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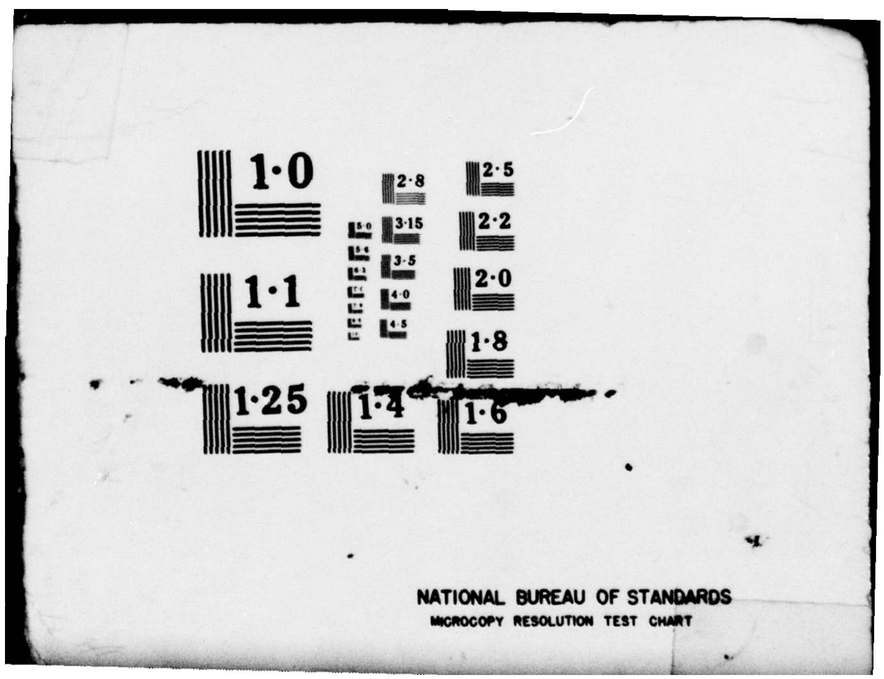
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On the Inference of Properties of Saturn's Ring E from Energetic Charged Particle Observations

by

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ABSTRACT

Assuming that Saturn has trapped radiation belts similar to those of Earth and Jupiter, it is shown that observations of the radial dependence of the intensities, energy spectra, electron-to-proton intensity ratio, and pitch angle distributions of energetic charged particles trapped outside of Ring A can potentially provide information (a) on the existence of Ring E, (b) on the size distribution of the particulate matter therein, and (c) on the magnitude of the radial diffusion coefficient for energetic particles. A parametric study of these possibilities is specialized to the characteristics of the University of Iowa detectors on Pioneer 11, which will make a close encounter with Saturn in August-September 1979.

INTRODUCTION

During the 1966 edge-on presentation of the ring plane of Saturn to Earth, Feibelman [1967] obtained photographic evidence for a very faint ring external to the well known visible rings. The evidence for this external ring (first called Ring D' and now, by I.A.U. convention, Ring E) has been reexamined by Smith et al. [1975] and Smith [1978]. Based on the latter reference, it appears that the normal optical opacity η of Ring E lies in the range 0.5×10^{-7} to 2.3×10^{-6}, if full credence is given to Feibelman's photograph of 15 November 1966, though there is no observational knowledge whatever on the size distribution of the particulate matter therein. (Note that η is of the order of unity for Rings A and B.)

The question of the existence of a Saturnian magnetic field and of the nature of a Saturnian magnetosphere has been discussed by Van Allen [1977] and Siscoe [1978a, b]. For the present analysis we assume that Saturn has a magnetosphere which, at least near the planet, is similar to that of Jupiter; that is, we assume a dipolar magnetic field configuration and a significant population of trapped particles for which the source lies outside the inner magnetosphere and for which the dominant transport mechanism is radial diffusion violating the third adiabatic invariant while the first and second are conserved. Such a picture has enjoyed considerable success in providing an understanding of the inner magnetosphere of Jupiter [Schulz, 1979].

