CHRIS P. PARANICAS and ANDREW F. CHENG

SATELLITE ABSORPTION OF ENERGETIC PARTICLES

Planetary satellites and rings are found within the magnetospheres of the outer planets and have important effects on the trapped charged-particle population. We present a theory for calculating the average plasma lifetimes against absorption by these generally nonconducting solid bodies. Some interesting features of the sweeping signatures are related to the tilt between the spin axis of the planet and the dipole axis, while others are a result of large particle gyroradius. The theory is used to compare the importance of satellite sweeping and other particle loss mechanisms.

INTRODUCTION

Six planets (Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune) are known to have intrinsic magnetic fields strong enough to deflect the solar wind above the planetary surface (in the case of Mercury) or the top of the atmosphere (all others). The solar wind is an ionized gas, or plasma, expanding radially outward at hypersonic speeds from the Sun and extending beyond the orbit of Neptune. A magnetized planet forms a blunt obstacle to the solar wind and creates a cavity within it, called a magnetosphere. A magnetosphere is permeated by the magnetic field of the planet and is filled by magnetically trapped plasma; that is, a magnetosphere is a "magnetic bottle."

For all of the magnetized planets, the magnetic field is, to first approximation, dipolar. This approximation is generally valid except near the magnetospheric boundaries or well downstream from the planet (in the tail region of the magnetosphere). At Mercury, Earth, Jupiter, and Saturn, the magnetic dipole is reasonably well centered in the planet and nearly parallel or antiparallel to the planetary rotation vector. For all of these planets, the offset of the dipole from the center is $<0.14\,R$ (where R is planetary radius), and the tilt angle from the rotation axis is $<12°$. For Uranus and Neptune, however, the magnetic dipole is significantly offset and tilted; the Uranus offset and tilt are $0.31\,R$ and $60°$,[1] while the Neptune offset and tilt are $0.55\,R$ and $47°$.

The dipolar planetary magnetic field traps charged particles within the magnetosphere, allowing plasma populations and radiation belts, like the Earth's Van Allen belts, to accumulate.[2] If the electric field can be neglected (and it can, in general, for energetic particles in an appropriate reference frame), the charged particle motion, in a roughly dipolar field, is viewed as a superposition of three motions: a gyration, a bounce, and a drift (see Fig. 1). The gyration is the most rapid motion and results from the dominant component of the Lorentz force, $(\mathbf{v} \times \mathbf{B})/c$, which causes the particle to execute a tight spiral around a magnetic field line. For a Van Allen belt proton at 1 MeV near $L = 3$ (L identifies a magnetic field line by its distance from the dipole at the magnetic equator in units of planetary radii), the gyration
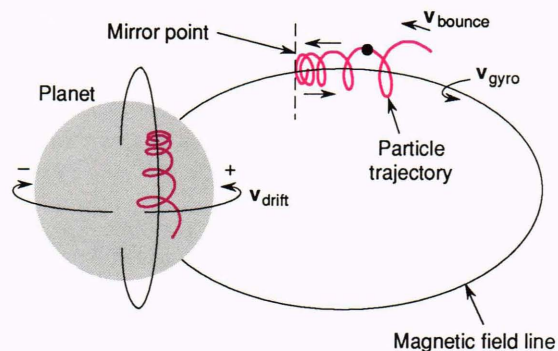

Figure 1. Particle motion in a dipolar field. Shown here is a segment of a charged-particle trajectory combining the cyclotron and bounce motions as the particle moves from the magnetic equator to its mirror point. The helix drifts around the planet in one of the directions shown, depending on the sign of its charge. $\mathbf{v}$ = velocity.

frequency is 30 Hz. Because of gyration, the particle is already confined in two dimensions, but it is still free to move along the magnetic field line. As it approaches a magnetic pole, however, the field strength increases, and the particle is reflected (magnetic mirror effect). The particle is then forced to bounce between the two magnetic poles on a magnetic field line and is said to be trapped. For the 1-MeV proton at $L = 3$ at Earth, the bounce frequency is 0.3 Hz—much slower than the gyration. The magnetically trapped particles also execute an even slower drift around the Earth because of the curvature and gradients of the dipole field. The $L = 3$, 1-MeV proton drifts toward the west and circles the Earth in 30 min.

