Plasma Measurements at Non-Magnetic Solar System Bodies

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Key points

- Plasma interaction depends on upstream conditions and nature of the object
- Common processes include ion pickup, ionospheric processes and escape
- Review measurements at comets, Mars, Venus, Saturn and Jupiter moons

Abstract

The solar system includes a number of non-magnetic objects. These include comets, Venus, Mars and the moon, as well as moons of Saturn, Jupiter and beyond. The plasma interaction depends on upstream conditions, whether that is the solar wind or a planetary magnetosphere, and whether the object itself has any atmosphere. Several space missions have explored these objects so far, with many carrying plasma and fields instrumentation, and have revealed some similarities and differences in the interactions. Processes such as ion pickup are the key to the cometary interaction but pickup is also present in many other locations, and ionospheric processes are important when an atmosphere or exosphere is present. In all cases plasma interacting with the surface or atmosphere can cause escape and modification over time. Here we will review plasma measurements at non-magnetic objects from the various missions, and summarise information about the key processes including plasma escape at these objects.

Index terms

2459 Planetary ionospheres (5435, 5729, 6026)
2756 Planetary magnetospheres (5443, 5737, 6033)
6210 Comets (4308, 6023)
6225 Mars
6295 Venus
6218 Jovian satellites
6280 Saturnian satellites

Key words: Plasma interactions, ion pickup, ionospheric processes, escape

1. Introduction

The interaction of plasma with non-magnetic solar system bodies started with early exploration of Earth's moon, Mars and Venus in the 1960s. Spacecraft have since additionally visited comets and the moons of Jupiter, Saturn, and briefly Uranus and Neptune, as well as Mars, Venus and the moon. New Horizons arrived at Pluto in 2015. The data interpretation and analysis from all of these objects have provided important comparisons to the magnetized objects. In Figure 1, we summarise the missions which have visited un-magnetized objects carrying suitable instrumentation. The mission names are superimposed on a comparison of interaction scales for both magnetized and unmagnetized solar system objects.

In this paper we will summarise some of the results on plasma interactions from non-magnetized objects. First we will highlight the importance of the environment of the objects as well as the nature of the body, including whether it has an atmosphere or not. We will then review some of the key plasma processes, including ion pickup, ionospheric processes and plasma escape.

2. Types of interaction:

The types of interaction are strongly dependent on the upstream conditions and the nature of the object, we now consider these in turn.

2.1 Upstream conditions

The plasma environment of any object is a key feature in determining the plasma interaction. Some objects interact with the solar wind (including the Moon for much of its orbit, Venus, Mars, comets, asteroids, distant outer planet moons and trans-Neptunian objects), while others are immersed in planetary magnetospheres (e.g the Moon in the magnetotail, Phobos, Deimos, and the principal moons of Jupiter and Saturn).

The solar wind conditions vary with distance from the Sun – for example the solar wind density N_{sw} and the radial magnetic field component B_r are both controlled on average by the inverse square law and are $\propto R_{AU}^{-2}$, while the azimuthal magnetic field component $B_\varphi \propto R_{AU}^{-1}$ [Parker, 1958, Hundhausen, 1995]. On average the Mach number increases with distance from the Sun, while the plasma β peaks near the orbits of Earth and Mars [Russell et al., 1990]. The actual solar wind conditions are highly variable and permeated by impulsive features such as interplanetary shocks, interplanetary coronal mass ejections (ICMEs) and corotating interaction regions (CIRs). This clearly has an impact on the interaction geometry, and on escape rates for example, as will be discussed in section 4.

2.2 Nature of obstacle

Although Mars has crustal magnetic fields [Acuna et al., 1998, Connerney et al., 2001, 2005] it lacks a global dipole field and is this classed as an unmagnetized object. In other cases, the presence or absence of an atmosphere and/or significant outgassing, and subsequent ionization, is important in determining the nature of the interaction. In Table 1 we summarise the unmagnetized objects in the solar system.

Luhmann [1995] summarised the stages of plasma interaction with an ionosphere. The sunlit atmosphere of a body will ionise and become an ionosphere. Production by photoionization is balanced by recombination. A flow of plasma upstream, such as the solar wind, would naturally create a wake behind the object. If the upstream plasma is magnetized this ultimately leads to a magnetic barrier or ionopause forming, where the inside thermal pressure balances the upstream magnetic pressure, and magnetic field draping around the obstacle results in an induced magnetotail. This picture is valid while the upstream magnetic field varies and the field does not have time to diffuse through the object, as in the solar wind interaction with Mars, Venus and Titan (upstream of Saturn's magnetopause).

