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THE ENCELADUS AND OH TORI AT SATURN

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ABSTRACT

The remarkable observation that Enceladus, a small icy satellite of Saturn, is actively venting has led to the suggestion that ejected water molecules are the source of the toroidal atmosphere observed at Saturn for over a decade using the *Hubble Space Telescope* (*HST*). Here we show that the venting leads directly to a new feature, a narrow Enceladus neutral torus. The larger torus, observed using *HST*, is populated by charge exchange, the process that limits the lifetime of the neutrals in the Enceladus torus.

Subject heading: planets and satellites: individual (Enceladus, Saturn)

1. INTRODUCTION

A large torus-shaped population of atoms and molecules is present in Saturn's inner magnetosphere. Such a "toroidal atmosphere" can be produced by magnetospheric plasma-induced sputtering of the surfaces of the icy satellites and grains that orbit in this region (Johnson et al. 1989). However, Shemansky et al. (1993), using *Hubble Space Telescope* (*HST*) data, detected the OH component of a toroidal atmosphere that was much more dense than that predicted by sputtering. Based on *HST* data and simulations, Jurac et al. (2001, 2002) showed that the "missing source" for this torus must be associated with the small icy moon Enceladus (radius ∼252 km). This moon was also thought to be the source of a tenuous ring of micron-sized grains called the E-ring (Showalter et al. 1991). Because Enceladus has the brightest surface in the solar system, some resurfacing processes were suggested to be related to the missing source of water vapor.

In 2005 July, using the *Cassini* spacecraft instruments, Hansen et al. (2006), Porco et al. (2006), Spahn et al. (2006), and Waite et al. (2006) made the remarkable discovery that, in spite of its size, Enceladus is actively venting both gas and grains. This not only accounted for the resurfacing, but a number of papers suggested that Jurac's missing source of water vapor had been identified. The observed gas appears to be venting from crevices, tentatively dubbed "tiger stripes," roughly centered on the south pole (Hansen et al. 2006; Porco et al. 2006). This exciting discovery, which clearly has implications for the evolution of planetary bodies, led us to question whether or not these vents directly populate Saturn's giant toroidal atmosphere, a feature that has been studied using *HST* for over a decade. Here we show that these vents are not the *direct* source of that torus. Rather, they are the source of a new feature, which we call the Enceladus torus, and charge exchange processes within the Enceladus torus produce the giant torus observed using *HST*.

2. THE ENCELADUS TORUS

Gas venting from Enceladus was directly detected by the Ion and Neutral Mass Spectrometer (INMS; Waite et al. 2006) and the Ultraviolet Imaging Spectrograph (UVIS; Hansen et al. 2006). Whereas INMS measured the density of the evolving gas along the spacecraft trajectory, from about a half a satellite radius above the surface to a few satellite radii, UVIS used the occultation of Orionis (Bellatrix) to obtain line-of-sight column densities across the south polar surface. An earlier occultation, using λ Scorpii, showed that the venting and the resulting atmosphere are not global. Venting was inferred prior to the Enceladus encounter by the disturbances in the local fields using the Magnetometer (MAG; Dougherty et al. 2006), and during the Enceladus encounter it was also seen by the disturbance in the plasma flow (Tokar et al. 2006). Both effects are a result of the interaction of the rotating magnetic field and its trapped plasma with the evolving gas cloud. This interaction alters the spatial distribution of the ejected neutrals as discussed below. Based on *Cassini* data, water vapor is the primary ejecta with additional volatiles (N_2, CO_2, CH_4) at the few percent level and ejected grains that are predominantly ice. The cause (Porco et al. 2006) and location (Nimmo & Pappalardo 2006) of the vents are of considerable interest, but here we focus on the fate of the ejected water molecules.

Although the *Cassini* instruments measured the gas density near Enceladus, the average speed of the ejecta was only inferred. Therefore, the source rates are not well constrained. In Table 1, estimated rates are compared with the source rates for the OH torus by Jurac and coworkers (Jurac et al. 2001, 2002; Jurac & Richardson 2005). Although only a fraction of the observed ice grains had escape speeds, detection of the gas beyond the Hill sphere suggested that a significant flux of gas molecules had speeds larger than the speed of escape from Enceladus, ∼0.2 km s^{-1}. The Composite Infrared Spectrometer (CIRS; Spencer et al. 2006) showed that the south polar region and, especially, the crevices are warmer than they would be based on solar heating. The highest local temperature inferred was ∼180 K, close to the temperature for producing an ammonia-water-ice melt. Average speeds (v_e) of ∼0.3–0.6 km s^{-1} have been suggested (Waite et al. 2006; Hansen et al. 2006), with the highest associated with the presence of subsurface liquid water exposed to space (Porco et al. 2006).

