results from the laboratory bench to nature at large. Having identified a change in the thermal properties of the air from diathermancy to athermancy, he explained the phenomenon in terms of chemical activity and its mechanical equivalent. As it wasn't totally accounted for by the synchronisation of the vibrations between the atoms of the bodies involved and the aether he postulated an additional unknown property of the atoms involved. Other issues concerning the mimicry of nature are discussed in Chapter 5, subsection 5B.1, pp. 192-195 of this dissertation.

4C.7. Changing Role for Radiant Heat – Discovery of Calorescence

In this section I examine Tyndall's path to the discovery of calorescence. Stokes's discovery of fluorescence in 1852 by lowering of the refrangibility of radiant

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[654]Tyndall [1863a for 1862] volume 152, pp.80-81..

[655]Brand (1995), p. 82. Brand quoted Tyndall without providing a reference, but see note 831.

[656]Chang (2004), p. 162.

[657]Tyndall (1874a), volume 10, 308-319, 312.

heat, hence the slowing down of the period of vibrations,[658] led to speculations on the possibility of the opposite effect, that of accelerating vibrations by raising refrangibility.[659]

As demonstrated above, initially Tyndall used radiant heat purely as a tool,[660] "an explorer of molecular condition."[661] As his research progressed, he also examined "the laws and properties of heat propagated through the ether, in which form it is called *Radiant Heat*."[662] This change of outlook in his natural philosophy is highly significant in the research procedures that led to his discovery of calorescence. He anticipated the discovery in his Bakerian Lecture of 1864. In this lecture he demonstrated the rise in refrangibility as the platinum wire, plunged into hydrogen flame, was raised into visible white heat producing all the colours of the spectrum when viewed through a prism.[663] Tyndall understood this phenomenon to be due to the slow period of vibration of obscure radiation that was being changed to the quick period of the visible radiation through its encounter with the incandescent platinum.[664] He named this phenomenon 'calorescence.'[665] In 1865 Tyndall studied thermal radiation from electric light. On separating and focusing obscure thermal radiation, substances placed at the focus either caught fire or exploded, due to the rise in temperature, manifesting the conversion of obscure luminous radiation to visible, due to the raised refrangibility of its waves. In his lecture to the Royal Society on calorescence, Tyndall stated: "A point of considerable theoretic importance was

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[658]Stokes (1854), RI discourse 18 February 1853, volume 1, pp. 84-89.

[659]Tyndall (1866a), volume 156, pp. 1-24.

[660]Tyndall (1864b), volume 154, pp. 327-368, 327-328.

[661]Tyndall (1872c), p. vii.

[662]Tyndall [1880]1898, pp. 276-277.

[663]Note 650, Tyndall, pp. 360-362.

[664]Ibid., Tyndall pp. 360-361.

[665]Tyndall (1865b), pp. 33-35.

involved in these experiments."[666] Having taken experimental precautions to exclude luminous radiation from the heat source by filtration, he stated:

> The action of the atoms of platinum, copper, silver and carbon upon these rays transmutes them from the heat rays into light rays. They impinge upon the platinum at a certain rate; they return from it at a quicker rate. Their refrangibility is thus raised, the invisible being rendered visible.[667]

Tyndall, therefore, altered the status of heat in his 'thermal mode of investigation' when he demonstrated the transmutation of thermal obscure radiation into one of higher refrangibility, luminous radiation. The long periods of oscillations were broken up into the short ones of visible radiation. I view this as an example of radiant heat not as a tool, but a force of nature actively participating in the process of the conversion of forces, in this instant from that of heat to light. The product of the combustion by the hydrogen flame was water vapour, its molecules raised the temperature of the platinum spiral which in turn affected the oscillations of the flame: increasing its diathermancy for radiation from the platinum. For Tyndall this was another demonstration of the identity of thermal and luminous radiations, differing only in their respective wavelengths.[668]

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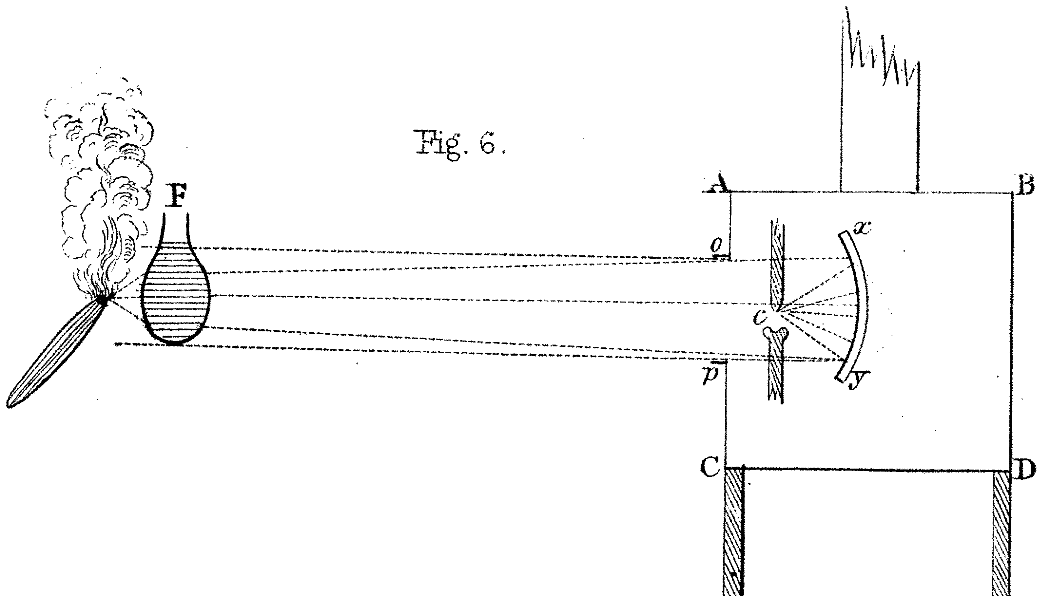
[666]Tyndall [1866a], RS lecture 23 November 1865, volume 156, pp. 1-24, 14.

[667]Ibid., Tyndall pp. 16-17.

[668]Tyndall 1915[1873], pp. 176-180.



The Calorescence Apparatus

ABCD: an outline of the camera

x y: the mirror silvered on both sides

c: the carbon points of the electric light

o p: the opening at the front of the camera through which the slightly convergent beam of the electric light, reflected by the mirror, is passed

F: the spherical glass containing the iodine solution performs a dual purpose: it acts as a filter, absorbing the luminous radiation, and as a lens, converging the obscure radiation at the focus beyond it. Various substances, placed at this focus, either caught fire or exploded demonstrating the increase in the intensity of thermal radiation.

Tyndall's study of the influence of coloured screens on the extent of the calorescence present, prompted theoretical notions. Applying the principles of dispersive spectroscopy, he speculated on the possibility of selective vibrations of the platinum atoms, only in the blue and red portions of the spectrum. To that end he chose Faraday's colloidal gold solution to compare the thermal properties of red glass coloured by compound substances with that of the red glass coloured by means of the elementary gold: only the element gold-coloured glass exhibited high diathermancy in common with other elements, confirming the theoretical basis of Tyndall's discovery. He pointed out the fallacy of using black bulb thermometers in meteorology, since like colloidal element gold, the element carbon as employed in molten glass, would not absorb obscure thermal radiation.[669] As already mentioned, James has shown Faraday's 'optical mode of investigation'. In the magnetic rotation of polarised light experiment, light became an agent, instrumental in establishing Faraday's theory of matter, and its interaction with the forces of nature.[670] This research by Faraday, appreciated by Tyndall as "the Weisshorn among mountains-high, beautiful and alone"[671] may have been an inspiration for his own work on calorescence.

In conclusion, by demonstrating the transmutation of thermal obscure radiation into luminous radiation with a higher refrangibility, Tyndall altered the status of radiant heat. It was no longer merely a tool, but a force of nature actively participating in the process of conversion of force from heat to light. He achieved this by devising the means to raise the refrangibility of radiation from the invisible to the visible part of the light spectrum. He determined the proportion of the heat radiation from an electric source was approximately four times as powerful as that of luminous radiation, (which is of importance to energy concerns nowadays). He devised a technique to separate luminous and obscure radiations, enabling investigation into the phenomena of each of them separately. He provided yet another confirmation of the theory of the identity of light and radiant heat. He also confirmed his fundamental discovery concerning the thermal properties of elements and compounds. Stokes saw

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[669]Note 656, Tyndall, p. 23.

[670]James [1985]1989, pp. 137-161.

[671]Note 167, Tyndall [1868], p. 146.

analogies between Tyndall's work on calorescence and the generation of x-rays from solar phosphorus by physicist and early Nobel Prize winner A.H. Becquerel (1852-1908), and physicist and electrical engineer S.P. Thompson (1851-1916).[672] Further investigation of the production of x-rays may reveal whether these later researchers consciously used Tyndall's techniques.

4D. Postscript on Tyndall as a Theoretician

This section scrutinises some other aspects of Tyndall's theorising as reported by his peers and the press, followed by the verdict of historians. In an Explanatory Note at the beginning of his *Essays on the Use and Limit of the Imagination in Science*, Tyndall says: "As in the case of the recent Discourse, opinion was divided with regard to the objects and merits of the [BAAS] Norwich Address (1868)."[673] Among those on the positive side was J.C. Maxwell (1831-1879), who rated Tyndall's address as "virtually on the limits of Physical Philosophy"; Maxwell enthused: "I have been carried by the penetrating insight and forcible expression of Dr Tyndall into that sanctuary of minuteness and of power where molecules obey the laws of their existence, clash together in fierce collision, or grapple in yet more fierce embrace, building up in secret the forms of visible things."[674] Two years on, press reports on Tyndall's lecture "On the Scientific Use of the Imagination" at the 1870 Meeting of the British Association were also mixed. He urged the use of imagination in science "to dissipate the repugnance, and indeed terror, which in many minds are associated with the thought that science has abolished the mystery of man's relation to the universe;" also to overcome objections "to legitimate scientific speculation."[675] The *Saturday Review* challenged the appropriateness of assigning, for instance,

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[672]Stokes to Kelvin 12 March 1896, in Wilson (1990), p. 649.

[673] Tyndall (1870b). He explained further: "On the one hand, two eminent clergymen, one of the Church of England, the other a Dissenter, proposed and seconded respectively a vote of thanks, which was liberally carried by the section; on the other hand I was publicly warned that as a consequence of my impiety, the bolts of heaven were in a state of potential suspension above my head, ready to descend if further drawn upon." It is not clear precisely what was regarded as impious in this address.

[674]Maxwell [1870], in Garber, Brush and Everitt, (1986), pp. 90-91.

[675]Note 663, Tyndall.

"Thomson's admirable inductive methodology of empirical and mathematical rigour" as due to the imagination. Likewise,

> ... is what we admire the leap of imagination, or the firmly balanced graduated tread of a mind trained in the discipline of logic and careful to plant every step on the assured ground of fact and experience? It is simply a misnomer to apply the name of imagination to the process or the faculty to which this onward march into the realm of unexplored nature is really due.[676]

The Times commented: "The discoveries of science have been so astonishing ... that there is, perhaps, more danger in our imagination being exercised too freely…" The article suggested that what was being referred to as the scientific use of the imagination was really the imaginative use of science.[677] A few weeks later *The Times* relented: they were " … not a little gratified ... at the eloquent lecture on the use of the imagination in science …." In their view the importance of the lecture could not be overestimated at the time of reigning prejudice rooted in religious intolerance, endangering the progress of science and the implementation of science education. They urged emulation of Tyndall's "spirit of reverence, … the earnestness of purpose and philosophical acumen", as being of benefit to the cause of truth.[678] The *Manchester Guardian* referred to the "magnificent" and "admirable" lecture, and did not quibble whether it was a feat of imagination, but wrote of him as;

> ... possessed by his subject, his thoughts ... [flowing] with perfect ease, fresh minted in the most appropriate ... words. He led his hearers gently and almost unconsciously through the most perplexed mazes and subtlest passages of thought, keeping their ears enchained and their fancy charmed by the endless succession of apt metaphor

[676] Anon. *The Saturday Review of Politics, Literature, Science, and Art*, 24 September 1870, volume 30, (7780), pp. 399-400, in Tyndall (1870b), p. 3.

[677] Anon. *The Times,* 17 September 1870, p. 7, columns c-f, in Tyndall (1870b), [1]-2, 2.

[678] Anon. *The Times*, 3 October 1870, p. 6, columns c-d, in Tyndall (1870b), pp. 11-12.

> … It was the manifest work of a master in his art, handling with ease and grace the weighty tools ….”[679]

The historian of science E. Garber regards most post-1850s physicists as both experimentalists and theoreticians. She excludes Tyndall as “the only example of a physicist who did significant experimental but not theoretical work”[680] On the other hand, S. Sugiyama considers the particulate conception of matter as guiding Tyndall’s experimental research and theoretical notions, and sitting at the root of Tyndall’s “wide ranging scientific activities.” Although the particulate nature of matter was accepted by many of his peers, “none of them exceeded Tyndall in its extended and thorough growing employment”, concludes Sugiyama.[681] At a public lecture in 1994 A. Warwick looked back to 1860s at the state of physics as a discipline in Britain, remarking that because of the absence of the physics departments in universities, no experimental or theoretical physics as understood now, was in existence.[682] I would argue that there were, however, pockets of significant academic activities in the field, led by the Scottish and Cambridge trained mathematicians and theoretical physicists who investigated the physical basis of natural phenomena. They were discovering laws in mathematical terms, which governed the events in what came to be recognised as branches of Physics, including light, heat and mechanics. These included Faraday at the Royal Institution, who was performing experiments and devising physical theories, but bypassing the mathematics. Tyndall followed in his steps. Because of their relevance to the science of the day, these research activities were reported at the meetings of the British Association for the Advancement of Science, the Royal Society, and the Royal Institution, amongst others. They were recorded in the press.

Maria Yamalidou regards Tyndall’s ‘molecular discourse’ as a rhetorical device.[683] I would argue that its content also bears closely on the theoretical issues of

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[679] Anon. The Guardian, 20 September 1870, p. 6, columns ‘a’ and ‘b’; 21 September, p. 4, column ‘a’, quoted in Tyndall (1870b), pp. 4-5.

[680] Garber (1976), volume 9, 51-65, 64.

[681] Sugiyama (1992), volume 2-2, pp. 119-138, 134.

[682] Warwick (1994), pp. 57-86.

[683] Yamalidou (1999a), volume 53 (2), pp. 231-242; 319-331.

the day. Revising the status of the concept of molecularity in the nineteenth century, Yamalidou suggests that its multifaceted character provided a fecund environment for the fertilisation of ideas on the structure of matter. She acknowledges Tyndall's contributions to the visual representation of the invisible through the use of the faculty of the imagination.[684] Yamalidou deliberately eschews Maxwell, "the leading molecular scientist" of his day, but comments on Tyndall's view of experiment as a means of ascertaining the truth of theories; its function also to chasten, control and guide imagination. It was connected to the moral aspects of science.[685] Tyndall's advocacy of the use of imagination in science has made an enduring impact on the pedagogical aspect of science.[686]

I see the transition from natural philosophy to physics as a mature scientific discipline with well-defined specialties as a significant event in the nineteenth century, pertinent to Tyndall's work. This transition enabled the study of experimental and theoretical physics as separate, but closely related entities.[687] In this section the different sources provide a variety of judgements on Tyndall's theorising, testifying to the richness of the experience. His appeal is assured, even to his critics. The varied opinions of later historians, in my view, reflect the richness and the versatility of Tyndall's research, as well as of the science of his day.

4E. Conclusion

In this chapter Tyndall as a theoretician was set in the context of theoretical physics of his time. Contrary to the opinion of some of his peers and historians, his contributions to theoretical science have proved their worth, leading to well established propositions on empirical grounds. Inspired by Faraday, but guarding his independence, he did not accept indiscriminately his famous mentor's pronouncements, notably on the nature of matter. He chose, unlike Faraday, the more enduring legacy of Dalton. Tyndall's critical and hence innovative approach to his

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[684]Yamalidou (2001), volume 10 (2), pp. 423-451, 435-436.

[685]Garber, Brush, Everitt (1986), p. 1.

[686]Sutton (1998), volume 79 (288), pp. 21-26.