When inside Saturn's magnetosphere, Titan's interaction is complicated by Saturn's corotating plasma, which sweeps past Titan creating a different angle with the solar wake depending on Titan's position in local time. In addition, magnetospheric electrons add to photoionization as a source of ionisation. Titan also has no bow shock when the upstream flow is subsonic and sub-Alfvenic.

3. Objects

3.1 Comets and ion pickup

As a comet approaches the Sun, neutral water (and other) molecules sublime from the nucleus and drift away as neutrals. When a neutral particle is ionized in a magnetized plasma, it feels an electric field ***E*** = - ***v*** x ***B*** where ***v*** is the plasma velocity and ***B*** the magnetic field. It then gyrates around the magnetic field, producing a cycloid in real space (illustrated schematically in Figure 2). In velocity space this corresponds to a ring. The ring is unstable and waves are produced, and wave-particle interactions produce pitch angle scattering of the pickup ions, leading to a shell in velocity space. The interacting waves move parallel and antiparallel to the magnetic field, producing a bispherical shell (see reviews by Coates, [2010], Coates & Jones, [2009] and references therein].

With respect to the neutral particles, the maximum energy of the ring can be written:

$$E_{max,ring} = 2mv_{sw}^2 \sin^2 \vartheta_{vB} = 4m_{amu}E_{sw}\, sin^2\, \vartheta_{vB}$$

where ϑ_{vB} is the angle between the flow velocity v_{sw} and the magnetic field. Similarly, the maximum (simple) shell velocity is:

$$E_{max,shell} = 4m_{amu}E_{sw}$$

This can reach ~70 keV for a water group ion in the solar wind. This is clearly seen in the cometary data and in data from other objects, e.g. from Giacobini-Zinner [Hynds et al., 2006], Halley [Johnstone et al., 1986a, Neugebauer et al., 1989, Coates et al., 1989, Terasawa et al., 1986], Grigg-Skjellerup [Johnstone et al., 1993, Coates et al., 1993a,b], Borrelly [Young et al., 2004) and Churyumov-Gerasimenko [Nilsson et al., 2015]. Figure 3 shows some examples of pickup water group ion ring and shell distributions seen on the inbound trajectory at comet Halley [Coates et al., 1989]. Each plot is a V_{perp}-$V_{parallel}$ representation of the pickup water ion distribution functions in the solar wind frame, with a ring indicated by a * and a simple shell shown by a dashed semicircle. At large distances (3.9, 2.9 Gm), the distributions are ring-like, closer (2.0 and 1.9 Gm) pitch angle scattering has occurred and they are fairly shell-like, while each side of the bow shock (1.2 and 1.1 Gm) significant energy scattering is seen.

Using the Halley data, Coates et al. [1990] showed evidence for bispherical shell distributions by estimating the water group ion bulk speed in a magnetic field-aligned solar wind frame. The early Rosetta data shows ions in the early phase of pickup [Nilsson et al., 2015, Goldstein et al., 2015], with some similarities to the AMPTE releases [Coates et al., 1986, Johnstone et al., 1986b, Coates et al., 1988] and to non-gyrotropic ions seen at comet GS [Coates et al., 1993b]. In Figure 4, we illustrate the change in the comet-solar wind interaction as a comet approaches the Sun. Far from the Sun, the interaction is asteroidal with additional ion pickup increasing with decreasing heliocentric distance, and close to the Sun the interaction is developed with a contact surface and bow shock.

Following these initial stages of pickup, additional acceleration (and deceleration) may be provided by the Fermi I and/or II mechanisms [see Coates, 1991 for a review].

3.2 Mars

Mars has no global magnetic field, instead a network of crustal remanent fields mainly associated with the older Southern highlands, left over from when the planet was magnetized 3.8 billion years ago (e.g. Acuna et al., [1998], Connerney et al., [2001, 2005]). However, Mars has an exosphere larger than its ionosphere, and ionization and ion pickup can occur above the ionopause [Luhmann and Brace, 1991, Luhmann et al., 1992, Lundin et al., 1989 and references therein]. Also, direct pickup from the upper atmosphere as well as the extended exosphere is possible.

At the orbit of Mars, the gyroradius of pickup heavy (e.g. O^+) ions is larger than the planetary radius, and solar wind scavenging has been observed [Barabash et al., 2007]. The estimated loss rate based on Phobos data was ~10^{25} s^{-1} [Lundin et al., 1989]; this is significant on the timescale of the solar system, corresponding to a loss of ~ tens of % of Earth's atmospheric mass.

