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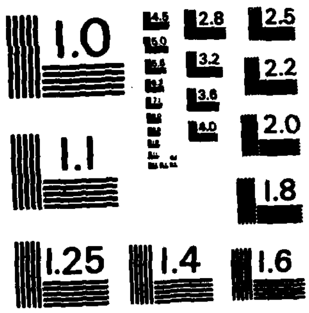

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ABSORPTION OF ENERGETIC PROTONS BY SATURN'S RING G

by

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ABSTRACT

A restudy has been made of Pioneer 11 data on the distribution of energetic protons $E_p > 80$ MeV in Saturn's inner magnetosphere. An improved value of the ratio of the Crand source strength β to the radial diffusion coefficient D is 6.9×10^{-24} cm^{-5} at $r \sim 2.67$ R_s (1 R_s = Saturn's equatorial radius = 60,000 km). Using the recently calculated lower limit on β by Blake et al., one finds an upper limit on the mean residence time T against diffusion 4.6×10^8 s (15 years) in the major peak of the distribution, whereas using our earlier estimate of β, one finds $T \sim 2.2 \times 10^8$ s (7.0 years). The two corresponding determinations of D are $> 1.3 \times 10^{-11}$ and $\sim 2.8 \times 10^{-11}$ R_s^2 s^{-1}, respectively. A generous upper limit on D is 7×10^{-10} R_s^2 s^{-1} as found from study of the slot region associated with the co-orbiting satellites 1979 S2 (1980 S1) and 1980 S3. The mean lifetime τ of energetic protons against absorption by particulate matter in Ring G is $< 1.1 \times 10^8$ s (3.5 years) and $\sim 5.1 \times 10^7$ s (1.6 years) corresponding to the two choices of β. Then, using the Voyager data of Terrile on normal optical opacity $\eta \sim 3 \times 10^{-5}$ and on radial width $\Delta r \sim 500$ km, one finds that the particulates in Ring G have an effective radius $R \gtrsim 0.035$ cm,

an areal mass density $\sigma > 1.4 \times 10^{-6}$ g cm^{-2}, and an areal number density $n < 8 \times 10^{-3}$ cm^{-2}. It is quite unlikely that R exceeds 0.1 cm. The foregoing values of R (for assumed spherical particulates of water ice, all of the same size) are in effect the ratio $< R^3 >/< R^2 >$ for a distribution of sizes where the symbol $< >$ denotes the mean value over the distribution. It is reasonably certain that there are no satellites having radii of the order of a kilometer or larger associated with Ring G and that objects having radii ≥ 10 cm contribute less than 10^{-3} of its opacity. The radius of Ring G is 170,200 ± 900 km.

INTRODUCTION

In a preliminary paper on Pioneer 11 observations of energetic particles in Saturn's inner magnetosphere, Van Allen et al. [1980a] reported a distinctive absorption feature at a radial distance $r \approx 2.82\ R_S$. ($1\ R_S$ = Saturn's equatorial radius = 60,000 km.) This feature ~~(Figure 1)~~ was accurately the same in form, magnitude, and radial position on inbound and outbound segments of the encounter trajectory; the lapse of time between the two traversals of the feature was 3.9 hours and the difference in planetocentric inertial longitudes was 178°. Hence, the feature appeared to be time-stationary and independent of longitude. It was labeled 1979 S3 and identified in the text as "provisional evidence for a heretofore unknown satellite". In the summary table of that preliminary report it was designated as a satellite with the qualifying remark: "suspected [to be the absorption signature of a satellite] but interpretation of [the] signature [is] ambiguous". The nature of the ambiguity was that the available data could not distinguish between the absorption signature of a longitudinally uniform ring of particulate matter and the macro-signature (time-stationary and uniform in longitude) of a small satellite [Van Allen, 1982].

The particles whose absorption was observed were identified [Fillius et al., 1980] [Simpson et al., 1980] [Trainor et al., 1980] [Van Allen et al., 1980b] as being trapped protons having energies $E_p > 80$ MeV.

During the subsequent Saturn encounter of Voyager 1, an image was obtained of a segment of what appeared to be a faint, narrow ring of particulate matter at a radial distance of ~170,000 (2.83 R_s). [Figure 31 (c) of Smith et al., 1981]. This feature was given the provisional designation Ring G. Implicit in this designation was the presumption that the feature encircles the planet and is longitudinally uniform. Images by Voyager 1 and later by Voyager 2 [Figure 35 of Smith et al., 1982] are too fragmentary to truly confirm this presumption but it is generally regarded as physically plausible. The best available geometric and photometric studies of Ring G (after approximate correction for image smearing) yield a radial width $\Delta r \sim 500$ km and an average normal optical depth of 10^{-4} to 10^{-5}, as attributed to that width [R. J. Terrile, private communication, 1983]. The axial thickness Δz is not measured but appears to be less than Δr.

The subsequent discussion assumes that such a ring of particulate matter is the cause of the absorption feature observed by Pioneer 11 at r ≈ 2.82 R_s.

PRELIMINARY CONSIDERATIONS

In Figures 2 and 3 are shown the counting rates of the University of Iowa detector C as a function of radial distance r for inbound and outbound passages through the region of interest. The latitude of Pioneer 11 in the region 2.8 to 2.9 R_s was less than 0°.3 from the planet's equatorial plane (ring plane). By virtue of this fact and the further fact that the magnetic dipolar moment of the planet is accurately aligned with the rotational axis of the planet and is very nearly at the center of the planet [Smith et al., 1980] [Acuña et al., 1980], the geometric radial distance r and the McIlwain magnetic shell parameter L are negligibly different in value along Pioneer 11's trajectory in this region. The counting rate data of Figures 2 and 3 are at the highest available time resolution; the accumulation time for each sample is 0.75 second and the interval between samples is 8.25 seconds. Detector C (a miniature Geiger-Mueller tube) is an omnidirectional one but its sensitivity is not spherically symmetrical because of the cylindrical shape of its sensitive volume and the nonuniformity of its shielding. The cyclic modulation of its counting rate is the beat note between the telemetry sequence and the rotation of the spacecraft.

