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MAGNETOSPHERE OF SATURN

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ABSTRACT

Models of the Saturnian magnetosphere based on the application of magnetospheric scaling relations to a spin-aligned planetary magnetic dipole that produces a surface equatorial field strength in the range 0.5 to 2 gauss exhibit the following properties: (1) the orbit of Titan lies inside of the magnetosphere essentially all of the time, even when variations in the size of the magnetosphere resulting from solar wind pressure changes are taken into account; (2) the Brice-type planetary plasmasphere reaches a peak density of about 10 protons cm^{-3} at $L \approx 7$ (L = planetocentric distance in units of planetary radii); (3) Saturn's rings have a profound effect on the energetic particle population and the plasmaspheres derived from interstellar neutrals and Titan's torus; (4) the model calculation suggests that the Titan-derived plasmasphere may be self-amplifying with a feedback factor greater than unity, which implies the possibility of a nonlinearly saturated, highly inflated Saturnian magnetosphere; (5) this same source can have important eroding effects on the outer edge of the rings as determined by Brown-Lanzerotti sputtering rates.

INTRODUCTION

The observation of radio bursts from Saturn strongly imply that that planet, like Mercury, Earth and Jupiter has a rich and interesting magnetosphere. We here apply the arguments and relationships that comprise the subject of comparative magnetospheres to explore in terms of specific models some of the likely properties of the Saturnian magnetosphere. Each magnetosphere presently known has one or more distinguishing characteristics which set it apart from the others: at Mercury a small, quick, ionospherically-unrestrained magnetosphere; at Earth a compromise magnetosphere, intermediate in almost all respects, and at Jupiter a rotation and, as now appears likely, satellite dominated magnetosphere. In the case of Saturn, unique characteristics can be expected to result from the presence of the rings which act as a particle absorption feature extending far into the magnetosphere, and from the presence of Titan with its relatively massive atmosphere and neutral particle torus acting as a strong ion source in the outer magnetosphere.

The principal results from the subject of comparative magnetospheres to be used here are taken from Kennel (1973) and Siscoe (1978a). Concerning the magnetospheres of Jupiter and Saturn specifically, the articles by Scarf (1973, 1975), Coroniti (1975), and Kennel and Coroniti (1975, 1978) should also be consulted. To go through our subject systematically, we consider separately the magnetospheric features and processes arising from the solar wind interaction, from the ionization of the planetary atmosphere and interstellar medium, and from the ionization of Titan's neutral particle torus (see Figure 1).

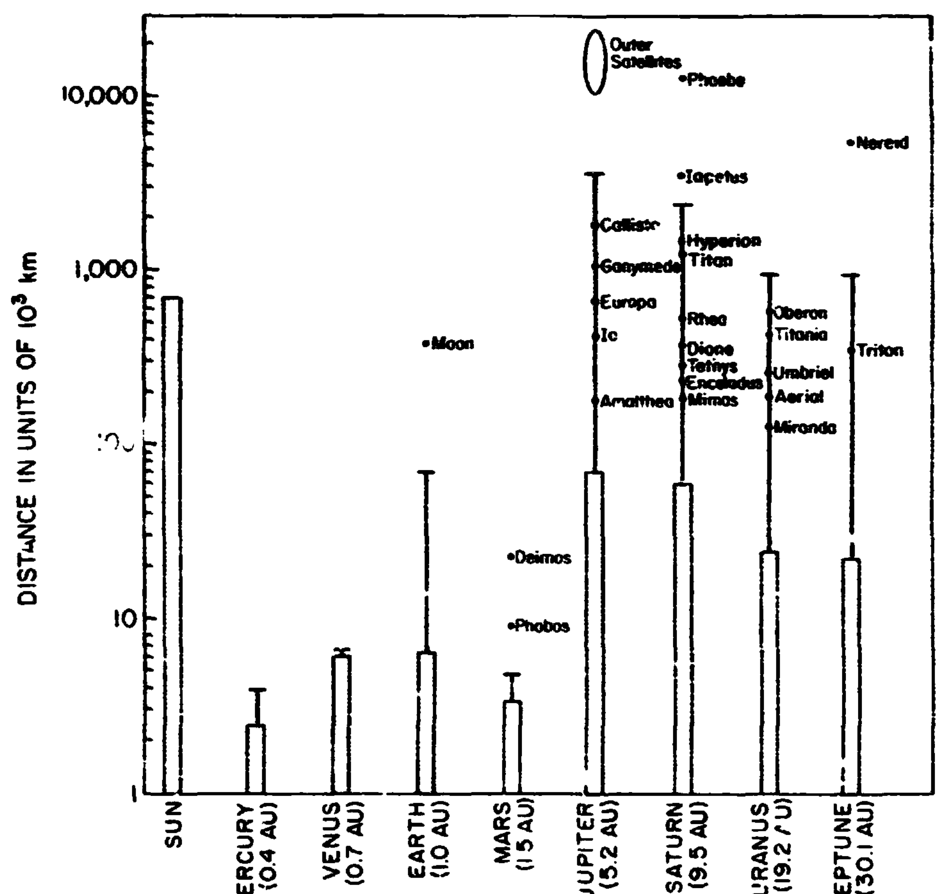

Figure 1. Scale sizes of the planets, their satellite systems and their magnetospheres as characterized by the distance from the planet's center to the subsolar stagnation point. Planetary and solar radii are indicated by the hatched bars and the magnetospheric dimensions by the T's. (From Siscoe, 1978a).

SOLAR WIND FEATURES AND PROCESSES

The solar wind boundary, or magnetopause, is the first item we will consider under this heading. The distance from the planet into the wind at which the shielding effect of the planetary magnetic field brings the solar wind to rest and causes the flow to be deflected in the manner of a flow past a blunt body is given in the case of Saturn, under the assumption of a pure dipole field and a vacuum magnetosphere, by

$$R_m = 34 \left(\frac{\langle nV^2 \rangle}{nV^2}\right)^{1/6} B_{ES}^{1/3} \text{ (gauss)} \tag{1}$$

where R_m is in units of Saturnian radii, nV^2 is the product of solar-wind proton density and speed-squared at Saturn, expressed as in Figure 3 in terms of the ratio to the mean value 8×10^{13} $cm^{-1}s^{-2}$ extrapolated from measurements at 1 AU (Formisano *et al.*, 1974), and B_{ES} is the surface equatorial field strength in gauss. We assume here that the planetary field is a spin-aligned dipole (see Figure 2).