However, recent measurements of loss rate from Mars Express were a factor 100 lower [Barabash et al., 2007]. This is thought to be due to a lack of coverage of low energy (~10eV) ions. The instrumental settings have since been changed and the rates are now being revised upwards [e.g. Lundin et al., 2008, Kallio et al., 2010] to ~10^{25} s^{-1}, though solar wind forcing is also important, making the loss rate higher towards solar maximum (Kallio et al., 2010). In addition, thermal hydrogen escape is higher at Mars [Lammer et al., 2008].

As at a comet, field draping and an 'induced magnetosphere' form a barrier, upstream of which a bow shock forms. It was also anticipated that asymmetric pickup would be the result of reabsorption by the planet, producing further pickup ions. These are also seen by ASPERA-3 on Mars Express [Lundin et al., 2008, 2009, Kallio et al., 2010]. Recent work has also highlighted the interplanetary electric field orientation, and this organises the interaction region (e.g., Fedorov et al. [2008]; see Figure 5). Figure 5 shows oxygen ions escaping along the Martian tail, and their intensity is controlled by the electric field direction.

Effects from pickup protons are also seen due to the extended hydrogen exosphere at Mars. The Martian bow shock is different to the cometary bow shock in that it is not caused by mass loading, although the effects of mass loading start to be significant near the shock location [Dubinin et al., 1993]. Pickup protons have been observed directly, and form additional evidence for an extended exosphere [Dubinin et al., 2006]. An asymmetry controlled by the interplanetary electric field orientation is observed in related proton cyclotron wave emissions [Wei et al., 2006]. The magnetic field orientation has been inferred from pickup proton observations [Yamauchi et al., 2006].

Pickup may be augmented by other processes, such as ambipolar outflow due to the escape of ionospheric electrons [Coates et al., 2011a]. Photoelectrons are seen in the tail of Mars well away from their production region in the dayside ionosphere [Frahm et al., 2006a,b, Liemohn et al., 2006, Frahm et al., 2010] as well as at other objects such as Titan (Coates et al., 2007a), and Venus (Coates et al., 2008); see also Coates et al., [2011a]. Figure 6(a) shows ionospheric photoelectrons, identified by their distinctive energy peaks in the 20-30 eV region, seen in the Martian tail at distances up to 10,000 km (from Frahm et al., 2006b). Observations in the tail of the objects has highlighted the possible role of a polar wind mechanism, as the energetic photoelectron may travel along the magnetic field relatively easily, to enhance plasma escape [e.g., Coates et al., 2011, 2015a].

The Mars aurora was one of the important discoveries by the Mars Express mission. Bertaux et al. [2005] used the SPICAM ultraviolet spectrometer to find concentrated areas of emission at the foot of magnetic cusps caused by the crustal fields on Mars. This interesting discovery was followed up by Leblanc et al [2006] who found that the precipitating electrons were electrons with tens of eV, by Lundin et al [2006] who likened the electron signatures to inverted 'V's at Earth, and by and Leblanc et al [2008] who found additional examples and studied the morphology in greater detail. This will be one of the interesting features for MAVEN to study, as well as looking at escape processes in more detail.

3.3 Venus

Venus has no magnetic field. It has a thick atmosphere and ionosphere. The ionopause position is governed by a pressure balance between the ionospheric thermal pressure and the magnetic field pressure immediately outside, which is ultimately related to the solar wind dynamic pressure upstream (modified by pickup; Brace et al., [1987], Russell et al., [2006] and references therein]. Outside the ionosphere, ionized neutrals may again be picked up. The pickup ion gyroradius is smaller than the planetary radius in this case. Again, solar wind 'scavenging' plays a role in the evolution of the atmosphere. Pickup ions (O^+) were seen escaping Venus from PVO [Brace et al., 1987] although they play little role in shaping the overall interaction unlike at comets [Russell et al., 2006]. Venus Express, which has mass discrimination capability, measures hydrogen and oxygen as the dominant escaping species along the tail, with a stoichiometric ratio of 2, indicating loss of water [Barabash et al., 2007].

The estimated loss based on PVO data was ~10^{24} s^{-1}, a steady loss down the tail – however solar wind intensifications were suggested to increase the average by a factor ~50 [Brace et al., 2007]. Initial Venus Express measurements indicated a rate of ~10^{25} s^{-1} via the tail, with approximately 10% via pickup [Barabash et al., 2007]. Again, ambipolar diffusion caused by ionospheric photoelectrons may augment or even feed the pickup and tail loss processes [Coates et al., 2011a].

Fedorov et al., [2008] compared the light and heavy ion losses at Mars and Venus. At both objects, hydrogen escape occurred on the flanks within, and somewhat planet-wards of, the magnetosheath, while the heavy ion escape was predominantly in the tail. The data were also ordered by the interplanetary electric field, showing an enhancement of oxygen escape in the positive E_{sw} sector. This indicates that the ion escape is controlled by the magnetic field [Fedorov et al., 2008]. Some of these may be pickup ions but other processes of ionospheric escape are also present.