From the modulation pattern, Randall has inferred the approximate value $m = 4$ at $r \sim 2.7\ R_s$ in an angular distribution of unidirectional integral intensity of the form $j \propto \sin^m \alpha_o$ where α_o is the equatorial pitch angle [Van Allen et al., 1980b]. The mean counting rate R in counts s^{-1} is taken to be proportional to the omnidirectional integral intensity J with

$$J = 8.2\,R . \qquad cm^{-2}\,s^{-1} \quad (1)$$

In turn, the number density of particles N is given by

$$N = 8.2\,R < 1/v > \qquad cm^{-3} \quad (2)$$

where $< 1/v >$ is the average reciprocal speed of the particles being measured. For a threshold energy of 80 MeV and a spectrum of the form

$$\frac{dj}{dE_p} \propto E^{-0.2},\ 10 < E_p < 120 \text{ MeV}$$

and

$$\frac{dj}{dE_p} \propto E^{-1.7},\ E_p > 120 \text{ MeV}$$

[Blake et al., 1983], there are about equal contributions to J by protons of energy less than and greater than 200 MeV. I have adopted $\langle 1/v \rangle$ to be the reciprocal speed of a 200 MeV proton, namely $(0.57\ c)^{-1}$, where c is the speed of light. Hence

$$N = 4.80 \times 10^{-10} R . \qquad \text{cm}^{-3} \qquad (3)$$

The inbound and outbound curves are virtually identical except that the outbound counting rates are uniformly 10% less than those inbound. The reason for this difference is not known.

At the level of refinement that appears appropriate to the problem at hand, I have adopted the following simplifying assumptions in the small radial range, $2.56 < r < 3.00\ R_s$.

(a) The source strength of protons of energy $E_p > 80$ MeV is independent of r.

(b) The radial diffusion coefficient D is independent of r and of E_p.

(c) Absorption losses are zero except at Ring G.

(d) The geometry is one-dimensional with r as the independent variable.

(e) The particle energy during the process of inward and outward diffusion is independent of r.

(f) The physical situation is time-stationary.

The corresponding one-dimensional diffusion equation for the number density N in a time-stationary situation is

$$D \frac{d^2N}{dr^2} = -\beta \tag{4}$$

except at Ring G.

The solution of (4) subject to the boundary conditions $N = 0$ at $r = a$ and $dN/dr = 0$ at $r = b$ where $b > a$ is

$$N = \frac{\beta}{2D}(-r^2 + 2br + a^2 - 2ab) \tag{5}$$

and

$$N_{max} = \frac{\beta}{2D}(b - a)^2 \tag{6}$$

at $r = b$.

The best fits of equation (5) to the inward sides of the major peaks in Figures 2 and 3 correspond to $a = 2.56\ R_s$ and $b = 2.67\ R_s$ in both cases. These half-parabolas are drawn as smooth curves in the figures and continued beyond $r = b$ until $N = 0$ at $r = 2.78\ R_s$. The departure of the data from a symmetrical parabola for $r > b$ is thought to be attributable to an increase of D with increasing r, an effect that was neglected by assumption (b) above, and to the non-zero value of N at Ring G.

The counting rate vs r curve in the vicinity of Ring G is fit graphically by three line segments as shown in each of Figures 2 and 3. The respective intersections of these lines occur at 2.795 and 2.866 R_s, inbound, and 2.801 and 2.882 R_s, outbound. The mean of these four numbers is taken to provide a best estimate of the radius of Ring G, namely

$$r = 2.836 \pm 0.015 \ R_s = 170{,}200 \pm 900 \text{ km}, \qquad (7)$$

a result consistent with Voyagers 1 and 2 values. The respective differences between inner and outer intersections are 0.071 and 0.081 R_s, for an average of 0.076 R_s or 4,560 km. Twice the equatorial gyroradius r_g of a 200 MeV proton at an equatorial pitch angle $\alpha_o = 90°$ in the observed magnetic field at $r = 2.84 \ R_s$ is 4,700 km (shown by the horizontal arrows labeled 2 r_g in Figures 2 and 3). The accuracy of the agreement between the foregoing two numbers is fortuitous, of course, but the general nature of the agreement supports the imaging evidence that the radial width Δr of Ring G is much less than 2 r_g and the expectation that absorption occurs only for those particles whose guiding centers are within 1 r_g of the ring.

The absolute value of N_{max} at $r = 2.67 \ R_s$ as inferred from the observations by using equation (3) is

$$N_{max} = 1.51 \times 10^{-6} \text{ cm}^{-3} \qquad (8)$$

(mean of inbound and outbound data) for $E_p > 80$ MeV.

