Plasma-induced clearing and redistribution of material embedded in planetary magnetospheres

R. E. Johnson,[1,2] M. Liu,[1] and E. C. Sittler Jr.[3]

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[1] Charge exchange collisions between the ions trapped in a planetary magnetosphere and the ambient neutrals are a principal material loss process in evolving planetary systems (Johnson, 2004). Here we show that low energy charge exchange collisions, in which orbiting occurs, can drastically modify the redistribution and loss of materials in evolving planetary disks. Using Saturn as an example, these collisions can account for the fact that water products, produced primarily in the inner magnetosphere, are found to be the dominant ions throughout Saturn's magnetosphere.
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1. Introduction

[2] The alteration and dispersal of material embedded in a magnetospheric plasma is a critical process in the late evolution of a planetary system. Attention is now focused on the evolution of the disk of icy material in Saturn's magnetosphere. This includes its many moons, particles in its main rings and grains in its tenuous rings. These are the source of large toroidal gaseous envelopes: the giant OH torus [*Shemansky et al.*, 1993; *Jurac et al.*, 2002], a toroidal oxygen atmosphere over the main rings and in the inner magnetosphere [*Tokar et al.*, 2005; *Johnson et al.*, 2005; *Ip*, 2005], and a toroidal plasma of water products throughout the magnetosphere [*Eviatar et al.*, 1983; *Sittler et al.*, 2005]. The dispersal of this material by its interaction with the magnetospheric plasma is described as a model for evolving planetary disks.

[3] The materials embedded in Saturn's magnetosphere have a broad distribution of sizes, including gas-phase species produced from the grains, rings particles and small icy bodies. These neutrals are removed by their interaction with the trapped plasma, so that the rings and satellites are gradually eroded. The OH torus requires $\sim 10^{10}$ kg/yr from the embedded icy materials [*Jurac and Richardson*, 2005] and larger rates may be required for the recently observed atomic oxygen [*Esposito and the UVIS Team*, 2005].

[4] An important process limiting the build-up of gas-phase neutrals in a magnetosphere is charge exchange. It is a process in which an ion moving with the magnetic field collides with an atom or molecule capturing an electron. Since the neutralized ion is no longer constrained by the fields, it can be on an escape trajectory. This process accounts for the fact that the space around planetary bodies is remarkably empty and leads, for instance, to the extensive sodium nebula at Jupiter [*Mendillo et al.*, 1990]. However, when the relative collision speed is low, the nature of the charge-exchange process changes, becoming one of a number of ion-molecule interactions that affect the spatial distribution of neutrals. This is the case in early stages of the evolution of a disk of planetary debris and is also the case in Saturn's inner magnetosphere. Here we describe the redistribution of gas phase species by charge exchange and account for the dominance of water products in Saturn's outer magnetosphere.

2. Charge Exchange

[5] Saturn's plasma has a dominant thermal component with energies determined, primarily, by the speed of rotation of the magnetosphere ($\sim$eVs/u to $\sim$keVs/u) and a less dense 'hot' component (10's of keVs to MeVs). Here we focus on the thermal component for which the flow speed is roughly proportional to the planet's rotation rate [*Young et al.*, 2005; *Sittler et al.*, 2005]. Therefore, the average speed of these ions relative to the orbiting neutrals varies considerably with distance from the planet, R. In the equatorial plane the relative collision speed, v, between a co-rotating ion (v_{co}) and a neutral in a circular orbit (v_o) is $v = v_{co} - v_o = v_{co}[1 - (R_x/R)^{3/2}]$, where R_x is the equatorial radius at which the co-rotation and orbiting speeds are equal: $R_x \sim 1.85\ R_S$ (R_S is a Saturn radius). Because the interactions change in character in going from large to small v (appendix) the effect of charge exchange varies with distance from the planet.