Recent observations of proton cyclotron waves in the solar wind near Venus [Delva et al., 2008 a,b, 2009] indicate that their source may be ion pickup-produced waves from an extended neutral hydrogen exosphere there. As yet no direct particle observations have been made to confirm this.

In-situ measurements of the Venus ionosphere have been made by Venus Express. Some interesting observations include the expansion of the ionosphere to a 'teardrop' shape during low solar wind activity [Wei et al. 2012], cross-terminator ion flow [Szego et al., 2009, Wood et al., 2012] and the magnetization of the Venus ionosphere [Angsmann et al., 2011]. In addition, ionospheric photoelectrons were characterised in detail in the sunlit ionosphere for the first time [Coates et al., 2008]. As at Mars, such electrons are seen in the tail at up to 2.3 R_V along the tail, away from the production point [Tsang et al., 2015, Coates et al., 2011a, Coates et al., 2015a]. The escape rate at Venus was also estimated from the ionospheric plasma observation in the tail and compared with that of other solar system objects [Coates et al., 2015a]; see section 4.

Some recent observations were presented on magnetic reconnection in the tail of Venus [Zhang et al., 2012] – the first time this process has been seen in-situ at an unmagnetized object. Although seen in the Martian tail [Eastwood et al., 2008] the presence of crustal fields may be relevant in that case. In addition, hot flow anomalies were studies at Venus [Collinson et al., 2012]; this is an effect seen at Earth where the bow shock may bulge during interaction with solar wind discontinuities. Also, it was shown that the escape rate from Venus increases by almost a factor 2 during a Corotating Interaction Region (CIR) event in the solar wind [Edberg et al., 2011] and up to a factor 100 during a CME [Luhmann et al., 2007].

3.4 Saturn's moons

Some features of the plasma interaction conditions at Saturn's moons are summarised in Table 2. Clearly, upstream conditions and presence of an atmosphere are important.

3.4.1 Titan

At Titan, a strong local interaction with Saturn's magnetosphere forms a complex plasma tail (e.g., [Coates 2009, Coates et al., 2011b and references therein]). Titan's orbital position at 20 Saturn radii means that it can encounter a range of conditions in the magnetosphere (e.g., Rymer et al. [2009], Simon et al. [2013], Arridge et al. [2011a]) and sometimes encounters the magnetosheath [Bertucci et al., 2008] and also the solar wind [Bertucci et al., 2015]. Early suggestions were that within the magnetosphere, average conditions would include an electric field directed away from Saturn [Blanc et al., 2002] assuming nominal conditions, i.e. a dipole magnetic field and exact corotation. This would set up the electric field seen by new pickup ions from Titan's extended atmosphere. However the data have shown that conditions are rarely nominal and each encounter has its own geometry.

In particular, Saturn's bowl-shaped magnetodisk [Arridge et al., 2008] changes with season and has a direct effect on upstream conditions at Titan [Arridge et al., 2011a]. An additional complexity is that the solar and corotation wake orientations change through Titan's orbit around Saturn [e.g. Coates, 2009].

Atmospheric loss rates are large and the subject of some debate [Johnson et al., 2009] although ion loss rates have been measured [Coates et al., 2012]. Magnetospheric energy and composition drive some complex chemistry, also sunlight is a driver, but Titan's location in Saturn's outer magnetosphere (20 R_S) prevents significant contributions of mass or significant dynamic effects on the magnetosphere

Chemical complexity in Titan's ionosphere was one of the major new discoveries of the Cassini mission, using in-situ measurements from the Cassini Plasma Spectrometer (CAPS) and Ion and Neutral Mass Spectrometer (INMS) instruments. The complexity is seen in neutral and positive species by INMS and CAPS, as well as the newly-discovered negative ions seen by CAPS [Waite et al., 2007, Coates et al., 2007b, 2009, 2010a, Crary et al., 2009]. In addition, related 'tholins' are seen using occultation measurements [e.g. Liang et al., 2007]. Negative ions were unexpected at such high altitudes. Cassini found very heavy negative ions up to 13,800 amu/q [Coates et al., 2007b, 2009] as well as positive ions up to ~1000 amu/q [Waite et al., 2007, Crary et al., 2009, Coates et al., 2010a], and it was suggested that the linked neutral-cation-anion chemistry plays a key role in haze formation. The low mass negative ions were identified as CN^-, C_3N^- and C_5N^- [Vuitton et al., 2009] while the formation process for higher mass ions is under study. The ion configuration is unconstrained, e.g. chains, rings or even fullerenes are possible, the latter may transport oxygen to the surface [Sittler et al., 2009]. Recent studies show that agglomeration due to charging [Michael et al., 2011] or chemical processes [Lavvas et al., 2013] may be operating.