For the outer planets, the magnetically trapped particles interact with planetary rings and moons within the magnetosphere. The Earth's Moon is usually outside the magnetosphere. The planetary satellites are, generally, inert solid-body absorbers of charged particles, meaning that they are not electrically conducting and that they allow magnetic fields to pass freely through them without significant distortions. The exceptions are Io, Titan,

and Triton, which are large moons of Jupiter, Saturn, and Neptune; these moons have significant conducting ionospheres despite their low surface temperatures and great distances from the Sun.

The numerous remaining moons and rings are basically inert, solid bodies that absorb charged particles from the magnetospheres of the outer planets, a process called satellite sweeping. This process can, in principle, cause severe depletions of charged particles in the specific regions of the magnetospheres that are swept by the moons. The relative importance of satellite sweeping, however, compared with other particle loss mechanisms such as interaction with plasma waves remains controversial.

Significant complications in the satellite sweeping process arise from the offsets and tilts of planetary dipole moments. Nearly all of the planetary satellites are found in regular systems, meaning that they are in prograde, nearly circular orbits at small inclinations to the rotational equator of the planet (Triton is the only important exception with its 158° orbital inclination implying a retrograde orbit). While the satellites remain at an almost fixed radial distance very near the rotational equator, they move far from the magnetic equator because of the dipole tilt and offset. Therefore, each regular satellite moves through a large range in L for offset, tilted dipole fields.

As a moon occupies a particular L for a brief period, it generally absorbs only a small fraction of the particles at that L, even if all the particles that strike the moon's surface are considered to be absorbed. It is convenient to define the particle-guiding center, which is the instantaneous center of gyration around the field line. The guiding center can be visualized as executing bounce and drift motions. When a moon passes through a particular L, it need not absorb a given particle at the same L, because the guiding center may be far from the moon. This can happen for two reasons: (1) the guiding center was at the wrong (azimuthal) drift longitudes, or (2) the guiding center was at the wrong (bounce) latitudes when the moon occupied the same L and longitude. The latter is called the "leapfrog effect" (see the following section). Moreover, even if the guiding center intersects the moon, the particle may still escape absorption if its radius of gyration is large (comparable to or greater than the moon radius). Then, for some or all gyrophases, the particle can escape absorption even when its guiding center passes through the moon; this is called the "corkscrew effect" (see the following section).

This article is intended as an introduction to a more definitive work in progress that includes sweeping by moons and rings in an offset, tilted dipolar magnetic field.

CALCULATION OF THE SATELLITE SWEEPING RATE

Paonessa and Cheng[3] introduced a procedure for calculating the longitudinally averaged lifetime of a charged particle against absorption by an inert planetary satellite, taking into account the leapfrog and corkscrew effects. Their calculations included an arbitrary

dipole tilt, but an offset along only the planetary spin axis. This approximation is appropriate for Uranus but not for Neptune, which has a dipole offset in a completely different direction. We have extended the Paonessa and Cheng calculations to include a general offset vector.

The satellite sweeping rate is a product of probabilities determining the relative locations of particles and moons. For particles on a particular L-shell, we identify which moons intersect that L; for each of those moons, we calculate the longitudes at which they sweep (there are at most four values for each moon and L-shell). A moon sweeps at each longitude for a short time that is determined by the position and dynamics of the absorber with respect to the shell. The probability of absorption is then proportional to the probability that a drifting particle will be at the sweeping longitude when the moon is sweeping it. We next compute the probability that the particle is in the same position on its helical trajectory as the moon is sweeping. This part of the calculation, which is now done assuming the particle and moon are at the same longitude, determines the probability both that the particle and moon are at the same latitude (leapfrog effect) and that the gyroradius and gyrophase are such that the particle is absorbed (corkscrew effect).