Arguments based on the absence of detectable Saturnian radio emissions at earth analogous to Jovian decimetric emissions (Scarf, 1973), on the detection of Saturnian magnetospheric radio bursts analogous to Jovian decametric bursts and geomagnetospheric kilometric bursts (Kaiser and Stone, 1975; Kennel and Maggs, 1976), and on an empirical planetary scaling relation (Kennel, 1973) suggest that B_{ES} lies in the range 0.5 to 2 gauss.

The solar wind quantity proportional to momentum flux, nV^2, varies in response to solar wind streams, which undergo appreciable nonlinear evolution between the orbit of Earth, where the characteristics of the flux are well known, and the orbit of Saturn, where the characteristics must be determined by nonlinear extrapolation from 1 AU. Such calculations have been performed by Hundhausen and Pizzo (private communication, 1976) and are shown in Figure 3. The effect of stream evolution is evident in the comparison of the histograms at 1 AU and 10 AU. At 1 AU the modal and average values are approximately equal whereas at 10 AU the modal value is considerably less than the average, and there is a compensating increase in the population of the high value tail. This change in the character of the histogram reflects the fact that at 10 AU the streams have evolved into narrow regions of high compression separated by wide regions of rarefaction. The magnetospheric consequence of this stream evolution is that compared to Earth the value of R_m for Saturn will be relatively more variable and values larger than average will occur relatively more frequently (see Smith *et al.*, 1978).

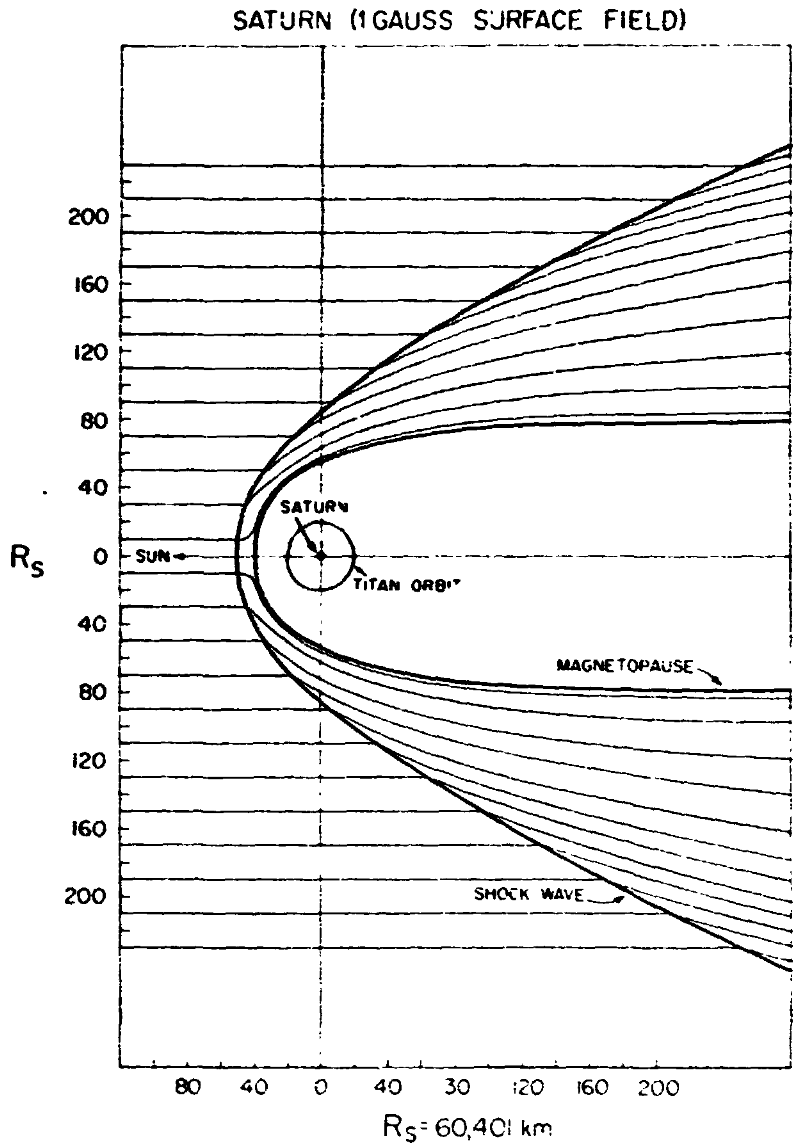

Figure 2. Schematic of the solar wind flow pattern past a hypothetical saturnian magnetosphere with an upstream dimension of 40 R_S (Saturnian radii)

The histogram in Figure 3 can be used in combination with equation (1) to determine probability distributions for the size of the Saturnian magnetosphere as measured by R_m and these are shown in Figure 4. We see from the figure that the probability that the subsolar magnetopause lie beyond the orbit of Titan is greater than 90% even for the case $B_{ES} = 0.5$ gauss. For the case $B_{ES} = 2$ gauss, there is a 50% probability that it will lie beyond twice the orbital distance of Titan.

The values of R_m determined from equation (1) are actually lower limits that would be revised upwards when the effects of interior plasma populations are considered. In the case of earth such revisions are relatively small, except possibly during geomagnetic storms, when the solar wind-derived interior plasma feature referred to as the ring current becomes important. In the case of Jupiter, interior plasma populations evidently dominate in providing the stagnation pressure at the subsolar magnetopause, creating in effect a magnetic dipole 2 to 3 times greater than that of Jupiter alone (Davis and Smith, 1976). As equation (1) shows, such an effective increase in B_{ES} would increase R_m by a factor of 1.3 to 1.4. The increased internal pressure might result simply from the addition of the static thermal and magnetic pressures of the resident, quasi-trapped charged particle populations, or from the dynamic pressure of a centrifugally driven, radially flowing magnetospheric wind (Coroniti and Kennel, 1977, and references therein). As we will see, in the case of Saturn, Titan might be the source of a major internal plasma feature with a magnetic moment exceeding that of Saturn. Thus, the actual size of Saturn's magnetosphere might be considerably larger than predicted on the bases of a vacuum interior.