The maximum mass of negative ions at Titan was studied as a function of altitude, latitude and solar zenith angle [Coates et al., 2009] finding that the maximum mass is found at the lowest altitudes.

Recently, the density variation with these parameters has been examined [Wellbrock et al., 2013] to further constrain the chemical processes.

Negative ions have been confirmed in the Langmuir probe data, initially using observations at the lowest altitude encounter T70 [Ågren et al., 2013] where CAPS was not oriented in the ram direction, and subsequently at other encounters [Shebanits et al., 2013].

Ionospheric photoelectrons at Titan provide a key indication of ionospheric plasma, or of a magnetic connection to Titan's tail [Coates et al., 2007, 2011a, Wellbrock et al., 2012]. Figure 6(b) illustrates ionospheric plasma seen in the tail of Titan at distances up to 6.8 Titan radii (R_T), identified again using distinctive photoelectron peaks. This was used to estimate plasma escape rates [Coates et al., 2012, see also Westlake et al., 2012]. Photoelectrons also provide an ambipolar electric field driving plasma escape [Coates et al., 2007a, 2012]. Plasma escape rates at Titan showed that Titan loses 7 tonnes of material per day [Coates et al., 2012]. Recent work has shown an upper limit for the field aligned potential at Titan of 2.95 eV [Coates et al., 2015b].

3.4.2 Rhea and Dione

Saturn's moons Rhea and Dione are additional sources of pick-up ions. Analysis of pickup ion trajectories led to the discovery of exospheres at Rhea [Teolis et al., 2010] (using positive and negative pickup ions to identify the near-surface source), and at Dione [Tokar et al., 2012]. The exosphere production is due to magnetospheric particle bombardment of these icy moons, a process which also occurs at Europa, Ganymede and Callisto.

3.4.3 Enceladus

The importance of Enceladus as a source was first found from magnetometer observations of a draped field [Dougherty et al., 2006]. Flow deflection was also seen by the CAPS ion mass spectrometer (IMS), and the derived production rate was ~100 kgs^{-1} [Tokar et al., 2006], second only to Io in gas production rate from a solar system moon. The source was found to be plumes from 'tiger stripes' close to the South pole of Enceladus.

The concentration of charged particles in the plume is sufficient that a 'plume ionosphere' forms, with a region of stagnant plasma flow immersed in Saturn's rapidly rotating magnetosphere [Tokar et al., 2009]. Saturn's magnetosphere approximately corotates with the planet at 4 R_S. Positive and negative ionospheric ions were found within the plumes [Tokar et al., 2009, Coates et al., 2010b]. The positive ions appeared as water group ions (mass 16-19) and heavier ions. Pickup ions were also seen in a ring distribution, both close to Enceladus [Tokar et al., 2006] and in the magnetospheric region close to Enceladus' orbit [Tokar et al., 2008]. The negative ions appear as multiples of the water or OH mass, with clusters of up to 100 [Coates et al., 2010a,b]. This further identifies Enceladus as a water source and is consistent with a subsurface ocean there.

Cassini established that Enceladus is the main source of water in the inner magnetosphere, with additional sources from the rings. The almost co-rotating inner magnetosphere, which includes hydrogen ions mainly from Saturn's ionosphere, is dominated by water-based neutrals (O, OH). Enceladus, supplemented by the rings and the associated neutrals, populates the outer magnetosphere as well [Smith et al., 2008, Thomsen et al., 2010, Arridge et al., 2011b]. Some of the remarkably complex chemistry at Titan appears to involve particles, oxygen in particular, originally from Enceladus [Coates et al., 2007a, Sittler et al., 2009].

INMS confirmed that the neutral gas is concentrated over the South pole [Waite et al., 2006]. Composition data from INMS show that as well as water, carbon dioxide, methane, ammonia, ^{40}Ar and organics are present in the neutral gas in smaller quantities. CAPS measurements also indicate nitrogen which may be from ammonia, and that Enceladus, rather than Titan, is the dominant nitrogen source at Saturn [Smith et al., 2009, Thomsen et al., 2010, Arridge et al., 2011b]. In addition, the plume appears to be a variable source with gas production ~10^{27}-10^{28} s^{-1} [Smith et al., 2010].