[6] Since charge exchange can occur efficiently at large separations between an ion and a neutral, forward scattering can dominate. Therefore, it has become customary to ignore the deflections. That is, a fast ion becomes a neutral retaining its speed but is no longer affected by the fields. Therefore, a co-rotating ion capturing an electron at $R \gg R_x$ forms a neutral having an orbit with a much larger average radius. It can exit the planetary system if the co-rotation energy is twice the Kepler energy for a circular orbit ($v_{co} > 2^{1/2}\ v_{or}$). This occurs for $R > 2^{1/3}\ R_x = 2.33\ R_S$, which is close to the outer limits of the main rings ($\sim 2.27\ R_S$). However, plasma ions have a distribution of speeds and deflections cannot be ignored.

[7] At low relative speeds ($v < \sim 100$ km/s), attractive interactions due to the sharing of the electron and polarization of the neutral can cause significant deflections. There is a critical distance between the ion and the neutral within which the colliding pair orbit each other [*Brown et al.*, 1983; *Johnson*, 1990]. In these 'orbiting collisions' the

[1]Engineering Physics Program and Astronomy Department, University of Virginia, Charlottesville, Virginia, USA.
[2]Physics Department, New York University, New York, New York, USA.
[3]Goddard Space Flight Center, Greenbelt, Maryland, USA.

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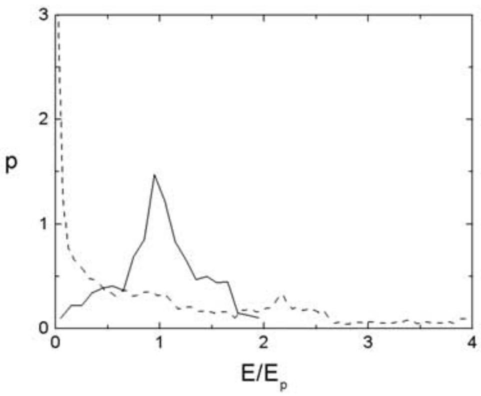

Figure 1. Normalized 'thermal' distributions, p, for A^++A orbiting collisions depend only on E/E_p (appendix). A^+ has gryo-energy E_p plus the co-rotation velocity $\mathbf{v_{co}}$ and A is in a circular, equatorial orbit, $\mathbf{v_o}$. Solid curve: ion energy distribution in the co-rotating frame [$E = (E'_i)_r$ in appendix]; mean, $E/E_p \sim 1.0$. Dashed curve: neutral energy distribution in the Kepler orbit frame [$E = (E'_o)_K$ appendix]; mean, $E/E_p = 0.81$, with 19% > $E/E_p = 1$. Dotted curve: neutral energy distribution in the Kepler orbit frame with forward scattering only [$E = (E'_o)_K$ appendix]; neutrals exit with initial gyro-speed of the ion; mean, $E/E_p = 2$.

interaction time increases so that exothermic processes can occur. Such collisions are the basis for ion-molecule chemistry and give a cross section that increases with decreasing v. Therefore, both exothermic and resonant charge exchange collisions are efficient at very low v and the deflections can be large. The average energy of the exiting neutral and ion from such a collision is equal to half their combined initial energies. Therefore, a collision between a co-rotating ion and a molecule of equal mass must occur at larger distances for the average speed of the exiting neutral to exceed the planet escape speed: $\sim 3^{1/3}$ R_x = 2.7 R_S near the G-ring. Since the heavy ion population in Saturn's inner magnetosphere is dominated by relatively low temperature pick-up ions [*Sittler et al.*, 2005], a significant fraction of the neutrals from charge exchange remain on gravitationally bound orbits.

[8] When the polarization force dominates, the Langevin cross section ($\sigma_L \sim v^{-1}$) is used, giving a reaction rate that is independent of the ion temperature (appendix). This applies when $(\sigma_L)^{1/2}$ is greater than the size of the outer shell electron orbit on the neutral: v < ~20 km/s for O_2. At Saturn ($v_{co} - v_o$) is ~20 km/s at ~3.5 R_S, which is between the orbits of Mimas and Enceladus. However, a fraction of such collisions occur at very low velocities out to much larger distances due to the distribution of ion speeds [*Sittler et al.*, 2005], and charge exchange usually has an attractive interaction that exceeds the polarization force [*Johnson*, 1990], so that significant deflections can occur at higher collision speeds. Detailed potentials will be needed to accurately describe the redistribution and loss; below we consider the region in which orbiting collisions are likely.