To determine which moons sweep at the appropriate L-value, we use the relation for dipole fields,

$$L \cos^2 \lambda_m = r_0 , \qquad (1)$$

where λ_m is the magnetic latitude of the moon and r_0 is the distance from the dipole center to the moon's center (see Fig. 2). For simplicity in the article, we neglect the offset and consider only a tilted dipole field, where the planet's center and the dipole center coincide and r_0 is constant. It is easy to show that the moon's longitude, ϕ, taken in the coordinate system whose z-axis is along the rotation axis of the planet, is related to its magnetic latitude by the equation,

$$\sin \lambda_m = \sin \eta \cos \phi , \qquad (2)$$

where η is the tilt angle between the magnetic dipole axis and the spin axis. Using Equations 1 and 2, we see that for a moon at distance r_0, the minimum L-value at which it sweeps is $L_{min} = r_0$, and the maximum L-value at which it sweeps is $L_{max} = r_0/\cos^2\eta$. At Uranus, where the tilt is $\eta = 60°$, the Uranian moons and rings consequently survey a large range of L-values. The Uranian moon, Miranda, for example, is located at 5.055 R_U (where 1 $R_U = 2.56 \times 10^4$ km) from the center of the planet and would sweep particles trapped between $L = 5.055$ and $L = 20.22$. (Because of an offset, these numbers are actually $L_{min} = 5.06$ and $L_{max} = 25.45$.) A second moon, Ariel, is located at 7.46 R_U, so that particles just beyond this value will be swept by both of these moons.

Given a particular value of L, we then use Equations 1 and 2 to find the longitudes at which the moon sweeps. In this case, we find those longitudes are given by
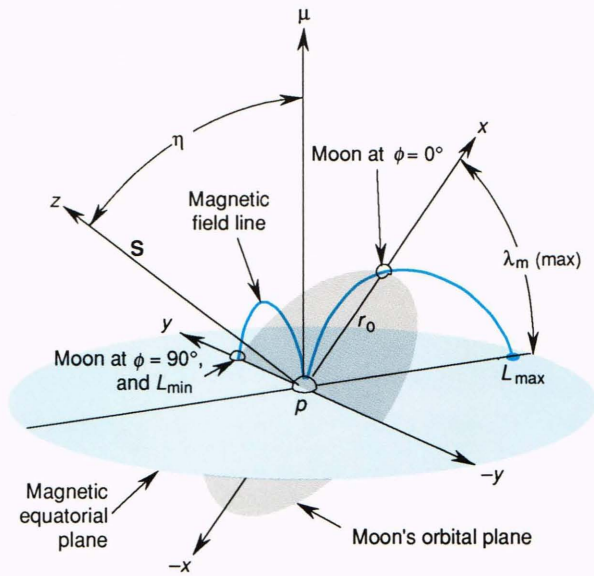
Figure 2. Determination of magnetic *L*-value at different longitudes. Shown here are the minimum and maximum values of *L* for a given moon and dipole tilt. The magnetic field line, which passes through the moon, is shown; its intersection with the magnetic equatorial plane (the plane perpendicular to μ) determines the moon's *L*-value. *p* is the location of the plane, m is the moon, ϕ is the moon's longitude, μ is the magnetic dipole, **S** is the planet's angular momentum vector, η is the tilt angle between μ and **S**, r_0 is the fixed distance from the planet to the moon, and λ_m is the latitude of the moon measured from the magnetic equator. $\phi = 0°$, *L* attains its maximum value; $\phi = 90°$, *L* is at its minimum value.

$$\cos \phi^{\pm} = \pm \frac{\sqrt{1 - r_0/L}}{\sin \eta} . \qquad (3)$$

Particles orbiting Uranus at $L = 6$, for example, would be swept at the four longitudes $\phi_1 = 62.7°$, $\phi_2 = 117.3°$, $\phi_3 = 242.7°$, and $\phi_4 = 297.3°$ (ignoring the offset). The absorption probability is then a double sum of probabilities, first over all moons and rings that sweep at a particular *L*-shell, and then over all longitudes at which each sweeps.

