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THE MAGNETOSPHERIC PLASMA–DRIVEN EVOLUTION OF SATELLITE ATMOSPHERES

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ABSTRACT

Atmospheric loss induced by an incident plasma, often called atmospheric sputtering, can significantly alter the volatile inventories of solar system bodies. Based on the present atmospheric sputtering rate, the net loss of nitrogen from Titan in the last 4 Gyr was small, consistent with Titan retaining a component of its primordial atmosphere. However, atmospheric sputtering by the magnetospheric plasma ions and by pickup ions, even at present levels, would have caused the loss of a large, residual Titan-like atmosphere from Io and Europa and a significant fraction of such an atmosphere from Ganymede. At Callisto, higher magnetospheric plasma densities would have been required for the loss of such an atmosphere. Since higher plasma densities were probable in earlier epochs, the evolution of the volatile inventories of each of the Galilean satellites has been profoundly affected by the interaction of their atmospheres with the Jovian magnetospheric plasma.

Subject headings: planets and satellites: formation —
planets and satellites: individual (Callisto, Europa, Ganymede, Io, Titan)

1. INTRODUCTION

Because of its substantial atmosphere, Titan, the largest moon of Saturn and the second largest moon in the solar system, is an important endpoint for understanding the evolution of the volatile inventories of planets and planetary satellites. Although its radius is ∼40% of the Earth's radius and ∼75% of Mars' radius (Table 1), Titan retains an atmosphere with a column density of $\sim 7 \times 10^{27}$ amu cm^{-2}, where amu is the atomic mass unit. This is more than an order of magnitude larger than that of the Earth or Mars (Table 1). Titan's atmosphere is also large as a result of its relatively low gravitational binding energy (Table 1). That is, the exobase altitude, that altitude above which escape occurs efficiently and below which the atmosphere is collisional, is about 60% of the planet's radius (∼1500 km), whereas at the Earth it is ∼6%, and at Mars ∼3%. The relatively large extent and low gravitational escape energy is consistent with Titan losing many of its lighter molecular species. But, in comparison to its mass, Titan has retained a very large atmosphere comparable to that of Venus and almost 2 orders of magnitude larger than that at Earth (Table 1). Understanding the origin and survival of this remarkable atmosphere is a goal of the *Cassini* spacecraft mission, which will launch the *Huygens* probe into Titan's atmosphere in 2005.

Titan's atmosphere, like that of the Earth, is dominated by molecular nitrogen (∼97%), with methane and other hydrocarbons making up most of the remaining atmosphere (Yelle et al. 1997). Its nitrogen component has been suggested to be a radiation product of ammonia that outgassed or was delivered by comets (Hunten et al. 1984). It has also been suggested to be a remnant of a much larger nitrogen atmosphere (Lunine et al. 1999; Lammer et al. 2000). The Galilean satellites of Jupiter are objects of similar size with comparable escape energies (Table 1). However, they have extremely thin atmospheres ($\sim 10^{17}$ molecules cm^{-2}). Evolutionary models often assume that the present volatile inventory of the Galilean satellites is roughly representative of their volatile inventories after formation in the planetary nebula (for reviews see Lunine et al. 2004 and Schubert et al. 2004). Since the evolution of these bodies is still debated (McKinnon & Zolensky 2003), it is important to know whether or not they had an early, dense atmosphere. Here we examine whether a substantial residual atmosphere or a later delivered atmosphere could have been removed by processes occurring at present.