3. Model

[9] Molecules ejected from the surface of a body embedded in a planet's magnetosphere typically orbit until they are ionized. The newly-born heavy ions are accelerated by the local fields adding to the plasma, a process referred to as pick-up. Charge exchange collisions ($A^+ + B \rightarrow A + B^+$) do not affect the ion density, but the neutral is replaced by a neutral with a very different orbit. If a co-rotating ion is neutralized by charge exchange at equatorial radius R < R_x, it will orbit with a perihelion closer to the planet. If it is neutralized at equatorial R > R_x, it will, on average, orbit with a larger average radius. Therefore, neutrals produced from a planetary disk by collisions or sputtering are dispersed by charge exchange.

[10] In Saturn's inner magnetosphere, as in other icy disks, the heavy ions formed from the embedded material are dominated by slow species [*Sittler et al.*, 2004, 2005]. Therefore, for simplicity, we describe the interaction of the ambient neutrals with fresh pick-up ions that are produced near the magnetic equator and exhibit only gyro-motion. Ignoring deflections but accounting for the gyromotion, the neutrals produced would have a distribution of energies in the Kepler orbit frame shown by the dotted curve in Figure 1 which peaks at 0 and 4 with a mean, $E/E_p = 2$: E_p the initial ion gyro-energy. When significant deflections occur, here described by orbiting collisions, the 'thermal' distributions for the exiting ions and neutrals are also shown. The ions (solid curve), which have an initial 'thermal' speed $E/E_p = 1$ in our model, attain a distribution of energies and pitch angles in the co-rotating frame [*Johnson et al.*, 2005]. The exiting neutrals (dashed curve) have a distribution in the Kepler orbit frame that peaks only at $E/E_p = 0$ with a mean ~0.9. Therefore, including deflections gives a very different distribution of neutral speeds.

[11] For low speed, orbiting collisions of fresh molecular pick-up ions with neutrals of equal mass, the energies for the exiting neutrals in the rest frame, E'_o, scaled to the initial Kepler orbital energy, E_o, are shown in the insert to Figure 2. This is calculated at 2.3 R_S, near the edge of the main rings, and at 3 R_S, near the orbit of Mimas. Neutrals with $E'_o/E_o > 1$ (~90%) will orbit with a larger radial extent and may be ionized in the outer magnetosphere. Those with $E'_o/E_o > 2$ will escape if they do not impact a body or become ionized before crossing the magnetopause. Undeflected neutrals produced from co-rotating ions in these regions would, of course, escape with unit efficiency. However, in our model the escape fractions are ~25% and ~60% at 2.3 R_S and 3 R_S respectively. In addition, ~65% and ~32% of the neutrals, respectively, are in stable orbits with larger aphelion. These populate the outer magnetosphere reducing the required source rate for the OH torus.

[12] The radial distribution of neutrals, f, produced in charge exchange collisions with freshly-formed pick-up ions between the edge of the main rings and the orbit of Enceladus is given in Figure 2. Assuming a uniform source, for simplicity, f is calculated using a Monte Carlo choice of scattering angles for orbiting collisions (appendix) and a particle tracking code [*Smith et al.*, 2004]. Ignoring deflections, every charge exchange in this region would lead to loss from Saturn. However, although ~60% escape from the system or impact the main rings, a large fraction of the neutrals produced by charge exchange spend considerable time close to their region of origin. They are also seen in Figure 2 to inflate the water product torus [*Jurac et al.*, 2002] and to populate the outer magnetosphere where Titan