We have dwelt at length on the magnetopause and what determines its size because of the importance of the answer to this question to later discussions. With regard to the remaining solar wind features and processes, it is both reasonable and expedient to adopt the philosophy first expressed by Scarf (1973 and also 1975). In all essentials that are likely to be important in determining magnetospheric features and processes, both in regard to solar wind parameters and planetary parameters, Jupiter and Saturn are very similar. To arrive at Saturn's magnetosphere then, we should start with Jupiter's magnetosphere and make appropriate adjustments. The Jovian magnetospheric tail is expected to be very long, perhaps 2 to 4 AU (Kennel and Coroniti, 1975, 1977), and the same expectation should apply to Saturn. The polar caps that map along field lines from the plane into the tail have angular radii

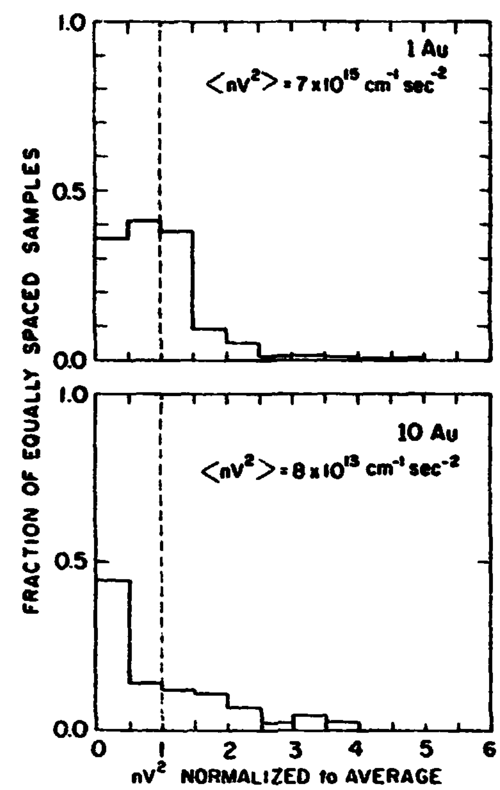

Figure 3. Histograms of the solar wind nv^2 as measured at 1 AU (top) and as computationally extended to 10 AU (bottom) (Hundhausen and Pizzo, 1976 personal communication). The averages at 1 AU have been set equal to those obtained by Formisano et al. (1974).

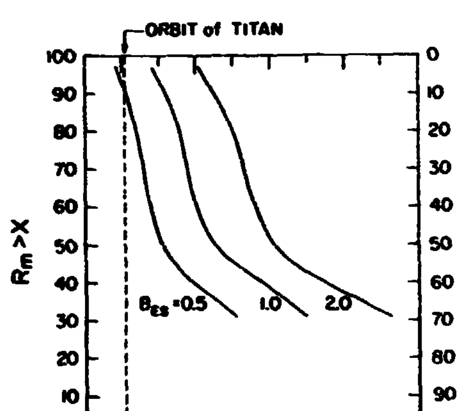

Figure 4. Probabilities relating to the location of the subsolar stagnation point of Saturn's magnetosphere based on the histogram of Figure 3 and the vacuum dipole scaling relations.

expressed in degrees measured from the magnetic poles of 10° for Jupiter and 11° for Saturn, compared to 20° for the case of Earth. The naive scale length that characterizes the extent of planetary control through the domination of corotation over solar wind-induced convection is 530 R_J for Jupiter and 320 R_S for Saturn, compared to 12 R_E for the case of Earth. This characteristic length is called naive because its computation ignores several complicating factors, all of which tend to reduce its size (Kennel and Coroniti, 1975; Chen and Siscoe, 1977). In the case of Earth, the actual size is closer to 5 R_E. We will assume in the following that the unknown reduction factor in the case of Saturn does not exceed an order of magnitude. This has the consequence that Titan lies in the corotation dominated portion of the magnetosphere.

With regard to the final solar wind-derived feature that we will consider, the trapped energetic particle radiation belts, the argument first advanced by Scarf (1973) would still seem to apply. Solar wind-derived particle intensities at Saturn should be less than at Jupiter at corresponding magnetospheric locations for two reasons. Compared to Jupiter, the magnetosphere of Saturn is expected to be smaller, and large particle intensities result essentially from compression through large volume ratios. The second, and probably more important reason is that compared to Jupiter, the rings of Saturn extend outward by more than a factor of two the inner absorption boundary to the inward diffusing particles. The effect of moving the absorbing boundary closer to the source is to reduce the intensities everywhere in between. However before this appealingly simple argument can be accepted, the effects of particle losses resulting from pitch angle scattering into the loss cone and from satellite sweep-up need still to be looked at. If electron intensities are set by the stably trapped limit determined by whistler mode turbulence, as appears to be the case at Jupiter between L = 6 and L = 20 (Coroniti, 1975), then at a fixed value of L, the intensity at Saturn should be about half that at Jupiter. In spite of prior expectations of larger effects, Pioneer 10 measurements revealed relatively small, factors of 2 to 5, reductions in particle intensities across the orbit of Io, and lesser reductions at the other satellites. Thus without going into the detailed calculations required for a definitive answer, the anticipation is that it would be surprising if the intensities at Saturn exceeded those at Jupiter at corresponding locations in the magnetospheres.

Figure 5 shows schematically the local sources for internal magnetospheric plasma features that result from ionization of the planet's atmosphere, the interstellar medium passing through the magnetosphere, and the neutral particle torus and atmosphere of any satellite. We consider here the first two sources and treat the Titan-derived plasmasphere in a separate section.

In all three cases we are faced with a basic transport problem in which specification of the source characteristics, loss mechanisms, and mode of transport determine the density and kinetic properties of the plasma everywhere in the solution domain. As stated above, we assume initially at least that the magnetosphere is corotation dominated, which implies that the mode of transport is cross-L diffusion as opposed to convection or a centrifugally driven wind. The appropriate transport equation is for this case

$$\frac{d}{dL}\left[\frac{D_{LL}}{L^2}\frac{d}{dL}(L^2N)\right] + S - R = 0 \qquad (2)$$

where we assume steady state, NdL is the total number of ions in a flux shell of thickness dL, SdL and RdL are the source and loss rates in the same shell, and D_{LL} is the diffusion coefficient.

