Enceladus: Plume Composition and Interactions in the Saturnian System

Physics and Astrophysics
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Enceladus is Saturn's sixth largest moon and orbits at a distance of approximately 4 Saturn radii. The recently discovered plume of the South Polar Region ejects vast amounts of material into the E ring and its own torus which have been shown to have a significant effect on the entire Saturnian system. The general composition, structure and other features of the plume is discussed in this review. Also, Enceladus' interactions with Saturn's magnetosphere and the effect on E ring will be discussed.

Introduction

"The discovery of a tenuous atmosphere and a plume of water, carbon dioxide, methane, and possibly nitrogen erupting from warm and tectonically and volcanically active regions near Enceladus' south polar terrain confirms that Enceladus ranks alongside Io (and possibly Triton) as one of the few currently geodynamically active satellites in the solar system." (Barr & McKinnon 2007).

A small, icy satellite of Saturn, known as Enceladus, orbits at a distance of 3.95 R_{Sat} (where R_{Sat} is one Saturn radius = 60,268km). Enceladus orbits Saturn at a speed of 12.6 km/s and is accompanied by a plasma torus corotating with Saturn at a speed of 39 km/s. This positioning allows the corotating plasma flow to remain unaffected by solar wind. (Kivelson 2006, Jia *et al*. 2010). The Cassini spacecraft made three close flybys to Enceladus in 2005 and an additional four in 2008 to observe the Saturnian system (Khurana *et al*. 2007, Jia *et al*. 2010). Observations from Cassini (CAPS, CDA, CIRS, INMS and UVIS instruments are used) suggested that Enceladus was geologically active (Barr & McKinnon 2007). Enceladus is accompanied by a plasma torus which is mostly composed of water group ions (Jia *et al*. 2010).

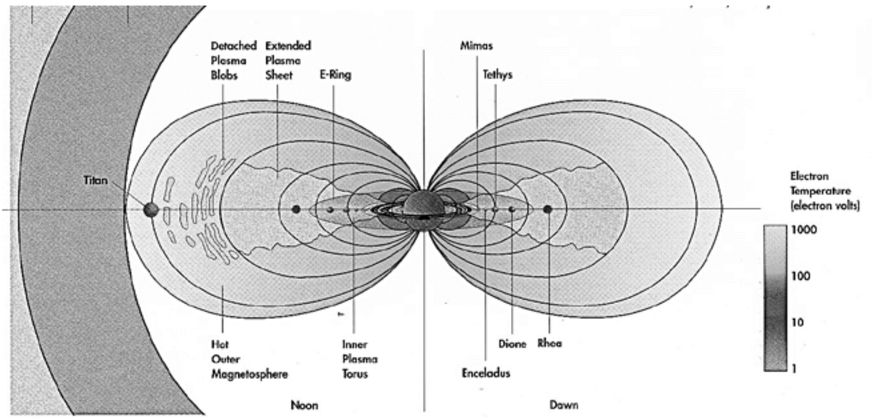

Figure 1: *Schematic diagram of Saturn's magnetosphere with Enceladus and other moons shown. The plasma torus and E ring are also shown (Sittler et al. 1983).*

The outermost E ring of Saturn is dominated by water vapour and ice particles. It is suspected that the tiny moon, of radius 250 km, is the source of these particles and is considered to be a major replenishing source of the E ring (Postberg *et al.* 2007). In 2005, large water vapour plumes were discovered in Enceladus' south polar region (Matson *et al*. 2006, Hansen *et al*. 2011). The Cassini flybys confirmed the existence of such plumes and also observed that such a plume is expelling approximately 10^{28} gas particles per second into the inner Saturnian system. These particles become ionised and join the plasma disk of Saturn's magnetosphere (Jia *et al*. 2010).

The Saturnian system is complex and intriguing. There is a vast range of interactions between Saturn's magnetosphere and its moons: "from the addition of significant quantities of gas, dust and plasma causing significant consequences for the dynamics and energetics of the entire Saturnian magnetosphere, to the simple absorption of plasma and energetic particles by the icy moons" (Jia *et al*. 2010). Also, it has long been suspected that the E ring is replenished by the material ejected from Enceladus' plume. Evidence for this comes from the higher particle density that has been observed at and near Enceladus than in any other region of the E ring (Postberg *et al*. 2007).