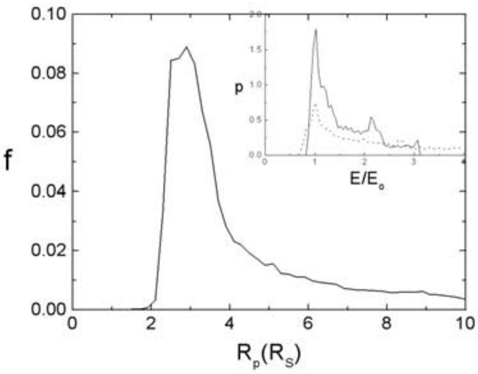

Figure 2. The spatial distribution, f, of molecules A (O, H_2O, OH, etc.) exiting from symmetric (A^++A) or nearly symmetric collisions with orbiting neutrals. Calculated using the Langevin cross section and assuming ions have gyromotion only. f is the fraction of scattered neutrals found at any time between R_p and $R_p + 0.2\ R_S$ where R_p is the radial distance along the equatorial plane: obtained using a Monte Carlo choice of incident and exit angles (appendix) and a particle tracking code. Source rate of fresh pick-up ions in the equatorial plane is assumed to be uniform from 2.3 to 4 R_S. The probability of a neutral hitting the main rings is proportional to $[1 - \exp(-\tau)]$ with τ the optical depth. The fraction escaping is ~58% with 14% hitting the main rings or Saturn. Insert: Distribution, p, of the energy [$E = E'_o$ appendix] of a neutral A from an orbiting collision given as a fraction of the initial orbital kinetic energy, E_o, for R = 2.3 R_S (solid line) and for R = 3R_S (dashed line). The fraction escaping ($E/E_o > 2$) is ~0.25 and ~0.59 respectively vs. ~0.55 and ~0.78 if deflections are ignored (appendix); the fraction ejected into larger bound orbits ($2 > E/E_o > 1$) is ~0.65 and ~0.32 respectively.

orbits. Therefore, heavy water products produced in the inner magnetosphere, by out gassing from Enceladus or by sputtering of grains, are redistributed throughout Saturn's magnetosphere.

[13] Because of the distribution of ion speeds, low v collisions occur at larger radii than that considered above and non-negligible deflections occur for a large range of Saturn radii. Therefore, the rate at which scattered neutrals populate a region in the outer magnetosphere must be determined by accounting for deflections in all regions of Saturn's magnetosphere.

4. Summary

[14] In an evolving planetary system having debris in the form of grains, ring particles and satellites embedded in a magnetosphere, a toroidal envelope of gas-phase neutrals is produced by outgassing, collisions and sputtering. Ionization of these neutrals populates the magnetospheric plasma. The ions so formed have charge exchange collisions with the orbiting neutrals, causing loss of material from an evolving planetary system [*Johnson*, 2004]. Therefore, it is exciting that such processes occurring in Saturn's disk of icy materials are being studied in-situ by the Cassini spacecraft.

[15] Since it is typically assumed that charge exchange occurring beyond the edge of Saturn's main rings leads to the loss of neutrals, *Eviatar et al.* [1983] suggested charge exchange occurring just inside the edge of the main rings could redistribute material into the outer magnetosphere. However, we show here that ion-neutral orbiting interactions populate the outer magnetosphere from a broad region of the inner magnetosphere [*Johnson et al.*, 1989]. Therefore we described the redistribution of molecules ejected from the icy bodies and grains in Saturn's inner magnetosphere.

[16] The magnetospheric water source rate for the OH torus is $\sim 10^{28}$ H_2O/s [*Jurac and Richardson*, 2005] and the molecular oxygen source rate was estimated to be $\sim 10^{27}$ O_2/s [*Johnson et al.*, 2003, 2005]. These inner magnetospheric sources are orders of magnitude larger than the rate at which nitrogen escapes from Titan ($\sim 10^{25}$ N/s [*Michael et al.*, 2005]). Accounting for the fraction of Titan nitrogen that is either directly lost from Saturn or is ionized far from Titan, the source rate within ~5 Saturn radii of Titan's orbit is only a few times 10^{24} N/s [*Smith et al.*, 2004]. Therefore, less than ~0.1% of the water products must be scattered into and ionized in the outer magnetosphere in order to dominate the nitrogen source rate. Using the simple model leading to Figure 2, a few percent of the neutrals produced in charge exchange between 2.3 and 4R_S in the inner magnetosphere reside at anytime within ~5 Saturn radii of Titan's orbit. Therefore, the plasma in the outer magnetosphere is dominated by ionization of water products initially produced in the inner magnetosphere consistent with Cassini data [*Krimigis and the MIMI Team*, 2005; F. J. Crary and CAPS Cassini Team, Dynamics and composition of plasma in and around Titan, submitted to *Science,* 2005]. This ends the long-standing controversy on whether the heavy ions detected in Saturn's magnetosphere by the Voyager spacecraft over 20 years ago were predominantly produced from the icy bodies or Titan's atmosphere. It also indicates that the water products from the inner magnetosphere can be swept up by Titan affecting the chemistry in its thermosphere. Obtaining quantitative agreement with Cassini data will require the models of the energy distribution and composition of the plasma with distance from Saturn. However, as shown here, it will also require charge exchange cross sections that account for deflections at all energies. An accurate description of the redistribution and loss of material tested against Cassini data will help in understanding evolving disks of material in other planetary systems as well as disks of icy materials in young stellar objects.

