Surprises from Saturn - and implications for other environments

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Abstract. The exploration of Saturn by Cassini has provided many surprises on Saturn's rapidly rotating magnetosphere and its interaction with the diverse moons, as well as its interaction with the solar wind. Enceladus, orbiting at 4 Saturn radii (R_S), was found to have plumes of water vapour and ice which are the dominant source for the inner magnetosphere. Charged water clusters, charged dust and photoelectrons provide key populations in the 'dusty plasma' seen here. Direct pickup is seen near Enceladus and field-aligned currents create a spot in Saturn's aurora. At Titan, orbiting at 20 R_S, unexpected heavy negative and positive ions are seen in the ionosphere, which provide the source for Titan's haze. Ionospheric plasma is seen in Titan's tail, enabling ion escape to be estimated at 7 tonnes per day. Saturn's ring ionosphere was seen early in the mission and a return will be made in 2017. In addition, highly accelerated electrons are seen at Saturn's high Mach number ($M_A \sim 100$) quasi-parallel bow shock. Here we review some of these key new results, and discuss the implications for other solar system contexts.

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INTRODUCTION

Before Cassini-Huygens, our knowledge of the Saturn system was from telescopes and from the Pioneer and Voyager flybys. Titan was known to have the densest atmosphere of any moon, with principal constituents being nitrogen and methane. A surface temperature of 93 K, near the methane triple point, was known and it was anticipated that weather systems, lakes and seas were likely as parts of a methane cycle. Similarities were drawn to Earth's early atmosphere. It was predicted that in the ionosphere, complex chemistry involving positive ions and neutrals would occur (e.g. [1]). Also, Titan was expected to be a major source for Saturn's magnetosphere, with a torus deposited around the orbit (e.g., [2]). Enceladus was considered an icy moon with little activity, although a possible source for E-ring particles.

Cassini-Huygens has revealed many new results which have changed our view of the Saturn system. In particular, the role of Enceladus as the major plasma source for the inner and outer magnetosphere provides a significant difference to our pre-Cassini view, as does chemical complexity in Titan's ionosphere. Here we will discuss some of the new discoveries, emphasising those from the Electron Spectrometer (ELS), part of the Cassini Plasma Spectrometer (CAPS, [3]).

ENCELADUS

The importance of Enceladus as a source was first found from magnetometer observations of a draped field [4]. Flow deflection was also seen by the CAPS ion mass spectrometer (IMS), and the derived production rate was ~100 kgs^{-1} [5], 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 [6]. Saturn's magnetosphere approximately corotates with the planet at 4 R_S. Positive and negative ionospheric ions were found within the plumes [6,7]. 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 [5] and in the magnetospheric region close to Enceladus' orbit [8]. The negative ions appear as multiples of the water or OH mass, with clusters of up to 100 [7,9]. 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 [10,11,12]. Some of the remarkably complex chemistry at Titan appears to involve particles, oxygen in particular, originally from Enceladus [13,14].

INMS confirmed that the neutral gas is concentrated over the South pole [15]. 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 [10,11,12].

In addition to the population of neutral ice particles, charged nanograins were found by CAPS [16]. 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 [16], negatively and positively charged water clusters [7,6], magnetospheric photoelectrons from ionisation of neutrals throughout the magnetosphere near Enceladus [17] and plume photoelectrons [18] (see Figure 1(a)). Further detailed study of the charged dust [19] 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 [18], which adds to magnetospheric photoelectrons to provide electron impact ionization, which may be a key process in the magnetosphere at this position (e.g., [20]).

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 [21], 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 molecules (O, OH, H_2O, H_3O) from the major sources (Enceladus, main rings, others) slowly being turned into water-group ions**.** Ions are picked up by the rapidly rotating magnetosphere and eventually lost into the solar wind.

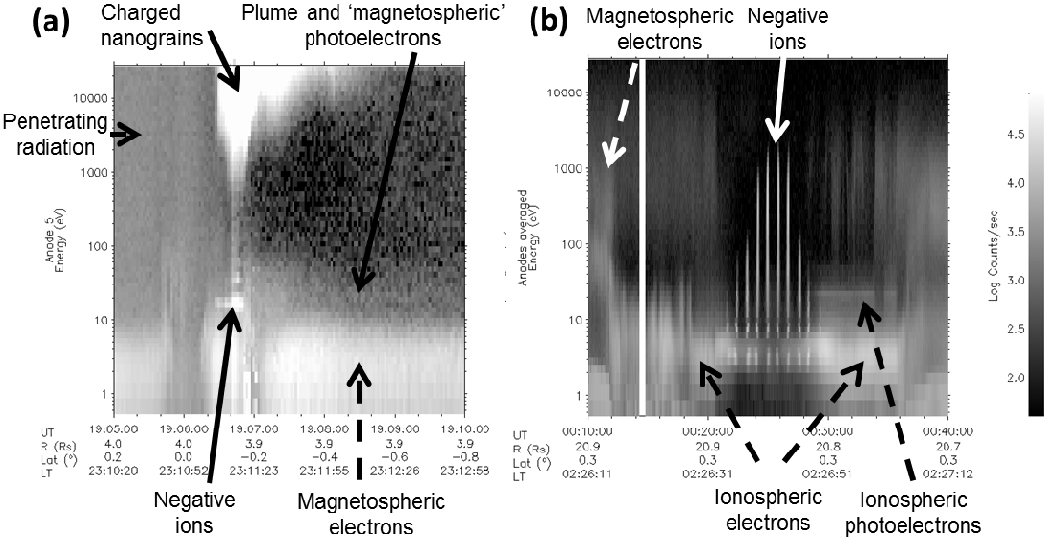

FIGURE 1. Some surprising discoveries (solid arrows), and expected features (dashed arrows), from CAPS-ELS. (a) Cassini's E3 Enceladus encounter shows charged nanograins [16,19], negative ions [7,9], plume [18] and magnetospheric [17] photoelectrons. (b) Cassini's T16 encounter shows cold, heavy negative ions in Titan's ionosphere with m/q up to 13,800 amu/q (converted from E/q) [13].