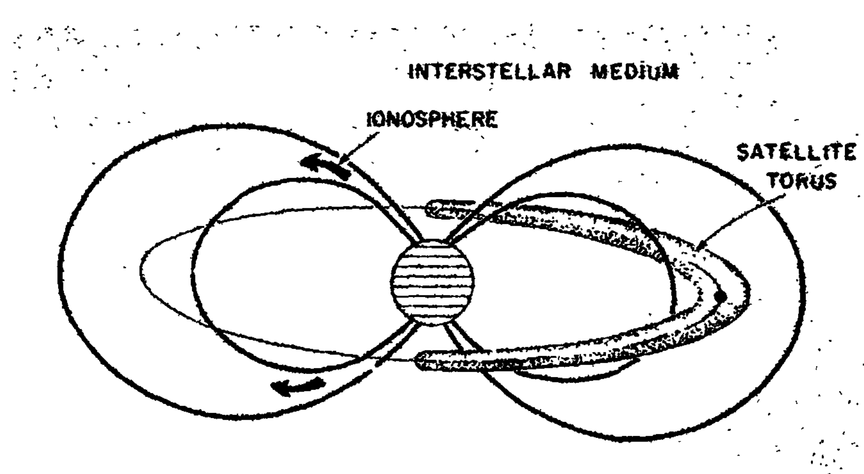

Figure 5. The three sources of plasmaspheres for the giant planets, ionization of the planets atmosphere, the local interstellar medium, and the neutral particle torii of any satellites.

Solutions of this equation appropriate to the planetary and interstellar plasmaspheres in the Jovian magnetosphere have already been presented (Siscoe, 1978a, b). The first reference also treats the Saturnian magnetosphere, but ignores the absorption of the particles by the rings. We refer the interested reader to these articles for a fuller discussion of the problem. A couple of points, however, should be repeated here. The boundary conditions are full absorption at inner and outer boundaries. The outer boundary is set at 30 R_S or 40 R_S. For the planetary plasmasphere there are two "opposite extreme" models. One, the maximum plasmasphere model, is based on the idea of complete magnetospheric trapping of the ionospheric photoelectron-plus-ion flux (Goertz, 1976). The other extreme allows a return flux to the ionosphere in the strong diffusion limit (that is it assumes an isotropic pitch angle distribution) and represents an application of the familiar idea of ambipolar diffusion (first applied to the Jovian magnetosphere by Ioannidis and Brice, 1971, and extended by Mendis and Axford, 1974). For the maximum planetary and interstellar plasmaspheres, the inner boundary to the cross-L diffusion domain is the outer edge of the rings, which is assumed to absorb and neutralize fully the inward diffusing flux. For the ambipolar plasmasphere, the inner boundary to the cross-L diffusion domain is marked simply by the transition to the ambipolar diffusion dominated domain. The cross-L diffusion coefficient, D_{LL}, is taken to be KL^3, with $K = 2 \times 10^{-10}\ s^{-1}$, a theoretically based expression successfully used to interpret Jovian data. We apply it here to Saturn assuming similarity to the Jovian situation (justified more fully in Siscoe, 1978a). The source functions for the two types of plasmaspheres can be specified with little uncertainty. The only loss mechanism considered other than flux into the loss cone, included in the ambipolar model, is recombination, which for the problem in hand turns out to be negligible.

Figure 6 shows the characteristic shape of the ambipolar planetary plasmasphere for the giant planets (Ioannidis and Brice, 1971; Mendis and Axford, 1974; Scarf, 1973; Siscoe, 1978 a, b). The ambipolar diffusion and cross-L diffusion domains interface near $L = 7$, where a maximum density of roughly 20 cm^{-3} is achieved. The density decreases outward because of the absorption boundary at $L = 40$, and decreases inwards because of a field aligned flux into the atmosphere. If field aligned fluxes are prohibited, we arrive at the maximum planetary plasmasphere shown in Figure 7. In this case the density continues to increase inward, reaching roughly 500 cm^{-3} at $L \approx 3$ before dropping to zero at the contact with the rings.

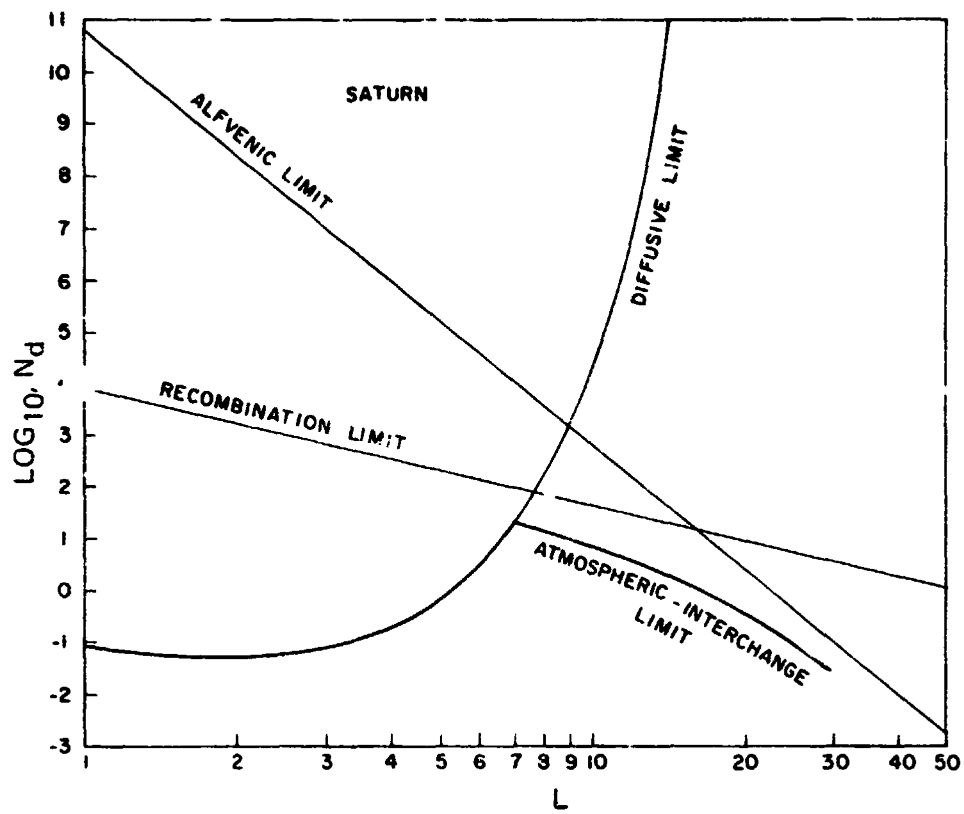

Figure 6. The planetary plasmasphere resulting from the combined effects of ambipolar and cross-L diffusion (See Siscoe 1978a, b for details).

