

## Saturn's neutral torus versus Jupiter's plasma torus

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[1] With the recent discovery of an atmospheric plume of H<sub>2</sub>O it is thought that Enceladus could deliver as much as 300 kg/s of neutral gas to Saturn's inner magnetosphere. Io is the source of roughly 1 ton/s of sulfur and oxygen gas at Jupiter. Despite the apparent similarity, the neutral/ion ratio at Saturn is 3 orders of magnitude higher than at Jupiter. We explore the flow of mass and energy at Saturn and Jupiter using a simplified homogeneous physical chemistry model to understand why these two systems are so different. Our results suggest that ionization at Saturn is fundamentally limited by the slower corotational flow velocity at Enceladus, resulting in a factor of 4 lower ion pickup temperature. The net result of cooler ions at Enceladus is a cooler thermal electron population ( $\sim 2$  eV) that is insufficient to generate significant ionization. **Citation:** Delamere, P. A., F. Bagenal, V. Dols, and L. C. Ray (2007), Saturn's neutral torus versus Jupiter's plasma torus, *Geophys. Res. Lett.*, *34*, L09105, doi:10.1029/2007GL029437.

### 1. Introduction

[2] Io delivers  $\sim 1$  ton/s of neutral gas to Jupiter's inner magnetosphere (e.g., see models by *Shemansky* [1988], *Barbosa* [1994], *Schreier et al.* [1998], *Lichtenberg et al.* [2001], and *Delamere and Bagenal* [2003]). The neutral gas is ionized and the resulting plasma forms a dense, UV-emitting torus (see review by *Bagenal et al.* [2004]). Recent calculations by *Jurac and Richardson* [2005] suggest that Enceladus delivers  $\sim 300$  kg/s of neutral gas to Saturn's magnetosphere, but unlike Jupiter only a small fraction is ionized, leading to a neutral dominated inner magnetosphere. The neutral source rates differ by less than an order of magnitude yet the neutral to ion ratio at Saturn is nearly 3 orders of magnitude larger than at Jupiter. We present a highly simplified model of mass and energy flow at Saturn and Jupiter to understand why these two systems are so different.

[3] Prior to the Cassini mission, our knowledge of the internal processes that may influence Saturn's magnetosphere were based on in situ measurements made by Pioneer 11 (1979), Voyager 1 (1980) and 2 (1981), and more recent observations using the Hubble Space Telescope. The early work of *Frank et al.* [1980], *Lazarus and McNutt* [1983], *Sittler et al.* [1983], *Richardson* [1986], *Richardson et al.* [1986], *Richardson and Eviatar* [1988], *Richardson and Sittler* [1990], and *Gan-Baruch et al.* [1994] described the plasma temperature, density, velocities and thermal anisotropies along the spacecraft trajectories. Plasma

composition could not be uniquely determined by Voyager. Neutral populations were also poorly determined until HST observations revealed an abundance of OH at  $4.5 R_S$  [*Shemansky et al.*, 1993]. This observation drastically altered our understanding of Saturn's inner magnetosphere from plasma dominated to neutral dominated. *Richardson et al.* [1998] modeled the plasma/neutral interactions and concluded that the observed OH brightness was consistent with an H<sub>2</sub>O source of  $1.4 \times 10^{27} \text{ s}^{-1}$  and OH densities in excess of  $700 \text{ cm}^{-3}$  at  $4.5 R_S$ . However, the most recent self-consistent neutral cloud and plasma transport models of *Jurac and Richardson* [2005] suggest that the total neutral source for the inner magnetosphere is  $10^{28} \text{ H}_2\text{O s}^{-1}$ , and that 82% of the total source comes from Enceladus/E ring.

[4] The Cassini magnetometer detected a highly asymmetric plasma interaction at Enceladus during an initial distant flyby [*Dougherty et al.*, 2006]. Subsequent flybys confirmed an atmospheric plume near the icy moon's south pole and preliminary studies suggest a total neutral source rate ranging from as little as  $0.1 \times 10^{27} \text{ H}_2\text{O s}^{-1}$  to as much as  $8 \times 10^{27} \text{ H}_2\text{O s}^{-1}$  [*Hansen et al.*, 2006; *Waite et al.*, 2006; *Tokar et al.*, 2006; *Jurac and Richardson*, 2005].

