An update on the ring exosphere and plasma disc of Saturn

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[1] A re-examination of the mass budget of the ring exosphere of Saturn – as prompted by the most recent Cassini measurements in the vicinity of the ring system - indicates that the corresponding number density could reach the level of 2–3 $\times$ 10^5 cm^{-3} at maximum. Such extended exospheric structure in equilibrium with a thin ring plasma disc could be an important supplier of suprathermal oxygen ions of a few tens of keV in the Saturnian magnetosphere.
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1. Introduction

[2] One unique feature of the Saturnian system is its rings of large dimension. The study of its origin and evolution is a key objective of the Cassini-Huygens mission. Besides the dynamics and orbital structures of the numerous ring particles, the possible existence of a thin layer of ring atmosphere has been investigated since the Voyager flyby observations [*Ip*, 1984a, 1995]. There are good reasons to believe that the ring system should be embedded within a gas cloud. First, the ring system must be constantly bombarded by interplanetary meteoroids, interstellar dust, and solid grains of satellite origin. Such high-velocity impacts will undoubtedly generate a population of particulate ejecta and vapour gas [*Koschny*, 1997]. Some of these ejecta and collisional fragments will be recycled back to the rings via ballistic transport [*Ip*, 1984b; *Cuzzi and Durisen*, 1990]. Different investigators have given estimates to the total mass erosion rates ranging from 5.8 $\times$ 10^4 g s^{-1} to 2.2 $\times$ 10^6 g s^{-1} [*Morfill et al.*, 1983; *Ip*, 1984a]. If a significant fraction of the impact ejecta is in gaseous form, say H_2O vapour, the ring plane should indeed be covered by a layer of tenuous exosphere. Because of photodissociation and possibly electron impact dissociation, the H_2O molecules will in turn lead to the formation of H_2 and O_2 molecules via gas-surface reactions.

[3] Assuming a production rate of Q(H_2O) of 5 $\times$ 10^{27} molecules s^{-1} or 1.5 $\times$ 10^5 g s^{-1} and a sticking coefficient of unity for the water molecules on the surface of the icy ring particles, the average number density of the O_2 molecules in the vicinity of the ring plane was derived to be n(O_2) $\sim$ 3 $\times$ 10^3 molecules cm^{-3} [*Ip*, 1995]. Since O_2 molecules would not condense on the surface of the ring particles, they will remain in the gas cloud. Note that in the post-Voyager estimate by *Ip* [1995], it was assumed that after photodissociation with a rate of 4.2 $\times$ 10^{-8} s^{-1}, the oxygen atomic fragments of the O_2 molecules will be immediately lost. In fact, the photolytic excess energy of 1.3 eV [*Huebner and Carpenter*, 1979] will not be sufficient to eject the oxygen atomic products away from the ring system. They will therefore be recycled and form O_2 molecules again. Even photoionization will not lead to immediate loss except for the region inside the C ring [*Ip*, 1983a]. The photoions (O_2^+) will gyrate around the magnetic field and tend to reimpact the ring particles when crossing the magnetic equator. With such recycling mechanisms taken into consideration, the actual number density of the O_2 molecules in the ring atmosphere could be orders of magnitude more than the value of 3 $\times$ 10^3 cm^{-3} as computed before. A complementary mechanism investigated by R. E. Johnson et al. (Production, ionization, and redistribution of Saturn's O_2 ring atmosphere, submitted to *Geophysical Research Letters*, 2005) is connected with the photosynthesis of water ice into O_2 molecules by solar ultraviolet radiation. This specific mechanism has the advantage that its efficiency could be carefully tested by laboratory experiments. The new measurements above the ring plane by the plasma and ion mass spectrometer instruments onboard the Cassini spacecraft during the Saturn Orbit Insertion have shown clearly the presence of a population of O^+ and O_2^+ ions above the B ring with number densities of around 2 cm^{-3} [*Waite et al.*, 2005; *Young et al.*, 2005; *Tokar et al.*, 2005]. While this finding is consistent with the prediction of the formation of a ring atmosphere of O_2 molecules [*Ip*, 1995], it is nevertheless important to re-evaluate the relative contributions from different source mechanisms. This is because - as discussed below - the ring atmosphere and the associated plasma cloud could have interesting implications on the ring dynamics and the Saturnian magnetosphere as a whole. In this work, the sizes of the impact-driven ring atmosphere and the associated "ionosphere" will be re-examined in Section 2. In addition, we will examine the scenario on how the ring gas and plasma could have direct consequences on the dynamics and composition of the energetic charged particles in the Saturnian magnetosphere (see Section 3). A discussion on the general picture of neutral water gas cloud in the Saturnian system is given in Section 4.