2. ACTIVE ESCAPE PROCESSES

A number of processes determine the evolution of atmospheres on planetary bodies (Hunten 1982). In the first ∼0.5 Gyr of the solar system, the evolution of planet and satellite atmospheres was catastrophic. During this period, postaccretionary outgassing, delivery and removal of atmosphere by impactors, and hydrodynamic escape dominated. Later, volcanism, slow outgassing, or comet delivery determined the rate at which trapped volatiles would have entered the atmosphere. At present, two loss processes determine the evolution of the atmospheres of Titan and the Galilean satellites: direct ejection of atoms and molecules and atmospheric loss by ion formation, followed by pickup and removal. These are induced by the absorption of solar UV and EUV photons and by the bombardment by the incident plasma ions and electrons, and are often referred to as atmospheric sputtering (Johnson 1994). Since they are operating at present, models can be tested by observation. Therefore, it is shown that if after ∼0.5 Gyr any of the Galilean satellites had retained or acquired a Titan-like atmosphere, Io and Europa would have lost it because of the interaction with the Jovian magnetosphere even at present atmospheric escape rates. However, larger magnetospheric plasma densities would have been required early in Jupiter's history for Ganymede and Callisto to have lost such an atmosphere.

Whereas the Galilean satellites orbit well within Jupiter's magnetosphere, Titan orbits near Saturn's magnetopause at a distance of $20.6R_\mathrm{S}$ ($R_\mathrm{S} = 60{,}268$ km, the radius of Saturn). Under present solar conditions, this is typically inside the Saturnian magnetopause. However, when the solar wind pressure is high, Saturn's magnetosphere is compressed, and Titan can be outside of Saturn's magnetosphere and in direct contact with the solar wind for part of its orbit. This was the case more often in the early solar system when the solar wind pressure was higher. Because these satellites have either no intrinsic magnetic fields or, in the case of Ganymede, a small field, plasma ions and electrons trapped in the parent planet's magnetosphere can interact with the molecules near the exobase. This bombardment results in the collisional ejection of atoms

TABLE 1
Atmosphere Parameters

Atmosphere	Escape Energy (eV amu^{-1})	Pressure (bar)	Radius (10^3 km)	mN [a] (10^{27} amu cm^{-2})	M_{at}/M_p [b] (10^{-5})
Mars	0.13	0.08	3.4	0.13	0.049
Earth	0.65	1.0	6.4	0.6	0.087
Venus	0.56	90	6.1	61.0	9.7
Titan	0.036	1.5	2.6	7.0	6.8

[a] Molecular mass in amu times the molecular column density.

[b] Ratio of atmospheric mass to mass of the planet.

and molecules (atmospheric sputtering) and the expansion of the corona (Johnson 1990, 1994). The incident ions and electrons, as well as the EUV photons, also cause ionization and dissociation of atmospheric molecules (Hunten 1982; Cravens et al. 1997). The energetic products from such events add to the expansion of the corona and atmospheric escape (Johnson 1994). Those new ions produced in the expanded corona can be accelerated and picked up by solar wind or magnetospheric fields (Brecht et al. 2000). These pickup ions can be swept away, contributing to atmospheric loss (McGrath & Johnson 1987), but a fraction immediately reimpacts the atmosphere in a feedback process that enhances atmospheric loss (Johnson & Luhmann 1998). When these processes occur on satellites orbiting in a planetary magnetosphere, the loss of atmosphere can populate the magnetospheric plasma. That is, a trapped plasma, formed from ejecta that are subsequently ionized, can build up (Huang & Siscoe 1987; Johnson & McGrath 1993). This results in a second feedback process in which the accumulated plasma reimpacts the exobase, enhancing atmospheric loss, a process well documented at Io (McGrath et al. 2004).

Loss, driven by impacting ions, electrons, and photons, has been described in Monte Carlo simulations (Johnson et al. 2000). That is, photoabsorption and electron and ion impacts result in energetic molecules or molecular fragments whose motion through the atmosphere is tracked. Such models have been used to describe atmospheric loss from Titan (Shematovich et al. 2001; Shematovich et al. 2003), Io (McGrath & Johnson 1987), Europa (Shematovich & Johnson 2001; Shematovich et al. 2004; Leblanc & Johnson 2002), and Mars (Leblanc & Johnson 2002). Such processes also produce a large hydrogen-loss rate at Titan even though hydrocarbons are only a few percent of the atmosphere. Therefore, if, in an earlier epoch, the atmosphere was dominated by lighter, hydrogen-containing species, even larger hydrogen-loss rates would have occurred. However, the loss of hydrogen results in the formation and accumulation of heavier products that are harder to remove, such as nitrogen molecules and hydrocarbons at Titan and oxygen molecules at Europa and Ganymede (Yung & McElroy 1977; Johnson et al. 2003). Therefore, we focus here on the removal of an atmosphere of the heavier molecules, such as the nitrogen retained at Titan.