To compute how long a moon sweeps at given *L*-value, Δt, we consider the moon to be sweeping from the time its leading edge reaches *L* to the time its trailing edge leaves *L*. In this amount of time, the center of the moon moves at least a distance equal to the moon's diameter, $2R_m$. But because particles are gyrating around field lines, this distance is effectively $2R_m + 2r_g$ ($\equiv 2r_m$, the effective diameter of the moon), where r_g is the particle gyroradius. (When the moon is off the magnetic equator, there is an additional correction that is neglected here.) The sweeping time is then $\Delta t = 2r_m/(dL/dt)$. Using $dL/dt = (dL/d\phi)(d\phi/dt)$, we can differentiate Equations 1 and 2 to find $dL/d\phi$. Here, $d\phi/dt$ is the angular frequency of the moon around the rotation axis of the planet. (For Miranda, $R_m = 9.4 \times 10^{-3} R_U$, and the rotation frequency around Uranus is $d\phi/dt = 4.95 \times 10^{-5}$/s. The gyroradius of
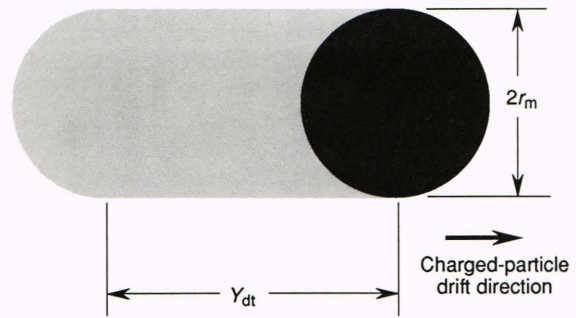

Figure 3. Determining P_a. Shown is a cross section of the moon (dark) and the upstream region over which the absorption probability is averaged (shaded). Y_{dt} represents the distance an energetic particle drifts in one bounce period. The effective moon diameter is $2r_m$.

a 1-MeV proton at $L = 6$ is about $1.5 \times 10^{-2} R_U$ at the moon, so that $2r_m = 4.8 \times 10^{-2} R_U$. At the first sweeping longitude, ϕ_1, $dL/d\phi = -4.4$, and so the sweeping time, Δt, at that longitude for Miranda is about 220 s.)

If the particles are uniformly distributed in longitude, they travel $\Delta t(\omega_d - \Omega_m)$ radians with respect to the moon in Δt, where ω_d is the drift frequency of the particle, and Ω_m is the rate of change of magnetic longitude of the moon around the dipole axis as seen in the co-rotating frame. This can be calculated in terms of the tilt angle and the Kepler orbit velocity in an inertial frame. The probability of a drifting particle encountering the appropriate sweeping longitudes in the time interval, Δt, is then the fraction,

$$f = \frac{1}{2\pi}[\Delta t(\omega_d - \Omega_m)] . \qquad (4)$$

The probability of absorption by a moon in Δt at one sweeping longitude is then given by $P_1 = fP_a$, where P_a is the probability that the particle will be at the appropriate latitude and gyrophase for absorption. (For the case of 1-MeV protons at the $L = 6$ shell of the Uranian magnetosphere, $\omega_d = 1.01 \times 10^{-3}$/s, and $\Omega_m = 2.93 \times 10^{-5}$/s, so that the longitudinal fraction of particles that can interact with the moon as it sweeps at $\phi = 62.7°$ is $f = 0.03$.)

The probability, P_a, is computed following particle trajectories.[4] Figure 3 shows the plane passing through the moon's center and perpendicular to the magnetic field. All particle guiding centers that pass through the moon must pass through some point in the shaded region. This is true because we have chosen the length of the shaded region to be the azimuthal distance the particle drifts in one bounce time, labeled Y_{dt}. If we divide the shaded region into a grid and label each grid point, we can ask what the probability is that a particle passing through that point will be absorbed by the moon. This probability is calculated numerically following a particle trajectory until the particle is past the moon. As mentioned previously, there are two ways a particle can miss being absorbed by the moon. First, the particle can

leapfrog over the moon if, as it is drifting through a longitude and L-value at which the moon is absorbing, the particle is not at the same latitude as the moon. In Figure 4, we plot the latitude versus the longitude of the particle trajectory as it encounters the moon. The moon latitude as it crosses the L-shell is also shown.