Saturn's inner magnetosphere is unique in that the neutral density dominates the plasma density. Since the neutrals are primarily molecular, the electrons in Saturn's inner magnetosphere cool rapidly. Therefore, in the vicinity of Enceladus's

TABLE 1
SOURCE RATES

Instrument and/or Model	Source Rate (10^{27} H_2O s^{-1})	Region
Jurac et al. (2001)	0.2 (sputter only)	E-ring+Enceladus
Jurac et al. (2002)	3.7	E-ring+Enceladus
Jurac & Richardson (2005)	10	E-ring+Enceladus
MAG (Leisner et al. 2006)	0.57	E-ring+OH cloud
INMS (Waite et al. 2006)	0.15–0.5	Enceladus
UVIS (Hansen et al. 2006)	5	Enceladus
CAPS (Tokar et al. 2006)	3	Enceladus

orbit, charge exchange is the principal ionization process resulting in relatively long average neutral lifetimes (Tokar et al. 2006): $\tau_{CE} \sim (0.2\text{–}1) \times 10^7$ s^{-1}, ~20–100 times the orbital period, $\tau_o \sim 1 \times 10^5$ s. Since the ejecta speeds discussed above are smaller than the Enceladus orbital speed, $v_o = 12.6$ km s^{-1}, the gas is confined to a relatively *narrow* region about Enceladus's orbit. That is, for $v_e/v_o \ll 1$ and isotropic ejection, analytic models give a mean vertical extent $H \sim R\,(v_e/v_o)$ and a mean radial extent in the orbit plane $\triangle R \sim 4H$, where R is the distance from Saturn (Johnson 1990). Using $v_e = 0.5$ km s^{-1} with Enceladus located at $R = 3.96R_S$, where R_S is a Saturn radius, gives $H \sim 0.15R_S$ or $\triangle R \sim 0.6R_S$. For preferential ejection from a region about the south pole, a narrower radial extent is expected. This clearly differs from the torus observed by *HST*, which has a mean radial extent about an order of magnitude larger (Jurac et al. 2002), as described in more detail below.

3. THE ENCELADUS AND OH TORI

Using Monte Carlo selections of angles and energies, we launch water molecules from a small region about Enceladus's south pole, roughly the site of the vents identified by the *Cassini* instruments (Hansen et al. 2006; Porco et al. 2006). To account for the observed venting, we use a cosine distribution about the polar axis and a Maxwellian flux distribution, $f(E) = [E/(kT)^2]\exp(-E/kT)$ with $T = 180$ K. The latter gives a mean energy, $2kT$, which corresponds to a mean thermal energy of $3kT/2$ plus a mean flow speed of 0.36 km s^{-1}. The ejected neutrals, assumed here to be primarily water molecules, are tracked in the combined field of Saturn, Enceladus, and the other satellites until they are ionized by charge exchange (Johnson et al. 2005, 2006). Because the electron temperatures are low in this region, only a fraction of the water molecules will be dissociated prior to charge exchange. The small change in the OH kinetic energy caused by the loss of the hydrogen atom only slightly broadens the resulting torus. An average source rate of $\sim 5 \times 10^{27}$ s^{-1} is used that can be scaled as more information on the Enceladus sources is obtained. An average ionization lifetime of $\sim 6 \times 10^6$ s^{-1} is used based on the charge-exchange cross sections and the mean collision speeds. Although the source is not steady, the neutral lifetimes are long (~70 days). Therefore, we present here azimuthally averaged column densities to compare to the azimuthally averaged column densities of OH based on *HST* data taken over a decade. As expected from the above discussion, a narrow, nearly uniform torus is formed, as shown by the radial dependence of the azimuthally averaged vertical column density of neutrals (dashed curve in Fig. 1).