3. IO AND TITAN

The importance of atmospheric sputtering first became clear at Io (Sieveka & Johnson 1984; McGrath & Johnson 1987). Because of the ability to observe neutral and ion species from Earth, detailed modeling of Io's atmospheric loss has confirmed that sputtering by the incident plasma ions and pickup ion removal dominates atmospheric loss, as indicated in Table 2 (Wilson et al. 2002). The photodissociation-induced loss at Io is a much smaller effect (for a review see McGrath et al. 2004). Since Io has an exobase over much of its surface, we can use the present rates to estimate a lower limit to the net loss of atmosphere throughout Io's history.

Because atmospheric sputtering depends inversely on the escape energy (Johnson 1994), the mass-loss rate is, to first order, independent of the molecular composition. That is, if the species ejected from an early Io were N_2 or O_2 instead of SO_2, the escape energy would be smaller. However, the mass per molecule is also smaller, so that the mass-loss rate would be similar. The most recent estimate of the present loss rate of

TABLE 2
Satellite Parameters

Satellite	Escape Energy (eV amu^{-1})	Orbit[a]	Plasma Pressure Total[b] (10^{-9} N m^{-2})	Photo-induced Loss (4 Gyr)[c] (10^{26} amu cm^{-2})	Sputter Loss (4 Gyr)[d] (10^{26} amu cm^{-2})
Io	0.034	5.9R_J	1800	4.5 (0.06)	2000 (30)
Europa	0.021	9.4R_J	140	4.5 (0.06)	~150 (2)
Ganymede	0.039	15.0R_J	20	4.5 (0.06)	~20 (0.3)
Callisto	0.031	26.4R_J	1.6	4.5 (0.06)	~2 (0.03)
Titan	0.036 (0.024)[e]	20.3R_S	0.16 (0.15)	1.3 (0.02)	0.3 (0.004)

[a] Saturn's radius: $R_S = 6.03 \times 10^4$ km; Jupiter's radius: $R_J = 7.14 \times 10^4$ km.

[b] Sum of plasma ram and thermal pressures and magnetic field pressure (e.g., Johnson 1990, Table 4.1). The parentheses indicate solar wind pressure.

[c] Used global average loss rate for nitrogen from Titan (Shematovich et al. 2003), times 3.4 to scale to Jupiter's orbit and a factor of 3.1 to account for the average increase in the EUV flux between present and 4 Gyr ago (Luhmann et al. 1992). Scaled to the physical surface at Titan. The parentheses indicate the fraction of a Titan-like atmosphere.

[d] For Titan, the present estimates are applied over 4 Gyr evaluated at the physical surface and should be reduced by the fraction of the time that Titan is in the solar wind. For Io, twice the present rate is applied over 4 Gyr. The factor of 2 is half the enhancement for the increased size (~2.5) and reduced escape energy (~1.6) of a Titan-like atmosphere. Europa, Ganymede, and Callisto are scaled to Io by the present plasma pressure. Even though Europa does not have a thick atmosphere, this rough estimate is not very much larger than recent estimates of the pickup plus atmospheric sputtering loss (Saur et al. 1998; Shematovich et al. 2004).

