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 pick-up ions, even at present levels, would have caused the loss of a large, residual Titan-like atmosphere from Io and Europa and a signifcant 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: pleanets and satellites: formation — planets and satellites: indvidual: (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 end point 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 I), Titan retains an atmosphere with a column density ~7 x10^{27} u/cm^2, where u is the atomic mass unit. This is more than an order of magnitude larger than that of the Earth or Mars (Table I). Titan's atmosphere is also large due to its relatively low gravitational binding energy (Table I). 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 ($\sim$1500 km) whereas at the Earth it is $\sim$6% and at Mars $\sim$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 two orders of magnitude larger than that at Earth (Table I). Understanding the origin and survival of this remarkable atmosphere is a goal of the Cassini Spacecraft 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 ($\sim$97%) with methane and other hydrocarbons making up most of the remaining atmosphere (Yelle et al. 1997). Its nitrogen component has been suggested to be a radiation product of ammonia that out-gassed or was delivered by comets (Hunten et al. 1984). It has also been suggested to be a remnant of a much larger nitrogen atmosphere (Lunine et al. 1999; Lammer et al. 2000). The Galilean satellites of Jupiter are objects of similar size with comparable escape energies (Table I). However, they have extremely thin atmospheres ($\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); Schubert et al. (2004)). Since the evolution of these bodies is still debated (McKinnon 2003), it is important to know whether 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 $\sim$0.5 Gyr of the solar system, the evolution of planet and satellite atmospheres was catastrophic. During this period, post-accretionary outgassing, delivery and removal of atmosphere by impactors, and hydrodynamic escape dominated. Later, volcanism, slow out-gassing 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 pick-up 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 due to 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 20.6 R_s [R_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 collisional ejection of atoms and molecules (atmospheric sputtering) and 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 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 pick-up ions can be swept away, contributing to atmospheric loss (McGrath & Johnson 1987), but a fraction immediately re-impact 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 re-impacts 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, photo-absorption 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, 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 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 pick-up ion removal dominates atmospheric loss, as indicated in Table II (Wilson et al. 2002). The photo-dissociation-induced loss at Io is a much smaller effect [for a review see McGrath et al. (2004)]. Since Io has an exobase over much 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 mass loss rate would be similar. The most recent estimate of the present loss rate of heavy species is $\sim$1000kg/s (Wilson et al. 2002) or $\sim$2 x10^{29} [u/cm^2] for 4Gyr. Correcting for implantation of the bombarding sulfur and oxygen ions reduces the net loss rate by $\sim$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 $\sim$2.5 at Titan) and by the reduced escape energy (a factor of $\sim$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 $\sim$0.1 Gyr using present plasma conditions (Table II). 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 photo-electrons produced, as well as dissociation following electron-ion recombination. Recently, an estimate of the local pick-up 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 re-impacting pick-up ions; and direct pick-up 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 co-rotation speeds and densities. However, the average yield is small for incident H^+ and less than one 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 re-impact the atmosphere is significant. This, combined with pick-up ion loss by sweeping (Hartle et al. 1982; Sitter et al. 2004), results in a net loss of nitrogen (Table II).

The nitrogen loss rate due to the incident plasma and pick-up was estimated to be $\sim$1 x10^8 u/(cm^2/s) 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 gives a net loss of $\sim$3 x10^{25} u/cm^2 in 4 Gyr. This is two 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 II. 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-induce loss, was larger in earlier epochs (Zahnle and Walker 1982). Employing the simple model that was used to describe the loss of Mars' atmosphere, the EUV flux was roughly six times the present flux 3.5 Gyrs ago and about three times the present 2 Gyrs ago (Luhmann et al. 1992). Based on the present global loss rate, $\sim$ 1.3 x 10^8 u/cm^2/s, 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 $\sim$1 x10^{26} u/cm^2. This is still almost two orders of magnitude smaller than the present column abundance. The increased loss rate in earlier epochs would have led to enhanced pick-up-ion sputtering, but this is a self-limiting process (Johnson & Luhmann 1998). We note that these estimates are inconsistent with 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 ($\sim 10^{17}$ u/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 they have a global exobase (McGrath et al. 2004). The sodium observed near Europa appears to escape directly to space from its surface (Leblanc & Johnson 2002) suggesting that a collisionally thick atmosphere is unlikely. Although the non-alkali component of the Europa torus (Eviatar et al. 1985) has been detected recently (Lagg 2003; Mauk 2003) it is not suggestive of a large Io-like loss rate. Therefore, plasma-induced atmospheric sputtering and pick-up loss is occurring at Europa (Saur 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 further from Jupiter, in Jupiter radii, than Titan is from Saturn, in Saturn radii (Table II), 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 II, the pressures associated with the plasma and fields at each satellite are listed. It is seen that at Titan this pressure is more than three orders of magnitude smaller than that at Europa. It is also one order of magnitude smaller than that at Callisto, when Titan is within the magnetopause, and two 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 II). 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 two larger than recent estimates for Europa's present, very thin atmosphere (Saur 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 4Gyr. 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 II). The photo-sputtering 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 x 10^{26} u/cm^2 in 4 Gyr accounting for the enhanced EUV flux in the earlier epochs. Therefore, based on present rates, the net loss in 4Gyr 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 4Gyr. Based on present rates, Titan would not lose a significant fraction of its present atmosphere in this time period due to 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 II. Therefore, the present volatile inventory of these bodies is not likely to be representative of that inventory $\sim$4 Gyrs ago, so that evolutionary models for these moons must account for their magnetospheric environment.

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Table 1: Atmosphere Parameters

	Escape Energy (eV/u)	Pressure (bar)	Radius (10^3km)	mN[(1)] (10^{27}u/cm^2)	Mat/Mp[(2)] (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

[(1)] Molecular mass in amu times the molecular column density.

[(2)] Ratio of atmospheric mass to mass of the planet.

Table 2: Satellite Parameters

	Escape Energy (eV/u)	Orbit[2]	Plasma Pressure Total[3] (10^{-9}N/m^2)	Photo-induced Loss 4Gyr[4] (10^{26}u/cm^2)	Sputter Loss 4Gyr[5] (10^{26}u/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)[1]	20.6R_S	0.16 (0.15)	1.3 (0.02)	0.3 (0.004)

(1) Evaluated at Titan's nominal exobase: R∼4100km. For Galilean satellites, the present exobase is either a small fraction of the satellite radius or at the surface.

(2) Saturn's radius: R_S=6.03x10^4km; Jupiter's radius: R_J = 7.14x10^4km

(3) Sum of plasma ram and thermal pressures and magnetic field pressure(e.g., Johnson 1990: Table 4.1) Brackets:Solar wind pressure

(4) 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 4Gyr ago (Luhmann et al. 1992). Scaled to the physical surface at Titan. Brackets: fraction of a Titan-like atmosphere.

(5) For Titan: present estimates applied over 4Gyr evaluated at the physical surface; should be reduced by the fraction of the time that Titan is in the solar wind. For Io: twice present rate applied over 4 Gyr. Factor of two is half the enhancement for the increased size (∼2.5) and reduced escape energy (∼1.6) of a Titan-like atmosphere. For Europa, Ganymede and Callisto: 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 pick-up plus atmospheric sputtering loss (Saur et al. 1998; Shematovich et al. 2004)