In addition to the population of neutral ice particles, charged nanograins were found by CAPS [Jones et al., 2009]. The timing of the negative and positively charged grain densities were used to trace the trajectories back to particular sources within the tiger stripe regions. In addition to identifying the location of emission, the trajectories of the charged nanograins were different between the charged species, implying separation with respect to each other and the neutral plume. Saturn's magnetic field effectively acts as a huge mass spectrometer for these particles. Ice grain-plasma interactions play a role in Saturn's inner magnetosphere.

Several pioneering discoveries of new populations near Enceladus were possible using CAPS data. These include charged nanograins [Jones et al., 2009], negatively and positively charged water clusters [Coates et al., 2010b, Tokar et al., 2009], magnetospheric photoelectrons from ionisation of neutrals throughout the magnetosphere near Enceladus [Schippers et al., 2009] and plume photoelectrons [Coates et al., 2013]. Further detailed study of the charged dust [Hill et al., 2012] has indicated the charging mechanism is likely from the surrounding plasma. It is clear that Enceladus provides a remarkably complex plasma environment. The unexpected species add to the anticipated cold magnetospheric electrons. Enceladus is one of the key locations in the solar system where 'dusty plasma' can be studied (others include comets). The CAPS energy spectral data revealed several unexpected populations. For example, plume photoelectrons provide an ionization source [Coates et al., 2013], which adds to magnetospheric photoelectrons to provide electron impact ionization, which may be a key process in the magnetosphere at this position [e.g., Fleshman et al., 2012].

The plasma environment of Enceladus is determined by the approximately corotating magnetosphere of Saturn and its interaction with (a) mass loading through charge exchange and negative grain charging and (b) the plasma produced from the plumes via ion pickup. The interaction drives field aligned currents which can reach the Saturn auroral region and produce an auroral spot

[Pryor et al., 2011], a weaker version of the auroral spots at Jupiter associated with Io, Europa and Ganymede.

The overall picture emerging is that Saturn's magnetosphere is filled with water-group atoms, radicals and molecules (O, OH, H_2O) from the major sources (Enceladus, main rings, others) slowly being turned into water-group ions (O^+, OH^+, H_2O^+, H_3O^+). The ions are picked up by the rapidly rotating magnetosphere and are eventually lost into the solar wind.

3.5 Jupiter's moons

3.5.1 Io, Europa and Callisto

The volcanic moon Io is a source of heavy (S, O based) neutrals, and a major source of particles for Jupiter's magnetosphere (~1 tonne s^{-1}). Io has a plasma torus from ionization of these [Bagenal, 1994 and references therein]. The orbit of Io is well inside the Jovian magnetosphere, where corotation of the rapidly rotating magnetosphere is faster than the moon's orbital speed. Io's wake is therefore ahead of Io in its orbit. Io thus presents a partially conducting obstacle to a subsonic magnetospheric flow, resulting in Alfven wings [Neubauer et al., 1998]. Pickup ions are produced at a rate of ~3×10^{28} s^{-1}.

Initially, the pickup ion distribution is ring-like (in the dipole approximation, $v \perp B$). Pitch angle scattering occurs as elsewhere in solar system, with a timescale of a few days here [Huddleston et al., 1998]. As the speed is sub-Alfvenic, the bispherical shell produces almost perpendicular pickup as shown in Figure 7, which schematically shows pickup ion distributions at Io. Note that due to the low flow speed, the centres of the bispherical arcs are outside both the arcs themselves Huddleston et al., [1998].

The effects of ion pickup are also observed at other Galilean satellites (e.g. ion cyclotron waves at Europa and Ganymede as well as Io [Russell et al., 2000, 2001, Volwerk et al., 2001]. In these cases, the neutrals are from sputtering under plasma bombardment [e.g. Johnson et al., 2009 and references therein]. The JUICE Mission, and Europa Clipper if approved, will study these processes in more detail via measurements of the pickup ions.

3.5.2 Ganymede

Ganymede has an intrinsic magnetic field which fundamentally affects its interaction with the plasma environment. This body is unique in the solar system, representing a 'magnetosphere within a magnetosphere' (Jupiter's). Although magnetized, there are common processes with unmagnetized moons such as energetic particle interaction with the surface, exosphere production and mass loading processes in the surrounding plasma. JUICE will study the interaction in detail from orbit.

3.8 Moon

Earth's Moon is usually in the solar wind but spends a fraction of time in Earth's magnetotail. The Moon has some crustal magnetic fields. The plasma interaction is dominated by a wake behind the Moon in the flow direction, as the embedded magnetic field diffuses through the Moon while the particles impact onto the lunar surface. Interesting new kinetic effects have been found by recent missions. Pickup ions have been detected [Hilchenbach et al., 1992, Mall et al., 1998] and reflected ions also. Halekas et al. (2011) summarized some of the new results from recent missions.