[e] Evaluated at Titan's nominal exobase: $R \sim 4100$ km. For Galilean satellites, the present exobase is either a small fraction of the satellite radius or at the surface.

heavy species is ∼1000 kg s^{-1} (Wilson et al. 2002) or ∼2×10^{29} amu cm^{-2} for 4 Gyr. Correcting for implantation of the bombarding sulfur and oxygen ions reduces the net loss rate by ∼30%–50%. However, if Io had a large Titan-like atmosphere, the net loss rate would increase by the ratio of the area at the exobase to that at the surface (a factor of ∼2.5 at Titan) and by the reduced escape energy (a factor of ∼1.6 at Titan). Therefore, if at some point in time Io had an atmosphere equivalent to that now observed at Titan, atmospheric sputtering would have removed it in ∼0.1 Gyr using present plasma conditions (Table 2). Because of this, the state of Io's volatile inventory after early evolution and cooling of the planetary nebula was likely very different from its present inventory. An atmosphere delivered later by comets would also have been removed rapidly.

In the present epoch, the loss of atmosphere from Titan has been modeled using the *Voyager* observations of the atmosphere and the plasma. If the magnetospheric plasma or solar plasma has access to the exobase, the plasma-induced loss rate can be calculated. This process was initially estimated to be less efficient than the photon-induced loss (Lammer & Bauer 1993; Shematovich & Johnson 2001). The latter includes direct dissociation by the incident photons and the photoelectrons produced as well as dissociation following electron-ion recombination. Recently, an estimate of the local pickup ion flux onto Titan's exobase was used to recalculate the plasma-induced loss rate (Shematovich et al. 2003). Using a description of the plasma-atmosphere interaction (Brecht et al. 2000), the ion-sputtering contribution was found to be comparable to, or larger than, the global photon-induced loss rate (Shematovich et al. 2003). The plasma-atmosphere interaction has three contributions to atmospheric loss: sputtering by the deflected and slowed magnetospheric plasma ions; sputtering by reimpacting pickup ions; and direct pickup ion removal. The contribution due to the slowed and deflected nitrogen ions was shown to be larger than that which would occur if the nitrogen ions impact at corotation speeds and densities. However, the average yield is small for incident H^+ and less than 1 N atom per incident N^+ giving no net loss. Since the atmosphere and ionosphere are molecular at the exobase, sputtering due to the molecular ions that are picked up and reimpact the atmosphere is significant. This, combined with pickup ion loss by sweeping (Hartle et al. 1982; Sitter et al. 2004), results in a net loss of nitrogen (Table 2).

The nitrogen-loss rate due to the incident plasma and pickup was estimated to be ∼1×10^8 amu cm^{-2} s^{-1} when Titan is in the magnetosphere and about half this when it is not (Shematovich et al. 2003; Michael et al. 2004). Assuming similar magnetospheric and solar conditions and correcting for the ratio of the exobase area to the surface area give a net loss of ∼3×10^{25} amu cm^{-2} in 4 Gyr. This is 2 orders of magnitude less than the present content (Michael et al. 2004). Such a small loss rate is consistent with Titan retaining most of its N_2 atmosphere over the last 4 Gyr. The relatively low loss rate is partly due to the larger distance from the Sun and the spatial distribution of the ejected neutrals at its distance from Saturn. However, it is primarily due to the fact that, unlike the situation at Io, the magnetosphere at Titan's orbit does not efficiently confine and build up a large trapped ion density at Titan's orbit. The ability to accumulate and maintain a plasma at Titan is affected in part by the fact that Titan moves into and out of the magnetosphere. It is also affected by the local fields, as indicated by the plasma pressure in Table 2. This quantity is a measure of the ability to accelerate and confine a plasma. Therefore, the local magnetic field properties must be accounted for in order to understand the evolution of the volatile inventory on outer planet satellites.