Second, particles may miss the moon because of the corkscrew effect. A particle travels on a helix whose axis is temporarily at a fixed longitude. If the radius of gyration of the particle is at least comparable to that of the moon, the particle may not be absorbed, even though its guiding center passes through the moon. As shown in Figure 5, the gyroradius is larger than the moon radius, and potentially all particles, regardless of gyration phase, can miss the moon. A probability for each grid point, P_i, is calculated by averaging over all initial gyrophases and over the two initial orientations; the particle intersects the grid traveling northward and southward. The probability of absorption, P_a, is then the average over the grid,

$$ P_a = \frac{\int P_i \, dA}{\int dA} \ . \qquad (5) $$

The total probability of absorption per moon synodic orbit period, $2\pi(\Omega_k - \Omega_p)$, is given by

$$ P_2 = \sum_{moons} \sum_{long} f \, P_a $$
$$ = \sum_i \sum_j \frac{2r_m}{2\pi} \frac{(\omega_d - \Omega_m)_{ij} P_a^{ij}}{(dL/d\phi)_{ij} \, (d\phi/dt)_{ij}} \ . \qquad (6) $$

If we consider the sweeping to occur continuously, instead of at fixed longitudes, we get an average absorption probability,

$$ P = \frac{P_2 \dfrac{d\phi}{dt}}{2\pi} = \tau_{ss}^{-1} \ , \qquad (7) $$

where τ_{ss}^{-1} is the sweeping probability.

DISCUSSION

While it is not established whether satellite sweeping can be the dominant mechanism for particle loss, Voyager charged-particle data from Uranus and Saturn suggest that satellite sweeping may be an important process. Figure 6 shows fluxes of energetic particles in the innermost regions of the Uranian magnetosphere. The figure indicates that plasma depletions occur at or near the minimum L-shells of several of the large Uranian moons. Satellite sweeping, however, is not the whole story. In some cases, the dips are not well-aligned with the minimum L-shells; furthermore, electron and ion signatures are not aligned with each other. Detailed analysis shows that there are source mechanisms for both ions and electrons, as well as loss processes (in addition to satellite sweeping), that shape these profiles. For example, a high-energy proton injection occurred at 1545 UT on 24 Janu-
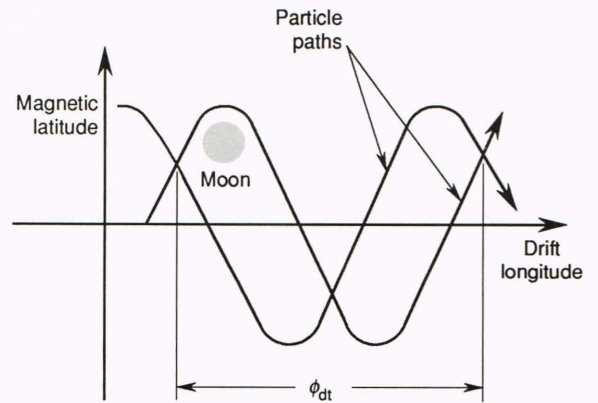

Figure 4. Sketch of leapfrog effect. In this schematic of charged-particle and satellite magnetic latitude versus drift longitude, the particle passes through a longitude and L-shell occupied simultaneously by the satellite, but its latitude is too large for it to be absorbed. ϕ_{dt} is the angle in longitude a particle moves in one bounce period.
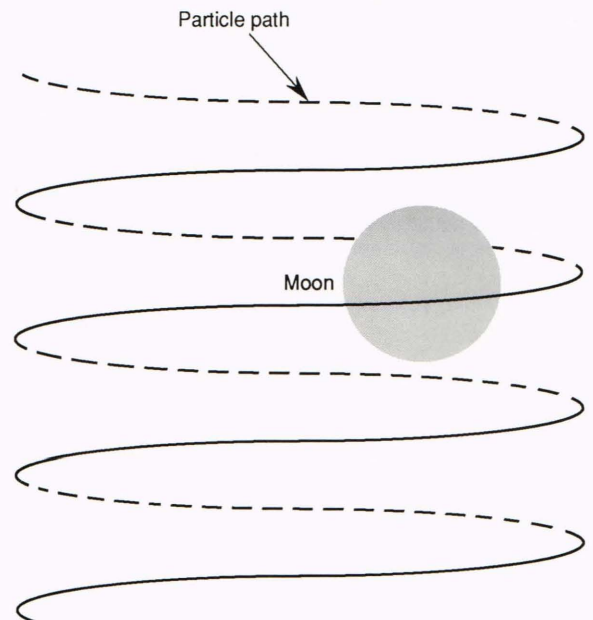

Figure 5. Sketch of corkscrew effect. Because of its large gyroradius, a particle, in executing cyclotron motion, may spiral around the moon without being absorbed by it.

ary 1986, probably indicating a Uranian substorm. There are also important losses of electrons to scattering by plasma waves, causing precipitation to the Uranian atmosphere, and evidence for electron sources spatially distributed between the satellite minimum L-values.