[687]Cahan (2003), pp. 174-190.

experimental strategy and his bold use of imaginative theorising led to the physical confirmation of the elemental nature of the atmosphere, resolution of the composition of ozone, the physical interpretation of the phenomena of thermal absorption and radiation and their location in matter, and the anticipation of infrared (ultra-red or extra-red in Tyndall's terminology) spectroscopy. His discovery of calorescence indicated a departure in the use of radiant heat: he recognised the significance of the rising refrangibility of heat, the impact of this phenomenon on the invisible foci, and its relationship to the phenomenon of fluorescence discovered by Stokes in 1851. The passive character of radiant heat as a tool was transformed into a new role through the transmutation of obscure heat rays into luminous heat rays, pointing to a new phenomenon that required a physical interpretation. His daring theorising mirrors his fearless mountaineering exploits, and he remained conscious of the unpopularity of his style with some of his peers whose approval he sought.

The uncertainty about ozone's constitution, and hence continued interest in it from eminent contemporary physicists and chemists, in my view, epitomises ambivalence about the nature of matter, and the absence of standard instrumentation and procedures. In due course these problems, recognised by the British Association, led to the establishment of the Chair of Experimental Physics and the Cavendish Laboratory in Cambridge to remedy the situation.[688] Moreover the recognition of physical chemistry as a distinct discipline, manifested in the work of Faraday and Tyndall in their application of physical methods to chemical problems, contributed to the collaborative approach of physics and chemistry, and in due course led to the establishment of physical chemistry departments in universities.

Tyndall's appeal to sceptics to regard the useful dynamic theory of heat as molecular motion differing from light only in the wavelengths of its vibrations as symbolic, encapsulates his pragmatism. He granted those against Dalton's atomic theory their right to dissent, while aiming at their support for the fecund consequences that were clarifying puzzling occurrences, and explicable in terms of the atomic theory.[689] In the prestigious Rede Lecture delivered before the University of

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[688]Kim (2002).

[689]Tyndall (1860c), pp. 226-247, 241.

Cambridge, Tyndall further expounded his philosophical ideas. In his view an experiment was a question put to nature, stripped of all the superfluous aspects to obtain ‘a clear mental picture’. Guided by Dalton’s atomic theory, for him atoms were elementary forms in the shape of spheres to which all matter was reducible. They were endowed with a power of mutual attraction to form molecules of compound bodies. If Dalton’s atomic theory and the existence of the aether filling all space including that between the molecules as a vehicle for atomic motion, were rooted in fact, then the vibrations of the elementary bodies would differ from those of their compounds.[690] He fully confirmed this hypothesis.

The lack of awareness by some historians of his achievements as a theoretician, despite this having been widely reported at the Royal Society and the British Association meetings, and reproduced in specialised and popular periodicals, is puzzling.

[690]Tyndall [1865c] 1871, pp. 170-217, 179 -180.

CHAPTER 5

Tyndall's Contributions to the Science of Meteorology

In this chapter I will investigate Tyndall's contributions to meteorology in the context of the science of his time, as well as responses to them over the last one hundred and fifty years. His view of nature enabled him to grasp the relevance of the thermal and optical properties of gases for meteorology. The reliable experimental procedures for the study of gases and their interaction with radiant heat and light pioneered by Tyndall, facilitated investigation of meteorological phenomena on a scientific basis. As discussed in previous chapters, Tyndall's original research was appreciated by many leading scientists of his time, and the doubts raised about his work by Magnus and his followers were dispelled. The eminent chemist E. Frankland (1825-1899) replicated some of Tyndall's experiments on water vapour that had been contested by Magnus and were of crucial importance in meteorology. Moreover, he also devised test experiments of his own and commented:

> I cannot but express my surprise and admiration at the precision and sharpness of the indications of your apparatus...I should not have thought it possible to obtain those qualities in as high a degree in determinations of such extreme delicacy, and which are so well known to be exposed to numerous sources of derangement.[691]

Some implications of Tyndall's research for meteorology were already evident in the discussion in the last two chapters. Here I wish to provide a detailed account of Tyndall's results, as they were relevant to meteorology, and also to discuss their reception through time.

5A. Meteorology in Nineteenth-Century Britain

In this section I discuss some of the factors that brought about the transformation of meteorology in the nineteenth century from its amateur status to that of a science.

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[691] Frankland to Tyndall 19 June 1863, in Tyndall (1863d), 26, pp. 44-54, 46-49.

Robert Fitzroy (1805-186.5) FRS RN, an eminent Royal Navy Captain, famed for his navigation of the Beagle, 1832-1836, and an extensive surveying of distant lands, was appointed head of the new Government marine department as meteorological statistician. He took care to implement policies that would, in his opinion, save the lives of sailors. He advocated the training of sailors in the use of instruments; he used the accumulating numbers of observations to construct synoptic charts and study weather patterns. Fitzroy's ambition to issue storm warnings by telegraph was approved by the Department, unsurpassable as a means of effective, simple communication. By 1861, weather forecasting was introduced by Fitzroy, partially based on the eminent German meteorologist H. Dove's work on the laws of storms, and controversy erupted about his methods. After Fitzroy's suicide in 1865 and an investigation by the Royal Society, the verdict on Fitzroy was mixed. The data from observations on land applied to marine meteorology did Fitzroy injustice. His contributions have been recognised by Burton as substantial, though his record-keeping chaotic, and the review by the President of the Royal Society, F. Galton (1822-1911) at times faulty. Predictions were stopped, and despite protests, not resumed for a decade. In 1867 the successor to Fitzroy, Robert Scott (an Irishman trained in Germany like Tyndall), was appointed to head the new meteorological office, responsible to the Kew Observatory which at the time was under the management of BAAS.[692]

For Katherine Anderson, for the Victorians solving the riddle of the weather depended on the vast quantity of data provided no longer by amateurs, but by professionals, and based on planned coordinated observations of the weather at a global scale.[693] She also remarks on the growth of theoretical knowledge of the forces of nature.[694] This knowledge, in my view, enhanced by Tyndall's remarkable experimental procedures, examined in Chapter 3, enriched by his vivid theoretical pronouncements as scrutinised in Chapter 4 of the dissertation, for a long time made little impact on meteorology. Acquainted with Tyndall's work, J.F.W. Herschel

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[692] Anderson (2005), p. 91.

[693] Anderson (2005), p. 1.

[694] Ibid., p. 131- 169. both edges of the page

(1792-1871) criticised the vast resources given over meteorology, although it was accepted by the public, unaware that prediction was not the only aim of the new discipline. He warned forecasters against too great a reliance on observations. Their interpretation depended on other factors as well.[695] Considering meteorology as a science in the early stages of its development, Herschel thought that the forecasting in addition to the interpretation of observations, should be based also on factors, such as the formulation of a few easily recalled and universally applicable laws to replace a vast amount of individual records, the telegraph warnings at short notice of bad weather on the way, and the study of the causes of the particular weather conditions.

Also uneasy about the inadequate scientific procedures, Maxwell urged the acceptance of K.F. Gauss's (1777-1855) methods of observation and mathematisation of terrestrial magnetism as models for "those … engaged in the measurement of any of the forces of nature."[696]

An improvement in the precision of meteorological instruments also contributed to an awareness that there were patterns in the recurrence of meteorological phenomena. Consequently, the possibility of predicting the weather began to be seriously entertained. However, a comment by a member of parliament that "not withstanding the variable climate of this country, we might know … the weather twenty-four hours beforehand" met with derision in the House of Commons,[697] since predictions were associated with the unscientific pursuits of charlatans and clairvoyants. A. Winter notes that the issues of meteorological predictions had epistemic impact, leading to debates on the nature of prediction.[698]

The recognition of a difference between the scientific work of data collection and evaluation, as opposed to guesswork or magic, had to await the application of statistics. The probability theory and the distribution law elaborated by Maxwell,

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[695]Herschel (1867), pp. 142-175, 144.

[696]Maxwell to Spencer 5 December 1873, in Harman (1990), volume 2, pp. .956-961.

[697]Burton (1986), 19, pp. 147-176, 151.

[698]Winter (1997), pp. 24-50, 31.

when applied to meteorology [699] resulted in the improvement of safety at sea and on land. Procedures for a systematic accumulation of data, essential to establishing trustworthy facts, hence reliable weather forecasting, were created. The laying of subterranean telegraph cables enabled rapid dissemination of the relevant information throughout the Empire, encouraging trade and enabling safe travel. The engagement of the British government, the Royal Society, the British Association for the Advancement of Science, the Royal Institution, as well as the newly established Meteorological Society, assisted further promotion of meteorology as a scientific discipline. In conclusion, the transition from an amateur discipline to a science of meteorology involved amateurs from various walks of life, professional scientists and politicians, traditional and newly created institutions for the promotion of science.

5A.1. Local Participation

In this section local contributions from Cornwall, London and Oxford illustrate the growing concerns of amateurs in the professionalisation of meteorology. Through the study of acquisition of meteorological data within the local community in Cornwall, with its century-old "acknowledged centre of meteorological labour," S. Naylor demonstrates the transformation of meteorology in Britain between the 1830s and 1860s into an institutionalized professional science. He points to the success of science grounded "in its ability to ensure that procedures and findings from one place can be reproduced elsewhere."[700] He stipulates that the success of this endeavour depended on the standardization and precision in instrumentation, and the accumulation of data by trained observers, in contrast to the uncoordinated, hence unsystematic methods from the multitude of sources which had characterized the interest of keen amateurs recording the weather over centuries.

The work of L. Howard (1772-1864), a chemist and an amateur meteorologist, the first to study the structure of clouds, constitutes an early landmark in the scientific transformation of the status of meteorology in nineteenth century Britain. In 1802 he

[699]Maxwell, in Garber, Brush and Everitt (1986), pp. 9, 52, 69-89, 133-137.

[700]Naylor (2006), 39 (3), pp. 407-433, 408.

introduced the subject in a popular lecture to the Askesian Society in the City of London:

> Since the increased attention which has been given to meteorology, the study of the various appearances of water suspended in the atmosphere has become an interesting and even necessary branch of that pursuit.[701]

By classifying clouds, and inventing a nomenclature for their different configurations, he provided a base for the systematization of the elusive weather phenomena, creating a scientific framework for the burgeoning discipline. An admirer of H. Davy (1778-1829), Howard attended his lectures at the Royal Institution. J. Gough (1757-1825), renowned blind scholar and natural philosopher, a hero of S.T. Coleridge's (1772-1834) and W. Wordsworth's (1770-1850) poems, publicized Howard's work.[702] Howard's classification of clouds is still in existence today.

Inspired by Howard, the art critic and amateur geologist J. Ruskin (1819-1900), student at Christ Church, Oxford, (friend and at times an adversary of Tyndall in years to come), published, at the age of twenty, an impassioned plea on behalf of meteorology. Ruskin was preoccupied by atmospheric phenomena, "as a challenge … to the intellect and the soul."[703] Complaining about indifference to meteorology as a science he remarked on its aesthetic qualities, but above all its utility. Whilst it was a topic for leisure and amusement, serious men of science ignored it. Ruskin, therefore, encouraged the scientists cum natural philosophers to study meteorology as a subject at the laboratory bench "of universal interest – everywhere and for all time," manifesting constant change, eternal motion and mystery. Ruskin argued that causes were identifiable, but unlike subjects of other sciences, meteorological phenomena could not be studied in isolation. To be of use, observations had to be collected methodically and simultaneously at many different locations. Isolated observations would relate not to the phenomena, but "the dancing of the atoms," misrepresenting the character of the meteorological events as being a random occurrence. The remedy

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[701]Howard [1803], 1969, p. 3..

[702]Hamblyn [2001] 2002, pp. 146 -148.

[703]Ibid.,Hamblyn, p. 202.

lay in the cooperation of individuals, resulting in “a part of one mighty mind” leading to a solution of “the hidden problems of nature and the discovery of the most occult causes.”[704] Ruskin stressed the value of collecting meaningful observations through a planned, coordinated and structured effort to detect patterns that would reveal the principles directing the phenomena. I contend that he advocated an early example of a team effort.

Another member of the same college as Ruskin, T. I. M. Forster (1789-1860), the author of a pioneering book on the atmosphere, had remarked twenty-five years on the interest of ancient nations in the study of meteorology, who sought to mitigate the danger in meteorological upheavals by anticipating them. He praised oriental shepherds and eastern tribes for their accurate observations and use of analogy as they had “collected, compared and recorded” meteorological events. Ancient Greeks and Romans adopted their methods. According to Foster, further progress in the study of causes of the atmospheric effects occurred in the eighteenth century.[705] Howard’s theory on cloud modification and his own subsequent work, led Forster to ascribe the dynamic character of meteorological phenomena to ‘electrical operations.’ This was in keeping with the prevalent notion of electricity as “the universal agent in all the changes of form” of matter, endorsed by the research of Davy.[706] To examine the electrical condition of the atmosphere, Forster employed an aerial electroscope consisting of a battery with a bell at each terminal, and a suspended clapper free to move between them, invented by the Swiss meteorologist and diplomat, J.A. De Luc (1727-1817). The quality of the sound of the bells depended on the electrical condition of the air.[707] The use of sound is of particular interest, because of Tyndall’s research on behalf of the British government on the foghorn in the 1870s.[708] Forster encouraged detailed study of the appearance of clouds in relation to meteorological

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[704]Ruskin (1839), volume 1, pp. 56-59.

[705]Forster [1813] 1823, pp. vi-viii.

[706]Ibid., pp. vii, 7-8, 207-208.

[707]Tunbridge (1971), 26 (1), pp.15-33. Forster [1813]1823, pp. 228 – 230.

[708]Tyndall (1874b), 164, pp. 183-244.

phenomena, and commended realistic representation of meteorological events in art.[709] J. Constable (1776-1837) annotated his copy of Forster's work, probably motivating the artist's scientific interest in meteorology. In conclusion, the transformation of meteorology from an amateur to a professional science was achieved through the participation of dedicated people from all walks of life. The scientific study of the weather enabled the discovery of the forces governing meteorological events. The indifference by men of science to meteorology, which upset Ruskin, I contend, may have also been manifest later in the lack of appreciation of Tyndall's achievements.

5A.2. Institutional Role

Necessary for the process of this new science coming into existence was the collaboration between disparate organisations, and skilful coordination of their facilities. To support the advancement of meteorology as a scientific discipline, the British Association for the Advancement of Science, the Royal Institution of Great Britain, the Royal Society, and the new Meteorological Society exerted their authority on a global scale. At the origin of this movement, the reluctant British government was persuaded to commit the resources to what had been regarded as an unfathomable subject of weather prediction. Safety at sea became a potent argument.

The British Association for the Advancement of Science played an important role in encouraging the science of meteorology. The commissioning of reports on meteorology from distinguished men of science by the British Association indicated the growing status of the new science. J.D. Forbes (1809-1868), professor of natural philosophy at Edinburgh presented the British Association with reports in 1831 and 1840, stressing the need to replace haphazard records by amateurs with proven standard procedures of meteorological observations, recorded in a disciplined manner.[710] In the spirit of these reports, progressive in character, the authors discussed developments in the subject, and its successes and failures (which Forbes considered equally instructive). However, the suggestion that the reports were to stimulate new

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[709] Yamalidou (2001), 10 (2), pp. 423-51; 435-6

[710] Forbes (1832), pp. 196-258; 44 - 45.

inquiries was controversial. He reviewed the literature published in Britain and abroad critically. He defined meteorology as “a mere branch of the science of heat in its widest application.”[711] In 1840, D. Brewster (1781-1868), an independent respected Scottish physicist, reported detailed observations conducted for the first time by “educated individuals, with the aid of properly instructed assistants,”[712] using instruments made by A.J. Adie (1775-1858), an Edinburgh instrument maker,[713] who was also patronized by Forbes. Notions of meteorological laws, hitherto only suspected, began to emerge. In the BAAS 1854 report on radiant heat Baden Powell (1796-1830), Savilian professor of geometry at Oxford praised the work of Tyndall’s Marburg tutor, K.H. Knoblauch (1820-1895) on radiant heat.[714] The vigorous reorganization and efficient administration of the Kew Observatory between 1841-1871 by the British Association, further testified to its commitment to the new science of meteorology. It must have been a disappointment to meteorologists not to have the support of the eminent master of Trinity College, Cambridge, W. Whewell (1794-1866) who wrote on the subject, and presented reports over several years at the BAAS annual meetings. He recognized: “the precise theory of most meteorological phenomena is still to be determined.[715]” The study of heat and moisture in the atmosphere, the change from the invisible form of water vapour into its visible guises as dew, clouds and rain, Whewell saw as fraught with erroneous conclusions. While complementing Forbes on his reports, Whewell justified excluding meteorology from his history of the inductive sciences: in his eyes the interdisciplinary character of meteorology, necessary to account for the terrestrial and atmospheric phenomena, precluded it from being treated as a single inductive science.[716] In this case the interdisciplinary character evidently signified inadequate theoretical hypothetico-

[711]Forbes (1841), pp. 37-156, 37, 42.

