Looking closer at the Sun

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Abstract
The Sun's atmosphere is a dramatic and dynamically changing one. The domains encountered as the atmosphere is explored from the Sun's surface to the outer corona differ widely physically. The region where the differences are more dramatic is the interface region where the plan goes from optically thick to optically thin, and the regime goes from gas dominated to magnetic dominated. NASA's Interface Region Imaging Spectrograph (IRIS) is now observing this elusive region, and the first results from the mission are described. These are showing a world of twisted magnetic fields throughout the region, 'bombs' exploding at regular intervals, evidence of particle acceleration causing heating in coronal loops, and small jets and loops appearing at cool temperatures. These results are providing important input into how the solar atmosphere is created and maintained and how the solar wind is formed.

The Sun is the largest object in the solar system, providing us with the heat and light that allows us to survive. It is a middle-aged star that produces energy through nuclear fusion of Hydrogen to Helium at its core. The enormous energies propagate through the interior of the Sun by radiation and the convection. In the convection zone the churning, hot plasma creates magnetic fields. Our first view of the energy from fusion in the core, escaping the Sun is at the surface of the Sun (the photosphere). At the photosphere, evidence of convection that occurs in the interior is seen. Magnetic fields are seen at all size scales. The magnetic field helps form the heliosphere that the planets exist in, it drives the solar wind that flows past our planet continuously, and produces large explosions that can impact our delicate Earth environment. The magnetic fields are the source of 'the coronal heating problem' – as you move away from the Sun's surface – and the heat source in the core, the temperature increases. Scientists are aiming determine how the Sun produces a wind that at its slowest speeds reach fifty times that of the fastest hurricane on Earth, to create energies in flares that have tens of millions times the energy of a hydrogen bomb. Although the magnetic field is known to be key to this, the details of the energy transfer through the atmosphere are unclear as yet – the Sun is an ideal laboratory to explore these phenomena.

The latest in the line of solar observatories that are exploring the Sun is NASA's Interface Region Imaging Spectrograph (IRIS), which was launched in June 2013. It is a 20 cm telescope that observes near and far ultraviolet light from the Sun, which is normally blocked by the Earth's atmosphere. It was designed to explore spectroscopically the elusive interface region of the Sun's atmosphere between the surface of the Sun (photosphere) and the outer hot atmosphere (the corona). We have been blinded spectroscopically to this important region until now, making it challenging to understand how energy is transported from below the surface of the Sun into the heliosphere. It's been like being able to read the start and end of a story, but missing out the critical middle part. This region has been difficult to observe and understand– it goes from being optically thick to optically thin, from partially to fully ionized and from being dominated by gas to magnetic domination. In recent years the advances in computation have permitted the development of 3D radiative MHD models that can provide insight the observables obtained by IRIS.

IRIS has exceptional spatial resolution of 0.33" (see Figure 1). Its spectroscopic capability is focussed on the interface region and can remotely probe the hot plasma to determine parameters such as temperatures, speeds, turbulence and densities. An example image is shown in Figure 1 of a large explosion at the solar limb showing the incredible complexity of the Sun's atmosphere. The first results from IRIS published in Science, address some of the key unsolved questions in solar physics – and beyond.