A striking phenomenon believed to result from satellite sweeping is shown in Figure 7. This plot shows electron spectra in Saturn's magnetosphere, with peculiar peaks just below 1-MeV energy. The peaks are attributed to satellite sweeping resonances, when the particle angular drift rate in magnetic longitude exactly matches that of the moon. At such resonances, the particle neither over-
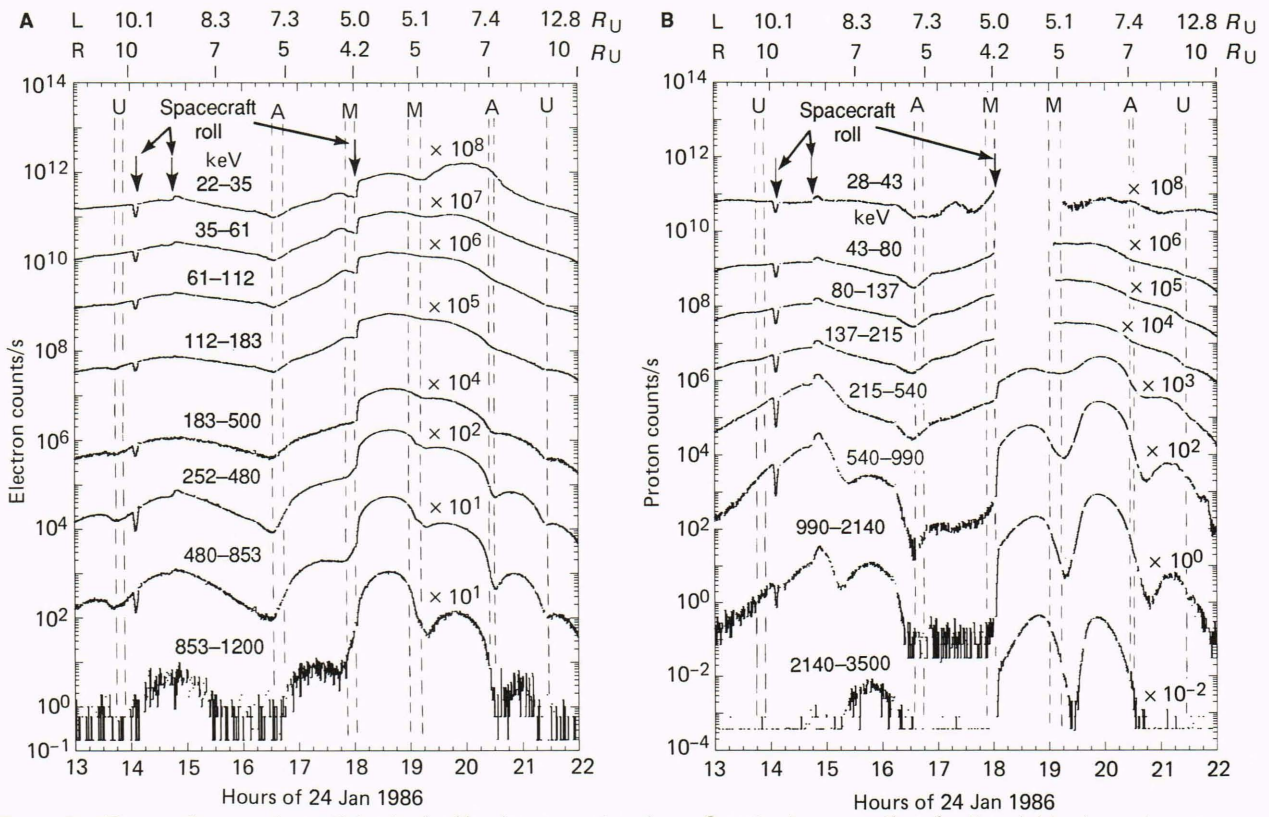