[5] In this paper, we explore the flow of mass and energy at Saturn and Jupiter using a simplified homogeneous physical chemistry model based on work by *Delamere and Bagenal* [2003]. The previous models of *Jurac and Richardson* [2005] and *Richardson et al.* [1998] only considered mass flow and used observational constraints to specify ion and electron temperatures. Our discussion is focused on understanding why Saturn's inner magnetosphere is dominated with neutral gas by considering the self-consistent flow of both mass and energy.

### 2. Model for the Flow of Mass and Energy

[6] We have developed a homogeneous (i.e., 0-D, "one-box"), time-dependent model of Io plasma torus physical chemistry for the purpose of investigating the sensitivity of torus composition to the following parameters: neutral source rate ( $S_n$ ), O/S source ratio (O/S), plasma transport loss ( $\tau$ ), hot electron fraction ( $f_{eh}$ ), and hot electron temperature ( $T_{eh}$ ). A detailed description of the model is provided by *Delamere and Bagenal* [2003]. The model is based largely upon several earlier models [*Shemansky*, 1988; *Barbosa*, 1994; *Schreier et al.*, 1998; *Lichtenberg et al.*, 2001], but uses the latest CHIANTI atomic physics database for computing radiative loss [*Dere et al.*, 1997].

[7] The model calculates the time rate of change of mass and energy for both ions and the core electrons based on the determination of mass and energy sources and losses until a steady state solution is reached. The primary sources of mass and energy are electron impact ionization and charge exchange reactions involving neutral gas. Energy is added

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**Table 1.** Comparison of Mass and Energy Flow at Jupiter and Saturn

	O-based "Saturn"	O-based "Jupiter"	S,O-based Jupiter <sup>a</sup>
<i>Nominal Input Parameters</i>			
Corotation velocity (km/s)	<b>26.4</b>	57.0	57.0
Neutral source <sup>b</sup> , $\dot{S}_n$ ( $10^{-4}$ cm <sup>-3</sup> s <sup>-1</sup> )	4.0	4.0	8.5
Neutral source O/S ratio	$\infty$	$\infty$	1.7
Neutral source (kg/s)	210	210	630
Transport time, $\tau$ (days)	45	45	45
Hot electron fraction, $f_{eh}$ (%)	0.30	0.30	0.30
Hot electron temperature <sup>c</sup> , $T_{eh}$ (eV)	1000	1000	40
<i>Results</i>			
$n_e$ (cm <sup>-3</sup> )	70.5	516	2640
$n_o$ (cm <sup>-3</sup> )	880	60	33
$n_o/n_e$	<b>12.0</b>	0.12	0.012
$T_e$ (eV)	1.3	6.8	4.8
$T_{O^+}$ (eV)	37	150	67
Total power throughput ( $10^{-4}$ eV cm <sup>-3</sup> s <sup>-1</sup> )	0.023	0.12	0.80
<i>Energy Sources (% Total Throughput)</i>			
S ionization	-	-	14
S charge exchange	-	-	8
O ionization	4.5	25	3
O charge exchange <sup>d</sup>	95	70	15
Hot/cold electron thermal coupling	0.5	4.3	60
<i>Internal Thermal Coupling (% Total Throughput)</i>			
Ion-electron thermal coupling	3.5	15	29
<i>Energy Loses (% Total Throughput)</i>			
Fast neutrals	92	59	5
Transport	4.5	22	6
UV ion radiation	0.1	17	89
UV neutral radiation <sup>e</sup>	2.4	0.2	-
Electron impact ionization	<< 1	1.1	-

<sup>a</sup>Based on best fit to Cassini UVIS observations of the Io plasma torus [Steffl *et al.*, 2004b; Delamere and Bagenal, 2003].

<sup>b</sup>The volumetric neutral source assumes an effective uniform torus volume of  $2 \times 10^{31}$  cm<sup>3</sup> and a total neutral source rate of  $8 \times 10^{27}$  s<sup>-1</sup> for the O-based chemistry and  $1.7 \times 10^{28}$  s<sup>-1</sup> for the S, O-based chemistry.

<sup>c</sup>Hot electron temperature of 1000 eV based on Cassini CAPS measurements [Young *et al.*, 2005].

<sup>d</sup>Rate coefficient for resonant charge exchange (i.e.,  $O + O^+ = O^+ + O$ ) at Io,  $k = 1.32 \times 10^{-8}$  cm<sup>3</sup> s<sup>-1</sup> [McGrath and Johnson, 1989] and at Enceladus,  $k = 6.2 \times 10^{-9}$  cm<sup>3</sup> s<sup>-1</sup> [Richardson *et al.*, 1986].