The ring material within Saturn's magnetosphere is a sink for trapped radiation, with the lifetime against absorption by the ring being a function of charged particle species and energy as well as a function of the ring properties. As discussed by Van Allen [1977], Rings A and B are sufficiently opaque that the lifetime against absorption by them is of the order of a latitudinal bounce period, so that they may be treated as perfect barriers to the inward diffusion of charged particles. Ring E, however, may be sufficiently transparent that a significant population of charged particles is able to survive long enough to diffuse into the outer edge of Ring A, at which complete absorption occurs. In this paper we study parametrically the absorption of charged particles by Ring E in order to investigate its effect on charged particle intensities, spectra, and pitch angle distributions, all of which are potentially observable by the energetic charged particle instruments on Pioneer 11.

PROCEDURE

Our procedure is to assume that particles are injected with a specified energy spectrum and pitch angle distribution at some outer boundary, which for convenience we take to be at the dipole L-value of 5. (All radial distances are given in units of Saturn's equatorial radius, 60,000 km.) The particles are then assumed to diffuse radially inward until they are absorbed at the outer edge of Ring A at $L = 2.27$. The diffusion coefficient governing the radial motion is taken to be of the form $D = D_o L^n$. In analogy to Jupiter's magnetosphere, we adopt the value $n = 3$, which is appropriate for diffusion driven by ionospheric winds, the driving mechanism which appears to dominate in Jupiter's inner magnetosphere [Schulz, 1979]. Absorption of charged particles by Ring E material is assumed to be the only loss process, with lifetime $\tau_o L^m$.

The differential unidirectional intensity at energy E, equatorial pitch angle α, and dipole L-value L is

$$j(E,\alpha,L) = p^2 f(\mu,J_2,L) \tag{1}$$

where p is the momentum of a particle with energy E, $\mu(E,\alpha,L)$ is the first adiabatic invariant, $J_2(E,\alpha,L)$ is the second adiabatic invariant, and the phase space density f is the solution to the radial diffusion equation

$$L^2 \frac{\partial}{\partial L} \left[D_o L^{n-2} \frac{\partial f}{\partial L} \right] = \frac{f}{\tau_o L^m} \tag{2}$$

with boundary conditions

$$f(L = 2.27) = 0.0 \tag{3a}$$

$$f(I = L_o = 5) = j_o(E_o,\alpha_o,L_o)/p_c^2 \, . \tag{3b}$$

E_o, p_o, and α_o are related to E, p, and α by conservation of the first and second invariants:

$$E_o = E_o(\mu,J_2,L)$$

$$\alpha_o = \alpha_o(\mu,J_2,L) \, .$$

The boundary condition (3b) is equivalent to specifying the differential unidirectional intensity at L = 5 as a function of α_o and E_o.

LIFETIMES AGAINST RING PARTICLE ABSORPTION

For ring particle absorption, the quantities τ_o and m in equation (2) can be determined as functions of μ, α, the ring particle radius r_o, and the optical opacity of the ring η in the following way.

The average thickness of a spherical ring particle with radius r_o is $4r_o/3$. The quantities τ_o and m depend on whether the range R of the charged particle in the ring material (which we assume is water ice) is greater than or less than this average thickness.

$R > 4r_o/3$

The average time for a charged particle to make a single encounter with a ring particle is

$$T_1 = T_B \cos\alpha/2\eta \tag{4}$$

where T_B is the latitudinal bounce period of the charged particle. Since the average thickness of ring material traversed in a single encounter is $4r_o/3$, the average thickness traversed per unit time is $8\eta r_o/3T_B \cos\alpha$. If we define the lifetime against absorption as the time it takes a particle traversing ring material at this rate to traverse a distance equal to its range, we have

$$\tau \equiv 3T_B R \cos\alpha / 8\eta r_o . \qquad (5)$$

To find τ_o and m, we need to express T_B and R as functions of μ and L. For this purpose we write the particle energy as

$$E = \begin{cases} \mu B_o / L^3 \sin^2\alpha \\ (2m_o c^2 \mu B_o / L^3 \sin^2\alpha)^{\frac{1}{2}} \end{cases}$$

where B_o is the equatorial surface field strength and $m_o c^2$ is the rest energy of the particle. (In this and subsequent relations, the upper expression is for non-relativistic particles, and the lower one is for ultra-relativistic particles.)