[712]Brewster (1841), pp. 349-352.

[713]Morrison-Low (2004).

[714]Powell (1855), pp. 337-354.

[715] Whewell [1857] 1976, volume 2, p. 423.

[716]Whewell [1857] 1976, volume 2, pp. 423 - 428, 423.

deductive features to meet Whewell's criteria.[717] In conclusion the BAAS provided the forum for scientists to review the state of meteorology. Tyndall remained aloof from the issues agitating contemporary meteorology, concentrating on the fundamentals of science at the base of the meteorological phenomena.

The Royal Institution's programme included frequent lectures on meteorology, testifying to the importance of the new science. Providing a unique independent platform for Tyndall's research, and the environment to inform the public of new developments through demonstration lectures and exhibitions, the Royal Institution was fulfilling its commitments, as stipulated in its prospectus and by-laws. Faraday publicised the Italian exiled physicist M. Melloni's (1798-1854) pioneering work on the transmission of radiant heat through liquids and solids, and gained for Melloni the Royal Society Rumford Medal as a pioneer of radiant heat studies. As the scientific adviser to Trinity House in charge of lighthouses along the coast of Britain, Faraday was involved in the modernising and construction of new light houses, including the introduction of electric lighting to them. Until old age he visited them in all weathers, and inspected them abroad. Tyndall continued this work, improving their efficiency through innovative studies of sound transmission in the air with a view to the installation of foghorns. He demonstrated these at the Science Museum in London in the presence of Queen Victoria (1819-1901).[718] In conclusion the Royal Institution's participation in the scientific issues of the day pertinent to meteorology through research and dissemination of information to the public, exemplifies its role through the two centuries of its existence. Tyndall's investigations raised the importance of the Royal Institution's function as a research organisation at the time when Faraday's health began to decline and to affect his distinguished record of scientific discoveries.

Howard's biographer R. Hamblyn calls the foundation of the Meteorological Society of London in October 1823 "a forward step…in the professionalisation of the science of the atmosphere. This was something for which many people had been agitating for years. Howard was among the founder members. W.H. Pepys (1775-

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[717]Achinstein (2004), pp. 130-132.

[718]Wirgman (c. 1876), Image: VOO13597.

1856), officer of the Royal Institution, in charge of its philosophical instrument collection for a time, was also among the early members, as well as W. Allen (1770-1843), chemist and anti-slavery campaigner".[719] Its first meeting took place at a coffee house in the City of London, October 1823.[720] In just over a year, its activities had ceased until 1836 when it met again under a different guise. Its first president, G. Birkbeck (1776-1841), founder of the Mechanics Institutes movement, deplored, like Ruskin, the "want of zeal." Hamblyn blames its demise on Howard's move away from the capital to Yorkshire.[721] Re-formed in 1836, the Meteorological Society of London became British Meteorological Society in 1850, and soon afterwards the Royal Meteorological Society in existence to this day. It was instrumental in the innovative application of photography to the new science of meteorology as objective evidence of the weather reports. J. Tucker, in her study of the Society's history, sees photographic techniques providing status for meteorological observations recorded in this manner and facilitating the participation of amateurs. The presence of artefacts, of artistic enhancement, interpreting the photographs, and coordinating the efforts of non-specialists, however, proved problematic.[722] According to the archives section of the Meteorological Office, there is no record of Tyndall having been a member. Other scientists' names do not appear either. I suggest that their fundamental research was potentially useful, but as they were unable yet to offer clear guidelines on its application, the scientists did not seek contact with the meteorologists, **although there were exceptions,** [723] such as B. Stewart (1828-1887), author of a book on the theory of heat, director of the Kew Observatory. F. James reveals serious interest by the founders of the science of thermodynamics, including Mayer, Thomson and

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[719] Hamblyn [2001] 2002, pp. 232-233.

[720] Howard (1823), N.S. 6, p. 317.

[721] Ibid., Howard pp. 231-233.

[722] Tucker (1997), pp. 379-408, 381-389.

[723] Kindly note the phrase in the original "although there were exceptions" which I have now put in bold font for the readers' convenience

Helmholtz, in the sources of the solar heat, of importance in meteorology.[724] Tyndall's contributions to meteorology will be studied in section 5B.

In its advisory and administrative capacity, The Royal Society also provided a prestigious platform for the dissemination of research, paramount in the progress of meteorology at an international scale. It demonstrated its recognition of the importance of the fundamental research in serving the advance of meteorology as a science by the awarding the Rumford medal to Tyndall in 1864, and honouring him as a Bakerian Lecturer on the subject of radiant heat and related topics on three occasions. It also participated in the introduction of innovative interdisciplinary procedures. In 1835 Herschel recommended to the meteorological committee of the Royal Society that it adopt a system of combining the geomagnetic and meteorological observations.[725] A historian of science at the National Museum of History and Technology at the Smithsonian Institution in Washington, W. Cannon dates the foundation of modern meteorology to this far-reaching proposal by Herschel, which increased the efficiency of the available resources.[726] She remarks on the extraordinary achievements of the first generation of the professionals in mid-nineteenth century in devising conceptual and empirical solutions to problems raised.

According to M. Boas Hall, the Royal Society traditionally supported sciences that did not have their own organizations; hence since its foundation the Society focused on meteorology. Advised by its physics and meteorology committee, the Society modernised its record keeping in 1840, which was eventually transferred to the Royal Greenwich Observatory. Meteorology was to include magnetism, perceived by some distinguished scientists, Faraday and Herschel among them, also to involve atmospheric phenomena. Nevertheless, at the time meteorology appeared to be "submerged beneath the rising tide of magnetism."[727]

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[724] James (1982), 15, pp. 155-181.

[725] Cawood (1979), 70 (4), pp. 493-518, p. 507.

[726] Cannon (1978), p. 238.

[727] Boas Hall (1984), pp. 155 – 157.

Concerns over safety at sea became of increasing importance to trade and military strategies. In particular a proposed cooperation with the USA in the study of storms resulted in the establishment of the Marine Department of the Board of Trade in 1850 and an international conference in Brussels in 1853. The British government who were in the habit of consulting the Royal Society on scientific matters, found the president elect, Lord Wrottesley (1798-1867) and the treasurer, Edward Sabine (1788-1883) in favour of the new department coming into being. Fitzroy was consulted on its organisation, and appointed in charge of it in 1854. At the instigation of the USA, it was intended also to improve navigation by providing accurate information about weather at sea and through the streamlining of meteorological observations on land. The Royal Society's guidelines for the procedures of the new office are still in force today. Sabine presented a summary of the discussions that took place from 1852 between the British government and the Royal Society concerning meteorological observations at sea and on land in an 1866 Royal Society report. Sabine was a soldier and explorer, surveyor of terrestrial magnetism, president of the Royal Society, and a veteran of the Arctic expedition in search of the North West passage. The report provided an insight into the extent of the discussions over those fifteen years.[728] It illustrated the growing status of meteorology, and the recognition by the government of the need to plan for international cooperation on meteorological observations. In conclusion, in this section the involvement of the Royal Society in furthering the progress of scientific meteorology was characterised by its multifaceted functions. Tyndall, through his innovative programme of experiments over a decade, reporting in the Royal Society lectures and papers, contributed to the fundamental science behind the new discipline.

5A.3. International Involvement

This section investigates international contributions to meteorological observations is studied. J. Cawood has examined the 'magnetic crusade' of the 1830s in Britain, and its influence on the international scene.[729] This plan to put pressure on

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[728]Sabine (1867), 15, pp. 29-38.

[729]Cawood (1977), 34 (6), pp. 551-587.

the government was orchestrated by Sabine, Herschel and natural philosopher, H. Lloyd (1800-1881). Of increasing importance was a link between geomagnetic and meteorological phenomena, terrestrial atmosphere being their shared space. Eminent scientists were in favour, including Faraday. Cawood's investigations of the growing interest in terrestrial magnetism during the nineteenth century reveal international collaboration, especially between Britain and Germany. In Britain, the role of Sabine and in Germany that of F. H. A. von Humboldt (1769-1859) exemplified collaboration between different countries across disciplines and across frontiers. In France in the same spirit, the French physicist, D.F. Arago (1786-1853), collaborator with A.-M. Ampère (1775-1836), initiated the collection and the publication of data in geophysics and meteorology in addition to geomagnetism.[730] French cooperation, in my view, symbolised the increasingly international nature of science, involving former enemies in peaceful enterprise. The successful collaboration between public observatories in Germany[731] encouraged the British government to finance the magnetic crusade in Britain, aiming to establish physical observatories for geomagnetism, astronomy and meteorology. W.V. Harcourt (1789-1871), president of the British Association in 1839 outlined the grandeur of the enterprise, stating that "the project might also yield the true cause of the phenomena — and … a completion of what Newton began — a revelation of new cosmical laws — a discovery of the nature and connexion of imponderable forces …."[732] In Whewell's opinion it was "the greatest scientific undertaking which the world has ever seen."[733]

Having invited foreign participation, the Foreign Office consulted the Royal Society on the systematization of observations throughout the world, notably Europe and America. The Royal Society, accepting in principle the advantage in international cooperation for the scientific and utilitarian reasons, did not recommend standardization on land, since many countries would have had their own long established respected procedures in the field. The foreign delegates at the Cambridge

[730]Ibid., Cawood, pp. 552, 569.

[731]Lamont (1841), pp. 26-27.

[732]Harcourt (1840), pp. 1-68, 4.

[733]Whewell [1857] 1976, volume 3, 55.

annual BAAS meeting in 1845 also favoured this individual approach. The standardisation of meteorology at sea however, received warm support, particularly with the adoption of the continuously self-recording instruments.[734] Thus international cooperation proceeded on two fronts: the advantages of a multi-disciplinary approach was recognised, allowing for the sharing of the existing facilities; the experience of the foreign countries served as a stimulus to diversify procedures and share knowledge.

5A.4 Artistic Representation of Nature

Artists also had a role in enhancing and shaping the appreciation of meteorological phenomena. Constable and J.M.W. Turner (1775-1851), the major landscape artists of the era, included the representation of meteorological phenomena in their art. Both were connected with the Royal Institution: Constable lectured there on the Science of Art. An exhibition *Turner and the Scientists* at the Tate Gallery in 1998 demonstrated his interest in the Industrial Revolution, and in the representation of the light phenomena. He is said to have consulted Michael Faraday on the nature of light.[735]

Another commentator, J.E. Thornes considers the weather observations recorded in Turner and Constable's paintings to have been useful to meteorology. Constable encouraged the artist's understanding of the scientific process involved: "We see nothing truly till we understand it .... " He concluded his Royal Institution course of lectures: "Painting is a science, and should be pursued as an inquiry into the laws of nature." He asserted that landscape painting should be recognized as "a branch of natural philosophy, of which pictures are but the experiments."[736] Thornes wrote on Constable's portrayal of nature, and the most elusive, windy weather, in particular. He quotes the artist: "Light-dews-breezes-bloom-and freshness; not one of which, has yet been perfected on the canvas of any painter in the world." He traced Constable's strategy to improve his technique of depicting wind, and the influence of

[734]Burton (1986), 19, pp. 147-176, 147-150.

[735]Hamilton, J. (1998).

[736]Constable, in Thornes (2001), p. 96.

F. Beaufort (1774-1857), a scientist who devised a wind scale, still in use.[737] He also studied Constable's landscape sketches with notes on the weather and the time of day. In the early 1820s Constable concentrated on painting the changing appearance of the sky. He worked in Hampstead Heath in oils in all weathers, mostly at noon, capturing "momentary glimpses of shape, process, colour and meteorological truth."[738] He studied the portrayed weather phenomena by the artists in the past. Thornes remarks on the difficulty of representing the sky in painting, and hence its neglect in art from "the scientific point of view."[739] Colour science had much to offer an artist, but little on the perspective of skies. A comment on the American landscape artists for whom "the sky is a finely tuned paradigm of art and science," Thornes thinks applicable to the early nineteenth century British artists.[740] Constable placed the sky in a landscape in a prominent position, observing: "the 'skey' is a source of light in nature – and governs everything."[741] Ruskin, discussing landscape painting, including the sky, suggested "the service of clouds."[742] For Thornes, Howard's classification of clouds constitutes the first scientific concept available to artists. Constable and Turner bring awareness of the dominance of sky in nature, but, unlike most artists, Constable regarded direct observation of the phenomena, imagination and scientific understanding necessary for painting a landscape. Quoting C. Klonk, that art and science should incorporate detailed observation in their method, excluding metaphysical speculations,[743] Thornes concludes that Constable "achieved a unique harmony of landscape art and contemporary meteorological science."[744]

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[737]Thornes (2001), pp. 93-94.

[738]Ibid., Thornes, pp. 97-98.

[739]Thornes (1999), pp. 21-22.

[740]Ibid., Thornes, pp. 17-18.

[741]Constable (1821), in Thornes (1999), pp. 22, 280.

[742]Ruskin (1904), volume iii, p. 265.

[743]Klonk (1996), p. 198.

[744]Note 52, Thornes, p. 90.

J. Hamilton differentiates between Turner's and Constable's interest in meteorology: although the sky was central to them both in its impact on the landscape, Turner's *Skies* sketchbook of annotations testified to his observation of alterations of colour and light in the same fragment of the sky for several days at a time; his interest, unlike that of Constable, was confined to visual representation rather than scientific understanding behind appearances. Hamilton ascribes Turner's precise representation of the weather to his instinctive understanding of meteorological phenomena, but the artist also consulted an eminent scientist, Brewster. Brewster was an expert on rainbows, they discussed this and other atmospheric phenomena. Hamilton quotes J. Skene (1775-1864), the author of an article on painting and Turner in Brewster's Encyclopaedia: "aided by the discoveries daily making in the mysteries of light, [Turner's] … genius seems to tremble on the verge of some new discovery in colour …." This confirms Turner's preoccupation with the spectrum, crucial to the scientific study of light. Through the careful systematic observing of the atmosphere, Turner grasped and expressed its dynamic quality on canvas.[745]

The terrestrial atmosphere, represented by artists, began to be recognized as an essential feature of human existence. The understanding of it and interaction with it, assumed importance in the science of meteorology, incorporating chemistry, physics and mathematics (of particular value in weather prediction). Local knowledge and experience of climate was appreciated. Although according to Hamilton, meteorologists ignored the appearance of the atmosphere to which artists were sensitive, scientists and artists, including Turner and Constable, met at London soirées and in stately homes in the country, which writers and patrons also visited. The Royal Institution, The Royal Society, the Royal Academy of Arts, the Society of Antiquaries were among the institutions hosting eclectic events that were eagerly attended by people of learning. J. Hamilton sees this interaction, exemplifying in the early nineteenth century "the edges of the fascinating breaking wave of understanding and revelation between the land of art, the sea of science and the sky that envelopes them

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[745]Note 722, Hamilton (1998), pp. 63-68.

all" in contrast to what he saw in the boundaries of learning nowadays.[746] The Royal Society obituary of Faraday testified to this social and cultural interaction. It included the recollections by his brother-in-law, the artist G. Barnard:

> At this time [c. 1830] we had … pleasant conversaziones of artists, actors and musicians at Hullmandel's[747] the renown printmaker, sometimes going up the river in his eight-oar cutter, cooking our own dinner, enjoying the singing of Garcia[748] and the society of most of the academicians, such as C. Stanfield,[749] Turner, Westall, Landseer[750] etc … After Hullmandel's excellent suppers … we had charades, Faraday and many of us taking parts. Faraday said to me once, 'I wonder you artists don't study the light and colour in the sky more, and try more for effect …' This quality in Turner's drawings made Faraday admire them so much. He made Turner's acquaintance at Hullmandel's, and afterwards often had applications from him for chemical information about pigments."[751]

In conclusion I contend that Constable and Turner reinforced the human perception of the turbulent effects of the natural forces and the fragility of the interacting environment. The meteorological effects communicated the energy of the universe in which human generations participated. The artists' representation of the weather revealed their concerns with the accuracy of the images, and their readiness to embrace the science of the phenomena.