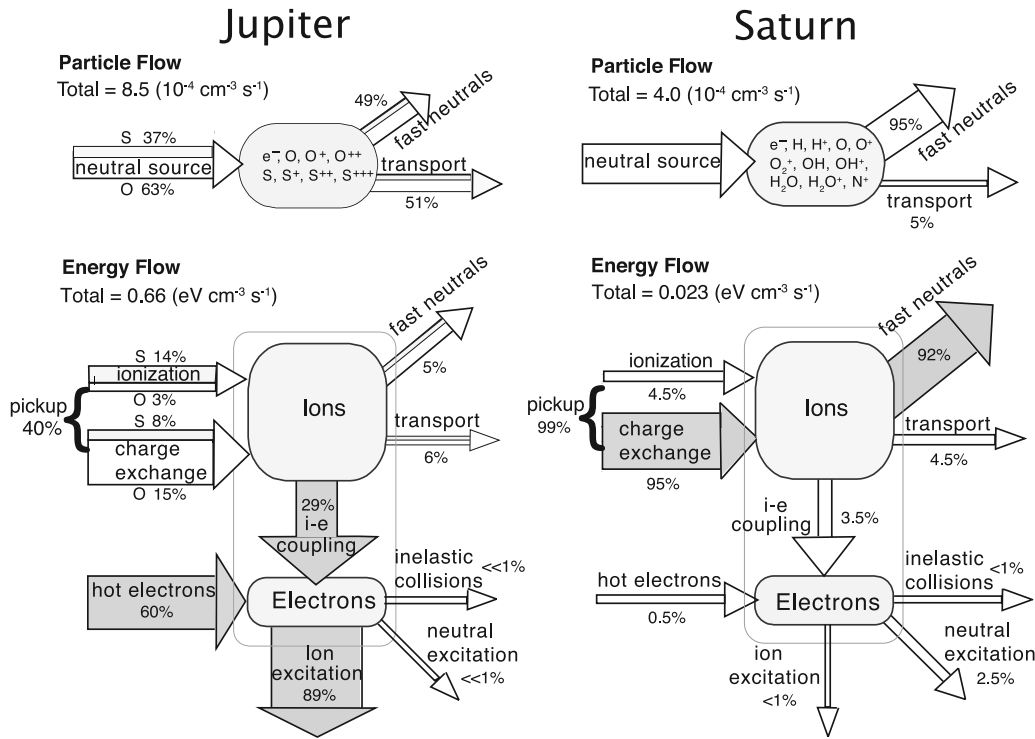
<sup>e</sup>Fixed rate coefficient from Shemansky and Hall [1992] for  $n_e = 31.7$  cm<sup>-3</sup> and  $T_e = 4.0$  eV.

to the system as fresh ions are accelerated to the velocity of the corotating plasma. We do not consider perturbations to the corotating flow by the ion pickup since the required energy and momentum can be extracted from Jupiter's rotation by currents coupling the equatorial plasma to the ionosphere. Charge exchange reactions determine the allocation of energy among the ion species and their respective ionization states. Charge exchange reactions involving neutrals also contribute significantly to the energy budget due to the pickup energy of plasma into the corotating flow. The velocity distribution for each ion species is approximated as Maxwellian. The electrons have a non-thermal component and a  $\kappa$ -distribution is known to best match torus observations [Meyer-Vernet *et al.*, 1995]. We approximate this non-thermal distribution with Maxwellian distributions for each of the core and hot populations. The hot electrons, through coulomb coupling with the core electrons, provide significant energy to the torus ( $\sim 20$ -60%). We assume that the hot electrons derive their energy from Jupiter's rotation and exist as a byproduct of magnetosphere-ionosphere coupling. Major losses of mass include radial plasma transport and fast neutral escape resulting from charge exchange reactions with thermalized ions ( $T_i = 70 - 100$  eV). Roughly 50% of the input energy is transferred from the ions to the electrons via coulomb coupling. Radiation in the (mostly UV) is the

major energy sink. The combination of these sources and sinks of mass and energy lead to an equilibration time scale of  $\sim 40$  days.