Figure 6. Fluxes of energetic particles in the Uranian magnetosphere. Count rate versus time for the eight primary low-energy charged-particle electron and ion channels. Spacecraft roll maneuvers are shown, as well as the two (because of offset) local minima in the *L*-shell for each of the moons, Miranda (M), Ariel (A), and Umbriel (U). (Reprinted, with permission, from Ref. 5. © 1987 by the American Geophysical Union.)
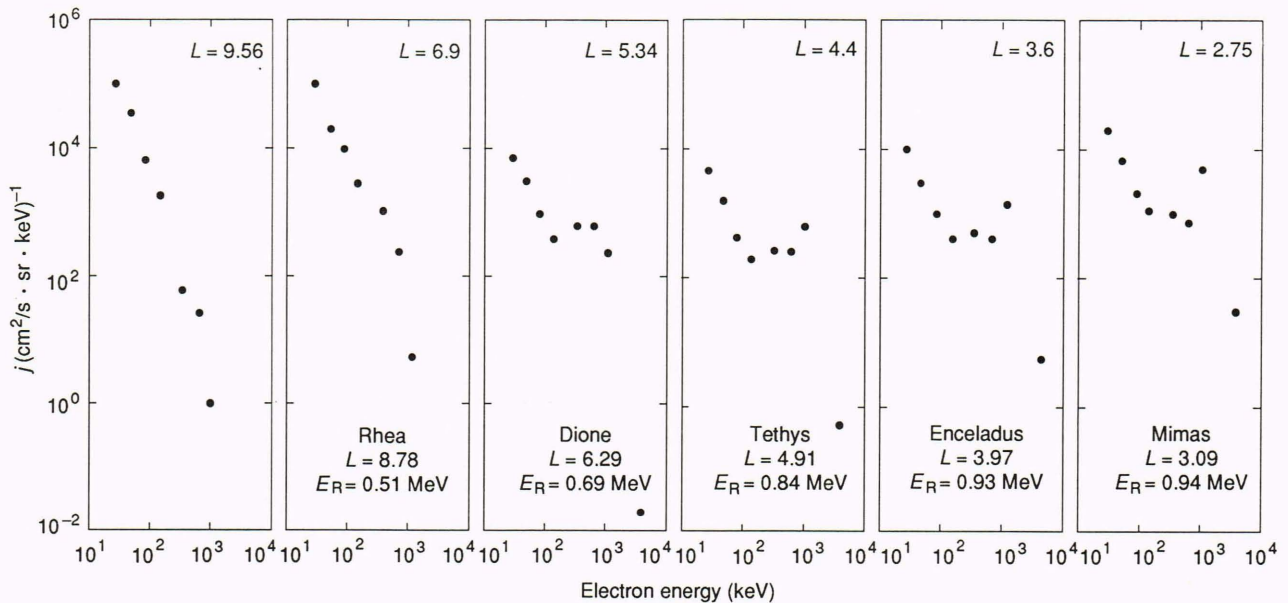