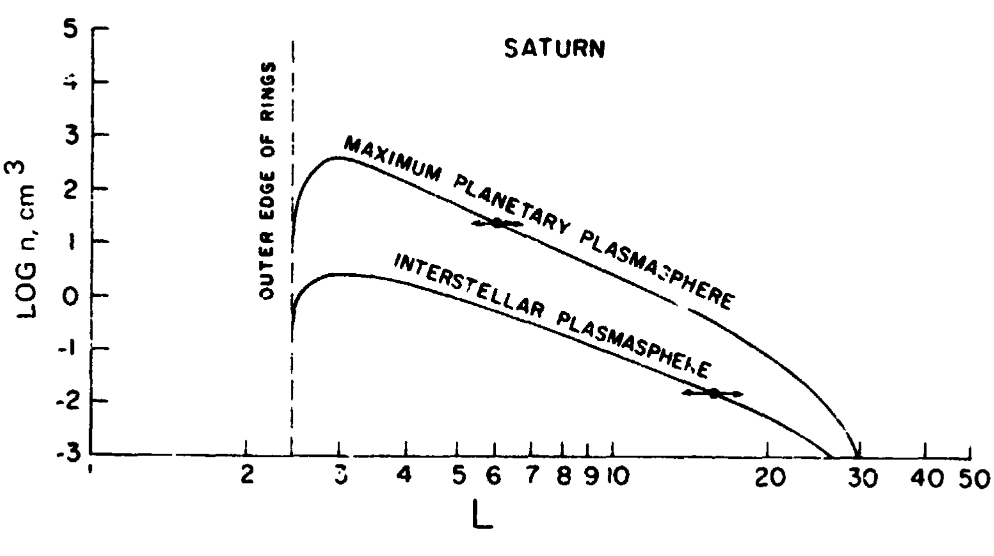

Figure 7. The planetary plasmasphere that results from complete trapping of the ionospheric flux coupled with cross-L diffusion. The interstellar plasmasphere based on a local interstellar hydrogen density of 0.1 cm^{-3} is also shown.

The back-to-back arrows mark the division between outward and inward diffusing fluxes. In this model, all of the photoelectron-plus-ion flux leaving the ionosphere between the latitudes corresponding to $L = 2.3$ ($49°$) and $L = 3$ ($55°$) diffuses into and is absorbed by the outer edge of the rings. This amounts to a maximum total flux of about $5 \times 10^{26}\ s^{-1}$ for the planetary plasmasphere. The maximum energy of the inward diffusing ions at the ring contact is $11\ M_i$ (eV) where M_i is the atomic mass of the ion in AMU. Most ions will arrive with lesser energy.

The calculated density for the interstellar plasmasphere is also shown in Figure 7. The actual plasmasphere resulting from this source will depend on the location of Saturn in its orbit relative to the asymmetric distribution of the interstellar neutral hydrogen around the solar system (Johnson, 1972). The profile shown corresponds to the maximum density encountered by Saturn, and assumes that the interstellar density, unaffected by the sun, is $0.1\ cm^{-3}$. The plasmasphere density reaches a maximum of roughly $2\ cm^{-3}$ at $L \approx 3$. Since the plasma density is linearly proportional to the interstellar density at Saturn n_{Is}, we can say more generally that the maximum density is about $20\ n_{Is}$. Between $L = 3$ and 5 or 6, the density of the interstellar plasmasphere illustrated here exceeds that of the ambipolar plasmasphere. The inward diffusing flux that results from ionization of the interstellar neutral hydrogen between $L = 2.3$, the edge of the rings, and $L = 15$, the edge of the inward diffusion domain, is $2 \times 10^{24}\ n_{Is}\ s^{-1}$ based on photoionization alone. The maximum energy of the particles comprising that flux at $L = 2.3$ is 36 keV. The flux at $L = 2.3$ for the illustrated case is $2 \times 10^{23}\ s^{-1}$, but we note that during encounters of the solar system with high density interstellar clouds, that flux can be greater by several orders of magnitude.

THE SATELLITE PLASMASPHERE

We come now to the plasmasphere derived from ionization of the neutral particle torus of Titan. Our purpose here is to determine the density, flux, and energy of such a plasmasphere assuming that Titan lies wholly in the corotation, cross-L diffusion dominated portion of the magnetosphere. The grounds for this assumption have been presented, but we must admit that the uncertainties of the matter are large enough that the applicability of the results based on the assumption are somewhat speculative.

We assume that the effective radius of the Titan torus is about 1 R_s (Fang *et al.*, 1976), and that the tilt angle between the dipole and rotational axes of Saturn is 10°. The satellite ion disc that then results from cross-L diffusion can be calculated (Siscoe, 1977) and it is shown in magnetic-meridian profile in Figure 8. The Titan-derived plasmasphere will under the stated conditions be confined to lie essentially within the indicated profile, except for violations of the first and second invariants by coulomb and wave scattering that occur during the diffusion process. Pitch angle scattering, which we ignore in the present treatment, will extend the boarders of the plasma disc to higher latitudes.

Consider first the plasma density at Titan's orbit, n_T. We assume the plasma to be derived from photoionization of the neutral hydrogen torus. The total ion production rate, F_T, is then N/τ_{ph} where N is the total number of hydrogen atoms in the torus and τ_{ph} the photoionization lifetime ($\sim 2 \times 10^9$ s). The total density N is related to the total neutral particle flux, F_{NT} which includes both H_2 and H (H_2 is assumed then to be dissociated in the ring) by

$$F_{NT} = \left(\frac{1}{\tau_{ph}} + \frac{1}{\tau_{ch}} \right) N \tag{2}$$

where τ_{ch} is the charge exchange lifetime ($= 1/V_T\, n_T\, \sigma_{ch}$, with $V_T = \Omega R_s L_T$ and $\sigma_{ch} = 1.6 \times 10^{-15}$ cm^2 the charge exchange cross section). Thus we find

$$F_T = \frac{F_{NT}}{1 + 7n_T} \tag{3}$$

Now F_T and n_T are also related by the solution to the diffusion equation, namely by

$$n_T = \frac{F_T}{4\pi\theta R_s^3 K} \frac{ln \frac{L_o}{L_T}\, ln \frac{L_T}{L_i}}{ln \frac{L_o}{L_r}} \frac{1}{L_T^4} \tag{4}$$

where θ is the 10° magnetic tilt angle, L_o is the distance to the outer absorption boundary and is taken to be 30 R_s, $L_T = 20$ R_s, and $L_i = 2.3$ R_s are the distances to the orbit of Titan and the outer edge of the rings respectively. Equations (3) and (4) give a quadratic equation for n_T in terms of F_{TN} and other known or assumed quantities. The solution is

$$n_T = \frac{\left(1 + 6.3 \times 10^{-25} F_{NT}\right)^{\frac{1}{2}} - 1}{14} \text{ cm}^{-3} \tag{5}$$