### 3. A Simplified Model for Comparing Saturn and Jupiter

[8] At Io's location ( $\sim 6 R_J$ ) the difference between the Keplerian velocity of the neutrals and the corotating magnetic field is  $v_{rel} = 57$  km/s. Ions picked up by the corotating magnetic field acquire a temperature given by the pickup energy assigned to three degrees of freedom, or  $\frac{3}{2}T_{pu} = \frac{1}{2}mv_{rel}^2$ . (We assume that the unstable two-dimensional ring beam distribution of the pickup ions are fully isotropized.) At Enceladus' orbit ( $\sim 4 R_S$ ) the pickup velocity is roughly 26 km/s. Thus the pickup energy for oxygen is 4 times less at Enceladus than at Io. In addition, the SO<sub>2</sub>-based chemistry at Jupiter introduces more massive ions than the H<sub>2</sub>O-based chemistry at Saturn. The ionization rate coefficients vary by roughly two orders of magnitude as a function of electron temperature between 2 and 6 eV. We note that the ionization potential of oxygen is 13.6 eV, so ionization occurs through the high energy tail of the electron distribution. Cooler electrons produce less ionization and we expect



**Figure 1.** Mass and energy flow for (left) the S,O-based Jupiter model and (right) the O-based Saturn model (see Table 1 for values). At Jupiter energy flows primarily from ion pickup and hot electrons to UV radiation (ion excitation), while at Saturn energy flows primarily from ion pickup to fast neutral escape.

the resulting non-linear feedback to result in a neutral-dominated gas torus at Saturn.

[9] To test this hypothesis we have simplified our Io torus model to include only oxygen so that the effect of ion pickup temperature can be isolated. The basic numerical experiment is to mimic conditions near Enceladus in the homogeneous model and then to “move” Enceladus to Io-like conditions in Jupiter’s magnetosphere (i.e., vary the pickup velocity,  $v_{rel}$ , from 26 km/s to 57 km/s). Table 1 gives the model input parameters. We use upper limits for the Enceladus case favoring conditions for generating plasma. For instance, *Jurac and Richardson* [2005] report a neutral source rate of  $8 \times 10^{27} \text{ s}^{-1}$  for Enceladus and the E ring. This is the upper limit with respect to other values found in the literature (see summary given by *Johnson et al.* [2006]). The one-box volume selected for Enceladus is comparable to our one-box volume for the Io plasma torus, or  $V = 2 \times 10^{31} \text{ cm}^3$  [*Delamere and Bagenal*, 2003]. *Johnson et al.* [2006] discuss a narrow Enceladus  $\text{H}_2\text{O}$  torus between 3 and  $5 R_S$ . This toroidal volume is roughly equal to our Jupiter one-box volume which is constrained by total UV emissions from the torus. Together these parameters give a neutral source rate at Io of  $4.0 \times 10^{-4} (\text{cm}^{-3} \text{ s}^{-1})$ , slightly less than our best fit S,O-based torus model for the Cassini era. We feel that this volumetric source rate is likely to be an upper limit for Saturn.

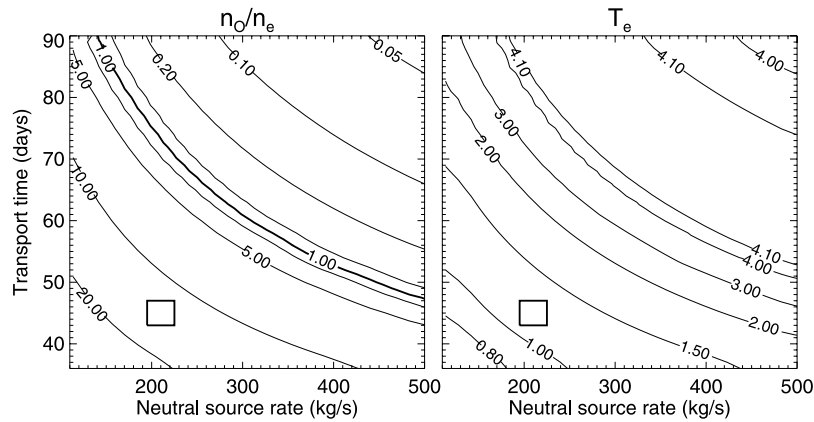
[10] The hot electron fraction and temperature are also constrained by Voyager and Cassini measurements. Our model results for Jupiter during the Cassini era gave  $f_{eh} = 0.3\%$  and  $T_{eh} = 40 \text{ eV}$ . We have selected  $f_{eh} = 0.3\%$  as an upper limit for Saturn. *Richardson and Sittler* [1990] used a hot electron fraction of  $<0.2\%$ , assuming an electron density