[746] Hamilton (2001), pp. 15-17.

[747] Hullmandel (1789-1850).

[748] M. Garcia (1775-1832), tenor and composer.

[749] C. Stanfield (1794-1867).

[750] E.H. Landseer (1802-1873).

[751] Anon. (1868-1869), 17, pp. i-lxxxviii, xxv-xxvi.

5B. Tyndall's Meteorological Researches: The Thermal Mode of Investigation

In his research on the composition of matter Tyndall employed heat and light interacting with matter as analytical tools. In his research on the meteorological phenomena of the blue colour and polarisation of skylight he employed the "optical mode of investigation" to be studied in section 5B.5. First however, in this section, Tyndall's choice of his research areas, and their application to meteorology using the 'thermal mode of investigation' are considered. His unique and fundamental contributions, mainly appreciated retrospectively, have played a pivotal role in the science of meteorology. Adopting the 'thermal mode of investigation' he identified carbon dioxide and water vapour, known now as the greenhouse gases, to be powerful absorbents of the infrared radiation. Initiating his programme of research, he broke entirely new ground in the application of science to meteorology. In the Bakerian lecture of 1861 at the Royal Society Tyndall told his distinguished audience of scientists how his research from the mid-1850s on glaciers had led him to accounts of the difference in the transmission of solar and terrestrial heat through the atmosphere by the eminent mountaineers, the Swiss physicist, H.B. De Saussure (1740-1799), the French meteorologists, C.G.M. Pouillet (1790-1868), J.B.J. Fourier (1768-1830) and W. Hopkins (1793-1866). They considered it "a most important influence on climate."[752] Tyndall thought their comment "a point of considerable interest," and, on the basis of his early experiments, expected that,

> … conclusions of great importance may be drawn from them … Their speculations and observations…gave practical effect to a desire long previously entertained to make the mutual action of radiant heat and gases … the subject of experimental inquiry. Our acquaintance with this department of Physics is exceedingly limited.[753]

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[752]Tyndall (1861a), pp. 1-36, 28.

[753]Ibid., Tyndall, p. 1.

Like Melloni and Forbes before him, Tyndall recognised the connection between radiant heat and meteorology. He initiated a decade of study of the nature of matter in gaseous phase, since the cohesive intermolecular interactions, significant in the solid and liquid states, were negligible in gases. This elimination of one variable led to an increased precision of experimental results, and accuracy in their interpretation. Unlike Pouillet's tentative assumptions on the properties of the atmosphere, and Forbes's pronouncements on its thermal properties through analogy with experimental results on liquids and solids, Tyndall's pioneering methodology applicable specifically to the thermal behaviour of gases, enabled direct study of the gases that compose the atmosphere, at the laboratory bench. In addition to the atmospheric constituents, other gases and vapours were studied, enriching understanding of the thermal phenomena pertaining to gases.

Tyndall's planning of an intensive programme was a significant new departure in research. He concluded that hitherto the efforts to study gases had failed, because existing techniques had been inadequate for the purpose. He employed the eminent French physicist, H.V. Regnault's (1810-1878) table of specific heats, identifying water as possessing an anomalously high specific heat, considering its relatively simple chemical constitution. This fundamental discovery revolutionised the study of meteorology. It provided the scientific basis for the investigation of the terrestrial atmosphere. Alerted to the scenes around him, Tyndall extracted the relevant phenomena from his environment. Conscious of unity in nature, in the course of his studies he related the events in the terrestrial atmosphere, the nature of the forces, notably heat and light in their radiant form, and the constitution of matter, to the way they shaped meteorological phenomena.[754] This theme has also been examined in Chapter 3 of this dissertation. The advantage of working in the laboratory became evident, yielding results unattainable in the open air, but of fundamental importance to the understanding of the scientific principles of meteorology.

Tyndall reveals in detail how his experience of nature suggested the design for his experiments. The phenomenon of atmospheric refraction, its appearance, its likely

[754]Tyndall (1865a), pp. 150-152..

location in the environment, was supplemented by a scientific explanation. Tyndall compares the effect with a mirage in a desert.[755] Spurred on by the comments by Pouillet and others on their experiences of meteorological phenomena in the mountains, Tyndall provided the explanations of their observations, and subsequently his own, in terms of underlying causes. Tyndall's involvement with infrared spectroscopy, utilizing the "thermal mode of investigation" whereby radiant heat was his tool, and his awareness of Faraday's "optical mode of investigation," may have alerted him to the possibilities of the application of radiation at the opposite end of the light spectrum to infrared radiation. His research on the atmospheric phenomena of the blue colour of the sky and the polarisation of skylight, in the steps of Faraday, Tyndall's 'thermal mode of investigation'[756] of meteorology will be considered in sections 5B.2-5B.4. His experience of the universality of the interaction of radiant heat with matter according to its composition, and his unreserved acceptance of J. Dalton's (1766-1844) atomic theory, led him to assess the experimental results in the context of the cosmic scale, guided by his conviction about the consistency and the unity in nature obeying natural laws in accordance with mechanical theory. In conclusion, this section demonstrates Tyndall's grasp of how his physical concepts, developed in a specifically designed programme of experiments, provided the scientific basis for the new discipline of meteorology.

5B.1. Controversy on Tyndall's Mimicry of Nature in the Laboratory

In this section the significance of Tyndall's research on the atmosphere at the laboratory bench and in the field will be examined. Notwithstanding Tyndall's impressive experimental research programme in the laboratory, and the consistency of his results, the mimicry of nature at the bench met with disapproval by some of his peers, as already discussed in Chapter 4, Section C.6. Tyndall, aware of the hostility in some quarters, commented:

> Meteorologists, I am informed, sometimes say that laboratory experiment, however well performed, has but little application to

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[755] Tyndall [1885] 1915, p. 19.

[756] Smith (1994), pp. 174-178.

> their field of observation. I, on the other hand, submit that such experiments are necessary to rescue their science from empiricism. What could WELLS have done with dew had he not been preceded by LESLIE and RUMFORD? His whole theory is an application of results obtained in the laboratory.[757]

Hopkins, in his criticism of Forbes, and commendation of Tyndall's experiments, regretted an absence of awareness of the connection between experiment and theory:

> Mr Hopkins insisted on ... a more exact definition of terms, and more accurate modes of mechanical reasoning than those which had too often characterized the discussion of glacial phenomena. Nor had careful experimental investigations ... been appreciated in laying the foundations of theories ... till the experiments of Mr Faraday and Dr Tyndall reminded us how defective and erroneous might be our conceptions ... without the guidance of such careful research.[758]

Hopkins supported mimicking nature in the laboratory, since it provided a precision that was not available in the field, but required for the establishment of physical theories. Forbes, on the other hand, maintained that mathematics could serve only to elaborate a theory that first needed to be established on the basis of data in the field.[759] K. Anderson in her comment on Tyndall's attitude to the meteorologists who were sceptical of laboratory experiments in their subject, implies that meteorologists were spurning theory:

> He had no tolerance for the meteorologists who claimed that difference between laboratory investigation and the open conditions of the atmosphere meant, that theoretical work was of little use.[760]

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[757]Tyndall (1882), volume 173, pp. 291-354, 345.

[758]Hopkins [1862] 1971, 1, pp. 205-212.

[759]Hevly (1996), s. 2, volume 11, 66-86, 72.

[760]Anderson (2005), p. 7.

Tyndall took the meteorologists' criticisms seriously, acknowledging professors S.A. Hill (1851-1890) of India and S.P. Langley (1834-1906) of the U.S.A., who had conducted their observations in the open air, and confirmed Tyndall's ideas on the atmospheric absorption of radiant heat, based on his experimental laboratory results. Tyndall acknowledged them both in his last Bakerian Lecture, delivered in 1881.[761] He was also himself an active worker in the open air, in the mountains, encouraging the mountaineers to take up work in the field:

> As regards Physical science … the contributions of our mountaineers has as yet been *nil* … our Alpine men will not find their pleasure lessened by embracing a scientific object … They have the strength, the intelligence … let them add the accuracy which the physical science now demands, and they may contribute work of enduring value.[762]

A member of the Balloon Committee of the British Association, in the early days Tyndall encouraged meteorological studies of the atmosphere by the balloon ascents, together with J. Glaisher (1809-1903), the superintendent of instruments at the Royal Greenwich Observatory.[763]. For Glaisher, the atmosphere was "the great laboratory of changes which contain the germ of future discoveries …." Prescribing a balloon-centred research programme, Glaisher posed a rhetorical question: "Do not the waves of the aerial ocean contain within their nameless shores, a thousand discoveries destined to be developed in the hands of chemists, meteorologists, and physicists?" Like Tyndall the mountaineer, Glaisher the balloonist explored the high regions of the atmosphere for the benefit of science. The balloon was a philosophical instrument, not only an exhibit or "a vehicle for … excursionists, desirous of excitement, mere seekers after adventure."[764] The image of the balloon as an entertainment for the masses, conflicted with that of a flying laboratory for the study

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[761]Thornes (2001), p. 202, Tyndall (1883), 173, pp. 291-354, 352-354.

[762]Tyndall (1860c), pp. 168-169.

[763]Tyndall (1860a), pp. 289-291.

[764]Glaisher (1871), p. 22.

of the atmosphere. Like the mountaineering men of science, the ascending meteorologists were admired for their endurance, but also subject to ridicule. Since the balloon ascents were spectacular and attracted large crowds, the Royal Society kept aloof from scientific projects in balloons, declining to finance the ascents, but willing to subsidize the instruments employed in meteorological investigations in the mountains. Glaisher compared the Alpine investigations unfavourably with those carried out in balloon ascents. He saw balloons as offering better scientific prospects and more accurate results. He reasoned that changing atmospheric conditions could be systematically examined through balloon ascents.[765] I contend that Glaisher could have applied the same argument to mountaineering. Tyndall made use of the comparative results under different atmospheric conditions from the Alps as well as from Surrey.

Field science in Britain, (a term applicable to both mountaineering and ballooning), is scrutinised in B. Hevly's study of the glacier controversy between Tyndall and Forbes. Both these scientists, amongst several others, appealed to their direct involvement *with* nature despite discomfort and danger, as a testimonial to the trustworthiness of their understanding of nature. They felt that the rigour of their experiences in the pursuit of science merited recognition. Hevly links this emphasis on the heroic physical exertion to the prevailing contemporary focus on "the worship of athletics," emanating from public schools, but soon pervading the British culture at large. It provided a potent rhetorical base in support of science in the field.[766]

In conclusion in this section we have followed two conflicting philosophies concerning the replication of claims about nature in the laboratory. They represent different interpretations of the extent to which instruments modify or accurately replicate natural phenomena.

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[765]Tucker (1996), 11, 144-176, p. 167.

[766]Hevly (1996), 11, pp.. 66-86, 67.

5B.2. Tyndall on Water Vapour in the Atmosphere

In this section Tyndall's study of the thermal properties of the terrestrial atmosphere will be pursued. Searching for the cause of Pouillet's observations that heat from the sun was absorbed less by the atmosphere, than heat from an obscure terrestrial source,[767] Tyndall, discovered the fundamental role of water vapour in the atmosphere. He identified extraordinary and unexpected properties, placing water in a unique position in the realm of nature. Having announced how strong water's absorptive power was for infrared radiation in January 1861 at the Royal Institution, Tyndall presented a paper a year later to the Royal Society on the relation between radiant heat and aqueous vapour. Although the presence of water vapour was occasionally put forward by others as a factor in atmospheric thermal absorption and radiation, Tyndall was the first to embark on a carefully planned programme of research relevant to meteorology. Tyndall was well briefed on the weather phenomena in various geographical locations, and quoted a director of the Kew Gardens 1865-1885, J.D. Hooker (1817-1911), the German scientist, H. von Schlagintweit (1826-1882), Pouillet, Leslie and Melloni, when he delineated a variety of meteorological events awaiting explanation.[768] The natural philosopher Herschel, mathematician and geologist Forbes, chemist J.F. Daniell (1790-1845), geophysicist Sabine, and the physicists Melloni and Thomson, also discussed the influence of the solar radiation on the earth's climate. In the opinion of von Humboldt, studies of the transfer of heat were made possible by the new science of physics.[769] Kidwell identifies this interest from eminent natural philosophers in solar radiation as part of a movement due to the growing awareness of physical influences on life, leading to an increase of scientific expeditions to map terrestrial magnetism, and the distribution of plants and animals.[770]

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[767]Pouillet [1838] 1846, 4, pp. 44-90, 66.

[768]Tyndall (1863e], 153, pp. 1-12, 10-11..

[769]Kidwell (1981), 38, pp. 457-476, 458-459.

[770]Ibid., p. 458.

Through his work, Tyndall revealed the role of water vapour in 'the economy of nature' as far more important, than had been realised hitherto. In his lectures on heat Tyndall used the concept of "extraordinary energy" of water in all its phases, an energy that was manifest in its powers of thermal absorption and radiation, far superior to that of any other body in nature. This property of water, he concluded, played a crucial part in the terrestrial climate.[771] Tyndall's discovery of the high absorptive powers by water vapour in the atmosphere were confirmed six years later by the French astrophysicist, P.J.C. Janssen (1824-1907) who demonstrated by dispersive spectroscopy high thermal absorption by water in the infrared region.[772] On a cosmic scale it imparted thermal motion to the ether in space thereby also affecting temperatures in the interstellar region.[773] Within a year of his pioneering experimental research, Tyndall made another momentous discovery of great importance to science, meteorology in particular: whereas elementary bodies were diathermic, compounds, including water vapour, (a compound of oxygen and hydrogen, which constituted less than 1% of the air), played a crucial part in the terrestrial climate as a powerful absorbent of radiant heat. To my mind this controversial discovery guided Tyndall towards subsequent research that aimed at every turn to convince his detractors of the truth of this claim. He stated the object of the paper: "to prove to meteorologists that they may apply without misgiving, the results which the author has already announced, regarding the relations of aqueous vapour to radiant heat."[774] He reinforced this statement:

> It is very important that the minds of meteorologists should be set at rest on this subject for this newly revealed physical property of aqueous vapour is certain to have numerous and important applications. I therefore thought it right to commence my

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[771]Tyndall (1861a), p. 28.

[772]Janssen (1867),S. 4, 33, pp. 78-79.

[773]Tyndall (1898), p. 389.

[774]Tyndall (1863e), volume 153, pp. 1-12, 10-11. volume 12, pp. 326-327.

> investigations this year with a fresh series of experiments upon atmospheric vapour.[775]

Tyndall asserted:

> The power of aqueous vapour being thus established, meteorologists may, I think, apply the result without fear. That 10 % of the entire terrestrial radiation is absorbed by the aqueous vapour which exists within ten feet of the earth's surface on a day of average humidity, is a moderate estimate. In warm weather and air approaching to saturation, the absorption would probably be considerably greater. This single fact at once suggests the importance of the established action as regards meteorology. I am persuaded that by means of it many difficulties will be solved, and many familiar effects, which we pass over without sufficient scrutiny because they are familiar, will have a novel interest attached to them by their connexion with the action of aqueous vapour on radiant heat.[776]

Tyndall suggested that the absence of water vapour observed in the mountains might contribute to the chilling of the air in the mountains after sunset.[777] The absorptive power of obscure thermal radiation by water vapour, and its transparency to luminous radiation might account for the phenomena observed.[778] He reasoned that since water vapour exercised significant influence, any alteration to the quantity present in the atmosphere would produce a change of climate: “the aqueous vapour of our air, attenuated as it is, checks the drain of terrestrial heat, and saves the surface of our planet from the refrigeration which would assuredly accrue, were not such substance interposed between it and the voids of space.”[779] He referred to other meteorological phenomena in terms of the presence of aqueous vapour in the

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[775]Note 756, Tyndall, volume 153, pp. 1-12, 1.

[776]Ibid., p. 8.

[777]Tyndall (1863c), p. 426.