Then by equation (6)

$$\frac{\beta}{D} = 6.9 \times 10^{-24} \text{ cm}^{-5}, \qquad (9)$$

a value about three times greater than that found in our earlier, less exact, analysis [Van Allen et al., 1980b]. In that earlier paper we estimated the source strength at r = 2.67 as

$$\beta \sim 7 \times 10^{-15} \text{ cm}^{-3} \text{ s}^{-1} \qquad (10)$$

by comparison with the Crand source strength at the earth. A recent paper of considerably greater calculational sophistication [Blake et al., 1983] reports a sample value for the injected flux at L = 2.65 at $\alpha_o = 65°$ as $\geqslant 8 \times 10^{-5}$ cm^{-2} s^{-2} for protons of energy $E_p > 10$ MeV. If one uses their calculated spectrum of the injected protons as quoted earlier, the lower limit of injected flux of protons $E_p > 80$ MeV is 5.7×10^{-5} cm^{-2} s^{-2}. This flux, assumed to be about the same over the principal part of the observed pitch angle distribution, corresponds to a theoretical source strength.

$$\beta \geq 3.3 \times 10^{-15} \text{ cm}^{-3} \text{ s}^{-1}, \qquad (11)$$

a lower limit value about one-half of our earlier estimate as quoted in equation (10).

The mean residence time T against inward and outward diffusion from the major peak of intensity centered at 2.67 R_s is given by

$$T = N_{max}/\beta . \tag{12}$$

The observed value of N_{max} from (8) and the lower limit value of β from (11) yield an upper limit

$$T < 4.6 \times 10^8 \text{ s (15 years)} \tag{13}$$

whereas the observed value of N_{max} from (8) and our earlier estimate of β from (10) yield

$$T \sim 2.2 \times 10^8 \text{ s (7.0 years)} . \tag{14}$$

ABSORPTION OF ENERGETIC PROTONS BY RING G

By inspection of Figures 2 and 3 it is evident that the lifetime against absorption τ of energetic protons by Ring G is less than T by a factor k, where $k \ll 1.0$.

A more detailed treatment follows. The scheme of the analysis is to write and solve the simple one-dimensional continuity equation for the Ring G region, using observed data insofar as possible:

$$\text{Inward Flux (from the left)} + \text{Source Rate}$$
$$= \text{Loss Rate} + \text{Outward Flux (to the right)}. \qquad (15)$$

The mean of observed inbound and outbound values of dN/dr on the left of the absorbing region is 1.44×10^{-15} cm^{-4} and, on the right of the region, 0.41×10^{-15} cm^{-4} (straight lines in Figures 2 and 3); and the mean value of N in the middle of the region is 4.6×10^{-7} cm^{-3}. Therefore, equation (15) for a region of radial width $2\ r_g = 4.7 \times 10^8$ cm becomes:

$$D\ (1.44 - 0.41) \times 10^{-15}$$
$$= \left(\frac{4.6 \times 10^{-7}}{\tau} - \beta \right) (4.7 \times 10^8)\ . \qquad (16)$$

Upon replacing τ by Tk and T by $1.51 \times 10^{-6}/\beta$ from (8) and (12), one finds from (16) that

$$2.19 \times 10^{-24} = \frac{\beta}{D} \left(\frac{0.305}{k} - 1 \right). \tag{17}$$

Further, $\frac{\beta}{D}$ by (9) $= 6.9 \times 10^{-24}$. Therefore,

$$k = 0.23 \tag{18}$$

It is noted that k is a reliably determined quantity because its magnitude is dependent only on observed quantities and elementary theory. By (13)

$$\tau < 1.1 \times 10^{8} \text{ s (3.5 years)} \tag{19}$$

or by (14)

$$\tau \sim 5.1 \times 10^{7} \text{ s (1.6 years)}. \tag{20}$$

SIZE OF PARTICULATES IN RING G

The results of the previous paragraphs will now be used to estimate the size of the particulates in Ring G.

(a) The latitudinal bounce period T_B of a 200 MeV proton at $r = 2.84\ R_s$ is 3.0 s [Thomsen and Van Allen, 1980], a value nearly independent of α_o. During each half bounce the proton passes through the ring plane. If its guiding center pierces the ring plane within 1 r_g of Ring G the gyro-phase-averaged probability that its trajectory will pass through the ring is $\sim \Delta r/2\ r_g$, a quantity of the order of 0.1.

(b) Let η be the normal optical opacity of the ring (also called the normal optical depth), i.e., the fraction of the total ring area that is obscured by particulates as viewed normal to the ring plane. If there are n spherical particulates of uniform radius R per unit projected area of the ring then

$$\eta = \pi R^2 n . \tag{21}$$

(c) The ring is assumed uniform over Δr and axially thin compared to the pitch of the spiral path of the energetic particles.

(d) The corresponding areal mass density of the ring

$$\sigma = 4\pi \rho R^3 n/3 \tag{22}$$

where ρ is the mass density of a particulate.

(e) By (21) and (22)

$$\sigma/\eta = 4\rho R/3 \, . \tag{23}$$

(f) The total mass of the ring

$$m = 2\pi r \sigma \Delta r \, . \tag{24}$$

where $r \sim 2.84 \, R_s$.

(g) Per Terrile, $\Delta r \sim 500$ km and $\eta \sim 10^{-4}$ to 10^{-5}, adopted in what follows as 3×10^{-5}.

(h) The ranges of 100 and 200 MeV protons in water are 7.64 and 25.7 g cm^{-2}, respectively. The latter figure is about the amount of material necessary to reduce the intensity of the Crand spectrum above an energy of 80 MeV by a factor of 1/e. This range (material path length) is labeled P_o.