$$T_B = 4R_s L f(\sin\alpha) \times \begin{cases} (m_o L^3 \sin^2\alpha / 2\mu B_o)^{\frac{1}{2}} \\ 1/c \end{cases} \qquad (6)$$

where $f(\sin\alpha) = 1.3802 - 0.3199\,[\sin\alpha + \sqrt{\sin\alpha}\,]$ [Schulz and Lanzerotti, 1974]. In addition, we can approximate the particle range as a power law in energy (which is valid over fairly wide ranges of energy), i.e.

$$R \approx A\,E^{a}$$
$$\approx A \begin{cases} (\mu B_o/L^3 \sin^2\alpha)^{a} \\ \\ (2m_o c^2 \mu B_o/L^3 \sin^2\alpha)^{a/2} \end{cases} \tag{7}$$

Combining (6) and (7) we find

$$m = \begin{cases} 5/2 - 3a \\ 1 - 3a/2 \end{cases} \tag{8}$$

and

$$\tau_o = \begin{cases} G(r_o\eta)\; g(\alpha)\; (\mu B_o)^{a-\frac{1}{2}} \\ H(r_o\eta)\; h(\alpha)\; (\mu B_o)^{a/2} \end{cases} \tag{9}$$

where

$$G = 3AR_s\,(\tfrac{1}{2}m_o c^2)^{\frac{1}{2}}/2c\,r_o\,\eta$$
$$H = 3AR_s\,(2m_o c^2)^{a/2}/2c\,r_o\,\eta$$
$$g = \cos\alpha\,\sin^{1-2a}\alpha\;f(\sin\alpha)$$
$$h = \cos\alpha\,\sin^{-a}\alpha\;f(\sin\alpha)$$

$R < 4r_o/3$

If the range of the charged particle is less than the average thickness of a ring particle, then a single encounter will result in complete absorption. The lifetime against loss is thus $\tau = T_1$, where T_1 is given by equation (4). With T_B as given by equation (6), we find

$$m = \begin{cases} 5/2 \\ 1 \end{cases} \tag{10}$$

and

$$\tau_o = \begin{cases} (2R_s/c\eta)(m_o c^2/2\mu B_o)^{\frac{1}{2}} \cos\alpha \sin\alpha \, f(\sin\alpha) \\ (2R_s/c\eta) \cos\alpha \; f(\sin\alpha) \end{cases} \tag{11}$$

PARAMETERS WHICH GOVERN THE SOLUTION

The solution to equation (2) is given by equation (8) in Thomsen et. al. [1977]. As discussed in that paper, the quantity which governs the nature of the solution is $D_o\tau_o$. This is because $D \sim 1/(\text{diffusion time})$ so that $D_o\tau_o$ is roughly proportional to the ratio of the loss time to the diffusion time. If $D_o\tau_o$ is very large, the particles suffer few losses; if $D_o\tau_o$ is very small, the losses are severe. From the above expressions for τ_o, we see that the quantity which governs the solutions for the ring sweep-up problem is $D_o/r_o\eta$ if $R > 4r_o/3$ and is just D_o/η if $R < 4r_o/3$.

In Figure 1 we explore qualitatively the dependence of the solution on the ring particle radius, the ring opacity, and D_o for the various species and energies of charged particles which are observable by the University of Iowa detectors on Pioneer 11. (For a description of the instrument, see Van Allen et al., 1975.) The curves plotted in Figure 1 show the value of D_o/η which results in $D\tau = D_o\tau_o L^{m+n} = 1$ at $L = 3.5$ for each value of the ring particle radius. Since the condition $D\tau = 1$ means that the diffusion time is of the same order as the lifetime against loss, the lines shown in Figure 1 roughly separate the range of parameters for which losses are severe from the range for which losses are negligible.