2. The Ring Exosphere and Plasma Disc

[4] The magnetometer measurements by the Pioneer 11 and Voyager spacecraft showed that Saturn's magnetic field can be best described by an axisymmetric octupole model with a northern off set of the plane of minimum magnetic field by about 0.04R_s [*Connerney et al.*, 1984]. This suggested that there might exist a disc-shape storage zone with a total thickness of nearly 0.1 planetary radii. For example, *Ip* [1983a] has linked such an equatorially confined plasma population to the detection of a small scale height ($\sim$0.2 R_s) of the thermal ions by the plasma instrument on Voyager 2 at a radial distance of about 3 R_s [*Stone*

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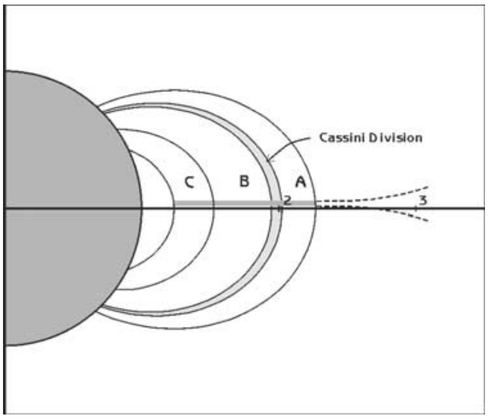

Figure 1. A schematic view of the structure of the thin plasma disc located just above the Saturnian ring plane. The empty space of the Cassini Division might permit the formation of a storage ring of "ring plasma" and the planetary ionospheric plasma. The outward diffusion of the ring plasma of oxygen composition would merge with the plasma disc in the inner magnetosphere.

and Miner, 1982]. Such a thin plasma disc could be partly result from the outward diffusion of the ring plasma stored above the ring plane. Assuming then the existence of a ring plasma disc composed of the water group ions and the oxygen ions derived from the ring oxygen exosphere, the question to ask is what is the ion density. Or we could turn the question around by asking what should be the number density of the neutral oxygen if charge exchange and electron dissociative recombination are the main loss effects. At equilibrium with the neutral production balanced by the loss, we have the following relations for the neutral and ion number densities: $\varepsilon Q = \alpha n_i^2 V = n_o (1/\tau_i + k n_i)V$, where n_o and n_i are the number densities of the neutrals and ions, respectively, α is the electron dissociatrive recombination coefficient, k is the rate constant of charge exchange process involving O^+ and O_2^+ ions, τ_i is the photoionization time, and finally ε is the integrated efficiency of conversion of H_2O into O_2 by photochemistry and surface chemistry. This value is mainly determined by the ratio of the Keplerian periods ($t_K \sim 5.4 \times 10^4$ s) of the emitted H_2O molecules in the impact vapor cloud and the photodissociation time ($t_D \sim 10^7$ s) of H_2O. With a unity coefficient for the H_2O molecules and an average optical depth of $\langle\tau\rangle \sim 1$, $\varepsilon \sim 5.4 \times 10^{-3}$ [*Ip*, 1995]. On the other hand, if the H_2O molecules would stick to the icy surface of a ring particle only after a few bounces and that the A ring where $\langle\tau\rangle \sim 0.2$ is the major source of the gas cloud because of the collisional impact process with the stray E-ring dust particles, ε could be increased by a factor of 10–20. This new estimate will make a difference as discussed below.