Case I: $4\rho R/3 \ll P_o$

The time rate of change of path length P traversed by a proton is given by

$$\frac{dP}{dt} = \left(\frac{\sigma}{\cos\,\alpha_o}\right)\left(\frac{2}{T_B}\right)\left(\frac{\Delta r}{2r_g}\right) \qquad g\ cm^{-2}\ s^{-1}\ . \tag{25}$$

The lifetime τ of a proton against absorption is given by

$$\tau = \frac{P_o}{\left(\frac{dP}{dt}\right)}\ . \tag{26}$$

In the case under consideration, the fractional energy loss per traversal of a particulate by a proton is very much less than 1.0 and many such traversals are required to reduce the proton's energy below the threshold for detection. Hence, σ in (25) can be replaced by $4\,\rho\,R\,\eta/3$ by (23) and then, using (25) and (26)

$$\tau = P_o\left(\frac{3\,\cos\,\alpha_o}{4\,\rho\,R\,\eta}\right)\left(\frac{T_B}{2}\right)\left(\frac{2\,r_g}{\Delta r}\right)\ . \tag{27}$$

Typical values are $\cos\,\alpha_o = 0.4$, $\rho = 1.0$ g cm^{-3} (water ice), $T_B = 3.0$ s, $\frac{2\,r_g}{\Delta r} = 10$, $P_o = 25$ g cm^{-2}, so that

$$\tau \sim 112/R\,\eta\ . \tag{28}$$

Using $\eta = 3 \times 10^{-5}$ and, from (19), $\tau < 1.1 \times 10^{8}$ s, one finds that

$$R > 0.035\ \text{cm}\ . \tag{29}$$

The value of R in (29) represents a lower limit on the radius of particulates of ice, all of the same size, in Ring G. The corresponding lower limits on the mass of an individual particulate and on the areal mass density σ of the ring are 1.8×10^{-4} g and 1.4×10^{-6} g cm^{-2}, respectively; and the corresponding upper limit on the areal number density n of particulates in the ring is 8×10^{-3} cm^{-2}.

It is noted that R is, by (23), essentially the ratio σ/η. Hence, if the particulates are not of uniform size but have a distribution of sizes, the above determined value of R in (29) is understood to be the ratio $< R^3 > / < R^2 >$, wherein the symbol $< >$ denotes the mean value over the distribution. There is little or no directly observed information on the distribution of sizes within the central part of Ring G. [See, however, the section on Relation to Other Work.]

The overall reliability of the lower limit on R in (29) is dependent principally on the reliability of η and on the lower limit on β by Blake et al. [1983]. Our earlier estimate of β [Van Allen et al., 1980b] would indicate that the actual value of R would not exceed the value in (29) by more than a factor of ~ 3.

<u>Case II</u> $\quad 4\rho R/3 \geqslant P_o$

In this case, each encounter of a proton with a particulate in the ring has a probability for total loss of approximately unity. Then, the quantity σ is irrelevant and the fractional loss of protons per unit time is simply

$$2\eta / T_B \cos \alpha_o \tag{30}$$

and

$$\tau = T_B \cos \alpha_o / 2\eta \, . \tag{31}$$

For $T_B = 3.0$ s, $\eta = 3 \times 10^{-5}$, and $\cos \alpha_o = 0.4$,

$$\tau = 2 \times 10^4 \text{ s}, \tag{32}$$

a value that is more than three orders of magnitude smaller than the estimated lifetime (20), thus showing that such large fragments make a very small contribution to the opacity of Ring G, if indeed they do exist there.

DIFFUSION COEFFICIENT AND DIFFUSION SPEED

The quantity β/D in (9) is related to directly observed quantities by elementary theoretical considerations and hence is judged to be reliably determined. The implied diffusion coefficient is proportional to β. Using the value of β from (10),

$$D \sim 1.0 \times 10^{9} \ \mathrm{cm}^{2} \ \mathrm{s}^{-1}$$

or (33)

$$D \sim 2.8 \times 10^{-11} \ R_s^{2} \ \mathrm{s}^{-1} .$$

Or using the Blake et al. lower limit on β from (11),

$$D > 4.8 \times 10^{8} \ \mathrm{cm}^{2} \ \mathrm{s}^{-1}$$

or (34)

$$D > 1.3 \times 10^{-11} \ R_s^{2} \ \mathrm{s}^{-1} .$$

It is difficult to think that either of these values of D differs from the true value by as much as a factor of ten.

The radial gradient dN/dr on the inward side of Ring G is 1.44×10^{-15} cm^{-4} and a typical value of N there is

5×10^{-7} cm^{-3}. Thus, the local radial diffusion speed (average net radial drift speed of the randomly diffusing guiding center of a proton),

$$V = \frac{1}{N} \left(D \frac{dN}{dr}\right) \sim 2.3 \text{ cm s}^{-1}, \qquad (35)$$

a numerical value that gives a visualizable meaning to the estimated diffusion coefficient and to the process of absorption by Ring G.

An independent limit on D can be based on the fact that there was no detectable intensity of protons $E_p > 80$ MeV in the deep microsignature of the satellite 1979 S2 at 2.534 R_s on Pioneer 11's inbound passage through this region interior to the main peak of energetic proton intensity (Figures 1 and 2). This observation sets a generous upper limit on the omnidirectional intensity J as 20 cm^{-2} s^{-1} [Van Allen, 1982] or on the number density N as 1×10^{-9} cm^{-3}. The observed microsignature is in the distribution of electrons of energy $E_e \sim 1.5$ MeV whose gyroradii there are ~ 5 km, a value much smaller than the radius of 1979 S2 (80 km) [Van Allen, 1982]. In contrast, the gyroradius of a proton of energy $E_p \sim 200$ MeV in this region is ~ 1,750 km, a value much greater than the radius of 1979 S2. Therefore, the observed narrow microsignature can not also be a microsignature in the distribution of energetic protons and the above quoted upper limits on J and N must be characteristic of the entire slot region of radial width $\sim 2\ r_g$ caused by the two co-orbital satellites 1979 S2 (1980 S3) and 1980 S1. This inference as well as the above numerical upper limits are confirmed by the data of Figure 5 of Fillius et al. [1980].