[778]Tyndall (1861a), 151, pp. 1-36, 29.

[779]Tyndall (1865c), pp. 57-58.

atmosphere: its absence in Central Asia accounted for the severe winters there; in the Sahara the very low temperatures at night contrasted with those in the daytime when "the soil is fire and the wind is flame;" in Australia the dry air caused a very wide range of temperature. For Tyndall, "This newly discovered property of transparent aqueous vapour" explained the apparent discrepancy of Leslie and others having recorded high humidity in moments when the atmosphere appeared to be clear. Wells's explanation of the ice formation in India was accounted for and extended by Tyndall in terms of the thermal properties of water that made it a powerful source of radiant heat.[780] Tyndall subjected his experiments to rigorous tests over the years to confirm his early speculations. In his last paper on the subject, Tyndall devised a simple experiment to demonstrate the effectiveness of the water vapour in the atmosphere. For him an experiment not only provided data, but illustrated a principle. The experiment was performed in the open air near his country home in Surrey. He noted the temperature of the ground and of the air at 4 feet above. He accounted for the large difference between the temperature on the ground and the air on a calm day, and the small difference between the ground and air temperature on a windy day, in terms of the presence of the aqueous vapour. The western wind brought moisture that absorbed the radiant heat from the atmosphere, and hence prevented its loss.[781] Tyndall also demonstrated on that occasion the power of snow as an absorbent of radiant heat from the surface of the earth, that is water in its solid phase. In conclusion Tyndall made a momentous discovery that, contrary to the general perception, gases possessed wide–ranging powers of absorption of radiant heat, including the water vapour in the atmosphere, accounting for hitherto unexplained meteorological phenomena.

5B.3. Thermodynamics of Cloud Formation

In this section I scrutinise the contemporary understanding of the process of cloud formation and precipitation, and Tyndall's contribution to it. The thermodynamics of cloud formation engaged the interest of early meteorologists and

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[780]Tyndall (1898), pp. 500-501.

[781]Tyndall [1882-1884], discourse 16 March, 1883, volume 10, 253-265, reprinted 1970, volume 3, pp. 268-280.

physicists, including Tyndall, Herschel[782] and Thomson. The study of the adiabatic compression and expansion of air in the eighteenth and at the turn of the nineteenth century, as investigated by Kuhn,[783] provided part of a physical explanation of meteorological phenomena for the supporters of the energy conservation principle, including Tyndall. Having demonstrated powerful thermal absorption in water vapour, Tyndall also demonstrated its properties as a powerful radiator of radiant heat in the process of cloud formation, where vast amount of the water vapour produced by the sun acting on the oceans, was condensed into clouds and precipitated as torrential rainfall, as characteristic in the tropics. Tyndall saw these processes as confirmation of his discovery of the thermal properties of water vapour, and also of the condensed and frozen phases of water as rain and snow. Whereas Melloni implicated water vapour in the atmosphere as an important influence on climate,[784] Tyndall provided firm experimental evidence.[785]

Presenting a physical interpretation of the atmospheric phenomena, Tyndall demonstrated the condensation of invisible water vapour into a cloud at a Royal Institution lecture in 1863. He explained it in terms of the prevailing theory of adiabatic cooling of the expanding air, “refrigerating” the vapour, but he attributed the most prominent part in the process to the chilling of the vapour by its own radiation, accompanied by the release of latent heat.[786] From his experimental results, confirmed by the meteorological phenomena, Tyndall concluded that the absence of water vapour from the atmosphere at any level would result in rapid cooling.[787] Through his research programme, he played a crucial part in the transformation of meteorology into a scientific discipline. Tyndall pointed out that the thermal properties of water vapour he had discovered, explained for the first time hitherto puzzling experimental

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[782]Herschel (1861), pp. 24-25; 106-107.

[783]Kuhn (1958), 49 (2), pp. 132-140.

[784]Melloni (1850a), p. 136.

[785]Note 745, Tyndall, 173, pp. 292-294.

[786]Tyndall [1866c] RI discourse 23 January 1863, 4, pp. 5-8.

[787]Note 772, Melloni, p. 384.

observations by eminent meteorologists. In addition to explaining Wells's speculations on ice formation in India (elaborated and extended by Tyndall),[788] a certain type of fog, as well as the intense cold in the high regions recorded by Hooker in the Himalayas, was explicable in terms of the absence of water vapour. It also supplemented the observations of J. Leslie (1766-1832), made using his aethrioscope, the first instrument designed specifically for the study of radiant heat that suggested a connection between the variety of temperatures observed in a single location under apparently identical conditions, with the amount of aqueous vapour in the air. It also impacted interpretation of the work of the German meteorologist, H. von Schlagintweit (1826-1882), who had made radiation experiments with a pyroheliometer, an instrument for the direct measurement of solar radiation devised by Pouillet, and posited the appearance of the clouds as suggestive of the changes in the quality of the air, not detectable by other means. Tyndall provided an explanation of these tentative observations through his discoveries of the thermal properties of the water vapour. Melloni, quoted by Tyndall, questioned the explanation by others of serein or fine rain from a clear sky in terms of thermal radiation from the air, since "no fact is yet known which distinctly proves the emissive power of pure transparent elastic fluids."[789] This statement indicated the inferior state of knowledge of thermal properties of gases in 1853, and therefore the limited status of meteorology as a science, before it was transformed by Tyndall's research of the 1860s.

With the assistance of the physicist J.P. Joule (1818-1889), Thomson provided a mathematical explanation of cloud formation.[790] According to J.E. McDonald of the Arizona Institute of Atmospheric Physics, it took more than a decade for these fundamental principles of meteorological thermodynamics to be accepted by meteorologists.[791] Considering the role of thermodynamics in meteorology, an investigation pioneered by physicists, but fully exploited by meteorologists to support their data, E. Garber poses a question: "Why was it that physicists delved into

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[788]Ibid., pp. 500-501.

[789]Melloni [1847] 1853, volume 5, p. 551.

[790]Thomson (1865), s. 3, volume 2, pp. 125-131, read 21 January, 1862

[791]McDonald (1963a), volume 44 (4), pp. 203-211, 203.

meteorology in the first place?" She refers to the reviewer of Thomson's paper on meteorology, J.E. McDonald for whom the physicists' interest in meteorology was allegedly "peculiar and … puzzling."[792] McDonald does consider Thomson's reasoning on the adiabatic phenomena "very awkward" and mathematics "strange" but only when considered "from the modern point of view."[793] In my view the reply to Garber's provocative question is provided by Tyndall's fundamental discoveries in the physics of the terrestrial atmosphere. The interest in the energy conservation from his contemporaries, Clausius, Thomson, Mayer and Helmholtz and their related work on the sources of solar heat as examined by F. James,[794] testify to the legitimate interest by physicists in meteorology.

In my view it was Tyndall's interest in the forces of nature as a physicist that prompted him to consider their impact on natural phenomena. In his theoretical work backed by a thorough experimental programme, Tyndall provided a cogent response to Garber's question, invalidating her opinion of him as "the only example of a physicist who did significant experimental but not theoretical work."[795] This assessment by Garber is irreconcilable with Tyndall's achievements in theoretical physics. His pioneering work, experimental and theoretical, contributed to the scientific basis for meteorology. Recognition of the significance of his work was slow to come. In conclusion, Tyndall, in tracing the processes of condensation and precipitation of water vapour in thermodynamic framework, identified the water vapour as a powerful source of thermal radiation in nature, accounting for hitherto unexplained meteorological phenomena.

5B.4. Carbon Dioxide and Ozone

Tyndall's research on the thermal properties of carbon dioxide and ozone are pursued in this section. In the Bakerian lecture of 1861 that inaugurated his

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[792]Garber (1976a), volume 33, pp. 51-65, 63-65.

[793]Tyndall (1861a), p. 28.

[794]James (1982), 15 (2), pp. 155-181.

[795]Janssen (1867), S. 4, 33, p. 789.

programme of research on the interaction of gases and radiant heat, Tyndall remarked that the very low absorptive powers of radiant heat by the transparent gases might make experimental work impossible. However, when coal gas became available to him, its absorptive power was enormous: "this single experiment … opened the door to all the [subsequent] research."[796] Since the initial experimental results were imprecise, Tyndall looked for the necessary improvements in his procedures, examined extensively in Chapter 3. Experiments with other gases followed. From an obscure source of heat, the absorptive power of carbonic acid gas (carbon dioxide), depending on its density, was 100-150 times as powerful as that of oxygen.[797] Referring to aqueous vapour in view of its powerful absorbent properties of radiant heat, Tyndall stated:

> ...every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid [carbon dioxide] diffused through the air, while an almost inappreciable admixture of any of the stronger hydrocarbon vapours would powerfully hold back the terrestrial rays, and produce corresponding climatic changes."

He remarked that such changes were probably the cause of all the "mutations of climate" revealed by geology.[798] Today the geological records are found in various environments, including water sediments, fossils, ice sheets, as evidence of climate change over hundreds of millions of years, providing clues to the probable changes in the future.[799]

Cannon refers to Lyell's efforts at establishing his controversial theory of climate change.[800] This was suggested to Lyell by geological formations containing fossils of plants and animals now living in the tropics,[801] in keeping with his

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[796]Tyndall (1872d), p. 19 footnote.

[797]Tyndall (1861a), volume 151, 1-36, 34

[798]Ibid., pp. 27-29.

[799]Geological Society of London Statement (November 2010), pp. 1-8.

[800]Cannon (1978), p. 155.

[801]Lyell [1830-1833] 1990 in three volumes, volume 1, pp. 92-124..

principles whereby present natural phenomena can be explained in terms of the past events.

At the University of Cambridge as the Rede lecturer for 1865, Tyndall addressed the crowded Senate House on radiation. The Rede Lectures endowed in the 1520s by the executors of the will of Sir Robert Rede, (d. 1519), continue to this day; the lecturers since 1858 have been chosen on the grounds of their eminence. Tyndall shared the honour with Maxwell, Tait, Kelvin and Helmholtz, among others. He spoke on the thermal properties of carbonic acid gas as "one striking example" to illustrate the influence of the vibrating period of the molecules of the substance on its power of absorption of radiant heat. Tyndall concentrated on a controversy concerning the influence of the heat source on the thermal properties of bodies; "the subject of frequent discussion among philosophers."[802] The results of his experiments had two vital consequences for meteorology. He identified carbon dioxide as the most powerful absorber of radiant heat of all gases if the heat source had an element in common with it, for example, a carbonic oxide flame. However carbon dioxide was virtually diathermic to most thermal radiation from a solid heat source such as copper sheet. This phenomenon, an increased absorptive and radiating thermal power by matter exposed to radiation from a source with which it possessed an element in common, was widespread or even universal. Another important consequence of this resolution by Tyndall of the disagreement among physicists lies in his speculations on the physical interpretation of this dependence of the thermal properties of a body on the kind of thermal radiation to which it is exposed. Tyndall ascribed the change in the power of absorption to the synchronization of the period of the molecular vibration of the gas with that of the period of vibration of heat rays emitted by the carbonic oxide flame:

> This question of period, though of the utmost importance, is not competent to account for the whole of observed facts. ... whatever may be the fate to visualise the physics of the process ... to account for the phenomena of radiation and absorption we must take into

[802]Tyndall (1865c), pp. 1-62.

> consideration the shape, size and complexity of the molecules by which the aether is disturbed.[803]

Significantly from the atmospheric point of view, Tyndall identified carbon particles, the product of combustion, as the main source of radiation ensuing from the carbonic oxide flame.[804] He declared that "even when the east wind blows, and pours the carbon of the city upon the west end of London, the heat intercepted by the suspended carbon particles is but a minute fraction of that absorbed by the aqueous vapour."[805] In conclusion, in his choice of subject for investigation, and his devising of suitable experimental procedures to extract essential information exposed by natural phenomena, in my view, Tyndall's remarkable powers of imagination as applied to science, resulted in repercussions for posterity.

I have given an extensive discussion on ozone in 4C.5. A brief reference is also made here in view of its importance now in meteorology. In 1862 Tyndall reported his important discovery of ozone's high absorptive power of radiant heat, suggestive of its molecular composition as an allotrope of oxygen: "If it be oxygen, *it must be packed into groups of atoms, which encounter vast resistance in moving through the aether.*[806]*"* He came to that conclusion because ozone did not behave like any elementary gases he had examined; only compound gases displayed a range of absorptive power of radiant heat in contrast to the diathermancy of elementary gases. Through the action of heat on ozone, Tyndall demonstrated that the alternative constitution that had been suggested for it as a compound of hydrogen was not viable, because of the absence of water vapour on heating the gas. He stated cautiously: "For the present…I hold *that ozone is produced by the packing of the atoms of elementary oxygen into oscillating groups."* Moreover this pioneering thermal mode of investigating its structure was performed on tiny traces of ozone, not detectable by

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[803]Ibid., Tyndall, pp. 56-57.

[804]Tyndall (1864b), 154, pp. 327-368, 357.

[805]Tyndall (1863e), 153, pp. 1-12. 2-3.

[806]Tyndall [1880] 1898, pp. 364-365.

other means.[807] His results on the generation of ozone by the electrolysis of water showed

> … a perfect correspondence [with] those of … a Swiss physicist, A. De La Rive [1801-1873], Professor of medical physics at the University of Geneva, J.L. Soret [1827-1890], and H. Meidinger, though there is no resemblance between our respective modes of experiment. Such a correspondence is calculated to augment our confidence in radiant heat as an investigator of molecular condition.[808]

Tyndall reiterated his commitment to the thermal mode of investigation, evidently aware of his unique approach to the study of matter, ahead of his time.

5C. Clouds and the Sky: Tyndall's Optical Mode of Investigation

This section studies Tyndall's discovery of the chemical effect of a light beam on gaseous matter. His employment of the ultra-violet end of the spectrum provided an analogy to infrared radiation, and also functioned as a tool to probe nature's phenomena. The discovery played a fundamental role in the elucidation of the phenomena of blue colour of the sky and the polarisation of skylight, considered in the nineteenth century as two great enigmas of meteorology; Tyndall's discovery of the chemical effect of the light beam also enabled the elucidation of the study of light scattering, also widespread in nature, and of value in its applications to the progress of science. Tyndall's research, moreover, had played a crucial part in the new science of photochemistry, an area that was of fundamental significance in meteorology. His accidental observation of a nebulous appearance in usually transparent gases and vapours in his experimental tubes caused him disquiet, but "intermittent discomfort … is the normal feeling of the investigator … it drives him to closer scrutiny, greater accuracy, and often, as a consequence to a new discovery," he commented.[809]

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[807]Tyndall (1863a for 1862), 152, pp. 59-98, 84-86.

[808]Tyndall (1865a), p. 370.

[809]Tyndall (1869a) RI discourse 15 January, volume 5, pp. 429-450., 430-431, 448; (1871f), pp. 247 287, 265.

Extending his area of investigations, he illuminated the experimental tube filled with transparent gases by means of a beam of electric light to observe the haziness, caused and revealed by the light, and due to the traces of vapours in his experimental tube. He confirmed his contribution, (particularly to the study of the blue colour of the sky in the laboratory), by carefully documenting the timetable of his research.[810] Using the ultra-violet end of the spectrum as an investigative tool in this research, Tyndall reproduced phenomena in the laboratory that hitherto had been known to occur only in "the laboratory of nature."[811] Tyndall surmised that the deep blue of the sky in nature was due to an effect similar to that in his experimental tube. He interpreted the observed effects of the decomposition by a light beam of the vapours of some volatile compounds, including that of allyl iodide, in terms of their molecular interaction with light. This process resulted in the splitting of the molecules; a liberation of the iodine atoms from allyl iodide occurred since they vibrated in synchronisation with the light waves impacting on the aether. Tyndall noted that the air loaded with vapour in the experimental tube was invisible until exposed to a convergent beam of the electric light. After a brief lag of time when the beam was invisible Tyndall noted a bright white cloud replacing the darkness. Providing a physical interpretation for this process, in his view the cloud consisted of molecules split up by the action of the light beam. Tyndall demonstrated that only the small fraction of the beam that was vibrating in synchronisation with the period of vibration of the amyl nitrite molecules was effective in splitting them up to form the cloud. Similar effect was produced by sunlight.