The torus in Figure 1 is seen to be *much narrower* than the torus detected by *HST* (Jurac et al. 2002), which is also shown as vertical column density using the model in Jurac et al. (2002). Therefore, contrary to suggestions, it is not obvious that the

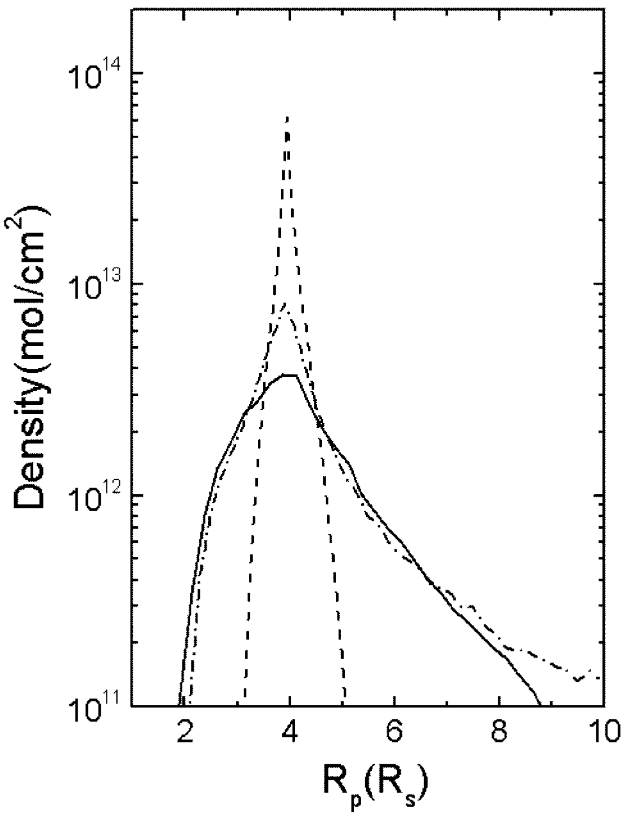

FIG. 1.—Toroidal column density vs. radial distance from Saturn along the equatorial plane. *Solid curve*, OH component of Saturn's giant toroidal atmosphere based on observations using *HST* for over a decade (Jurac et al. 2002; Jurac & Richardson 2005); *dashed curve*, torus of primarily water molecules venting from south polar region of Enceladus; *dot-dashed curve*, neutrals scattered from the Enceladus torus by charge-exchange and reactive collisions such as $H_2O^+ + H_2O \rightarrow H_3O^+ + OH$ or $H_2O + H_2O^+$, $OH^+ + H_2O \rightarrow OH + H_2O^+$, etc. The Enceladus source rate is 5×10^{27} H_2O s^{-1}, and an average lifetime of 6×10^6 s and a model average cross section were used.

water molecules venting from Enceladus are Jurac's missing source for the torus studied by *HST*.

What is absent in the above is a more detailed treatment of the process that limits the lifetime of the neutrals in the Enceladus torus. That is, the dominant loss process, charge exchange, does not eliminate an orbiting neutral but rather *replaces* it by a neutral with a different, typically larger, speed (Johnson et al. 2005). Unless the exiting neutral is ionized before leaving the magnetosphere (Wang et al. 2001), this is usually treated as a loss process (Jurac et al. 2002), since the mean ion flow speed at Enceladus is greater than the escape speed of a neutral from Saturn, $2^{1/2}v_o = 17.8$ km s^{-1}. However, the incident ions in the plasma near Enceladus have *a broad distribution of speeds* about the average flow speed, and the mean relative collision speeds between the ions and the neutrals are low: ~26 km s^{-1} dropping to ~14 km s^{-1} close to Enceladus due to mass loading by the newly formed ions (Tokar et al. 2006). Accounting for the ion temperature and the average flow speed in the Enceladus torus, one finds that low-speed, charge collisions occur between the ions and the neutrals. This is indicated by the observation that H_3O^+ is a major ion near Enceladus (Tokar et al. 2006), which is only formed in low-speed, reactive collisions (e.g., $H_2O^+ + H_2O \rightarrow H_3O^+ + OH$). Therefore, although the exiting neutrals are launched into more energetic orbits, a significant fraction do not escape from Saturn. In this way the "loss process" for the Enceladus torus produces a secondary, "hotter" neutral torus, which, we suggest, is the torus observed in its OH feature for over a decade by *HST*.