[5] With $\tau_i \sim 2.0 \times 10^8$ sec, $\alpha \sim 10^{-7}$ cm^3 s^{-1} (for O_2^+ ions) and $k \sim 10^{-10}$ cm^3 s^{-1}, we now obtain $n_i = (\varepsilon Q/\alpha V)^{1/2} \sim 180$ cm^{-3} and $n_o \sim 1.8 \times 10^5$ cm^{-3} for $\sqrt{\varepsilon} \sim 0.33$ and $V \sim 2 \times 10^{29}$ cm^{-3}. On the other hand, if the ring plasma is dominated by O^+ ions, we have $\alpha \sim 10^{-12}$ cm^3 s^{-1} and $n_i \sim 5.3 \times 10^4$ cm^{-3} and $n_o \sim 530$ cm^{-3}. In comparison, taking the empirical electron density model of *Bridge et al.* [1982] with $n_e L^3 \sim 2.4 \times 10^3$ cm^{-3} in the inner plasma sheet (L ~ 4–7.5 in unit of R_s) and extrapolating to the ring region with L ~ 2, we have $n_i \sim 300$ cm^{-3}. This is an interesting result because, first, it relates the neutral number density to the ion density in the ring plasma disc; and, second, if the Voyager 2 thermal electron measurements [*Bridge et al.*, 1982] could be used as a guide, the ring plasma density for the O_2^+-dominated case should be on the order of $n_i \sim 180–300$ cm^{-3} and $n_o \sim 1.8–3.5 \times 10^5$ cm^{-3} above and below the ring plane. The Cassini measurements near the ring plane crossing showed an ion number density of a much smaller value ($n_i \sim 4$ cm^{-3}) according to *Young et al.* [2005]. But the ion population detected high above the ring plane could be simply the tip of the iceberg with the bulk of the ring ions being stored in a flat plasma disc as discussed before [see *Ip*, 1983b]. An re-examination here suggests that both the exospheric density and plasma content could be substantially larger than previous estimates.

3. Extended Neutral Cloud

[6] Since the A ring is subject to continuous impact erosion by the charged dust in the extended E ring [*Horanyi et al.*, 1992; *Hamilton and Burns*, 1993], we expect its outer region to be an important source region of neutral gas and water-group ions. Because of its low ring mass density, the Cassini Division with radial distance between 1.949 R_s and 2.023 R_s from the center of Saturn could be enriched in neutral gas and corotating thermal ions forming a sort of storage ring. Besides the oxygen ions of ring exospheric origin, the Saturnian ionosphere could also inject a flux of photoelectrons and protons into the corresponding L shell (see Figure 1). The stored ions will be subjected to charge exchange (CX) loss and electron dissociatve recombination (EDR) loss such as $O_2^+ + e \rightarrow O + O$. Such a predicted feature of plasma storage ring in the vicinity of the Cassini Division has indeed been observed by the ELS (Electron Spectrometer) instrument of the CAPS experiment [*Coates et al.*, 2005].

[7] The neutral atoms and molecules created in the CX and EDR processes will be ejected into ballistic orbits not