There is however an upper limit on n_T imposed by the constraint that the corotational kinetic energy density should not exceed the magnetic energy density, the so-called Alfvenic limit (Michel and Sturrock, 1974). This gives

$$n_T \leq 1.7 \, B_{ES}^2 \text{ (gauss)} \tag{6}$$

Figure 9 shows n_T as a function of F_{NT} assuming a 1 gauss surface field. We see that for $F_{NT} \gtrsim 10^{27}$ s^{-1}, density is Alfven limited at the value of 1.7 cm^{-3}. Since fluxes larger than this are expected (e.g., Hunten, 1973a, b) the density at Titan for this case is in effect clamped at 1.7 cm^{-3}, and this fixes the interior solution.

Figure 10 shows the same effect for other surface field strengths. A 2 gauss surface field becomes Alfven limited at a flux of 10^{28} s^{-1} and a 3 gauss field at a flux of about 4×10^{28} s^{-1}.

Parameters for the Titan-derived plasmasphere normalized to the values at Titan's orbit are shown in Figure 11. The density peaks near L = 3 at a value ~200 n_T. The energy of all the particles at the inner boundary is about 150 keV. The particle intensity at the peak is close to 5×10^3 that at Titan. In the case of a 1 gauss surface field, the peak density is 340 cm^{-3} and the peak intensity is 2×10^{11} cm^{-2} s^{-1} at an energy per particle greater than 100 keV.

The beta of the plasma, the ratio of thermal to magnetic energy density, is greater than 1 between L = 3.4 to L = 20. The high β condition which results from the fact that the density is Alfven limited at the source, alerts us to the possibility that the Titan-derived plasmasphere can have major effects on the magnetosphere. To make a quantitative evaluation of one such effect, we calculate the magnetic moment of the ring current associated with the plasmasphere, which turns out to be given approximately by

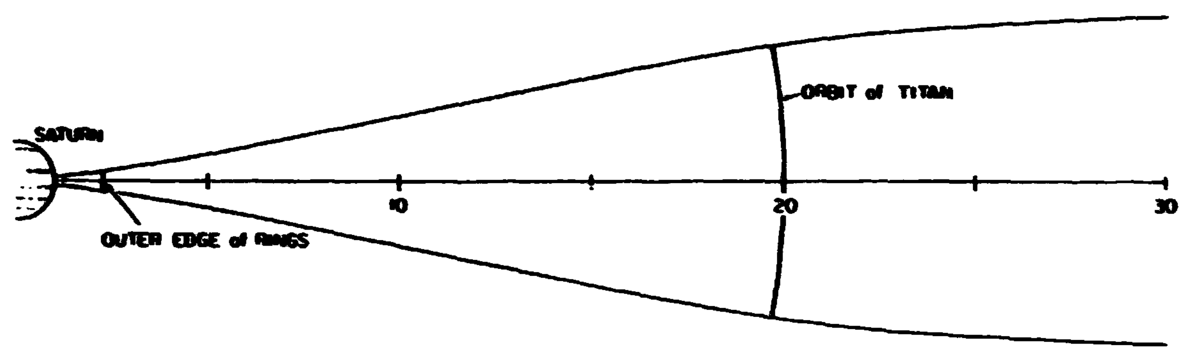

Figure 8. Meridian plane cross section through the confinement disc of a Titan-derived plasmasphere. The disc profile is based on the assumption of the neutral cloud being confined to within 10° of the magnetic equator of Saturn, and on the assumption of cross-L diffusion in the absence of pitch angle scattering (Siscoe, 1977).

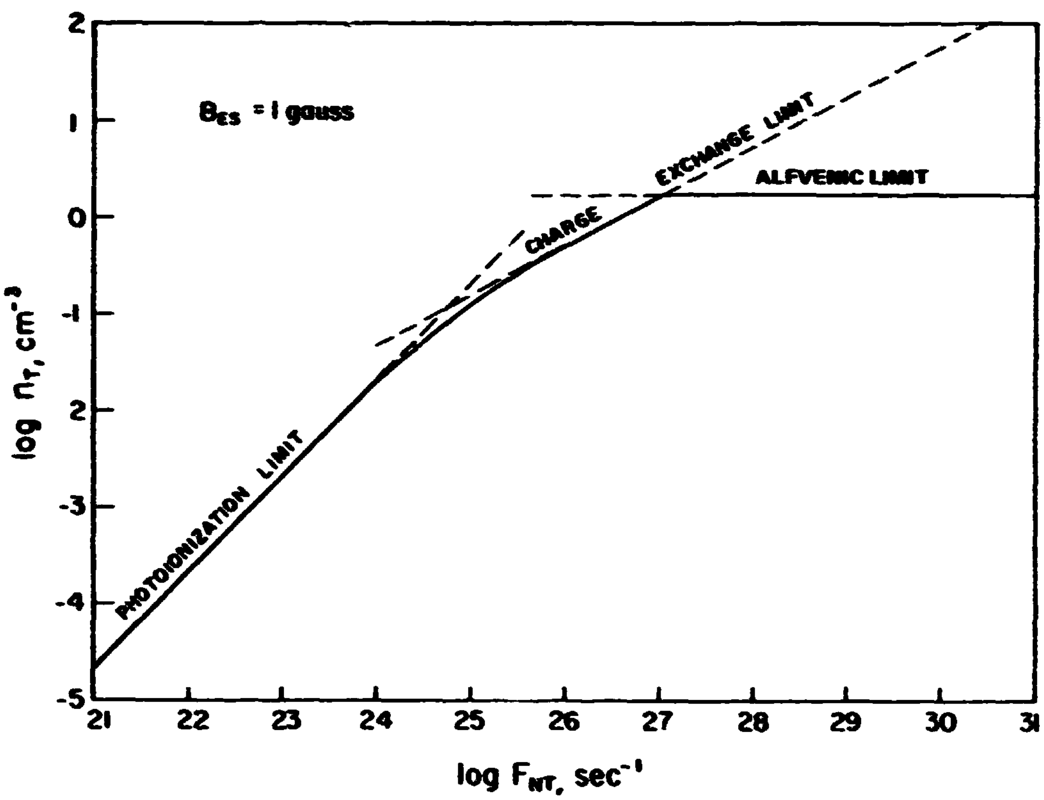

Figure 9. The proton number density at the orbit of Titan (n_T) as a function of the total (net) loss rate of H and H_2 from Titan. The mass-loading or Alfvenic limit is based on a surface equatorial magnetic field of 1 gauss at Saturn.