Tyndall's study of the atmosphere also included a subject raised by Herschel, the polarization and the blue of the sky,[812] which Herschel considered "a very mysterious and a very beautiful phenomenon".[813] Experimenting with different colourless highly attenuated vapours, Tyndall produced "incipient clouds," with particles of certain size capable of producing the colour of the sky, "a blue which

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[810]Tyndall (1870a), volume 160, pp. 333 -365, 342-352.

[811]Tyndall [1869a], in Tyndall (1871f), volume 5, pp. 247-287, 256.

[812]Tyndall (1869c), 17, pp. 223-233.

[813]Herschel (1861), p. 228.

shall rival…that of the deepest and purest Italian sky."[814] The decomposition occurred with the complete luminous spectrum, although the thermal part of the spectrum had been filtered off by passing it through a solution of hydrobromic acid, a high absorber of the thermal radiation, proving that only luminous radiation was instrumental in the production of the observed effects. The effect was the same, irrespective whether the vapour was used on its own, or mixed with air, oxygen or hydrogen. No scattering was recorded when the gases were used without the vapour. The phenomenon was evidently due to the presence of the vapour. Through the chemical decomposition of allyl nitrite Tyndall also reproduced other atmospheric phenomena in the laboratory: at a low pressure the vapour particles on precipitation grew in size accompanied by iridescence, producing the cloud "so luminous as to fill this theatre with light." He had previously seen this phenomenon in the Alps "with delight and wonder."[815]

The variety of different textures of clouds produced encouraged Tyndall to study the process of cloud formation in detail, noting spheres, sparkling flakes or plates. The clouds differed in their duration and the manner of disintegration. He searched for the causes of the differences in their character. He identified particles of different sizes, determined by the density of the vapour with respect to its liquid, as well as the size of the polyhedra of the vapour from which the cloud particles were formed.[816] He addressed himself to the chemists, aware that his discovery "in their hands will become a new experimental power."[817] The significance of dust and the scattering of light by it in the atmosphere were thus revealed by Tyndall.

Tyndall investigated the polarisation of skylight in nature using Nicol's prism. Subsequently Tyndall reproduced experimentally the natural phenomena of polarised light using a prism and an incipient cloud acting also as a prism, and with ordinary as well as polarised light to illuminate the particles.[818]

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[814]Tyndall (1871f), 247-287, 265.

[815]Ibid., Tyndall, pp. 256-257, 264.

[816]Tyndall (1869d), volume 17, pp. 317-319.

[817]Tyndall (1869b), volume 17, p. 92.- 102, 92.

[818]Tyndall (1869a), in Tyndall (1871f), pp. 247-287, 268-276..

Studying the solar spectrum revealed gaps that suggested the atmospheric absorption of the ultraviolet end of the spectrum, ozone being the absorbing substance. Having demonstrated for the first time the decomposition of certain vapours and the formation of clouds as photochemical reactions, Tyndall realised their significance for the study of the atmospheric processes, including the effects of pollutants:

> By this inquiry the range of radiant energy as a chemical agent is, therefore, considerably extended; the phenomena resulting from that energy are demonstrated in a new and exceedingly impressive form and they prompt reflexions regarding the possible influence of solar radiation on the gases, vapours, and effluvia of our atmosphere which could not previously be entertained.[819]

For Tyndall light, like radiant heat, became an instrument to study nature.

5D. The Reception of Tyndall's Contributions to Meteorology by 'Thermal Mode of Investigation'

The growing importance of meteorology as a science, and a recognition of the dynamic character of the terrestrial atmosphere which Tyndall had surmised through the motion of the clouds,[820] and which Thomson[821] and Joule,[822] among others, worked out mathematically, required a vigorous and innovative interdisciplinarity. It came about on international scale, coming gradually into existence through inter-governmental and scientific cooperation with astronomers and amateurs. Reporting on his work on radiant heat and water vapour in the atmosphere, Tyndall referred to its relevance to meteorologists, though he admitted the limitations of his own work:

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[819]Tyndall [1870a], volume 160, pp. 333-365, 335.

[820]Tyndall [1871] 1906, pp. 405-412, 406.

[821]Thomson (1865), s. 3, volume 2, pp. 125-131.

[822]Joule (1843-1850), volume 5, pp. 517-518.

> The applications of these results to their science must be innumerable; ... I cannot but regret that the incompleteness of my knowledge prevents me from making proper applications myself.[823]

The reception of his contribution to meteorology by means of "the optical mode of investigation" will be discussed in Section 5E.

5D.1. The Nineteenth Century

This section scrutinises the reception in Tyndall's lifetime of his investigations of the thermal properties of gases, as pertinent to meteorology. From 1861 Tyndall's research on radiant heat was enthusiastically received by the doyens of the Royal Society, physicists and chemists, who refereed his papers. This topic is explored in detail in Chapter 1. Despite their august support, the assessment by some writers and lecturers varied; some neglected and some acknowledged the value of his work. Approbation from Herschel, the former president of the Royal Astronomical Society and eminent Cambridge mathematician and natural philosopher, must have been pleasing to Tyndall. Herschel wrote in 1861: "Accept my best thanks for your valuable paper the Bakerian lecture on the diathermancy &c of gases-which is an immense step in the physics of aeriform bodies"[824] Following another publication by Tyndall on the absorption and radiation of radiant heat, Herschel wrote appreciatively: "The fact of air being non-absorptive and vapour highly so is indeed a very capital one and must afford a key to much that has hitherto been inexplicable in meteorology."[825] A few months later, Herschel remarked: "you have made a grand step in meteorology in showing that the dry air is perfectly transcalescent and that the invisible moisture is what stops the sun's heat."[826] In 1864, when awarding the Royal Society Rumford Medal to Tyndall, the president, Sabine spoke warmly of his personal regard for Tyndall, urged him to look after his health "so valuable to us all," and praised his scientific achievements with numerous and important bearings on

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[823]Tyndall (1865a), p. 394.

[824]Herschel to Tyndall 21 July 1861, pp. 505-506.

[825]Herschel to Tyndall 10 November 1861, p. 508.

[826]Herschel to Tyndall 12 April 1862, p. 516.

meteorology: “each last achievement may almost be said to have dimmed the lustre of those which preceded it.”[827] On the other hand, in a book from 1872 on the terrestrial atmosphere by an eminent French astronomer, C. Flammarion (1842-1925), Tyndall received only a marginal mention in connection with the passage of sound through the air.[828] The research on the constituents of the air by the French chemist, A.L. Lavoisier (1743-1794), French physicist and chemist, J.L. Gay-Lussac (1778-1850), von Humboldt, and German chemist, J.F. von Liebig (1803-1877), were however included. Flammarion recognized that ozone possessed interesting chemical properties, but linked it with the names of M. Van Marum, C.F. Schönbein, J.C.G. De Marignac, A. De La Rive, Faraday, and Andrews, among others. Flammarion added that despite a lot of research on ozone “the knowledge of it is from a physical and chemical point of view very imperfect.”[829] The English editor of the Flammarion volume was Tyndall’s contemporary, a distinguished meteorologist, J. Glaisher, FRS (1809-1903). As a discourse lecturer at the Royal Institution in the1860s, Glaisher would have been acquainted with Tyndall and presumably his work. It is therefore surprising that he neither commented on Flammarion’s misleading assertions about ozone, nor ensured fitting acknowledgement of Tyndall’s contributions to the understanding of the constitution and properties of ozone. Tyndall’s innovative experiments and theoretical work on ozone were first reported at the Royal Society Bakerian lecture of 1861, he followed with a detailed account of his work on ozone at the Royal Society the following year,[830] and a lecture on the subject at the Royal Institution.[831] Publications ensued. In view of his association with Glaisher of the ballooning renown, and the publications of his research and lectures in the academic and popular press, a contemporary lack of awareness of Tyndall’s contributions to meteorology is surprising.

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[827]Sabine (1863-1864), volume 13, pp. 497-517, 515-517.

[828]Flammarion [1872]1873, pp. 75, 77.

[829]Ibid., Flammarion, pp. 61-63, 75, 77.

[830]Tyndall (1863a for 1862), volume 152, pp. 59-98, 84-86.

[831]Tyndall (1862c), RI discourse, 7 June 1861, volume 3, pp. 387-396, 404-407.

According to S.L. Hill (1851-1890), the meteorological reporter in India, the meteorological community remained sceptical, despite Tyndall's efforts in 1881 to support and confirm the results of his 'classical' research:

> Notwithstanding the ingenuity with which Dr. Tyndall has made use of the most recent physical appliances to support and confirm the results of his classical research concerning the behaviour of gases and vapours with regard to radiant heat, his conclusions, in so far as they relate to the comparative diathermancy of dry air and water vapour, have not yet met with general acceptance among meteorologists. There is even, on the part of some, an evident reluctance to accept the decision of laboratory experiments on the question of atmospheric absorption as final, however ingenious, varied, and consistent with one another the experiments may be.[832]

In particular, they remained unconvinced by his reliance on laboratory experiments concerning atmospheric absorption. Hill, therefore, undertook independent meteorological investigations to identify which constituents of the atmosphere had the greatest absorptive power of radiant heat. Hill's results agreed closely with Tyndall's, and he concluded that the absorption power of dry air was negligible, and that "the total absorptive power of the atmosphere is due to the water vapour it contains." His computations were based on the data recorded outdoors in 1869 and 1879. Hill reported also that Professor Violle of Grenoble corroborated this finding in a lecture of 1878.[833] At the suggestion of Lieut. General R. Strachey (1817-1908), Hill also calculated the ratio of the water vapour to the air present, and found that a small fraction of radiant heat was absorbed by the air itself, a fraction which was probably invariable: "It is evident that in the Alps, as in the Himalayas, practically the whole absorptive power of the atmosphere is exercised by the water vapour it contains." The absorption by water vapour varied from day to day with the nature of the solar radiation.[834] This important result by Hill, I suggest, is what one

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[832]Hill (1881-1882), volume 33, 216-226, 216.

[833]Ibid., Hill, pp. 225-226.

[834]Ibid., Hill, pp. 435-437, 435.

would expect from Tyndall's research which had placed the highest thermal absorption by water vapour as coming from the infrared region of the solar spectrum, that is, beyond the visible. This outcome of Hill's investigations, corroborating Tyndall's results is an important testimony to the legitimacy of Tyndall's research at the bench. Another important unequivocal recognition of Tyndall's contribution to meteorology came from the distinguished American physicist, S.P. Langley (1834-1906). Langley was the inventor of the bolometer, who worked outdoors with this "complex and delicate apparatus" of his own design to investigate the absorptive power of radiant heat by the atmosphere. Using his outdoor records in the Sierra Nevada Mountains in California, in a letter to Tyndall he confirmed Tyndall's conclusions based on the experiments at the bench:

> These experiments ... being made on a scale different from that of the laboratory on one indeed as grand as nature can furnish-and by means wholly independent of those usually applied to the research, must, I think, ... put an end to every doubt as to the accuracy of the statements so long since made by you, as to the absorbent power of this agent over the greater part of the spectrum, and as to its predominant importance in modifying to us of solar energy.[835]

The Irish physicist T. Preston emphasised the importance of Tyndall's discovery of the high thermal absorptive power of water vapour, and its overriding importance in meteorology.[836] In his study of history of heat, he acknowledged the significance of Tyndall's first successful experimental demonstrations of the transmission of radiant heat through gases, overthrowing the mistaken notion that all gases were transparent to radiant heat. Before the Royal Swedish Academy of Science in 1895, the Swedish Nobel Prize winner in physical chemistry S.A. Arrhenius (1859-1927) presented a detailed study on a subject new to him, that of the presence of carbonic acid in the air and its relevance to the temperature on earth.[837] Much had

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[835]Langley to Tyndall, 10 September, 1881, quoted in Tyndall (1882a), volume 173, pp. 291 354, 353-354.

[836]Preston [1894]1919, pp. 516-537, 530.

[837]Arrhenius [1895]1896, s. 5, volume 41, pp. 237-276.

been published on the absorptive properties of the atmospheric gases, stated Arrhenius, but he attached most importance to Tyndall's recognition of the significance of the phenomenon for meteorology, particularly in moderating the daily and seasonal variations of the terrestrial temperature. Instead of referring to one of Tyndall's Royal Society research papers, he referred only to an early edition of Tyndall's popular work on heat.[838] In contrast, he pointed to the research papers of Fourier, Pouillet and Langley to substantiate his acknowledgement of their idea of the selective absorption of thermal solar radiation by the terrestrial atmosphere. Tyndall was presented as a populariser only; his Bakerian lectures and other research papers favourably refereed by Maxwell, Thomson, Stokes and Crookes, were ignored. In conclusion, the reception in Tyndall's lifetime of his pioneering 'thermal modes of investigation' pertinent to meteorology were recognised by the most eminent scientists and the Royal Society, one of the most distinguished scientific academies in the world. Personal animosity and poorly informed commentators may have been partly responsible for the lack of appreciation by others. The positive judgment and the foresight of his supporters have however, been vindicated in due course.

5D.2. The Twentieth Century

In this section the reactions during the century following Tyndall's death in 1893, are assessed in terms of their recognition of his thermal mode of investigation. In 1916, at a Friday evening discourse at the Royal Institution the Director of the Meteorological Office, N. Shaw, reviewed the progress of theory in meteorology. The speaker referred to work in the 1850s by Sabine, De La Rue, Stewart, amongst other well-established researchers. Tyndall was not mentioned. His epoch-making contributions were not recognized by the meteorologists. His 1860s research programme had been announced in more than ten lectures at the Royal Society on the physics of the atmosphere and published in the Philosophical Transactions, but was not mentioned by Shaw, despite his characterization of that decade as aiming at the geographical distribution of the weather, a theme particularly well suited to Tyndall's causal explanation of the weather phenomena in different geographical locations. The

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[838]Tyndall (1865a), p. 405.

theoretical work of Joule, Clausius, Maxwell, Stokes and Thomson on the kinetic theory of gases with its theoretical implications for meteorology, was also not mentioned by Shaw. The author was conscious of the shortcomings of the theoretical aspects of meteorology, "prone to creating illusory explanations, readily overturned by the discovery of some stony fact," yet he omitted to mention the physical basis of the science.

In 1921, J. Dewar (1842-1923), the Fullerian Professor of Chemistry at the Royal Institution, Tyndall's successor as resident professor-in-charge, lectured on the absorption of the solar radiation. Although Dewar covered the history, going back to Leslie, he did not include Tyndall's work in these areas.[839] In 1945, Eve and Creasy, Tyndall's first biographers, remarked on Tyndall's interest in radiant heat in consequence of his work on glacial theories. They noted the hazardous nature of Tyndall's efforts to gather data in the Alps in 1858 to study the absorption of solar radiation by the atmosphere. Eve and Creasey record Tyndall's early work on radiation with its ramifications, in which he also gained experience in the planning and performance of experiments. They describe Tyndall's awareness of the need to identify "the latent sources of error" and to work out "the technique of experiment … in infinite detail." They see his papers as having been written with care, and salient points brought out. They give insufficient emphasis however to Tyndall's momentous discovery of the cause of the phenomena observed by Fourier, Hopkins, Pouillet and De Saussure.[840]

In a new biographical essay in 1981, this understating of Tyndall's meteorological work was continued by A.J. Meadows, who failed to refer to the significance of Tyndall's pioneering work in the context of meteorology. He presented Tyndall the physicist without indicating the relevance of Tyndall's research. This is a recurring issue with the commentators on Tyndall, and betrays their ignorance of his research publications. Meadows only briefly noted Tyndall's interest in glacial theories, and his appreciation of the importance of the effect of the

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[839]Dewar [1924], RI discourse 28 January 1921, volume 23, pp. 412-440..