at Enceladus of  $100 \text{ cm}^{-3}$  and a hot electron density of  $<0.2 \text{ cm}^{-3}$ . Again, we feel that  $0.3\%$  is a reasonable upper limit resulting in the maximum plasma generation. We use  $T_{eh} = 1000 \text{ eV}$  at Enceladus based on Cassini CAPS measurements [*Young et al.*, 2005], and we note that the results are not sensitive to the hot electron temperature above  $\sim 70 \text{ eV}$ . At Jupiter, the hot electron fraction increases with radius [*Sittler and Strobel*, 1987; *Steffl et al.*, 2004a], but we find that the global-scale properties of the Io torus are largely determined by chemistry in a small radial interval close to Io (i.e.,  $5.9\text{--}6.5 R_J$ ) while the increasing hot electron fraction simply alters the ionization state of the plasma with radius [*Delamere et al.*, 2005]. A similar trend appears at Saturn in the Voyager observations [*Richardson and Sittler*, 1990] and in the Cassini CAPS measurements [*Young et al.*, 2005]. From our experience at Jupiter we infer that it is only the hot electron fraction close to Enceladus that is relevant in determining the large-scale properties of neutral/plasma tori at Saturn.

[11] The radial transport time scale at Saturn may be similar to Jupiter based on the transport diffusion coefficients of *Jurac and Richardson* [2005] for Saturn and *Delamere et al.* [2005] for Jupiter. Both models give comparable diffusion time scales. We have selected a transport loss time scale of 45 days for both Saturn and Jupiter.

#### 4. Results and Discussion

[12] The results are summarized in Table 1, which compares the flow of mass and energy for oxygen-based chemistry at Saturn and Jupiter. We provide, in addition,



**Figure 2.** Sensitivity of neutral to (left) ion ratio and (right) electron temperature to variations in transport time and neutral source rate. The box indicates nominal Saturn conditions.

the results from our sulfur and oxygen-based chemistry model for Jupiter showing the best fit to the Cassini UVIS data of the Io plasma torus [Delamere and Bagenal, 2003; Steffl *et al.*, 2004b]. Figure 1 provides a visual illustration of the flow of mass and energy for the O-based “Saturn” and S, O-based “Jupiter” cases (i.e.,  $v_{rel} = 26.4$  and  $57.0$  km/s respectively).

[13] The results support our hypothesis that the additional pickup energy at Io’s higher pickup velocity results in a plasma dominated torus at Jupiter while for the lower pickup velocity at Saturn the system is neutral dominated. The thermal electron temperature differs by more than a factor of five (1.3 eV versus 6.8 eV). As a result, the ionization at Enceladus is nearly entirely due to the super-thermal electron population. We note that an electron temperature of  $\sim 2$  eV is consistent with Cassini CAPS measurements near Enceladus [Young *et al.*, 2005].

[14] In both cases, resonant charge exchange between O and  $O^+$  provide the dominant energy input. For the Saturn case, resonant charge exchange is the dominant energy sink through fast neutral escape while at Jupiter UV radiation through electron impact excitation of the ions becomes the dominant energy sink. For our O-based “Jupiter” model, fast neutral escape is still significant ( $\sim 59\%$ ), but we note that UV radiation for the full S, O-based chemistry at Jupiter is nearly 90% of the energy output.

[15] Based on our set of “nominal” input parameters for the O-based Saturn and Jupiter models, we have demonstrated that the principle controlling factor is the ion pickup energy. However, we acknowledge that the radial transport rates are poorly constrained. Figure 2 shows the sensitivity of our results to variations in the neutral source rate and radial transport rates. The left plot shows the ratio of neutral to ion density and the right plot shows the electron temperature. The striking result is the abrupt transition from neutral dominated to plasma dominated conditions for long transport time and large neutral source rates. The abrupt transition is due to the non-linear feedback between electron temperature and ion production resulting in a dramatic increase in plasma density for high source or long transport time scales. For our nominal neutral source rate of 210 kg/s, the Saturn system would be plasma dominated for transport time scales longer than  $\sim 75$  days. For a fixed transport time scale of  $\sim 45$  days the source would have to increase to

$>500$  kg  $s^{-1}$  for the Enceladus torus to transition to a plasma-dominated state.