The solar EUV flux, which is responsible for photon-induced loss, was larger in earlier epochs (Zahnle & Walker 1982). Employing the simple model that was used to describe the loss of Mars' atmosphere, the EUV flux was roughly 6 times the present flux 3.5 Gyr ago and about 3 times the present flux 2 Gyr ago (Luhmann et al. 1992). Based on the present global loss rate, ∼1.3×10^8 amu cm^{-2} s^{-1}, and accounting for the area of the exobase relative to that of the surface, the net loss due to this process for the last 4 Gyr is ∼1×10^{26} amu cm^{-2}. This is still almost 2 orders of magnitude smaller than the present column abundance. The increased loss rate in earlier epochs would have led to enhanced pickup-ion sputtering, but this is a self-limiting process (Johnson & Luhmann 1998). We note that these estimates are inconsistent with the suggestion that Titan's nitrogen atmosphere was initially many times thicker than at present (Lunine et al. 1999; Lammer et al. 2000). The isotope ratio measurements for N_2 by *Cassini* will be able to constrain estimates of the net nitrogen loss.

4. EUROPA, GANYMEDE, AND CALLISTO

Europa, Ganymede, and Callisto have extremely thin atmospheres (∼10^{17} amu cm^{-2}) derived from their surface material. These atmospheres are formed from sublimation of water ice containing trapped volatiles and from radiation-induced decomposition products (Johnson et al. 2004; McGrath et al. 2004). At Callisto, the observed CO_2 atmosphere has been suggested to be a trapped gas evolving from its interior (Moore et al. 1999; Hibbitts et al. 2000), although it might instead be produced radiolytically (Johnson et al. 2000, 2004). Independent of the situation for CO_2, these moons are depleted in volatiles, but it is uncertain whether or not they have a global exobase (McGrath et al. 2004). The sodium observed near Europa appears to escape directly to space from its surface (Leblanc et al. 2002), suggesting that a collisionally thick atmosphere is unlikely. Although the nonalkali component of the Europa torus (Eviatar et al. 1985) has been detected recently (Lagg et al. 2003; Mauk et al. 2003; Hansen et al. 2004), it is not suggestive of a large Io-like loss rate. Therefore, plasma-induced atmospheric sputtering and pickup loss is occurring at Europa (Saur et al. 1998; Shematovich et al. 2004), but likely at a rate smaller than it would be for a collisionally thick atmosphere.

Scaled by the parent planet radius, Callisto is farther from Jupiter, in Jupiter radii, than Titan is from Saturn, in Saturn radii (Table 2), but Titan has retained a large atmosphere and Callisto has not. However, all three icy Galilean satellites orbit much deeper in Jupiter's magnetosphere than Titan does in Saturn's magnetosphere. That is, they reside a considerable distance from the magnetopause and in a region of much higher field strength. In Table 2, the pressures associated with the plasma and fields at each satellite are listed. It is seen that at Titan this pressure is more than 3 orders of magnitude smaller than that at Europa. It is also 1 order of magnitude smaller than that at Callisto, when Titan is within the magnetopause, and 2 orders of magnitude smaller when it is outside. Although the calculation of accurate atmospheric loss rates requires detailed consideration of the molecular physics, this pressure is a measure of the ability to remove atmosphere from an embedded satellite and to contain the ions formed (Table 2). Therefore, a very rough estimate of the net loss rate can be obtained by scaling to Io's loss rate. Based on the ratio of the pressures, the present loss rate from a global, thick Europa atmosphere is ∼10% of that at Io. It is interesting that this is only a factor of 2 larger than recent estimates for Europa's present, very thin atmosphere (Saur et al. 1998; Shematovich et al. 2004). Therefore, ignoring increases in these conditions early in its history, Europa also could have lost a Titan-like atmosphere in 4 Gyr.

This is not the case at Ganymede and Callisto if the present plasma conditions were the same for the last 4 Gyr. That is, the atmospheric loss rates at Ganymede and Callisto based on the present plasma pressures would be about 1% and 0.1%, respectively, of that at Io. Based on this rate and ignoring its intrinsic fields, Ganymede would have lost a significant fraction of a Titan-like atmosphere (∼30%), whereas Callisto would have lost only about 3% (Table 2). The photosputtering rate adds to this. That is, for a Titan-like N_2 atmosphere on a Galilean satellite, the rate is ∼3.4 times that for Titan: about 4×10^{26} amu cm^{-2} in 4 Gyr accounting for the enhanced EUV flux in the earlier epochs. Therefore, based on present rates, the net loss in 4 Gyr from Callisto could be of the order of an Earth-like atmosphere.