Recent results from the Kaguya spacecraft have distinguished four different ion populations produced by solar wind bombardment, including two populations of pickup ions [Saito et al., 2010]: (1) backscattered ions from the surface [Saito et al., 2008], (2) reflected ions from magnetic anomalies, (3) pickup ions (by the solar wind) from backscattered or reflected particles [Saito et al., 2008] and (4) pickup ions (by the solar wind) from the surface or exosphere [Yokota et al., 2009]. Population (4) represents classical pickup ions seen as rings in velocity space. However, the 'self-pickup' process ((3) above) of the reflected proton population (~0.1-1% of the solar wind flux [Saito et al., 2008], provides additional energy beyond the classical pickup process. The particles are also seen as rings.

Self-pickup provides a maximum velocity (for a proton) of up to 3 times the solar wind, and an energy 9 times that of the solar wind [Saito et al., 2008] in the spacecraft frame, due to the 'injection point' being at up to $-u_{sw}$ (see Figure 8, which illustrates the pickup ion geometry for both conventional pickup (inner circle) and for self-pickup (outer circle)). In addition, IBEX detected neutral lunar backscattered particles [McComas et al., 2009], while Chandrayaan-1 both confirmed the reflected protons, and found that up to 20% of the incident solar wind flux can be backscattered as neutrals [Wieser et al., 2009, Bhardwaj et al., 2010]. These may then ionize and form part of the 'self-pickup' population. The 'self-pickup' particles may then enter deep into the lunar wake, due to their larger cycloidal trajectories compared to classical pickup (e.g. the particles in (4) above) [Nishino et al., 2009, 2010, Holmstrom et al., 2010].

3.9 Pluto

Our knowledge of Pluto's solar wind interaction will be transformed later this year with the arrival of New Horizons. However, the expectations are that the solar wind Mach number is likely to be high at this location in the solar system (see Russell et al., [1990]). The solar wind interaction is expected to be somewhat comet-like when Pluto is near the Sun and has its exosphere is at maximum density. The atmospheric loss rate has been estimated at ~10^{25}-10^{27} s^{-1} [McNutt, 1989] and an extended mass loading region is anticipated. The gyroradius of CH_4^+ ions would be 250,000 km and for N_2^+ it would be 658,000 km. The kinetic nature of the interaction, including nongyrotropic distributions as seen at comet Grigg-Skjellerup [Coates et al., 1993b] will make the results very interesting. One aspect which is anticipated is momentum balance between the pickup ions and the solar wind deflection [e.g. Delamere and Bagenal, 2004]. This was seen in the AMPTE Lithium and Barium releases [Coates et al., 1986, 1988, Johnstone et al., 1986b], and is also seen in the early data from Rosetta at comet 67P [Nilsson et al., 2015, Goldstein et al., 2015]. Other aspects of the very early pickup interaction as at comet 67P are also possible although at Pluto the scale is larger and the neutral particle density is lower near the location where new ions are produced. One aspect is whether a Venus-type ionopause, or a diamagnetic cavity as at Halley, is present [Cravens and Strobel, 2015].

4. Escape – comparison

We have compared the escape rates for the unmagnetized objects in the solar system, and included some magnetized objects in the comparison (see Table 1). In Figure 9, we show a log-log plot of the loss rates for the solar system objects shown in Table 1 against the object radius. We find a remarkable grouping into planets, moons and comets. There are several different escape processes at work for all objects, including thermal and non-thermal mechanisms, which contribute to all of the rates. Some interesting trends are seen. The smaller objects, i.e. comets, have generally higher escape rates, due partly to their lower gravity. The moons shown are generally higher escape rates than the planets for similar size objects. In the cases of Io and Enceladus this is due to their intrinsic activity, and in the other cases shown because of their immersion in hot magnetospheres rather than the solar wind [Coates et al., 2015].

We note that the extremes of the Earth's escape rate are similar to those of unmagnetized objects, and the Pluto points included are based on expectations rather than measurements but these span the 'planets' and 'moons' areas of the plot.

5. Summary and conclusions

We have discussed some of the processes at work and plasma measurements made so far in the plasma interaction with unmagnetized objects. We discussed the types of interaction, including the effects of upstream conditions and the nature of obstacle. Our tour was organised by objects (comets, Mars, Venus, Titan, Rhea, Dione, Enceladus, Io, Europa, Callisto, Moon, Pluto) but some key processes are common to all these objects, including ion pickup, ionospheric processes such as photoelectron production, and plasma escape processes.