The supply of protons to populate the slot region is principally from diffusive influx from the nearby major peak in the distribution and trivially from diffusive influx from the minor peak internal to the slot and from Crand injection. At the outer face of the slot, the observed radial gradient of number density

$$\frac{dN}{dr} \sim 4.6 \times 10^{-15}\ \mathrm{cm}^{-4} \tag{36}$$

and, by an appropriately simplified version of the continuity equation (15),

$$D\ (4.6 \times 10^{-15}) < \left(\frac{1 \times 10^{-9}}{\tau}\right)(2\ r_g) \tag{37}$$

or

$$D < \frac{7.6 \times 10^{13}}{\tau}\ . \tag{38}$$

According to Rairden [1980], a proton of energy ~ 200 MeV with an equatorial pitch angle $\alpha_o \sim 90°$ has a probability of about 0.9 for surviving an encounter with 1979 S2 or about 0.8 for surviving encounters with both 1979 S2 and its co-orbiting companion 1980 S1. The interval of time T_E between such double encounters is 325 s. Hence the lifetime τ against absorption by two satellites is ~ 3000 s and by (38)

$$D < 2.5 \times 10^{10}\ \text{cm}^2\ \text{s}^{-1} .$$

or (39)

$$D < 7 \times 10^{-10}\ R_s^2\ \text{s}^{-1} .$$

This value is a generous upper limit on D and is, in fact, about 25 times greater than the estimate of D given in (33).

Finally, it is noted that the nearly complete absence of energetic protons in this inner slot region proves that there are no satellites having radii of the order of a kilometer or larger in or near Ring G.

RELATION TO OTHER WORK

During the passage of Voyager 2 through Saturn's ring plane at $r = 2.88\ R_s$ ($\sim 0.04\ R_s$ outside of the center of Ring G) Gurnett et al. [1983] observed a unique sequence of a large number of impulsive noise bursts on their plasma wave instrument (radio receiver) in the frequency range 10 Hz to 56 kHz. These bursts had a characteristic, distinctive waveform. The rate of occurrence was north-south symmetric about the ring plane and the maximum rate ($\sim 360\ s^{-1}$) was observed at the moment of ring plane crossing. They attributed each noise burst to a localized cloud of ionized gas resulting from the high speed (~ 14 km s^{-1}) impact of a particulate on the spacecraft. Among other results of their analysis they found that the causative particulates had radii principally in the range 0.3 to 3×10^{-4} cm and that the effective north-south thickness of the distribution $\Delta z \sim 106$ km.

Similar results have been obtained by other Voyager 2 investigators using a higher frequency radio receiver [Aubier et al., 1983].

For $\eta = 3 \times 10^{-5}$, a distribution of particulates having $R = 1 \times 10^{-4}$ cm in the heart of Ring G would by (28) yield

$\tau \sim 4 \times 10^{10}$ s, a value several hundred times greater than the upper limit found in (19). By the same token, such a distribution, even if present, would make an undetectable contribution to energetic proton absorption. Conversely, if an opacity of $\leqslant 10^{-6}$ at the point of Voyager 2's crossing of the ring plane were attributable entirely to particulates having $R \geqslant 0.035$ cm, the areal number density n would be $\leqslant 2.6 \times 10^{-4}$ cm^{-2}. If the particulates were distributed uniformly over an axial thickness Δz, the volume number density would be $n/\Delta z$. Such a cloud of particulates moving at speed v relative to Voyager 2 would result in $vnA/\Delta z$ impacts per second on the projected area A ($\sim$ 16,000 cm^2) of the spacecraft. The duration of its encounter Δt is $\Delta z/v_z$. Hence, the total number of impacts (v = 13.8 km s^{-1} and v_z = 11.1 km s^{-1}) would be $vnA/v_z \leqslant 5$. Such impacts are thought to have not occurred but the evidence is not conclusive.

Overall, therefore, it is not clear that the size distribution of particulates in the heart of Ring G is either the same as or different than it is in its outer fringe at r = 2.88 R_s.

NOTE ON NOMENCLATURE

At one stage in the analysis of Pioneer 11 data, I suggested [cf. Figure 5 of Van Allen et al., 1980b] the term Ring G for the possibility [Aksnes and Franklin, 1978] that there was a "ring" of many small satellites (tens of kilometers or more in diameter) in the vicinity of $r \sim 2.52\ R_s$. Following the Voyager findings (a) that there were only two satellites of such size in this radial region and (b) that there was an apparently continuous ring of fine particulate matter at $r \sim 2.83\ R_s$, I abandoned the earlier suggestion and adopted the Voyager term Ring G for this latter feature [Van Allen, 1982].

SUMMARY

A restudy has been made of Pioneer 11 data on the distribution of energetic protons $E_{(p)} > 80$ MeV in Saturn's inner magnetosphere. An improved value of the ratio of the Crand source strength β to the radial diffusion coefficient D is 6.9×10^{-24} cm^{-5} at $r \sim 2.67\ R_s$ ($1\ R_s$ = Saturn's equatorial radius = 60,000 km). Using the recently calculated lower limit on β by Blake et al., one finds an upper limit on the mean residence time T against diffusion 4.6×10^{8} s (15 years) in the major peak of the distribution, whereas using our earlier estimate of β, one finds $T \sim 2.2 \times 10^{8}$s (7.0 years). The two corresponding determinations of D are $> 1.3 \times 10^{-11}$ and $\sim 2.8 \times 10^{-11}\ R_s^2\ s^{-1}$, respectively. A generous upper limit on D is $7 \times 10^{-10}\ R_s^2\ s^{-1}$ as found from study of the slot region associated with the co-orbiting satellites 1979 S2 (1980 S1) and 1980 S3. The mean lifetime τ of energetic protons against absorption by particulate matter in Ring G is $< 1.1 \times 10^{8}$ s (3.5 years) and $\sim 5.1 \times 10^{7}$ s (1.6 years) corresponding to the two choices of β. Then, using the Voyager data of Terrile on normal optical opacity $\eta \sim 3 \times 10^{-5}$ and on radial width $\Delta r \sim 500$ km, one finds that the particulates in Ring G have an effective radius $R \geqslant 0.035$ cm,