5. SUMMARY

The substantial atmosphere of nitrogen on Titan suggests that the present volatile inventories of the Galilean satellites, which are comparable in size, might not be representative of their early volatile inventories. Here the results of recent models of atmospheric loss from Titan, Io, and Europa are used to estimate the net atmospheric loss for the last 4 Gyr. Based on present rates, Titan would not lose a significant fraction of its present atmosphere in this time period because of the low magnetospheric plasma density. However, an atmosphere much larger than that observed at Titan could have been removed from Io, an atmosphere equivalent to that at Titan could have been removed from Europa, and a significant fraction of such an atmosphere could have been removed from Ganymede based on present atmospheric sputtering rates. This is not the case for Callisto, although it also would have lost a large atmospheric column using present conditions and an enhanced EUV flux in the early solar system. However, if the Galilean satellites had large atmospheres in an earlier epoch, the net plasma supply rate to the Jovian magnetosphere would have been much larger than at present. Since, unlike Titan at Saturn, these bodies lie deep in the Jovian magnetosphere, larger plasma densities would have accumulated, enhancing the atmospheric sputtering rate. This feedback process (Huang & Siscoe 1987; Johnson & McGrath 1993), which depends on a number of uncertain plasma-loss rates, is not considered here. However, it is clear that the atmospheric sputtering rates of the Galilean satellites could have been larger than the estimates in Table 2. Therefore, the present volatile inventory of these bodies is not likely to be representative of that inventory ∼4 Gyr ago, so that evolutionary models for these moons must account for their magnetospheric environment.

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REFERENCES

Brecht, S. H., Luhmann, J. G., & Larson, D. J. 2000 J. Geophys. Res., 105, 13119

Cravens, T. E., Keller, C. N., & Ray, B. 1997, Planet. Space Sci., 45, 889

Eviatar, A., Bar-Nun, A., & Podolak, M. 1985, Icarus, 61, 185

Hansen, C. J., Shemansky, D. E., & Hendrix, A. R. 2004, Icarus, submitted

Hartle, R. E., Sittler, E. C., Jr., Ogilvie, K. W., Scudder, J. D., Lazarus, A. J., & Atreya, S. K. 1982, J. Geophys. Res., 87, 1383

Hibbitts, C. A., McCord, T. B., & Hansen, G. B. 2000, J. Geophys. Res., 105, 22541

Huang, T. S., & Siscoe, G. L. 1987, Icarus, 70, 366

Hunten, D. M. 1982, Planet. Space Sci., 30, 773

Hunten, D. M., Tomasko, M. G., Flaser, F. M., Samuelson, R. E., Strobel, D. F., & Stevenson, D. J. 1984, in Saturn, ed. T. Gehrels & S. Matthews (Tucson: Univ. Arizona Press), 671

Johnson, R. E. 1990, Energetic Charged Particle Interaction with Atmospheres and Surfaces (New York: Springer)

———. 1994, Space Sci. Rev., 69, 215

Johnson, R. E., Carlson, R .W., Cooper, J. W., Paranicas, C., Moore, M. H., & Wong, M. 2004, in Jupiter—The Planet, Satellites, and Magnetosphere, ed. F. Bagenal, T. Dowling, & W. B. McKinnon (Cambridge: Cambridge Univ. Press), in press

Johnson, R. E., & Luhmann, J. G. 1998, J. Geophys. Res., 103, 3649

Johnson, R. E., & McGrath, M. A. 1993, Geophys. Res. Lett., 20, 1735

Johnson, R. E., Quickenden, T. I., Cooper, P. D., McKinley, A. J., & Freeman, C. G. 2003, Astrobiology, 3, 823