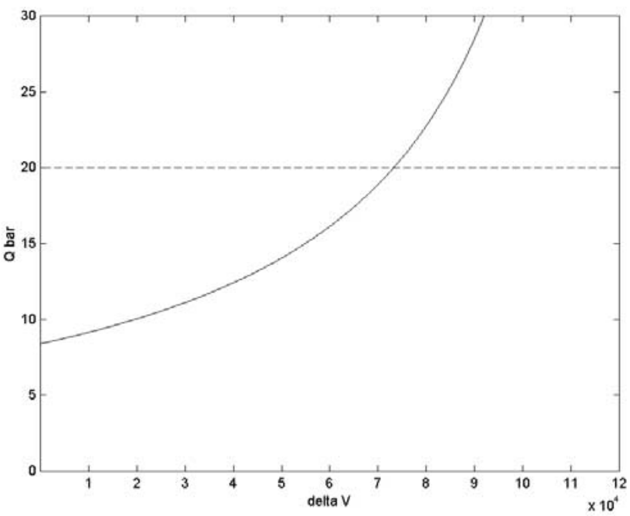

Figure 2. The range of the maximum radial distances to be reached by neutral atoms created by charge exchange or electron recombination near the A ring at L = 2.2 R_s.

affected by the Lorentz force. Their trajectories will be determined by the initial gyration velocities around the magnetic field at creation. The speeds range from zero to the pickup values which are given by $\Delta U = U_k - U_c$ with U_k being the local Keplerian speed and U_c the local corotation speed. Figure 2 illustrates the radial distances to be reached by these neutral atoms of ring origin with different launch velocities. It can be seen that a large fraction of them would be injected into the Saturnian magnetosphere thus forming a flat-disk like distribution of neutral cloud. A population will actually form a stably trapped population executing Keplerian motion until ionization by photoionization, electron impact ionization or charge exchange in the magnetospheric region. It is this population which will contribute significantly to the corotating plasma and energetic ions because of their long dynamical lifetime.

4. Suprathrmal Ions From Pickup Process

[8] The magnetopause of Saturn is at a distance of about 17–20 R_s on the dayside. The magnetic field strength is on the order of 5 nT [*Connerney et al.*, 1984] and the departure from rigid corotation (i.e., corotation lag) of the magnetospheric plasma could be within 10% out to 15 R_s [*Bridge et al.*, 1982] according to the Voyager measurements. Neglecting the Keplerian speed, the far-flung neutral atoms and molecules from the rings would obtain a gyration speed of $U_\perp \sim 138$ km/s at re-ionization at $L \sim 15$. The gyration energy of these new O^+ pickup ions is $E_\perp \sim mU_\perp^2/2$ ($\sim$1.6 keV) and the corresponding magnetic moment is $\mu_\perp = E_\perp/B \sim 0.32$ keV/nT. Inward radial diffusion to $L \sim 5$ with $B \sim 100$ nT will yield a particle energy of about 32 keV according to the first adiabatic invariant ($E_\perp \ \alpha\ B$). This simple consideration thus indicates that the ring atmosphere and plasma disc could be an important source of the energetic magnetospheric heavy ions with energy reaching a few tens of keV. A similar recycling acceleration mechanism has been proposed for the Jovian magnetosphere [*Barbosa and Eviatar*, 1987]. Because of the large size of the Jovian magnetosphere, the corresponding energy gain by the recaptured ions could be much larger.

5. Discussion

[9] In this paper we have updated our previous estimate of the number density of the neutral oxygen molecules in the ring plane of Saturn. By the same token, we are able to derive the ion density in the putative ring plasma disc. For an efficiency factor of $\varepsilon \sim 0.1$ in the photochemical transformation of H_2O to O_2, n_i could be on the order of 180 cm^{-3} if the plasma composition is mainly O_2^+ and $n_o \sim 1.8 \times 10^5$ cm^{-3}. On the other extreme, for O^+ plasma, $n_i \sim 5.3 \times 10^4$ cm^{-3} and $n_o \sim 530$ cm^{-3}. Detailed chemical modelling effort will be required to sort out the ion composition in this plasma storage zone. Another important consequence of a sizable ring exosphere and plasma disc is that – in addition to the neutral gas cloud of satellite origin [*Ip*, 1997; *Richardson*, 1998] - the associated ion-neutral interaction will lead to the injection of a flux of water-group and oxygen atoms and molecules into the Saturnian magnetosphere. The pickup ions created in such distributed neutral gas of ring origin will in turn provide a source of suprathermal oxygen ions. Thus sporadic impact events in the rings could often affect the global structure and dynamics of the Saturnian magnetosphere because of the corresponding mass loading effect. A combination of the in-situ plasma measurements and remote-sensing observations on Cassini would probably reveal such interplays.