Appendix A

[17] At very high speeds (v > speed of an outer shell electron: E > ~20 keV/u), charge exchange (CE) is inefficient requiring a significant momentum transfer to an electron on the neutral. The effect of the change in binding energy, ΔE, of the captured electron is negligible and small deflections (forward scattering) dominate. At lower speeds (E < ~20 keV/u) CE occurs by sharing of the outer shell electrons during the collision and the size of ΔE becomes important. For resonant collisions, $\Delta E = 0$ ($O^+ + O \rightarrow O + O^+$), the cross section grows slowly but monotonically with decreasing v. When ΔE is not zero, the cross section also increases slowly with decreasing v, reaches a maximum,

and then decreases rapidly with decreasing v [*McGrath and Johnson*, 1989]. The maximum occurs at $v \sim [2\pi\ \Delta E\ a/h]$ where a is an interaction length and h is Planck's constant. For $O^+ + N \rightarrow O + N^+$ of interest near Titan's orbit, ΔE = 0.9eV, giving a maximum at ~400eV/u. Below we consider very low velocity collisions of pick-up ions in which orbiting occurs.

[18] When the polarization force dominates, the Langevin cross section and rate constant for orbiting collisions are $\sigma_L = \pi[2\alpha(ze)^2/E]^{1/2} = \pi\ a_o^2[2\alpha' z^2/E']^{1/2}$; $k_L = 2\pi[\alpha(ze)^2/m]^{1/2} = 2\pi z a_o^2 v_o\ [\alpha'/1823\ m']^{1/2}$ [*Johnson*, 1990]. α is the polarizability of the neutral (5.4, 9.8, 10.7a_o^3 for O, H_2O, O_2), z is the ion charge, m is the reduced mass [$m = m_i\ m_o/M$] with $M = m_i + m_o$, E is the center of mass energy ($\frac{1}{2}mv^2$), a_o and v_o are the Bohr radius and velocity [$a_o = 0.529 \times 10^{-8}$ cm; $v_o = 2.19 \times 10^3$ km/s] and e the electronic charge [$e^2 = 27.2eVa_o$]. The primed quantities are in atomic units [$\alpha = (\alpha' a_o^3)$, $E = (E' \times 27.2$ eV), m′ in amu].