Johnson, R. E., Schnellenberger, D., & Wong, M. C. 2000, J. Geophys. Res., 105, 1659

Lagg, A., Krupp, N., Woch, J., & Williams, D. J. 2003, Geophys. Res. Lett., 30, 10-1

Lammer, H., & Bauer, S. J. 1993, Planet. Space Sci., 41, 657

Lammer, H., Stumptner, W., Molina-Cuberos, G. J., Bauer, S. J., & Owen, T. 2000, Planet. Space Sci., 48, 529

Leblanc, F., & Johnson, R. E. 2002, J. Geophys. Res., 107, 5-1

Leblanc, F., Johnson, R. E., & Brown, M. E. 2002, Icarus, 159, 132

Yung, Y. L., & McElroy, M. B. 1977, Icarus, 30, 97

Luhmann, J. G., Johnson, R. E., & Zhang, M. H. G. 1992, Geophys. Res. Lett., 19, 2151

Lunine, J. I., Coradini, A., Gautier, D., Owen, T. C., & Wuchterl, G. 2004, in Jupiter—the Planet, Satellites, and Magnetosphere, ed. F. Bagenal, T. Dowling, & W. B. McKinnon (Cambridge: Cambridge Univ. Press), in press

Lunine, J. I., Yung, Y. L., & Lorenz, R. D. 1999, Planet. Space Sci., 47, 1291

Mauk, B. H., Mitchell, D. G., Krimigis, S. M., Roelof, E. C., & Paranicas, C. P. 2003, Nature, 421, 920

McGrath, M. A., & Johnson, R. E. 1987, Icarus, 69, 519

McGrath, M. A., Lellouch, E., Strobel, D. F., Feldman, P. D., & Johnson, R. E. 2004, in Jupiter—the Planet, Satellites, and Magnetosphere, ed. F. Bagenal, T. Dowling, & W. B. McKinnon (Cambridge: Cambridge Univ. Press), in press

McKinnon, W. B., & Zolensky, M. E. 2003, Astrobiology, 3, 879

Michael, M., Johnson, R. E., Liu, M., Luhmann, J. G., & Shematovich, V. I. 2004, Icarus, submitted

Moore, J. M., et al. 1999, Icarus, 140, 294

Saur, J., Strobel, D. F., & Neubauer, F. M. 1998, J. Geophys. Res., 103, 19947

Schubert, G., Anderson, J. D., Spohn, T., & McKinnon, W. B. 2004, in Jupiter—the Planet, Satellites, and Magnetosphere, ed. F. Bagenal, T. Dowling, & W. B. McKinnon (Cambridge: Cambridge Univ. Press), in press

Shematovich, V. I., & Johnson, R. E. 2001, Adv. Space Res., 27, 1881

Shematovich, V. I., Johnson, R. E., Cooper, J. F., & Wong, M. C. 2004, Icarus, submitted

Shematovich, V. I., Johnson, R. E., Michael, M., & Luhmann, J. G. 2003, J. Geophys. Res., 108, 5087

Shematovich, V. I., Tully, C., & Johnson, R. E. 2001, Adv. Space Res., 27, 1875

Sieveka, E., & Johnson, R. E. 1984, ApJ, 287, 418

Sitter, E. C., et al. 2004, Icarus, submitted

Wilson, J. K., Mendillo, M., Baumgardner, J., Schneider, N. M., Trauger, J. T., & Flynn, B. 2002, Icarus, 157, 476

Yelle, R. V., Strobel, D., Lellouch, F. E., & Gautier, D. 1997, in *Huygens*: Science, Payload and Mission, ed. A. Wilson (ESA SP-1177; Noordwijk: ESA), 243

Zahnle, K. J., & Walker, J. G. C. 1982, Rev. Geophys. Space Phys., 20, 280