The aim of this review is to establish and discuss the relationship between Enceladus' plume and the Saturnian system. This will be done via two parts: one explaining the general structure, composition and other features of the plume, the other discussing the interactions between Enceladus and Saturn.

Composition and Structure of Enceladus' Plume and Some Implications for Enceladus' Internal Structure

Various models and simulations have been used to investigate the composition and structure of the plume at Enceladus' south pole. It is believed that this plume is centred at Enceladus' south pole with a latitudinal distribution of 10^{o} ~ 15^{o} (Jia *et al*. 2010). From Cassini's Infrared Spectrometer (CIRS), observations of the 'tiger stripe' fissures of Enceladus' south pole led to surface temperature estimates of 170 K with gas thermal velocities greater than 450 m/s (Hansen *et al*. 2011). However other sources (Cassini CIRS instruments) have shown different observed temperatures, as shown below in Figure 2.

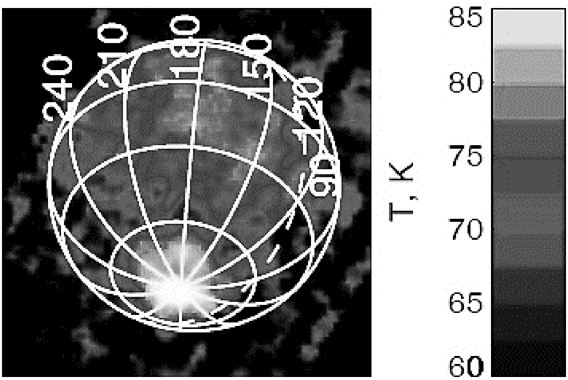

Figure 2: *Schematic of observed temperatures on Enceladus with a view of the south polar region. As mentioned above, some sources estimate a higher temperature than here. (Enceladus Reveals Geological Activity, 2006).*

It has been observed that during Enceladus' slightly eccentric orbit of 1.37 Earth days, gravitational variations, due to Saturn's gravitational pull, can affect the amount of material ejected into the Saturnian system (Hedman *et al.* 2013). This supports the idea that Saturn's tidal and gravitational forces affect the activity at Enceladus' south pole, even if the exact mechanism is still unclear (Barr & McKinnon 2007). There has been much debate about the source of heat for this region of the icy moon, and also about the origin of the plume and how this affects the interior structure and composition of Enceladus (Halevy & Stewart 2008).

Tidal dissipation at Enceladus should be distributed as a function of longitude and latitude. It is well known that the plume is centred near the south pole of Enceladus. This may be due to a large density perturbation in the ice shell or rocky interior that may have caused the moon to 'roll over' so this area settled onto the rotation axis. It is possible that tidal dissipation is a cause of density perturbations, or that some thermal, compositional or mechanical anomaly is present in Enceladus' ice shell to localize the heating to the south pole. The source of heat for the plume and volcanism of Enceladus is believed to be tidal dissipation which is maintained by the 2:1 mean motion resonance with Dione (Barr & McKinnon 2007). This means that for every one orbit of Dione, Enceladus orbits Saturn twice.

Burger *et al*. (2007) discuss the shape of the Enceladus plume and further evidence for the southern polar region as the plume's location. The Cassini INMS and UVIS instruments made observations of the water vapour of the plume, finding that the source is nonuniform. A nonuniform source would be expected to be asymmetric which is what is observed for the Enceladus water vapour plume. However, the peak is symmetric about the south pole, displaying a maximum density here indicating the location of the source.