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References

Barbosa, D. D., and A. Eviatar (1987), Planetary fast neutral emission and effects on the solar wind: A cometary exosphere analogue, *Astrophys. J.*, *321*, 1049.
Bridge, H. S., et al. (1982), Plasma observations near Saturn: Initial results from Voyager 2, *Science*, *215*, 563.
Coates, A. J., H. J. McAndrews, A. M. Rymer, D. T. Young, F. J. Crary, S. Maurice, R. E. Johnson, R. Baragiola, R. L. Tokar, and E. C. Sittler (2005), Plasma electrons above Saturn's main rings: CAPS observations, *Geophys. Res. Lett.*, *32*, L14S09, doi:10.1029/2005GL022694.
Connerney, J. E. P., L. Davis Jr., and D. L. Chenette (1984), Magnetic field models, in *Saturn*, edited by T. Gehrels and M. S. Matthews, p. 354, Univ. of Ariz. Press, Tucson.
Cuzzi, J. N., and R. H. Durisen (1990), Bombardment of planetary rings by meteoroids: General formulation and effects of Oort cloud projectiles, *Icarus*, *84*, 467.
Hamilton, D. P., and J. A. Burns (1993), OH in Saturn's rings, *Nature*, *365*, 498.
Horanyi, M., J. A. Burns, and D. P. Hamilton (1992), The dynamics of Saturn's E ring particles, *Icarus*, *97*, 248.
Huebner, W. F., and C. W. Carpenter (1979), Solar photo rate coefficients, *Informal Rep. LA-8085-MS*, Los Alamos Sci. Lab., Los Alamos, N. M.
Ip, W.-H. (1983a), On plasma transport in the vicinity of the rings of Saturn: A siphon flow mechanism, *J. Geophys. Res.*, *88*, 819.
Ip, W.-H. (1983b), Equatorial confinement of thermal plasma near the rings of Saturn, *Nature*, *302*, 599.
Ip, W.-H. (1984a), The ring atmosphere of Saturn: Monte Carlo simulations of the ring source model, *J. Geophys. Res.*, *89*, 8843.
Ip, W.-H. (1984b), Ring torque of Saturn from interplanetary meteoroid impact, *Icarus*, *60*, 547.
Ip, W.-H. (1995), The exospheric systems of Saturn's rings, *Icarus*, *115*, 295.
Ip, W.-H. (1997), On the neutral cloud distribution in the Saturnian magnetosphere, *Icarus*, *126*, 42.
Koschny, D. (1997), The relevance of laboratory impacts in ice and ice-silicate targets for the study of comets, *Adv. Space Res.*, *20*, 1569.
Morfill, G. E., H. Fechtig, E. Gruen, and C. K. Goertz (1983), Some consequences of meteoroid impacts on Saturn's rings, *Icarus*, *55*, 439.
Richardson, J. D. (1998), Thermal plasma and neutral gas in Saturn's magnetosphere, *Rev. Geophys.*, *36*, 501.
Stone, E. C., and E. D. Miner (1982), Voyager 2 encounter with the Saturnian system, *Science*, *215*, 499.
Tokar, R. L., et al. (2005), Cassini observations of the thermal plasma in the vicinity of Saturn's main rings and the F and G rings, *Geophys. Res. Lett.*, *32*, L14S04, doi:10.1029/2005GL022690.
Waite, J. H., Jr., et al. (2005), Oxygen ions observed near Saturn's A-ring, *Science*, *307*, 1260.
Young, D. T., et al. (2005), Composition and dynamics of plasma in Saturn's magnetosphere, *Science*, *307*, 1262.

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