[840]Eve and Creasey (1945), p. 310; Tyndall (1861a), 151, pp. 1-36, 28.

terrestrial atmosphere on the infrared radiation in meteorology.[841] Meadows referred to the part played by Tyndall's German background as a student of Knoblauch, a researcher in radiant heat. However, he also sees Tyndall's role as a reviewer and translator of foreign papers for the *Philosophical Magazine* as providing an opportunity for Tyndall to broaden his knowledge of the work by foreign researchers, including that of the German meteorologist, Schlagintweit.[842] Meadows mentioned Tyndall's adversary, Magnus, concerning the absorption of radiant heat by water vapour, but without relating this debate to the importance of Tyndall's research on radiant heat to meteorology. Fourteen years on, however, at a Royal Institution Discourse Meadows acknowledged Tyndall's work on three important topics with relevance to meteorology, two of them, ozone and the greenhouse effect - a part of his thermal mode of investigation.[843]

Tyndall's contributions to meteorology going "to the heart of the matter," particularly, his identification of the water vapour and carbon dioxide, powerful absorbers of thermal radiation in the infrared region, are acknowledged by the Canadian scientist J.C.D. Brand, who commended Tyndall's reasoning in terms of the shapes of the atoms to account for the diathermancy of the elements, and the athermancy of thermal radiation by compounds, which corresponds to today's consideration of the effect of dipoles.[844] Tyndall surmised an effect of polarity somewhere in the process of the interaction of radiant heat with matter. In a lecture on light, speculating on the polarity manifest in magnetism, Tyndall stated: "the probability is that the progress of science, by connecting the phenomena of magnetism with luminiferous ether, will prove these lines of force, as Faraday loved to call them, to represent a condition of this mysterious substratum of all radiant

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[841]Meadows (1981), pp. 81-91, 86.

[842]Ibid., p. 89.

[843]Meadows (1995), volume 66, pp. 239-249.

[844]Brand (1995), p. 82. Brand does not provide a reference to Tyndall who in his Rede lecture (1865c), pp. 56-57 attempts a physical interpretation of his discovery of the diathermancy of elementary bodies and the athermancy of compounds in terms of the shapes of the atoms.

action."[845] Brand's view of Tyndall's thinking in terms of polarity is therefore justified.

In 1996, Tucker mentioned Tyndall as a member of the BAAS Ballooning Committee, which had been established in 1858 on the instigation of Colonel William Sykes (1790-1872), a soldier with the East India Company, and a naturalist. The committee consisted of distinguished men of science, including Wheatstone and Faraday. In the balloon observations were made using the same instruments as in mountaineering.[846] Tyndall's participation with famous meteorologists and outdoor research is significant, as until then most of his data appeared to come from the laboratory.

J. Fleming's recent book on the *Historical Perspectives on Climate Change* refuted the commitment of Tyndall and S.A. Arrhenius (1859-1872) to the physics and chemistry of the atmosphere on the grounds of their "extremely broad scientific interests … climate-related research [being] one interest among many,"[847] but he acknowledged Tyndall, "an accomplished experimenter" as the first researcher to demonstrate experimentally the absorption of radiant heat by some constituents of the atmosphere, water vapour and carbon dioxide in particular. Referring to many of his discoveries, he particularly selected Tyndall's demonstration that gases, even at very low pressures, exercise a powerful influence on climate through their thermal absorptive properties.[848] However, he is adamant, that because of their many interests as polymaths, neither Tyndall nor Arrhenius deserves to be considered as a serious contributor to the present climate debate.[849] This is surprising considering that Tyndall's theoretical and empirical contributions are valid, and have provided a foundation for further scientific investigations. P Day, the director of the Royal Institution, 1991-1997 was instrumental in establishing the Tyndall Forum, an

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[845]Tyndall [1885] 1915, p. 96.

[846]Tucker (1996), s. 2, volume 11, pp. 144-176, 151, 168.

[847]Fleming (1998), pp. 65-82, 65.

[848]Ibid., p. 70

[849]Ibid., p. 65-66.

institution named in his predecessor's honour to debate the climate change.[850] The establishment of Tyndall Centre for the Study of Climate Change at the University of East Anglia is recognition of Tyndall's contributions to meteorology. In conclusion twentieth century ambivalence towards Tyndall's place in the science of meteorology has been demonstrated, but the appreciation of his research is growing. Ignorance of his important primary publications is revealed in some commentators.

5D.3. The Present

Tyndall's enduring controversial status as a scientist is also reflected in the current literature. In 2002 G.J. Retallack acknowledged Tyndall as the first to provide an experimental proof of the absorptive power of carbon dioxide.[851] Citing only the *Philosophical Magazine* reprint of the original Bakerian lecture at the Royal Society, Retallack doesn't acknowledge neither the importance attached to this paper by Tyndall's contemporaries, nor the distinction accorded to Tyndall for this work by the Royal Society.[852]

In 2003, the American physicist S.R. Weart, discussing Tyndall's study of the "greenhouse effect," misinterpreted Tyndall as having been intimidated by the prevailing scientific opinion that all transparent gases were diathermic. On the contrary, Tyndall's delay in embarking on his programmes of research was caused by many reasons, but not intimidation. Tyndall did not publish a preliminary notice of his research until nine years after reading Melloni, but he judged correctly that the techniques employed successfully for the study of liquids and solids, were inappropriate for the study of gases. He embarked on an arduous, and time-consuming adaptation of Melloni's instruments and procedures. These essential preliminaries required meticulous study and the implementation of suitable conditions for creating a successful experimental methodology for the notoriously elusive gaseous aggregate of matter, never attempted before. Some of the issues confronting Tyndall have been investigated in Chapter 3. The delay in launching his programme of research on the

[850]Personal communication, awaiting confirmation in Day's files.

[851]Retallack (2002), volume 360 (1793), pp. 659-673, 659.

[852]Tyndall (1861b), pp. 1-36.

diathermancy of gases was not due to Tyndall feeling discouraged by others' opinions, but to his demanding commitments: refining his experimental procedures, the completion of the diamagnetic research and the structure and the movement of glaciers, the heavy programme of lectures at the Royal Institution, the need to consolidate his career as a professional scientist, and the restricted research facilities, not eased till the 1859-1860 refurbishment of the Royal Institution laboratory space.[853] Weart reinforces the allegedly meek aspect of Tyndall's character when he ascribes Tyndall's interest in the meteorological phenomena purely to the existing disputes among the scientists concerning the Ice Age in prehistory. He does not mention that Tyndall, the fledgling Professor at the Royal Institution, was a protagonist, boldly challenging the established authority of an eminent Professor of Natural Philosophy at Edinburgh, Forbes. Weart also discusses the difference between the absorption of the solar spectrum and that of the terrestrial radiation. He attributes to Fourier the suggestion that this effect is due to the terrestrial atmosphere. He recognizes, however, that: "The correct reasoning was first explained lucidly by a British scientist, John Tyndall."[854] Tyndall himself notes how his multidisciplinary interests had arisen, invariably rooted in his research and previous findings in a different field. He referred to a poem by Coleridge as his guide to the study of nature. Alerted to atmospheric phenomena, Tyndall extracted from his environment the relevant features that were then exposed in his carefully designed and skilfully performed experiments. In general, events in the terrestrial atmosphere, his notion of the nature of the forces, notably heat and light in their radiant form and the constitution of matter, shaped his interpretation of the natural phenomena.[855]

5E. The Reception of Tyndall's Contributions to Meteorology by 'Optical Mode of Investigation'

There has been a growing interest in Tyndall's study of the phenomena manifest in the colour and the polarisation of skylight and in light scattering. The blue

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[853]R.I. Visitors' Annual Report (1860).

[854]Weart (2003), pp. 3-4, 3.

[855]Tyndall (1860b), pp. 37-39.

of the sky engaged the attention of scientists for centuries. In a historical overview of the study of light scattering phenomena across four centuries, the South African physicist J.D. Hey, considers that "the study of light scattering by molecules was to a great extent stimulated by the research conducted by John Tyndall on the action of light on various mixtures of vapours and air, a meteorologically significant source of inspiration to Rayleigh's work."[856] At the time Tyndall described to Herschel the exciting effects in the laboratory, mimicking the atmospheric events, hitherto seen only in the "laboratory of nature." "Go and prosper! It seems to me very clear that you are on the high road to something very remarkable," responded Herschel, who recalled having seen similar effects in the atmosphere.[857] The French physicist A. Morren (1804-1870) reported to the British Association in 1869 on Tyndall's "highly interesting research on a particular species of luminous reactions ... providing physicists and chemists with a new instrument, both of synthesis and analysis." Taking up "this scientific challenge," Morren replicated Tyndall's experiments, finding them as "rigorously exact as they are ably described."[858] Lodge and Ruskin in their correspondence both vilified and praised Tyndall's work. Refuting Lodge's arguments in favour of the dust particles in the atmospheric phenomena, Ruskin also criticised him for ignoring "some marvellous results of Tyndall's … in which he made small firmaments in tubes …."[859] Referring to Lodge's dust particles, Ruskin wrote: "I don't believe in them yet!-except in Tyndall's experiments at the Royal Institution."[860]

By the early twentieth century, however, at two Friday evening discourses neither the director of the Meteorological Office N. Shaw in 1916, nor the successor to Tyndall in charge of the Royal Institution J. Dewar (1843-1923) in 1921 acknowledged Tyndall's pioneering work on the subject. Progress in the appreciation

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[856]Hey (1983), volume 79, part 1, pp. 11-27, 21-27.

[857]Herschel to Tyndall 2 December1868, pp. 553-554. Typed copy in the RI collection, volume RI MS JT/1/TYP/2, mss in RI MS JT RI//1/H/111.

[858]Morren (1870), pp. 66-72, 66.

[859]Tyndall (1871g), RI discourse 15 January 1869, in Tyndall (1871f), pp. 245-287.

[860]Ruskin (1903-1912), volume 37, pp. 513-517; 520-527 quoted in J. Smith (1994), p. 175.

of Tyndall's work took time. In 1918, the fourth Lord Rayleigh, R.J. Strutt (1875-1947), lectured at the Royal Society on the scattering of light. Critical of Tyndall's apparatus providing insufficiently dark background, he stressed: "In saying this it is not intended to depreciate his work, which at the time marked an important advance."[861] However, in his Royal Institution Friday evening discourse in 1920 commemorating the work of his father, the third Lord Rayleigh (1842-1919), he performed Tyndall's experiments in a dismissive manner. This was perhaps, not surprising considering the occasion, he credited his father with the correct interpretation of the light scattering phenomena without acknowledging Tyndall' original contribution, which, according to Hey had motivated the third Lord Rayleigh's subsequent elaboration of the theory.[862] He claimed that misleading experimental evidence led Tyndall to wrong conclusions. According to an editorial note of the second edition of the RI proceedings, however, Tyndall had performed the right experiments, but his apparatus was the wrong shape, hence the darkness was not intense enough to reveal a feeble beam of light.[863] Aware of the pitfalls, Tyndall's remarks of 1881 were apposite:

> The great Goethe affirmed that by experiment nothing could be proved; That experiments might be accurately executed … but deductions must be drawn by every man for himself…but in the progress of humanity the individual, if he errs, is left stranded and forgotten…truth, independent of the individual, being more and more grafted onto that tree of knowledge which is the property of the human race.[864]

Tyndall's comments on the weather, selected by a biographer, R.W. Clark, reveal the physicist relished his experience:

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[861]Strutt (1918), 94 (662), pp. 453-459, 454.

[862]Note 842, Hey, p. 27.

[863]Rayleigh, fourth Lord (1970 [1920]), pp. 309-317, 311.

[864]Tyndall (1882), pp. 340-358, 353-354.

> In my weariness ... the icy air of the Alps seemed essential to my restoration. The upper air exhibited wild commotion ... clouds were driven wildly against the flanks of the Eiger ....Through the jagged apertures in the clouds, floods of golden lights were poured down the sides.[865]

The historian of science M. Kerker also considers Tyndall's research to be important to Rayleigh's mathematical treatment of the subject. Kerker appreciates Tyndall's judgement for two reasons: Tyndall recognized the cause of an unexpected phenomenon as a chemical reaction, enabling him to use light as a tool to study the aerosols; moreover, the scattered light became the main object of his research, connecting the natural phenomenon of the colour of the sky with the polarization of skylight, which declared by Herschel in Tyndall's words were "the two great enigmas of meteorology."[866] In Kerker's opinion, "the power of Tyndall's observations was in their generality."[867] Recognizing Tyndall as an exceptionally able experimenter, with a "physical intuition" like that of Faraday, the American musician and physicist P. Pesic sees Tyndall's research in this area to be motivated by the work of his contemporaries. He includes Herschel's enunciation of the "two great enigmas of meteorology"[868] and his experiments on sky blue, but also mentions the research of the German trained British chemist, H.E. Roscoe (1833-1915), the Italian physicist G. Govi (1826-1889), and the German physiologist and physicist, E.W. von Brücke (1819-1892). All agreed that the blue colour, produced in various circumstances, similar to that of skylight, appeared due to the scattering of light by particles in the air. Speculations abounded, but there was no agreement as to what these particles were. Pesic acknowledges Tyndall as the first scientist who, by an innovative application of photochemistry, provided the first physical explanation of the particulate quality of the blue sky. He did so in terms of a complex accumulation of a mixture of wavelengths confirming Brucke's hypothesis. Pesic also regards Tyndall

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[865]Clark (1981), pp. 61-68, 61.

[866]Tyndall (1869c), volume 17, pp. 223-233, 223.

[867]Kerker (1991), volume 30 (33), pp. 4699-4705, 4700-4701.

[868]Tyndall (1869b), volume 17, 92-102.

as “the source of inspiration” for the third Lord Rayleigh’s elaboration of an important theoretical explanation. Pesic remarks on Tyndall, “an inspired experimenter…with a gift for visualizing the physical crux of the matter. Tyndall’s experiments and deductions about the blue sky have a special beauty all their own.”[869] Hey also regards Tyndall as a pioneer who through his research, instigated the study of light scattering,[870] an important meteorological phenomenon, in my view of multidisciplinary interest in its applications. In conclusion the interest in Tyndall continues unabated, as his work appeals to some critics, and puzzles the others. The Canadian physicist Norman McMillan and his colleague I. Slade with a special interest in Tyndall, remarked on the difficulty of appreciating Tyndall’s research from the perspective of the present. They drew attention to the recognition of his experimental work on light scattering, named the Tyndall Effect heralding the development of quantum theory.[871]

5F. Conclusion

Tyndall did not consider himself as a researcher in meteorology. He expressed regret at his limited knowledge of the subject. This is why he left “to the scientific meteorologists” the application of his research in the fundamental physics of the atmosphere. W.E. Knowles Middleton asserted that the history of meteorology had had less attention than that of any other scientific discipline of comparable scope.[872]

Tyndall as an experimentalist was one of the distinguished researchers of the nineteenth century, a fact not recognised by some of his peers. P.G. Tait taunted Tyndall that he had forsaken his authority as a research scientist through his extraordinary success as a populariser. Tyndall was a populariser from the best of motives: he argued that in the UK, unlike in other countries, science was financed by the public; the public was therefore entitled to know what was happening in science,

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[869]Pesic (2005), pp. 95-114.

[870]Note 848, Hey, pp. 11-27, 21-27.

[871]McMillan and Slade (2005), volume 5827, pp. 679-688.

[872]Knowles Middleton (1965), p. vii.

but the arguments fell on deaf ears and Tait did not retract his words. Tyndall also campaigned vigorously for the government support of science curriculum in the primary, secondary and tertiary education. Tait did not take that into consideration.

Burchfield judged Tyndall as "unquestionably one of the central figures in Victorian science," original research constituting the focus of his professional life.[873] The appreciation of Tyndall's experimental method at the time is embodied in the recognition by the distinguished Royal Society referees of his scientific papers, Thomson, Maxwell and Stokes. His first independent communication on diamagnetism submitted to the Royal Society was honoured as a choice for the Bakerian lecture of the year,[874] despite the fact that in it Tyndall argued against the theoretical findings of Plücker and Faraday. W. Thomson wrote to Stokes and W.H. Miller about the paper: the letter is reproduced almost in its entirety as it conveys the turmoil among the scientists concerning the new force of diamagnetism.

> Theoretical conclusions derived from another experiment constitute in my opinion a longer and a very important addition to the knowledge of diamagnetism previously existing and well deserving of a place in the Transactions of the Royal Society. I enclose on another piece of paper notes of some trivial changes by which it appeared to me some points might be rendered rather clearer with some leaves of memoranda hastily put down in reading it. As regards the publication of it in the Transactions I think there is so much of important and curious experimental investigation in it, for instance the directional and absolute effects and words as experiments on powder of bismuth described in the appendix the numerical results [illegible] as ever since done. The relative forces of repulsion on the same mass held in different position. The investigation in which Mr Tyndall first showed what I think no other experimenter has ever since done) a case of magne-crystallic action depending on three principal axes at right angles to one another with 3 different inductive capacities and so much of interesting

[873]Tyndall (1981), in Brock, McMillan and Mollan (1981), pp. 1-13, 12.