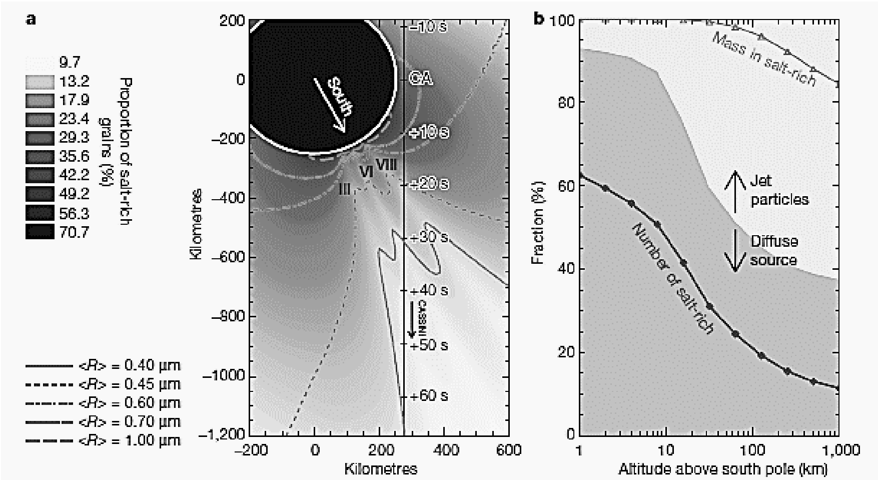

Figure 3: *(a) shows the shape of Enceladus' plume and contour lines showing the radius of particles found at each line. (b) shows the percentage of salt-rich ice as a function of logarithmic altitude above the south pole. (Postberg et. al. 2011).*

The inner magnetosphere (near the region of the E ring) contains a neutral cloud of H2O, OH and O and H molecules which are believe to originate from Enceladus' water vapour plume (Khurana *et al*. 2007). Data recorded in 2005 by the Cassini INMS instruments revealed that the plume is composed of H2O (91 ± 3%), N_2 or CO (4 ± 1%), CO2 (3.2 ± 0.6%), CH4 (1.6 ± 0.4%) with possible trace amounts of ammonia, acetylene, hydrogen cyanide and propane (Matson *et al*. 2006). The vast quantities of H2O being ejected by the plume, and as found throughout Saturn's E ring, lead to debate about the origin of this water. As one may suspect, it is difficult to erupt liquid water onto (or past) the surface of an icy satellite, due to the fact that liquid water has a higher density than solid ice. However, the thickening of the ice shell may increase the pressure in a subsurface ocean. This excess pressure may not be sufficient enough to allow the eruption of liquid water on larger satellites, such as Europa, but on a small moon such as Enceladus, ocean pressure can increase enough to cause an eruption of liquid water. These volume and pressure changes may be caused by coupled orbital and thermal evolution of the moon's interior or secular cooling (Manga & Wang 2007). Evidence for a subsurface ocean at Enceladus comes from Cassini's CDA observations of grains in the plume containing sodium salts.

This is consistent with an ocean at Enceladus being in contact with its rocky core (Hansen *et al*. 2011).

The most abundant species observed at or near Enceladus and the E ring is H_2O with smaller amounts of other species mentioned above. Cassini's observations allow for an estimate of velocities of these particles to be calculated. With Cassini at a distance of 175km from the surface of Enceladus and water detected at least 1000km from the surface, an estimated velocity of 225 m/s is found. This is slightly less than the escape velocity of 250 m/s for a body the size of Enceladus. It then seems obvious how a large portion of the ejected water particles can escape fully from Enceladus and end up in Saturn's E ring (Matson *et al*. 2006, Burger *et al*. 2007).

Matson *et al*. (2006) conclude that the composition of Enceladus' plume indicates the production of N_2 below the icy surface as a derivative of ammonia at a temperature above the melting point of water. This indicates that Enceladus' interior is composed of a "rich, warm, aqueous, organic 'soup'" which may imply that the environment is favourable for the production of other organic components such as methanol or amino acids, this however is beyond the scope of this review.

Interactions in the Saturnian System

It is the effect on the magnetic field which indicates the presence of the plume (Kivelson 2006). Cassini observations indicate that the plasma torus emanating from Enceladus spreads to fill the Saturnian magnetosphere. The magnetosphere of Saturn is strongly dominated by neutral water group atoms, with a magnetic field strength of 330 nT at Enceladus' orbit (Bagenal 2007, Jia *et al*. 2010). Saturn's magnetodisk is unique and is between that of Earth and Jupiter. The magnetodisk is bowl-shaped and bent upward from the equator toward ecliptic north and seasonally tilts toward the Sun (Gombosi & Ingersoll 2010).