[19] On ionization, a neutral with a circular orbit speed v_o becomes a pick-up ion. The ion's new velocity is the sum of the flow velocity and the gyromotion: $\mathbf{v_i} = \mathbf{v_{co}} + \mathbf{u}v$ with $v = |\mathbf{v_{co}} - \mathbf{v_o}|$ and $\mathbf{u}$ a unit vector in the instantaneous direction of the ion's circular motion. Assuming pick-up occurs close to the magnetic equator, we write $\mathbf{v_{co}}/v_{co} = \mathbf{v_o}/v_o = \mathbf{u_o}$. Ignoring deflections, CE between a pick-up ion and a neutral produces an ion with energy $(E'_i)_r = (m_n v^2/2)$ in the co-rotating frame, and an exiting neutral with $(E'_o)_K = (2 + 2e_o)E_p$ in the Kepler orbit frame: $E_p = m_i v^2/2$ is the initial gyro-energy and $e_o = \mathbf{u} \bullet \mathbf{u_o}$. The neutral distribution in the Kepler frame (dotted line Figure 1) is $p(r) = [2\pi r^{1/2}(4 - r)^{1/2}]^{-1}$, with $r = [(E'_o)_K/E_p]$. For $m_i = m_n$ the energy of the neutral in the rest frame, E'_o, compared to its initial orbital energy, E_o, is: $E'_o/E_o = \{1 + 2\ d\ (1 + e_o) + 2\ d^2\ (1 + e_o)\}$ and $d = v/v_o$. The distribution of energies, $p(E'_o/E_o) = [4\pi\ d(1 + d)(1 - e_o^2)^{1/2}]^{-1}$, peaks at the lowest and highest energies: $(E'_o/E_o) = 1$ and $[1 + 4d + 4d^2]$; for $R > R_x$ these correspond to speeds v_o and $(2v_{co} - v_o)$. The escape fraction, $(E'_o/E_o) > 2$, is $\mathrm{acos}\{-1 + [2d(1 + d)]^{-1}\}/\pi$ (~55% at 2.3 R_S and ~78% at 3 R_S).

[20] For an orbiting collision between a pick-up ion of mass m_i and a neutral of mass m_o the final velocities are: $\mathbf{v'_i} = [(m_i\mathbf{v_i} + m_o\mathbf{v_o}) + m_o\mathbf{u}'|\mathbf{v_i} - \mathbf{v_o}|]/M$ and $\mathbf{v'_n} = [(m_i\mathbf{v_i} + m_o\mathbf{v_o}) - m_i\mathbf{u}'|\mathbf{v_i} - \mathbf{v_o}|]/M$ with $\mathbf{u}'$ a random direction in the center of mass system. If $m_i = m_o$ charge exchange and elastic collisions are indistinguishable with ion (+) and neutral (−) velocities $\mathbf{v}_\pm' = \frac{1}{2}[(\mathbf{v_i} + \mathbf{v_o}) \pm \mathbf{u}'|\mathbf{v_i} - \mathbf{v_o}|]$. In the co-rotating frame $(\mathbf{v}'_+)_\mathbf{r} = \mathbf{v}'_+ - \mathbf{v_{co}}$ giving a ratio of the ion energy, $(E'_i)_r$, to its initial gyro-energy, $E_p = m_i v^2/2$: $(E'_i)_r/E_p = [1 + 2^{-1/2}\ (1 + e_o)^{1/2}(e' - e'_o)]$, where $e'_o = \mathbf{u}' \bullet \mathbf{u_o}$ and $e' = \mathbf{u}' \bullet \mathbf{u}$. We have used v_i defined above. The ion attains pitch angles, α_p: $[\cos\alpha_p]^2 = e'^2_z(1 + e_o)/[2 + 2^{1/2}(1 + e_o)^{1/2}(e' - e'_o)]$ with $e'_z = \mathbf{u}' \bullet \mathbf{z}$ [*Johnson et al.*, 2005]. The exiting neutral energy in the Kepler frame is $(E'_o)_K/E_p = f_n = [(1 + e_o) + 2^{-1/2}(1 + e_o)^{1/2}(e' + e'_o)]$ used in Figure 1. The exiting neutral energy in the rest frame compared to its initial orbital energy is $E'_o/E_o = \{1 + d[1 + 2^{1/2}e'_o(1 + e_o)^{1/2} + e_o] + d^2 f_n\}$. To construct the probability distributions, p, we chose the direction of $\mathbf{u}$ randomly in the orbit plane relative to $\mathbf{u_o}$ and $\mathbf{u}'$ giving e_o, e'_o and e'_z. The energy ratios for 10,000 Monte Carlo choices of directions were calculated and binned; p was obtained by normalizing the number binned at each energy ratio.

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R. E. Johnson and M. Liu, Engineering Physics Program and Astronomy Department, University of Virginia, Charlottesville, VA 22904, USA. (rej@virginia.edu)