[874]Tyndall (1855), pp. 1-52.

> illustrations and reactions experienced by reactions produced by diamagnetic bars as to fully entitle to a place in the transactions- Still I think that (especially with reference to the title of the paper) Mr Tyndall is frequently contending a [illegible] an imaginary adversary. In fact for Feilitzsch whose “theory” is founded on a mistake most obvious from the beginning and in my opinion not worthy of more notice than very shortly to point out that mistake. All Mr Tyndall's experiments and views are in perfect accordance with those indicated by Faraday from the beginning and advocated by myself as early as 1846 in the ? by myself uniformly on many different occasions of which short Reports have been published in the British Association volumes, the Philosophical Magazine and in the Comtes Rendus. The real question is “are the phenomena presented by diamagnetics to be explained by contrary magnetization to that of soft iron, or by a less magnetization than that of the medium (air or luminous ether) surrounding them. Which ever be the true result, the resultant action is undoubtedly the same as that which would be experienced by a small magnet with its axis reversed and therefore Mr Tyndall's experiments which amply confirm the view forced on us by Faraday… that the resultant action is such as that which does not at all contribute to in which one or the other alternative is essentially involved. Impressed with this belief I could wish much modification to be made in the controversial part of the communication, but should Mr Tyndall be disposed to making no change, I should advise its publication as it stands ….[875]

Tyndall’s research on the physics of the atmosphere, in my view, emerged from contemporary concerns in physics. The composition of matter and its interaction with the forces of nature provided the key to Tyndall’s study of the atmospheric phenomena. This is different from how Anderson describes the Victorians’ perception of how meteorology was to benefit from contemporary developments in science and technology. For Anderson they expected to benefit through improved communication

[875]Thomson to Miller and Stokes, 16 April 1855, RS/MSS/RR

and the application of mathematics to the interpretation of the data to ensure correct predictions. Anderson also provides a context for the discipline of meteorology in the middle of the nineteenth century as a discipline fraught with disputes concerning the accuracy of the recording instruments, and the reliability of the observational data obtained.[876] The problems of records, of the instruments and predictions, and the firmly established popularity of the almanacs, I contend, had little common ground with the research of the physicists like Tyndall whose interest was the physical factors entrenched in meteorological phenomena. More puzzling are the attitudes of some of his former colleagues and commentators of his and later generations who ignored his original contributions to the science of meteorology. I contend that many generations had contributed to the science of weather. In the nineteenth century their instruments and methods were familiar to both lay people and the professionals, called by Tyndall "scientific meteorologists."[877] The novelty and originality of Tyndall's procedures and apparatus must have been incomprehensible to them. There was no obvious direction for meteorology to incorporate and extend Tyndall's results into the body of knowledge constituting the new science.

Moreover, Tyndall's optical mode of investigation did not generate as much interest as his radiant heat studies. On the other hand I contend that this was due partly to the fact that in comparison with his thermal studies, the optical research was on a smaller scale, occupying only a quarter of his time towards the end of his programme of investigations, and resulting in fewer publications. There was only one seminal paper in the *Philosophical Transactions*, together with the accounts of his lectures on the subject in the *Proceedings of the Royal Institution*, and the abstracts in the *Proceedings of the Royal Society*. These sources, perhaps not readily available, generated fewer responses. Moreover, a lack of foresight in assessing the fecundity of his optical mode of investigation diminished interest. The unforeseen consequences of his research included confirmation of the atomic theory through the calculation of the Avogadro number, using estimated size of the atmospheric particles or molecules in

[876]Anderson (2005), pp. 2-14, 286.

[877]Tyndall (1882a), volume 173, pp. 291-354, 343.

the air,[878] contributions to aerosol science[879] and also to colloid and medical sciences. Interest in this work gathered momentum only gradually, I suggest, partly because Tyndall's work was overshadowed by Rayleigh's subsequent research. Only a gradual realisation over time of its intrinsic significance for science brought about a reassessment of the importance of Tyndall's pioneering work.

[878]Pesic [2001] 2003, p. xvi, in Maxwell [1888] 2003, xiii-xx.

[879]Gentry (1997), volume 28 (8), pp. 1365-1372.

CHAPTER 6

Conclusion

Joe Burchfield, in a recent article on Tyndall, asserted:

> By the time of Tyndall's death, it was generally agreed that his influence as an 'apostle of science' far exceeded his contributions to original research, and that assessment remains true today.[880]

This statement is reminiscent of the opinion of O. Lodge a century earlier, and like Lodge, Burchfield's view is not supported by evidence. He mentions Tyndall's more than one hundred and fifty scientific papers, his Bakerian lectures, honorary degrees and other awards, but surprisingly does not make use of this material, as if he did not consider it significant.

Burchfield provides a mixed judgement of Tyndall's talents as a research scientist, as an experimentalist in particular. On the one hand he belittles Tyndall's contributions as not matching those of Faraday, Kelvin or Maxwell. On the other hand he acknowledges Tyndall as an experimentalist of distinction.[881] To be awarded over thirty honorary degrees from around the world, elected to the fellowship of the Royal Society, awarded the Rumford medal, invited to deliver four Royal Society lectures designated as the Bakerian lectures, appointed to the chair of natural philosophy at the Royal Institution and recommended by Faraday himself at the time when the Royal Institution finally set on course of scientific research as its primary objective; in my view all these achievements testify to a widespread recognition of Tyndall's remarkable contributions to the progress of scientific knowledge. Burchfield quotes some of these in the same biographical article as he makes unfavourable unsubstantiated remarks that compare him with his contemporaries, two of them mathematical physicists. In a later biographical article on Tyndall from 2004, Burchfield reminds us that Tyndall received five honorary degrees including Oxford

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[880] Burchfield, in Lightman (2004), pp. 2053-58, 2056-57.

[881] Burchfield (1981), pp. 1-13, 5.

and Cambridge. He also asserts that, "Tyndall's research did not open important new fields of inquiry".[882]

I contend that an examination of Tyndall's publications in research journals of the day reveals that every paper contains contributions to scientific knowledge; broadening its scope, clarifying confusion, building on existing knowledge in the best tradition of Newton who, in his words, "stood on the shoulders of giants."

The importance of Tyndall's methodology has been revealed in its wide application to the study of the atmosphere. In the course of his researches, Tyndall came across elusive phenomena never before exposed. He grasped the implications of their subtle effects on science, and imaginatively interpreted their meaning. His extraordinary skill for mimicry in the laboratory and his manipulation of natural phenomena, endowed him with the power to explain the inner workings of nature.

In this dissertation I have identified Tyndall's main achievement as a research scientist, and presented his discoveries and innovations in the domain of physics; matter in particular those concerning the study of the diamagnetism and the interaction of radiant heat in full technical detail, within the context of the science and culture of the day. Below I summarise the main points discussed in earlier chapters:

6A. Accounting for the mixed reception of Tyndall's research

The adverse opinions on Tyndall's science require an explanation. The unfamiliarity of distinguished scientists with Tyndall's learned papers is difficult to justify. His momentous discovery of the powerful absorption of radiant heat by carbon dioxide and water vapour in the atmosphere, went unnoticed or were only incidentally referred to by most of his contemporaries despite Tyndall's stress on the influence of these properties on climate. The persistent neglect by some contemporaries of Tyndall's contributions I assign to six causes:

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[882] Burchfield (2004), in Lightman, ed. (2004), pp. 2003-2008.

(a) The traditional anonymity that cloaked Tyndall's distinguished referees deprived him of the opportunity to publicise the prestigious support that would have gained him the respect he needed as a foreign-educated outsider.

(b) The scientific naturalism that Tyndall espoused as a dissenter, was abhorrent to his adversaries who had been brought up in the conventional Church of England tradition.

(c) The underestimation of Tyndall's science suggests only a scanty reading of his research writings by those who judged him.

(d) Unlike his rivals and critics in the academic communities, Tyndall was a lone worker[883] outside a mainstream, recognised research community. Although Tyndall found his own community in the X Club, its members were working towards the grand schemes of science, and promoting its independence from theology; they were not concerned with their members' scientific output.

(e) The power of Tyndall's writing aimed at popularising science overshadowed the importance of his researches. Tait's devastating statement on the incompatibility of the popular and serious science must have discouraged favourable opinions of Tyndall's work by those engaged as both, researchers and popularisers.

(f) The hostility of the Cambridge-educated mathematical physicists to Tyndall's lack of mathematical training was indicated by Meadows. Elizabeth Garber alleged that "Tyndall was committed to an empirical and experimental physics in an era in which the mathematical development of theoretical ideas displaced this older tradition."[884] This statement, however, ignores Tyndall's campaign for the role of the imagination in science, which he regards of as much value as mathematics. Miller suggests that a pattern of adverse opinion was set by the successive commentators who were influenced by the attitude of the mathematical physicists.

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[883]Tyndall to Faraday 4 February 1851, in James (1999), volume 4, pp. 247-249, 249.

[884]Garber (1986), p. 157.

6B.Thermal mode of investigation

Tyndall's original researches on radiant heat and gases brought about a revolution in our understanding of the science of the atmosphere. Until then it was thought that it was only possible to study of the interaction of radiant heat with matter in its liquid or solid phase. It was assumed that matter in its gaseous phase was not amenable to this kind of investigation. Tyndall worked out the experimental conditions essential to the study of matter in its gaseous phase. He was the first one to modify Melloni's procedures successfully to that purpose..Prior to Tyndall's investigations, very little was known about the thermal properties of gases. Using Melloni's experimental researches on the interaction of radiant heat with liquids and solids as a model, only Tyndall succeeded in identifying the steps in Melloni's practice that needed to be adapted for substances in gaseous phase to ensure the consistently reliable results. He confronted specific problems that needed to be tackled to ensure the purity of the reagents, and the exclusion of the secondary phenomena liable to vitiate the results.

Tyndall's experimental researches on the thermal properties of gases revealed a fundamental fact: elementary substances were relatively diathermic, whereas compounds demonstrated a wide range of absorptive powers. This work was accomplished by the use of radiant heat as an analytical tool, interacting with gaseous matter. The elements and compounds became uniquely characterised, with important consequences for progress in understanding natural phenomena, including the independent confirmation of the composition of the atmosphere and its impact on the terrestrial climate. Subsequently Tyndall confirmed experimentally a correspondence between the thermal properties of the given substance irrespective of the phase of matter. Athermancy was proportional to the amount of matter present; if the quantity of matter in the different phases was identical, so was the thermal power of the given substance.

6C. Discoveries with Particular Significance to Meteorology

The new methodology established by Tyndall to enable experimenting on matter in the gaseous phase, and his subsequent discovery of greenhouse gases in the atmosphere, provided a scientific framework for meteorology. I discerned the specific steps implemented by Tyndall in his innovative experimental procedures**.** Detecting the inadequacy of the standard procedures for drying gases, Tyndall introduced improvements which revealed the powerful absorptive properties of the water vapour in the atmosphere, even if present in just a very small quantity. This constituted a breakthrough. Tyndall's scientific view of nature contrasted with Magnus's erroneous assumption that the small fraction of the water vapour in the atmosphere could not exert the powerful influence. He discovered that both water vapour and carbon dioxide in the atmosphere were powerful absorbents of radiant heat, and that this was particularly pronounced if the heat source contained the elements in common with them. Tyndall correlated these newly discovered thermal properties with changes in terrestrial climate recorded in the geological history of the planet, and accounted for hitherto unexplained meteorological phenomena. Tyndall concluded that any change in the quantity of these variable constituents of the atmosphere would affect the terrestrial climate. These pioneering achievements by Tyndall opened a new era in the science of the atmosphere and were a landmark in the developing science of meteorology. The thermal properties of the aqueous vapour, declared Tyndall, "must form one of the chief foundation-stones of the science of meteorology."[885]

Tyndall established his credentials as a pioneering experimentalist and theoretician through his work on radiant heat and gases, and his concomitant discovery of the action of light on vapours as a chemical reaction. His work, although fully supported by the eminent referees of his Royal Society papers, Maxwell, Stokes and Thomson among them, and endorsed by Faraday and Herschel, has been underestimated or overlooked by some of his contemporaries and successors, especially Tait, and Lodge. The twenty first century has seen a reconsideration of Tyndall as a scientist, and he is now viewed as the first with the foresight and a grasp of atmospheric science and its significance for life on earth.

6D. Contributions to Theoretical Physics

To account for the thermal absorption and radiation by matter and to demonstrate the equivalence of the thermal properties in all the three phases of matter, Tyndall located thermal absorption and radiation within a molecular structure that

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[885] Tyndall (1863d), s.4, volume 26, pp. 44-54, 54.

preserved its identity in nature in all its phases. He accomplished this by elaborating a mechanism involving the interaction of matter with the aether. Tyndall's experimental confirmation of this long-standing uncertainty demonstrated the rigour of his procedures.

The discovery of fluorescence by Stokes in 1852, involving the lowering of the refrangibility of radiation from the heat source, and had prompted a vain search for the opposite effect, that of raising its refrangibility. Over a decade later, to resolve the existing disagreement whether the temperature of the heat source influenced the thermal properties of the experimental substances, Tyndall employed a platinum spire as a heat source at varying temperatures. Having also discovered an effective way of separating the luminous from the thermal radiation, Tyndall succeeded in the transmutation of the thermal into the luminous radiation, which he named "calorescence." In the process of raising the refrangibility of radiation Tyndall transformed the role of radiant heat from that of a tool into an integral part of the conversion of the obscure to the luminous heat. The discovery of the phenomenon of calorescence is, in my view, analogous to the point when Faraday's use of light changed from that of a tool to an active force of nature in the discovery of the magnetic rotation of polarised light.

A fortuitous observation on the effects of light on certain vapours of volatile liquids, their molecules "shaken asunder," led Tyndall to devise experiments to elucidate two puzzling phenomena: the blue colour of the sky and the polarisation of skylight. He already had speculated on these in his book *Glaciers of the Alps* of 1860, and they were regarded as meteorological enigmas by the nineteenth century scientists, including J. Herschel. Tyndall posited the production of the blue colour of the sky by means of the particles in the air of varying sizes consisting of many molecules, that were small in comparison with the wavelengths of light acting upon them. He adopted Brewster's view that the scattering of light by the particles caused the reflection of light essential for polarisation to occur. Tyndall's empirical researches motivated the third Lord Rayleigh's mathematisation of the phenomena, and according to Gentry,[886] paved the way for the new discipline of aerosol science.

[886]Gentry (1997), p. 1365.

In my view this had implications for the contemporary studies of the science of pharmacology, as well as environmental, and food sciences.

6E. Conclusion

DeYoung's suggestion that Tyndall had been passed over and half forgotten by the next generation of scientists[887] invites the repost that there have been two world wars which changed the world rapidly. There have been mind-boggling advances in science. Being passed over is the fate of every generation, of scientists in particular. The allegation that Tyndall's success at popularising science came at the expense of his own credibility as a scientist, is not substantiated. It is an emotive phrase used by Tait who had his own agenda to undermine Tyndall to whom he felt antipathy at a personal level, possibly motivated by jealousy. In contrast I have provided a reasoned argument in favour of Tyndall's well-demonstrated ability as a researcher. The Royal Institution laboratory to this day, as throughout its history represents a place where the cutting edge scientific research is conducted. Tyndall did not support science against theology. He supported science for its own sake as a force for good, and for doing away with prejudice. Tyndall was also instrumental in introducing science into education at all levels.

This concluding chapter contains a summary of my work which comprises my original contributions. This study has accomplished, for the first time, a systematic review of Tyndall's pioneering scientific researches and discoveries, based on his key scientific papers and opinions expressed by his referees and other commentators included in this thesis. My account of Tyndall's contributions has been further enriched by his commentary in his diaries, letters and journals. I have also attempted to reach an understanding of the reasons why these significant contributions have often been ignored or underestimated.

In this thesis I have identified Tyndall's achievements as a researcher. They attest that Tyndall was a scientist whose work is of significance and enduring value for humanity and the natural world. The work of the internationally recognised

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[887] DeYoung (2011).

Tyndall Centre for Study of Climate Change, named after him, and established in the UK for the new millennium further attests to the permanent value of his researches.

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