Jia *et al*. (2010) applied a 3D magnetohydrodynamics (MHD) model to examine the flow around a body that is simpler than Enceladus and then by adding processes to occur simultaneously, a relatively accurate model of Enceladus is simulated. It was found that the plume expels approximately 10^{28} gas particles per second into the Saturnian system. Enceladus was found to be the main mass-loading source in the Saturnian magnetosphere and the main source for E ring replenishment.

Kivelson (2006) finds that the ejected particles affect local properties of Saturn's inner magnetosphere. As gas particles are ejected from Enceladus' plume, they become ionized and are added to the plasma disk of Saturn's magnetosphere. The particles may undergo one of three types of ionization: photoionization, electron impact ionization or ion-neutral charge exchange. The combination of these processes changes to mass and momentum of the plasma flow and so the effect is considered as mass loading to the Saturnian plasma (Khurana *et al*. 2007, Jia *et al*. 2010).

Jia *et al*. (2010) use a 'self-consistent' MHD model to examine the steady state interaction between the torus flow, Enceladus and its plume with the aim of creating a 3D plasma environment of Enceladus to compare with magnetometer data. It was found that nearer to the surface of Enceladus, mass-loading is less efficient. This effect is seen between the surface at the south pole and a radius of 2.8 Enceladus radii. There are a number or possibilities which could cause this: where neutral density is high inside the neutral jets, hot electrons may be depleted and so less electron impact ionization occurs; the ejecta may not be fully vaporized or; the model used here cannot fully predict the density concentration in thin jets closer than 2.8 Enceladus radii. It was found that approximately half of the loss of momentum in the plasma can be contributed to the charge exchange between torus ions and neutrals while this exchange between the neutrals and newly added ions account for the rest of the momentum loss. It was concluded in the paper by Jia *et al*. (2010) that the ionization processes result in a 50% increase of ion density in the mass-loading region of the plasma torus and also that the charge exchange effect contributes to 90% of magnetic field perturbations in the Saturnian system. It is also found that a global circulation of plasma is set up around Enceladus' orbit as follows: incoming flow with a radial force balance is slowed after and interaction with neutrals from the plume. After this interaction there is a decrease in centrifugal force and a mostly unaltered inward magnetic stress which leads to the plasma 'falling' inward toward Saturn.

Khurana *et al.* (2007) suggest that the newly formed ions are added to the magnetospheric plasma flow and extract momentum from the flow. This slowing of the plasma creates thermal and pressure gradients and curvature in the magnetic field which can change the direction of the flow to be diverted around the mass-loading region. By using magnetic field data from the Cassini flybys, it was found that the total mass picked up by the plasma within 5 Enceladus radii is <3 kg/s, with additional pick up most likely occurring in the neutral torus outward of the orbital location of Enceladus.

Conclusions

While the paper by Manga & Wang (2007) assumes a subsurface ocean exists at Enceladus, more recent findings and observations now give conclusive evidence for a subsurface ocean. With this in mind, their assumption that there is an ocean beneath the icy shell of Enceladus is valid and allows us to make definite conclusions about the mechanisms for eruptions of liquid water at Enceladus.

All papers discussed above show strong evidence for a plume at Enceladus which ejects primarily H_2O into the E ring of Saturn. Various models, such as Monte Carlo and magnetohydronamics models, are used to investigate the effect the plume has on the Saturnian system.

It can be concluded that the particles ejected from the plume are the main source for replenishment of the E ring of Saturn. Evidence for this comes from the observation of water vapour and H_2O particles throughout the E ring, but also in higher densities nearest to Enceladus. This water vapour plume has produced a unique environment for these interactions which involve various states of matter (solid ice, liquid water, gaseous material etc.). This system is coupled with the Saturnian magnetosphere by bending the magnetic field, causing magnetic perturbations.

From Cassini's observations and the results of various simulations it is concluded that Enceladus is a unique and intriguing satellite in the solar system with a huge effect on the Saturnian system.

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