an areal mass density $\sigma > 1.4 \times 10^{-6}$ g cm^{-2}, and an areal number density $n < 8 \times 10^{-3}$ cm^{-2}. It is quite unlikely that R exceeds 0.1 cm. The foregoing values of R (for assumed spherical particulates of water ice, all of the same size) are in effect the ratio $< R^3 > / < R^2 >$ for a distribution of sizes where the symbol $< >$ denotes the mean value over the distribution. It is reasonably certain that there are no satellites having radii of the order of a kilometer or larger associated with Ring G and that objects having radii $\geqslant$ 10 cm contribute less than 10^{-3} of its opacity. The radius of Ring G is 170,200 ± 900 km.

ACKNOWLEDGEMENTS

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REFERENCES

Acuña, M. H., N. F. Ness, and J. E. P. Connerney, The magnetic field of Saturn: Further studies of Pioneer 11 observations, J. Geophys. Res., 85, 5675-5678, 1980.

Aksnes, K., and F. A. Franklin, The evidence for faint satellites of Saturn reexamined, Icarus, 36, 107-118, 1978.

Aubier, M. G., N. Meyer-Vernet, and B. M. Pedersen, Shot noise and grain and particle impacts in Saturn's ring plane, Geophys. Res. Lett., 10, 5-8, 1983.

Blake, J. B., H. H. Hilton, and S. H. Margolis, On the injection of cosmic ray secondaries into the inner Saturnian magnetosphere, 1, Protons from the Crand process, J. Geophys. Res., 88, 803-807, 1983.

Fillius, W., W. H. Ip, and C. E. McIlwain, Trapped radiation belts of Saturn: First look, Science, 207, 425-431, 1980.

Gurnett, D. A., E. Grün, D. Gallagher, W. S. Kurth, and F. L. Scarf, Micron-size particles detected near Saturn by the Voyager plasma wave instrument, Icarus (in press), 1983.

Rairden, R. L., Satellite sweeping of electrons and protons in Saturn's inner magnetosphere, U. of Iowa Research Report 80-29, July 1980.

Simpson, J. A., T. S. Bastian, D. L. Chenette, G. A. Lenz, R. B. McKibben, K. R. Pyle, and A. J. Tuzzolino, Saturnian trapped radiation and its absorption by satellites and rings: The first results from Pioneer 11, Science, 207, 411-415, 1980.

Smith, B. A., L. Soderblom, R. Beebe, J. Boyce, G. Briggs, A. Bunker, S. A. Collins, C. J. Hansen, T. V. Johnson, J. L. Mitchell, R. J. Terrile, M. Carr, A. F. Cook II, J. Cuzzi, J. B. Pollack, G. E. Danielson, A. Ingersoll, M. E. Davies, G. E. Hunt, H. Mazursky, E. Shoemaker, D. Morrison, T. Owen, C. Sagan, J. Veverka, R. Strom, and V. E. Suomi, Encounter with Saturn: Voyager 1 imaging science results, Science, 212, 163-191, 1981.

Smith, B. A., L. Soderblom, R. Batson, P. Bridges, J. Inge, H. Mazursky, E. Shoemaker, R. Beebe, J. Boyce, G. Briggs, A. Bunker, S. A. Collins, C. J. Hansen, T. V. Johnson, J. L. Mitchell, R. J. Terrile, A. F. Cook II, J. Cuzzi J. B. Pollack, G. E. Danielson, A. P. Ingersoll, M. E. Davies, G. E. Hunt, D. Morrison, T. Owen, C. Sagan, J. Veverka, R. Strom, and V. E. Suomi, Voyager 2 encounter with the Saturnian system, Science, 215, 499-537, 1982.

Smith, E. J., L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, and C. P. Sonett, Saturn's magnetic field and magnetosphere, Science, 207, 407-410, 1980.

Thomsen, M. F., and J. A. Van Allen, Motion of trapped electrons and protons in Saturn's inner magnetosphere, J. Geophys. Res., 85, 5831-5834, 1980.

Trainor, J. H., F. B. McDonald, and A. W. Schardt, Observations of energetic ions and electrons in Saturn's magnetosphere, Science, 207, 421-425, 1980.

Van Allen, J. A., M. F. Thomsen, B. A. Randall, R. L. Rairden, and C. L. Grosskreutz, Saturn's magnetosphere, rings and inner satellites, Science, 207, 415-421, 1980a.

Van Allen, J. A., B. A. Randall, and M. F. Thomsen, Sources and sinks of energetic electrons and protons in Saturn's magnetosphere, J. Geophys. Res., 85, 5679-5694, 1980b.

Van Allen, J. A., Findings on rings and inner satellites of Saturn by Pioneer 11, Icarus, 51, 509-527, 1982.

CAPTIONS FOR FIGURES

Figure 1. The original presentation of Pioneer 11 data showing the time stationary absorption feature in energetic proton intensity at $r \sim 2.82\ R_s$. The observed points are 115.5 s averaged counting rates of two different miniature Geiger-Mueller tubes C and D as a function of earth received time (ERT) during inbound and outbound segments of the space-craft's encounter trajectory with Saturn on 1 September 1979. The time scales are chosen so that the abscissa corresponds to the same radial distance on all four curves [Van Allen et al., 1980a]

Figure 2. The inbound counting rates of individual 0.75 s-samples of data from detector C as a function of radial distance. Labeled features are described in the text.