This charge-exchange scattering from the Enceladus torus is also simulated using our Monte Carlo model. That is, when a neutral in the Enceladus torus makes a charge-exchange collision with a heavy ion, we calculate the relative collision speed using the neutral orbit speed, the mean plasma flow speed, and the ion temperatures. In order to describe the fate of the neutrals from charge exchange, we use an average charge-exchange cross section for the mix of water group ions (O^+, OH^+, H_2O^+, H_3O^+; Tokar et al. 2006) and a thermal energy distribution based on *Cassini* Plasma Spectrometer (CAPS) data (Sittler et al. 2005): ~35 eV$(R/4R_S)^2$ with $T_\perp = 5T_\parallel$. We then use a model of the exit angle distribution in the center of mass between the neutral and the ion to calculate the neutral ejecta speed. In this model, the scattering in the center of mass is isotropic for very low relative speeds (Johnson et al. 2006) and becomes forward scattering at higher speeds (>a few eV). The neutrals exiting from such collisions are then also tracked. Using the full corotation speed (~26 km s^{-1}), approximately 70% of these neutrals either escape or spend most of their time at very large orbital radii (Johnson et al. 2005). However, close to Enceladus, the average plasma speed slows to ~14 km s^{-1} (Tokar et al. 2006), reducing the loss. The azimuthally averaged column density of the resulting neutral torus is also displayed in Figure 1 (*dot-dashed curve*). It is seen to have a spatial distribution much closer to the OH component of Saturn's giant neutral torus constructed by Jurac et al. (2002) from *HST* observations. The radial dependence of the calculated column density will, of course, change somewhat as the composition of the plasma and the cross section are better determined. In addition, the dissociation processes, electron impact and electron-ion recombination, that affect these results at the ~10% level must eventually be included.

4. SUMMARY

The exciting discovery of the primordial gases venting from the south polar region of the small moon Enceladus has lead geologist to reexamine models for satellite evolution. This venting was immediately assumed to be the "missing" source of Saturn's giant toroidal atmosphere discovered by Shemansky et al. (1993) and modeled using *HST* observations by Jurac and coworkers (Jurac et al. 2001, 2002; Jurac & Richardson 2005). Here we point out that the venting produces a narrow Enceladus torus of, primarily, undissociated water molecules. We propose that charge-exchange collisions in the Enceladus torus populate the larger torus observed earlier in an OH band using *HST*. Therefore, the venting from Enceladus is indeed the source of the torus detected by *HST*, but only indirectly by the process that limits the lifetime in the Enceladus neutral torus and causes the mass loading of the plasma around Enceladus. Jurac et al. (2002) realized that a source near Enceladus could describe the OH observations if there was a "heating" process to cause an expansion of the neutral cloud. Because they treated change exchange as a loss process, they suggested that ion-neutral momentum transfer collisions expand the cloud of water molecules emitted from their proposed source, the sputtering of small grains co-orbiting with Enceladus. Since charge-exchange collisions dominate momentum transfer collisions, here we show that the principal loss process for the gases emitted from Enceladus, charge exchange in the Enceladus torus, produces the expanded secondary torus.

The Enceladus vents could, in principal, directly populate the *HST* torus if the ejecta speeds were large. Based on the model expressions above and on sample simulations, an average speed of ~2.5 km s^{-1} and isotropic ejection could produce a radial extent roughly consistent with the OH torus. For primarily south polar ejection, a larger speed, ~4 km s^{-1}, is required to very roughly produce the radial width of the OH cloud. However, such ejecta speeds correspond to source temperatures much higher than those expected, requiring the material to be in contact with a subsurface magma, as is the case at the much larger Jovian moon Io. Although the interior of the small icy moon Enceladus is not well understood, temperatures of the order of or less than the melting temperature of ice, like that used here, are more likely (Porco et al. 2006; Hansen et al. 2006; Waite et al. 2006).

The presence of toroidal atmospheres, associated with the giant outer solar system planets, remains an exciting research area. The material populating such tori is derived from the satellites and rings embedded in the giant planet magnetospheres, as describe here for the narrow Enceladus torus and the torus observed in OH by *HST*. Therefore, we have recently proposed that such features might also be detectable on extrasolar giant planets, allowing us to learn about the presence and nature of satellites or rings on such bodies (Johnson & Huggins 2006).

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