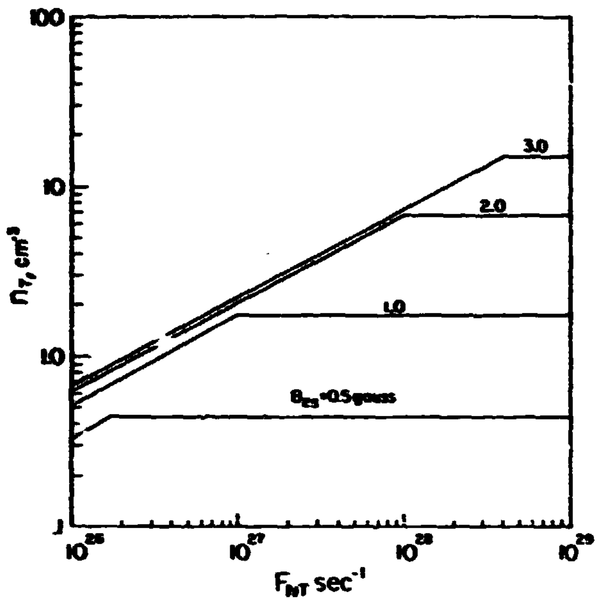

Figure 10. Same as Figure 9 but with different assumed strengths of the surface equatorial magnetic field.

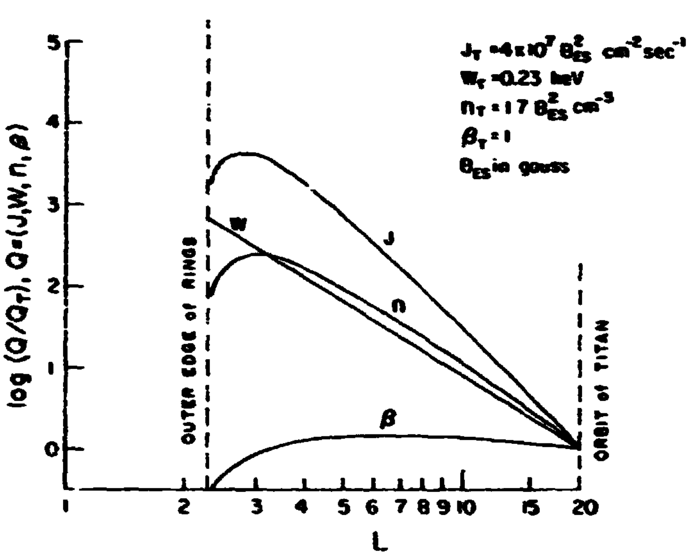

Figure 11. Parameters of the Titan-derived plasmasphere in the region between the outer edge of the rings and Titan's orbit. Values are normalized to Titan's orbit, which are given explicitly. J is the proton intensity, W is the proton kinetic energy, n is the proton number density, and β is the ratio of proton kinetic energy density to magnetic energy density.

$$M_R = \frac{1}{3.5} \frac{H_T}{R_s} M_s \qquad (7)$$

where H_T is the thickness of the disc at L_T and M_s is the Saturnian magnetic moment. If we continue to assume by analogy with the tilt angles for Mercury, Earth and Jupiter that $\theta \approx 10^\circ$, then $M_R \approx 2\ M_s$.

Now since the density at Titan is Alfven limited, or so it seems, the field at Titan now determined by the sum of M_s and M_R, will be larger, which corresponds to a higher density limit, by equation (6), which in turn leads to a higher value for M_R. When this feedback mechanism is considered explicitly, we find that if the proportionality factor in equation (7) is greater than about 1/2, the solution is unstable. That is, each increases in M_R brings in more particles which then produce an even greater increase in M_R. The result is that the magnetosphere either reaches a non-linear saturation, or the increase in M_R reaches a point where the density at Titan is no longer Alfven limited. As shown in Figure 12, which gives the dependence of n_T on B_{ES} (or in the present application on $M_s + M_R$) for given and fixed values of F_{NT}, once the field rises to the point where n_T leaves the Alfven limit curves, further increases in the field produce only small increases in n_T.

In conclusion if Titan lies in the corotation, cross-L diffusion dominated portion of the magnetosphere, it should cause the magnetosphere to become grossly inflated by the production of a massive, self-limiting plasmasphere. In effect in this model Titan blows up the Saturnian magnetosphere in a way that is unique in the solar system.

CONSEQUENCES FOR SATURN'S RINGS

Cheng and Lanzerotti (1978) have drawn attention to possibly interesting magnetospheric consequences for Saturn's rings. They invoke recently measured ice sputtering rates (Brown *et al.*, 1978) and energetic particle intensities scaled from Jupiter to infer a net rate of erosion of the outer edge of the rings of 10^{-6} cm year^{-1}. We note here that the ion flux from Titan can considerably increase this rate.

The inward flux from Titan in the Alfvenic limit is $1.2 \times 10^{25}\ (B^*_{ES})^2\ s^{-1}$, where B^*_{ES} is the effective equatorial surface field which takes into account the magnetic moment of the plasmasphere. In light of the previous discussion, a flux range