Figure 3. The outbound counting rates, as in Figure 2. The data interior to $r \sim 2.56\ R_s$ were meager because of poor telemetry quality and are not shown here.

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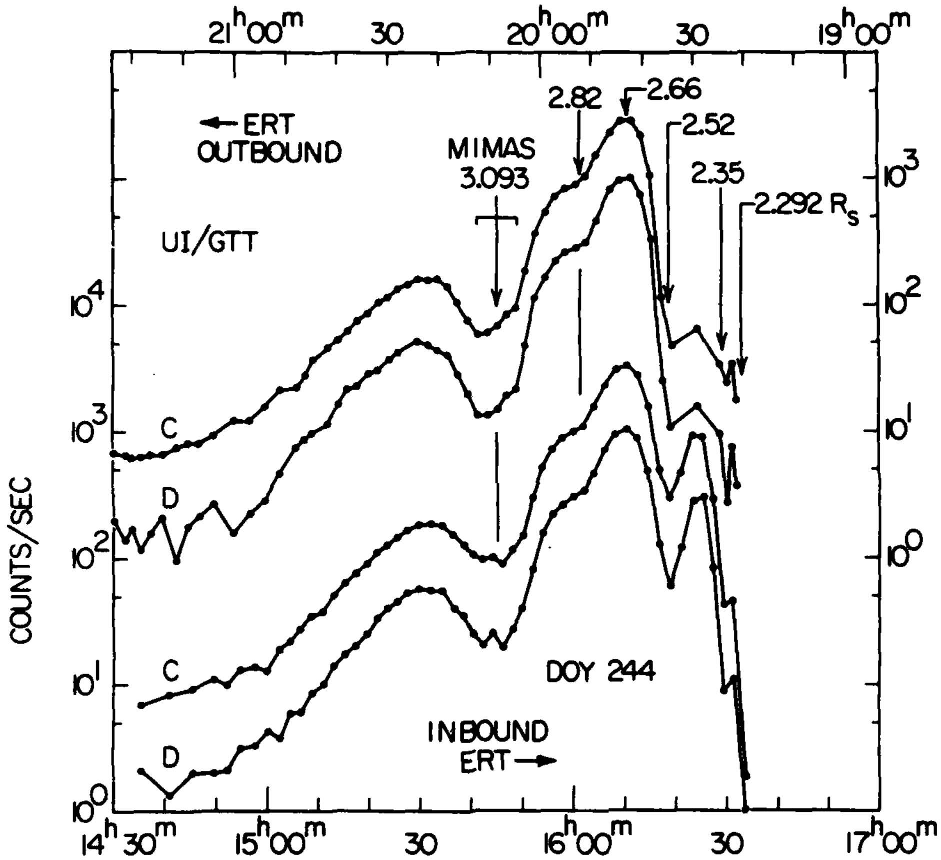
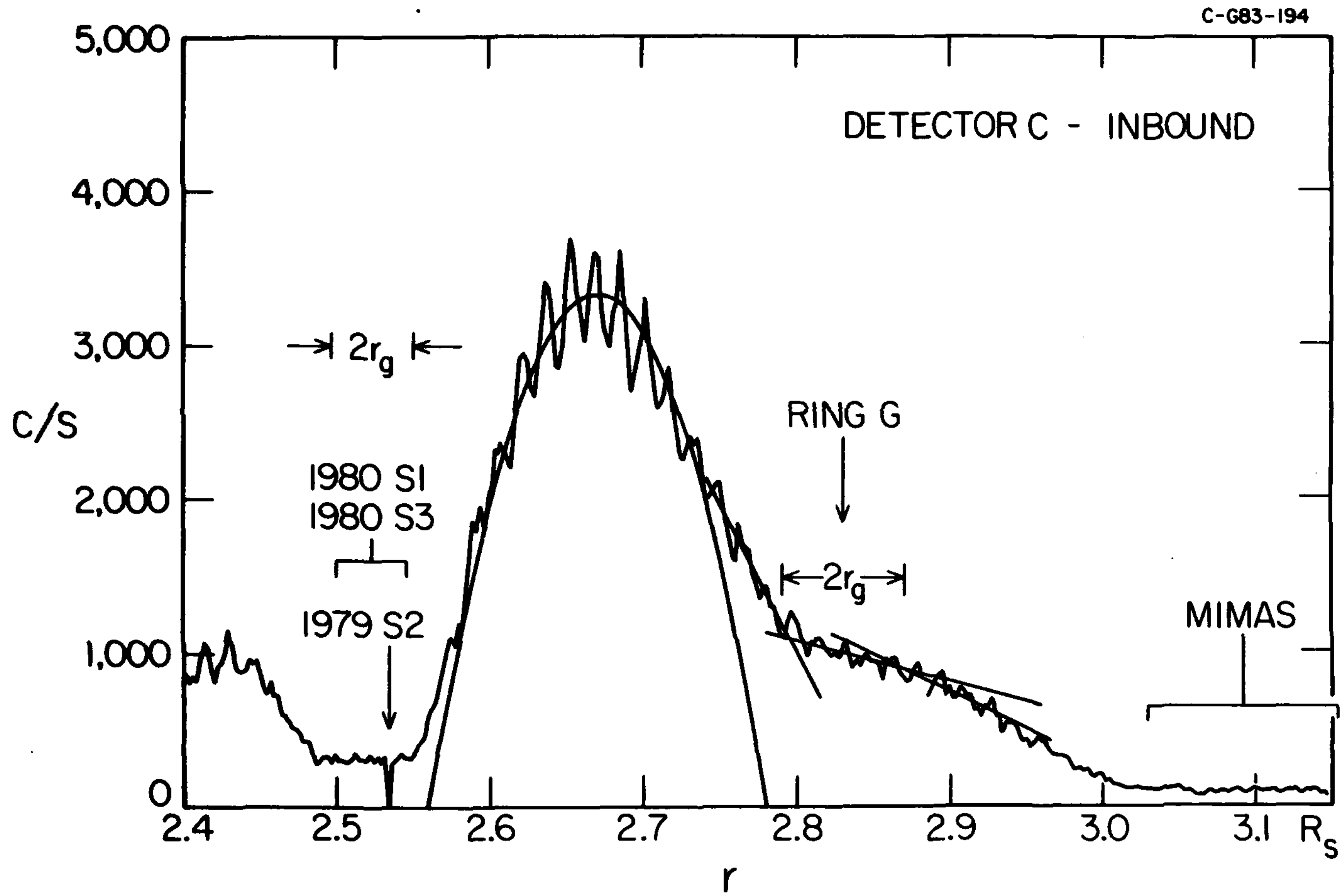