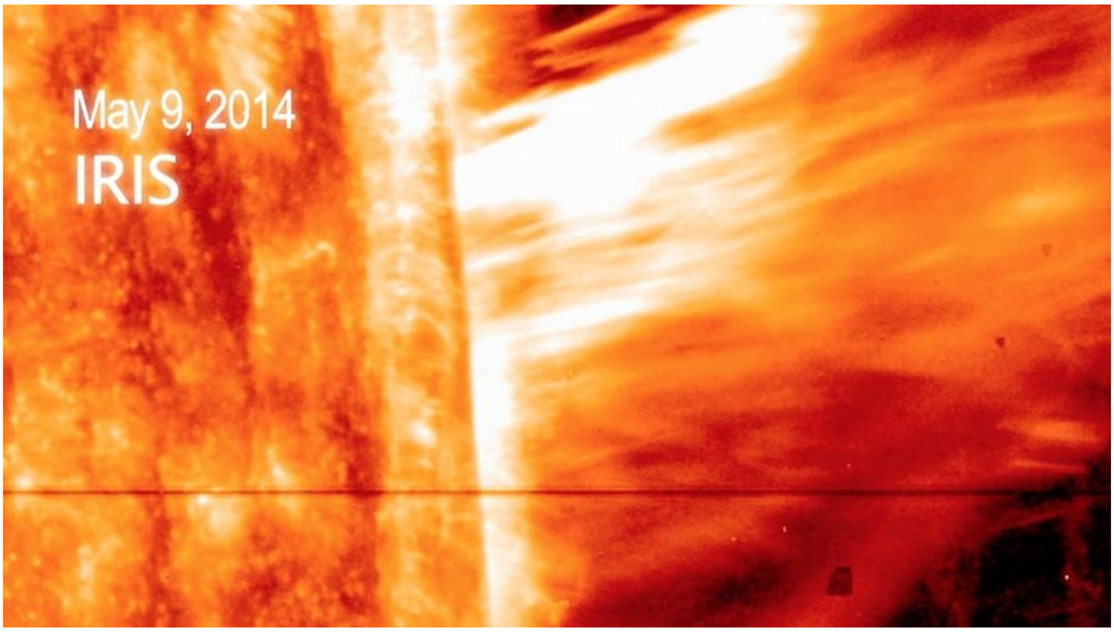

Figure 1: an explosion observed by the IRIS spacecraft on 9 May 2014

The high-resolution observations that IRIS can make of the interface region have revealed red and blue-shifted plasma that exist parallel and adjacent to each other (De Pontieu et al., this issue). This evidence for twist or torsional motions is seen in every magnetic domain on the Sun - from the quietest region, to the larger active region, and even in coronal holes where the magnetic field is dominantly open. Evidence of the magnetic fields being so twisted, allows an insight into how energy is created and indeed rapid heating is associated with these regions of strong twist. Another phenomena that has been revealed for the first time is that of very short, low lying magnetic loops in the quiet Sun (Hansteen et al, this issue). A debate had been raging for many years on whether or not these could exist, and now it has been proven. The measurements they made show that this emission cannot be accounted for just by thermal conduction back from the hot corona. These loops are short and dense and can lose their energy effectively through radiation. They are also found to occur naturally in advanced 3-D magnetic models that have recently become available. IRIS observations in coronal holes have also uncovered frequent high-speed small jets (Tian et al, this issue) that are located in the network structures that highlight the convective cells. These fast jets may contribute plasma to the solar wind.

IRIS has also explored the larger regions of strong magnetic field, called active regions. In a newly created active region Peter et al. (in this issue), found small regions of plasma within the active region that reach temperatures of 100,000K and are embedded in a much lower temperature region. They are found in small regions where magnetic flux of opposite polarity converges, and evidence of a bi-directional jet is seen, where the magnetic field lines that are being pushed together squeezing the plasma in both directions. These 'bombs 'that are firing off have much greater energies that were expected before.

In active regions, the dominant features in the atmosphere are the long magnetic loops stretching from one polarity region to another. Testa et al. (in this issue) found rapid variability at the footpoints of these loops, and explored what could create these. They found them to be heated by accelerated beams of non-thermal particles, which are generated in very small-scale flares called 'nanoflares'. Through comparison with advanced numerical models, they have developed diagnostics that can probe the non-thermal characteristics of the smallest scale particle acceleration ever observed. This provides much needed constraints on models of how these particles are accelerated to such high energies, a process that is expected to occur throughout the universe in other, more distant, astrophysical phenomena.

These early results show the power of spectroscopy in terms of understanding energy sources on the Sun. All the phenomena described so far are low energy or small-scale phenomena. With Sun close to reaching a maximum in activity, understanding the solar wind that emanates from the active latitudes, solar flares and coronal mass ejections will benefit enormously from IRIS observations in the future.