[16] The results presented here should be considered purely as an “order of magnitude” estimate for energy flow since we are using a highly simplified O-based chemistry model. The model focuses on energy flow using ionization of O and resonant charge exchange of O with  $O^+$ . Key elements of the water group chemistry that have been neglected include dissociative recombination of molecular ions at low electron energies. Dissociative recombination may possibly be a significant sink for the plasma component of Saturn’s gas tori as the dissociated products will escape from the system at roughly 26 km/s. In summary, we claim that the O-based chemistry provides a reasonable estimate for energy flow given that ionization rates for molecular water group species are similar [see Richardson *et al.*, 1986, Table 3] and that the mass of the various water group species are obviously similar.

## 5. Conclusions

[17] Our findings are summarized below:

[18] Energy flows from ions to electrons via Coulomb interactions. The slower pickup velocity at Enceladus ( $v_{rel} = 26$  km/s) generates pickup ions with energies  $\sim 4\times$  lower than at Io ( $v_{rel} = 57$  km/s). The ion energy reservoir is critical for maintaining the thermal electron population at a temperature that is sufficient to generate significant ionization. Based on nominal input parameters for Saturn (neutral source rate = 210 kg/s, transport time scale = 45 days, hot electron fraction = 0.3%, hot electron temperature = 1 keV), our results suggest that the key parameter the distinguishes Saturn from Jupiter is the ion pickup temperature.

[19] Our input parameters for Saturn represent upper limits that favor plasma generation (i.e., neutral source rate and hot electron fraction). Reduction of the neutral source rate and/or hot electron fraction will only increase the neutral/ion ratio.

[20] For a fixed neutral source rate of 200 kg/s, the Saturn model predicts an abrupt transition to a plasma-dominated state for transport time scales longer than  $\sim 75$  days due to a non-linear feedback between electron temperature and plasma production.

[21] Similarly, for a fixed radial transport time scale of 45 days, the neutral source would have to increase to



>500 kg s<sup>-1</sup> for the Enceladus torus to transition to a plasma-dominated state.

[22] The addition of the full water group molecular chemistry will introduce an additional plasma sink through dissociative recombination of the molecular ions. Therefore, our simplified O-based chemistry likely represents a lower limit for the neutral/ion ratio.