Figure 1


C-G83-194
DETECTOR C - INBOUND
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4,000
3,000
2,000
1,000
0
C/S
2r_g
1980 S1
1980 S3
1979 S2
RING G
2r_g
MIMAS
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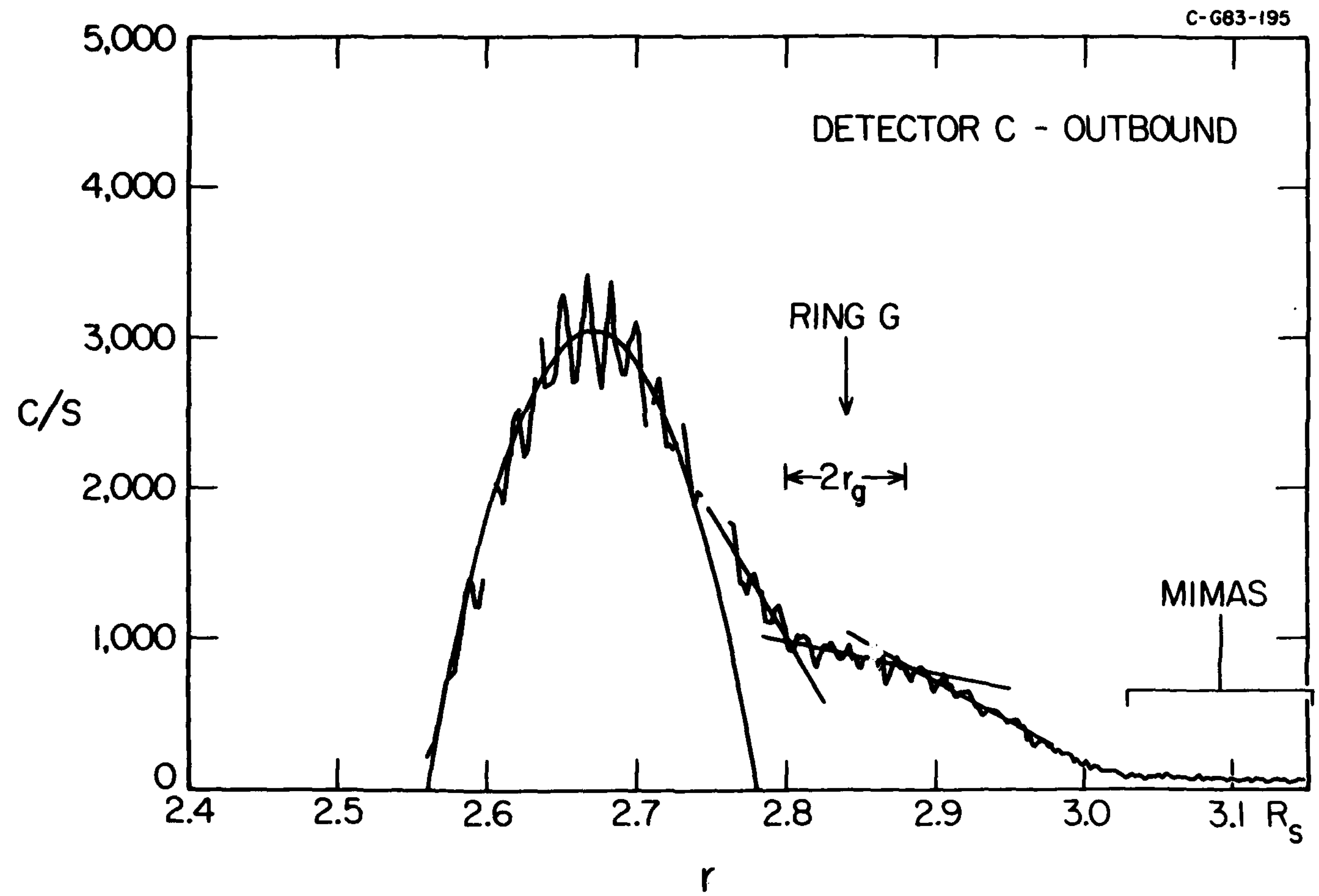
2.5
2.6
2.7
2.8
2.9
3.0
3.1
R_S
r

Figure 2


C-G83-195
DETECTOR C - OUTBOUND
RING G
2rg
MIMAS
5,000
4,000
3,000
2,000
1,000
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C/S
2.4
2.5
2.6
2.7
2.8
2.9
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3.1 Rs
r

Figure 3

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