TITAN

At Titan, a strong local interaction with Saturn's magnetosphere forms a complex plasma tail (e.g., [22, 23 and references therein]). Atmospheric loss rates are large and the subject of some debate [24] although ion loss rates have been measured [25]. 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. The complexity is seen in neutral and positive species, as well as the newly-discovered negative ions [26,13,27,9,28] (see

Figure 1(b)). In addition, related 'tholins' are seen using occultation measurements (e.g. [29]). Negative ions were unexpected at such high altitudes. Cassini found very heavy negative ions up to 13,800 amu/q [13,27] as well as positive ions up to ~1000 amu/q [26,28,9], 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^- [30] 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 [14]. Recent studies show that agglomeration due to charging [31] or chemical processes [32] may be operating.

The maximum mass of negative ions at Titan was studied as a function of altitude, latitude and solar zenith angle [27], and recently the density variation with these parameters has been examined [33] 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 [34] where CAPS was not oriented in the ram direction, and subsequently at other encounters [35].

Ionospheric photoelectrons at Titan provide a key indication of ionospheric plasma, or of a magnetic connection to Titan’s tail [36,37,38]. They may also provide an ambipolar electric field driving plasma escape [36,25]. Plasma escape rates at Titan showed that Titan loses 7 tonnes of material per day [25].

RHEA, 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 [39] (using positive and negative pickup ions to identify the near-surface source), and at Dione [40]. The expsphere production is due to magnetospheric particle bombardment of these icy moons, a process which also occurs at Europa, Ganymede and Callisto.

RINGS

The ring atmosphere and ionosphere were discovered during the ring crossing phase of the Saturn Orbit Injection (SOI) orbit [41,42]. UV-induced decomposition of ice on the sunlit side of the rings provides molecular oxygen neutrals, which are the source of O^+ and O_2^+ [43] which then populate the near-ring region (e.g., [44]). Photoelectrons are also produced [41]. The rings provide some oxygen for the magnetosphere (e.g., [45,46]) and also H_2 [47], these are highly season-dependent.

Recently, observations using the Keck telescope have indicated "ring rain" where water group ions (from neutrals) are transported from the rings along the magnetic field, producing cooling of Saturn’s upper atmosphere as observed in the infrared [48].

Also, there is evidence for interaction between lightning in Saturn’s atmosphere and ring features. This was suggested based on the plasma environment [49].

The first orbit was the only time in the mission when sampling immediately above the rings was possible, though occasionally Cassini passes nearby [45]. The proximal orbits late in the mission may give further opportunities for in-situ exploration here.

HIGH M BOW SHOCK

As Saturn is at ~10AU, the solar wind conditions are significantly different to those at Earth. It was expected that high Mach number shocks would be seen by Cassini, and observations [50] showed that this was the case, with Alfven Mach numbers (M_A) up to ~100, but more typically M_A ~ 12. Further analysis of the highest Mach number shock [51] showed that this was quasi-parallel with θ_{Bn} ~ 20°. Despite this, electron acceleration was seen up to ~MeV, as well as an escaping population of ~100keV electrons. This is the first observation of acceleration of electrons to relativistic energies by a quasi-parallel shock. The seed population was suggested to be solar wind electrons, possibly with escaping electrons in addition. Although the detailed acceleration mechanism is not understood, acceleration by high Mach number quasi-parallel shocks may have implications in astrophysics, including supernova shocks.

SUMMMARY & RELEVANCE TO OTHER ENVIRONMENTS

We have briefly discussed several processes and discoveries, some of which were surprising, from the Cassini mission at Saturn. These are summarized in Table 1. There are many other surprises, such as rotation-related periodicities, a low magnetopause reconnection rate, injection events and many others for which space precludes discussion here. Future missions such as Rosetta and JUICE may provide more information on the processes at locations marked '?' in Table 1.

TABLE 1. Plasma processes at locations in the Saturn system (T=Titan, E=Enceladus, Rh=Rhea, D=Dione, R=ring system, IM=inner magnetosphere) which arerelevant elsewhere (S=Saturn, Ma=Mars, V=Venus, C=comets, M=Moon, I-Io, G=Ganymede, E=Europa, Ca=Callisto, Tr=Triton,P=Pluto).

Process	Within Saturn system	Other contexts
Plume activity	E	E?, G?, Tr
Ion pickup	T,E,Rh,D,R,IM	Ma,V,C,M,I,G,E,Ca.Tr,P
Negative ions	T,E,Rh	C,Ma?,V?,E?,G?
Dusty plasma	E,IM	C?
Field aligned currents, auroral spot	E	I,G,E
Ionospheric electrons	T,E,R,IM	Ma,V,C,I?,G?,E?,Ca?,Tr?
Weak atmosphere production	Rh,D,R	G,E,Ca,Tr,P
High M shock acceleration	S	Uranus, Neptune, supernova

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