In conclusion, we look forward to the next months of Rosetta operations at comet 67P. This will allow, for the first time, the evolution of the comet-plasma interaction to be followed. Following orbit insertion around 67P at ~3.5 AU, the activity increases during the approach to perihelion at ~1.24 AU and then subsequently decrease with increasing heliocentric distance during the extended mission.

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Figure captions

Figure 1 – Comparison of scales for magnetized and unmagnetized objects in the solar system. (adapted by Coates [1999,2001] from Russell & Walker, [1995]). Object names are in **bold**, missions carrying relevant instrumentation within the last 30 years are in ***bold italics***, the last 10 years in normal font, and approved future missions are in (*bracketed italics*).

Figure 2 – Schematic diagram showing the early stages of the pickup of ionized neutrals. The cycloid in real space corresponds to a ring in velocity space.

Figure 3 – Examples of pickup water group ion ring and shell distributions seen at comet Halley [see Coates et al., 1989].

Figure 4 – Change in the comet-solar wind interaction as a comet approaches the Sun

Figure 5 – Organisation of the Mars Express ion escape data by the interplanetary electric field [Fedorov et al., 2008]

Figure 6 – Ionospheric plasma in the tails of (a) Mars at up to (from Frahm et al., [2006b]) and Titan (from Coates et al., [2007])

Figure 7 – Pickup geometry at Io showing bispherical shells [Huddleston et al., 1998]. (a) is for perpendicular pickup, (b) for ~80°, (c) for different values of the ratio between the wave phase velocity and the injection velocity $R=V_{ph}/V_{inj}$ and (d) for different v-B angles α. All moons in corotating inner magnetospheres of the outer planets will have a similar geometry although V_{ph} and V_{inj} may be different.

Figure 8 – Pickup geometry including the effect of reflection from the Moon's surface. The resulting energy is higher [Coates 2012].

Figure 9 – Summary of loss rates for solar system objects from Table 1 plotted as a function of object radius (adapted from Coates et al., [2015a])

Table 1 - Neutral gas production rates for comets and other solar system objects visited by spacecraft with plasma instrumentation. Where appropriate, ion loss rate estimates are indicated by *.

Object	**Atmosphere/exosphere composition**	**Production rate (s^{-1})**	
Venus	CO_2,N_2,O,CO	*2.2×10^{23}-10^{25}	Coates et al 15a, Brace 87, Barabash 07a
Earth	N_2,O_2	10^{24}-10^{26}	Haaland 13
Moon	Na,K		
Mars	CO_2,CO,O	*10^{23}-10^{25}	Barabash 07b, Lundin 08, Lundin 13, Lundin 89, Ramstad 13
Comet Giacobini-Zinner	H_2O,CO,CO_2	4×10^{28}	Mendis 86
Comet Halley	H_2O,CO,CO_2	6.9×10^{29}	Krankowsky 86
Comet Grigg-Skjellerup	H_2O,CO,CO_2	7.5×10^{27}	Johnstone 93
Comet Borrelly	H_2O,CO,CO_2	3.5×10^{28}	Young 04
Comet Churyumov-Gerasimenko	H_2O,CO,CO_2	3×10^{24}-5×10^{27}	Hansen 07, Motschmann 06
Io	SO_2,SO,S,O,Na,Cl	3×10^{28}	Bagenal 94
Europa	O_2,O_3,O,Na	2×10^{27}	Smyth 06
Ganymede	O_2,O_3,O	1.3×10^{27}	Marconi 07
Callisto	O_2,O_3,O		
Titan	N_2,CH_4,hydrocarbons	*4×10^{24}-10^{25}	Coates 12, Wahlund 05
Enceladus	H_2O	3×10^{27} –1-2×10^{28}	Tokar 06, Smith 10
Rhea	H_2O	2.45×10^{24}	Teolis 10
Dione	H_2O	9.6×10^{25}	Tokar 2012
Pluto	N_2,CH_4	10^{25}-10^{27}	McNutt, 1989

Table 2 – Comparison of plasma interaction conditions at Saturn's moons. In the location row the letters refer to Inner, Middle, Outer magnetosphsphere, Sheath, Solar Wind, Tail

Moon	**Mimas**	**Encel-adus**	**Tethys**	**Dione**	**Rhea**	**Titan**	**Iapetus**	**Hyper-ion**
Orbital dist. (R_S)	3.18	4.09	5.07	6.47	9.05	20.99	61.13	25.43
Radius (km)	198	252	531	561	763	2575	735	135
Location	I	I	I	M	M	O/Sh	SW/Sh/T	Sh/O/T
Activity/ atmosphere	No?	Active geysers	No?	Tenuous, O_2/CO_2	Tenuous, O_2/CO_2	Thick, N_2/CH_4	No?	No?