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## References

- Bagenal, F., T. Dowling, and W. McKinnon (Eds.) (2004), *Jupiter*, Cambridge Univ. Press, New York.
- Barbosa, D. D. (1994), Neutral cloud theory of the Jovian nebula: Anomalous ionization effect of superthermal electrons, *Astrophys. J.*, *430*, 376.
- Delamere, P. A., and F. Bagenal (2003), Modeling variability of plasma conditions in the Io torus, *J. Geophys. Res.*, *108*(A7), 1276, doi:10.1029/2002JA009706.
- Delamere, P. A., F. Bagenal, and A. Steffl (2005), Radial variations in the Io plasma torus during the Cassini era, *J. Geophys. Res.*, *110*, A12223, doi:10.1029/2005JA011251.
- Dere, K. P., E. Landi, H. E. Mason, B. C. M. Fossi, and P. R. Young (1997), CHIANTI—An atomic dataset for emission lines, *Astron. Astrophys. Suppl. Ser.*, *125*, 149.
- Dougherty, M. K., K. K. Khurana, F. M. Neubauer, C. T. Russell, J. Saur, J. S. Leisner, and M. E. Burton (2006), Identification of a dynamic atmosphere at Enceladus with the Cassini magnetometer, *Science*, *311*, 1406–1409, doi:10.1126/science.1120985.
- Frank, L. A., B. G. Burek, K. L. Ackerson, J. H. Wolfe, and J. D. Mihalov (1980), Plasmas in Saturn's magnetosphere, *J. Geophys. Res.*, *85*, 5695–5708.
- Gan-Baruch, Z., A. Eviatar, J. D. Richardson, and R. L. McNutt (1994), Plasma observations in the ring plane of Saturn, *J. Geophys. Res.*, *99*, 11,063–11,078.
- Hansen, C. J., L. Esposito, A. I. F. Stewart, J. Colwell, A. Hendrix, W. Pryor, D. Shemansky, and R. West (2006), Enceladus' water vapor plume, *Science*, *311*, 1422–1425, doi:10.1126/science.1121254.
- Johnson, R. E., H. T. Smith, O. J. Tucker, M. Liu, M. H. Burger, E. C. Sittler, and R. L. Tokar (2006), The Enceladus and OH tori at Saturn, *Astrophys. J.*, *644*, L137–L139, doi:10.1086/505750.
- Jurac, S., and J. D. Richardson (2005), A self-consistent model of plasma and neutrals at Saturn: Neutral cloud morphology, *J. Geophys. Res.*, *110*, A09220, doi:10.1029/2004JA010635.
- Lazarus, A. J., and R. L. McNutt (1983), Low-energy plasma ion observations in Saturn's magnetosphere, *J. Geophys. Res.*, *88*, 8831–8846.
- Lichtenberg, G., N. Thomas, and T. Fouchet (2001), Detection of S (IV) 10.51  $\mu\text{m}$  emission from the Io plasma torus, *J. Geophys. Res.*, *106*, 29,899–29,910.
- McGrath, M. A., and R. E. Johnson (1989), Charge exchange cross sections for the Io plasma torus, *J. Geophys. Res.*, *94*, 2677–2683.
- Meyer-Vernet, N., M. Moncuquet, and S. Hoang (1995), Temperature inversion in the Io plasma torus, *Icarus*, *116*, 202–213.
- Richardson, J. D. (1986), Thermal ions at Saturn: Plasma parameters and implications, *J. Geophys. Res.*, *91*, 1381–1389.
- Richardson, J. D., and A. Eviatar (1988), Observational and theoretical evidence for anisotropies in Saturn's magnetosphere, *J. Geophys. Res.*, *93*, 7297–7306.
- Richardson, J. D., and E. C. Sittler (1990), A plasma density model for Saturn based on Voyager observations, *J. Geophys. Res.*, *95*, 12,019–12,031.
- Richardson, J. D., A. Eviatar, and G. L. Siscoe (1986), Satellite tori at Saturn, *J. Geophys. Res.*, *91*, 8749–8755.
- Richardson, J. D., A. Eviatar, M. A. McGrath, and V. M. Vasyliūnas (1998), OH in Saturn's magnetosphere: Observations and implications, *J. Geophys. Res.*, *103*, 20,245–20,256.
- Schreier, R., A. Eviatar, and V. M. Vasyliūnas (1998), A two-dimensional model of plasma transport and chemistry in the Jovian magnetosphere, *J. Geophys. Res.*, *103*, 19,901–19,914.
- Shemansky, D. E. (1988), Energy branching in the Io plasma torus: The failure of neutral cloud theory, *J. Geophys. Res.*, *93*, 1773–1784.
- Shemansky, D. E., and D. T. Hall (1992), The distribution of atomic hydrogen in the magnetosphere of Saturn, *J. Geophys. Res.*, *97*, 4143–4161.
- Shemansky, D. E., P. Matheson, D. T. Hall, H.-Y. Hu, and T. M. Tripp (1993), Detection of the hydroxyl radical in the Saturn magnetosphere, *Nature*, *363*, 329–331, doi:10.1038/363329a0.
- Sittler, E. C., and D. F. Strobel (1987), Io plasma torus electrons: Voyager 1, *J. Geophys. Res.*, *92*, 5741–5762.
- Sittler, E. C., K. W. Ogilvie, and J. D. Scudder (1983), Survey of low-energy plasma electrons in Saturn's magnetosphere: Voyagers 1 and 2, *J. Geophys. Res.*, *88*, 8847–8870.
- Steffl, A. J., F. Bagenal, and A. I. F. Stewart (2004a), Cassini UVIS observations of the Io plasma torus. II. Radial variations, *Icarus*, *172*, 91–103, doi:10.1016/j.icarus.2004.04.016.
- Steffl, A. J., A. I. F. Stewart, and F. Bagenal (2004b), Cassini UVIS observations of the Io plasma torus. I. Initial results, *Icarus*, *172*, 78–90, doi:10.1016/j.icarus.2003.12.027.
- Tokar, R. L., et al. (2006), The Interaction of the atmosphere of Enceladus with Saturn's plasma, *Science*, *311*, 1409–1412, doi:10.1126/science.1121061.
- Waite, J. H., et al. (2006), Cassini Ion and Neutral Mass Spectrometer: Enceladus plume composition and structure, *Science*, *311*, 1419–1422, doi:10.1126/science.1121290.
- Young, D. T., et al. (2005), Composition and dynamics of plasma in Saturn's magnetosphere, *Science*, *307*, 1262–1266, doi:10.1126/science.1106151.

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