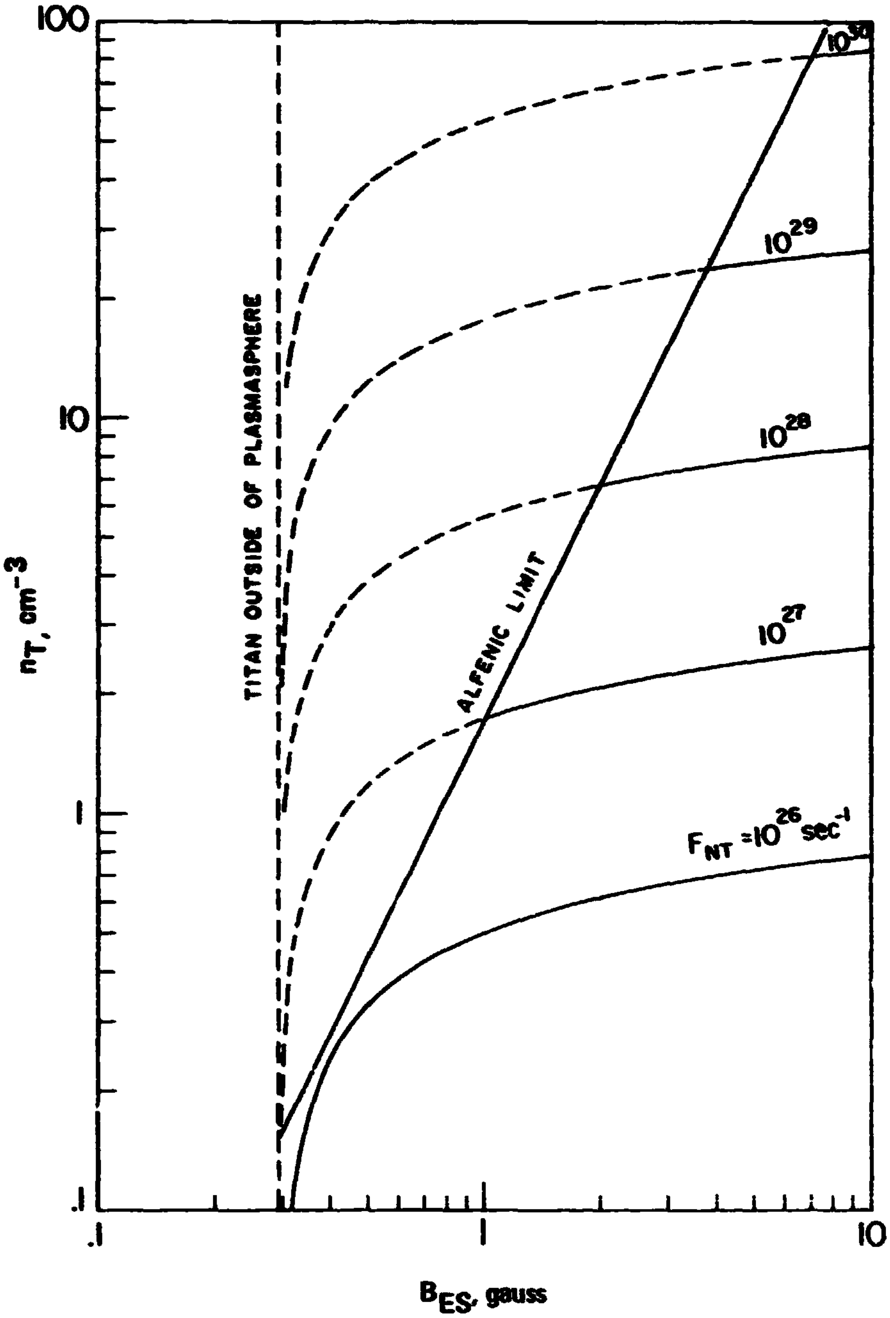

Figure 12. Proton number density at Titan's orbit (n_T) as a function of the (equivalent) strength of the surface equatorial magnetic field at Saturn (B_{ES}) for various assumed loss rates of H_2 and H from Titan (F_{NT}).

of 10^{25} to 10^{26} s^{-1} might reasonably be expected to result from a fully magnetospherically engaged, Titan-derived plasmasphere. At a particle energy of 150 keV, a sputtering efficiency of 0.5 is given, and thus a molecular erosion rate of 5×10^{24} to 5×10^{25} s^{-1} is here inferred to result from the absorption of the inward diffusing Titan-ion flux by the outer edge of the ring. If we assume a molecular density equivalent to a uniform disc of water ice with a thickness of 10 cm, we find an erosion rate between 5×10^{-3} to 5×10^{-2} cm yr^{-1}.

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DISCUSSION

D. CRUIKSHANK: The idea of sputtering from the edge of the rings is interesting. I wonder if you might not be sputtering water off the inner satellites and depositing it on the rings?

G. SISCOE: Yes, that's one of the calculations that should also be done. The satellites are going to be absorbing this inward flux just as the rings are. Current estimates suggest that the satellites will not absorb a significant fraction of the flux, that the rings are still going to get most of it. But from the point of view of the satellites, they're still absorbing their full complement. I would guess an absorption rate of perhaps 10 molecules per square centimeter per second.

S. CHANG: If Titan is inside Saturn's magnetosphere, what would be the flux of the particles into the atmosphere of Titan?

G. SISCOE: That would be just the product of the density (1.7 particles per cm^3) and the velocity (200 km s^{-1}).

B. SMITH: If the E Ring actually exists and extends out perhaps as far as 20 Saturnian radii, essentially out to the orbit of Titan, then it represents an important absorption surface. If the particles are oscillating back and forth across the ring plane with a period of a few seconds, and the E Ring has an optical thickness of the order 10^{-6}, then there's a depletion time constant of the order of months. The question is: Does the inward diffusion swamp that or will there be an appreciable effect on the distribution of particles?

G. SISCOE: It's comparable. If the actual time scale for depletion is of the order of months, there might be a significant effect.

B. SMITH: In that case, measurement of the particle flux as a function of the distance from Saturn would present an excellent way of mapping out this medium which is too thin to be seen optically.

E. STONE: What is the possibility that if Titan is such a pro[illegible] producer of plasma, then the magnetic field just cannot retain the plasma at all, and one has essentially a wind blowing?

G. SISCOE: That is a necessary consequence of the model I just presented. There would be a Titan wind of more than 10^{26} particles per second going out. You need a band with a thickness of about a thousand kilometers to carry that wind. It's not a big feature.

J. WARWICK: Do you have any comments on possible effects at Saturn analogous to those due to Io's interaction with Jupiter's magnetosphere, either from the rings or interior satellites or Titan?

G. SISCOE: The potential difference across Titan is about 10 kilovolts, which is probably not enough. The potential difference across the Earth's ionosphere is about 50 kilovolts and that does all kinds of interesting things. So my guess is that there probably is an electrodynamic coupling having some small effects, but nothing comparable to Io.

D. HUNTEN: All this work assumed that everything that gets emitted from Titan is quickly ionized, isn't that right?

G. SISCOE: It assumes that the mechanism of particle loss is through ionization. A neutral density will build up to the point where the ionization rate balances the loss rate. The amount of neutral hydrogen in the torus should build up to something like 10^{35} particles.