Figure 7. Electron spectra at various *L*-values (shown in upper right corner) of low-energy charged particles measured by Voyager 2. Minimum *L*-shells of Saturnian moons and resonant electron energies at each satellite are given. (S. M. Krimigis, personal communication, 1982).

takes nor is overtaken by the moon, so $\omega_d = \Omega_m$, and particles have zero probability of being absorbed. For a general tilted dipole, the resonances are broad because

Ω_m varies with the moon longitude, but at Saturn, the resonances are particularly sharp because the dipole is nearly aligned, within 1°, to the spin axis. For a perfect-

ly aligned dipole, Ω_m is constant and equal to the Kepler angular velocity seen in the reference frame rotating with the planet. For Saturn, sweeping resonances occur only for electrons because protons drift in the opposite direction to the moon.

As mentioned earlier, this theory neglects the offset of the dipole center. At planets where the offset is large, the sweeping rate predicted here is no longer correct, especially at small L-values, because circular drift shells, which are centered on the dipole, may dip into the planet's atmosphere over some longitudinal extent. Particle precipitation in these shells is enhanced (for example, the south Atlantic anomaly at Earth).

In Figure 8, we show examples of satellite sweeping rates calculated by the method outlined earlier, but including offsets. The sweeping rates calculated for Uranus are typical of the outer planets, showing that peaks in the loss rate occur at the minimum L-values of each moon (shown here are the minimum L-values of the moons, Miranda, Ariel, and Umbriel). Peaks also occur where the particle mirror latitude equals the moon latitude. This latter peak occurs because bouncing particles spend a long time close to the mirror point, where their parallel velocity goes to zero. Also, because the field is stronger at the mirror point, the radius of gyration is smaller. These circumstances make the probability of absorption by a moon at those latitudes more likely. The L-values shown in Figure 8 are too large to be affected by atmospheric precipitation due to the offset; however, the absorption peaks from the moons would shift in L-value if the effect of the offset were removed.

These calculated loss rates are compared in detailed analysis with losses from plasma wave scattering and charge exchange (with ambient neutral gas atoms, leading to neutralization and subsequent loss of energetic ions). This "strong diffusion rate" shown in Figure 8 is a theoretical upper limit to the rate of precipitation loss induced by plasma wave scattering and is a convenient benchmark for comparison with satellite sweeping. The strong diffusion loss rate is in fact approached within the Io torus at Jupiter, and satellite sweeping by Io itself is a relatively unimportant process. At Uranus and Neptune, however, the importance of satellite sweeping compared with other processes is still controversial and will be a topic for further study.

Figure 8. Total satellite sweeping loss rate τ^{-1} of 1-MeV electrons (blue) and protons (red) with equatorial pitch angles of 30°. The dashed red and blue lines are the pitch-angle diffusion loss rate, $\tau_{SD}^{-1} \times 10^{-3}$. The minimum L-values of the moons Miranda (M), Ariel (A), and Umbriel (U) are shown. SD = strong diffusion.

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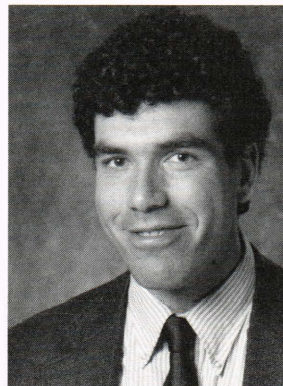
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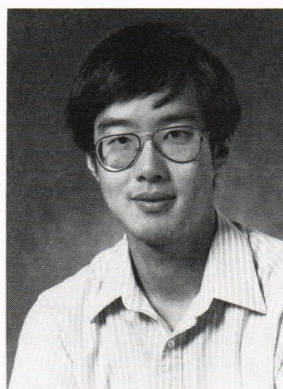
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[5] Mauk, B. H., Krimigis, S. M., Keath, E. P., Cheng, A. F., Armstrong, T. P., et al., "The Hot Plasma and Radiation Environment of the Uranian Magnetosphere," *J. Geophys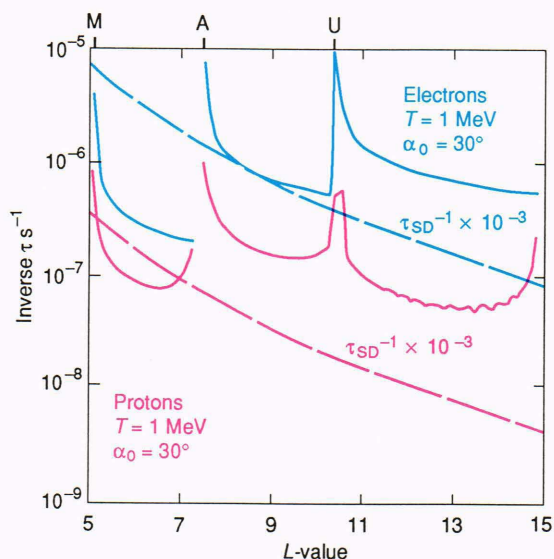. Res.* **92**, 15,283–15,308 (1987).