Thus, for example, if the ring particle radius is 1 cm and D_o/η has the value 10^{-1}, then we would expect protons with an energy of 0.61 MeV to suffer very few losses, while electrons with an energy of 0.56 MeV should be significantly depleted. In general, particles whose curve in Figure 1 lies highest for a given value of r_o will be the most strongly depleted. Thus below $r_o \approx 0.4$ cm protons with an energy of 0.61 MeV are more strongly depleted than electrons with an energy of 21 MeV, whereas above that energy the reverse is true. Therefore, if Pioneer 11 observes that 21 MeV electrons are more strongly depleted than are 0.61 MeV protons, we know that r_o is probably greater than 0.4 cm. Examination of Figure 1 shows that the crossing points for the various curves occur at different values of r_o so that by intercomparing observations made by the several detectors, one may be able to bracket the value of r_o.

SAMPLE RESULTS

In Figures 2-4 we investigate the effect of ring particle absorption on the integral intensities observable by Pioneer 11 detectors. To obtain these figures we have assumed that the unidirectional differential intensity at $L_o = 5$ is isotropic and is a power law in energy: $j_o(E_o, \alpha_o, L_o) = K\, E_o^{-2}$. We have then followed the procedure described above to determine $j(E, \alpha, L)$ over a range of energies at each value of L. The integral intensity corresponding to each detector is found by integrating $j(E, \alpha, L)$ over the energy range of the detector.

Figure 2 shows the radial profiles of unidirectional integral intensities that would be observable at a local pitch angle of 85° on the inbound pass of the Pioneer 11 Saturn encounter if the Saturnian magnetic field were a dipole aligned with the rotation axis of the planet. The three profiles shown for each detector correspond to the loss-free case and to the two sets of the ring particle parameters marked with an x in Figure 1. Note how the extent of the deviation from the loss-free profile depends on how far below the curves of Figure 1 the adopted parameter set lies.

Figure 3 illustrates the effect which ring absorption has on the energy spectrum and proton/electron intensity ratio for the three cases illustrated in Figure 2. Shown in Figure 3 are the ratios of intensities that would be seen by three of our detectors to the intensity that would be seen by the detector with an electron energy threshold of 40 keV. As expected from Figure 1, the effect of the ring absorption for the two cases shown is to deplete low-energy electrons more than high-energy electrons or low-energy protons.

Figure 4 illustrates the effect which ring absorption has on the pitch angle distribution of the particles, again for the three cases illustrated in Figure 2. In this figure are shown the ratios of the intensities at a local pitch angle of 85° to those at a local pitch angle of 45°. It is evident that there is a strong pitch angle dependence to the ring absorption losses, with large pitch angle particles suffering more severe losses. The result is a strong tendency for the pitch angle distributions to become more dumbbell in nature (i.e., peaked near 0° and 180°) at smaller radial distances. This is opposite to the effect of loss-free radial diffusion, which is for the distributions to become more pancake in nature (i.e., peaked near 90°). This effect on the pitch angle distributions is probably the best diagnostic for the presence of ring particle sweep-up as a significant loss-process. (Note, however, that the effect of a tilt between the dipole and rotational axes is to increase the lifetime of particles mirroring below the maximum magnetic latitude excursion of the ring [see, e.g., Mead and Hess, 1973] and thereby reduce the strength of the effect on the pitch angle distributions.)

SUMMARY AND CONCLUSION

To summarize the results of the above analysis:

(1) The presence of a tendency for pitch angle distributions (especially of low energy electrons) to become more dumbbell at smaller radial distances is probably the clearest potential evidence that Ring E absorption losses are significant.

(2) Other effects of diagnostic value are the inward radial dependence of the electron energy spectrum and the intensity ratio of protons $0.61 < E_p < 3.41$ MeV to electrons $E_e > 40$ keV. As shown in the several figures, there is a significant possibility for determining the approximate value of the mean radius r_o of ring particles.

(3) If r_o can be determined, the degree of the deviation of the observed profiles from the loss-free case can be used to infer an approximate value of D_o/η. Since η is found observationally to lie in the range $0.5 \times 10^{-7} < \eta < 2.3 \times 10^{-6}$ [Smith, 1978], one may then be able to place limits on the value of D_o.

In conclusion, we have demonstrated that observations of the radial dependence of the intensities, energy spectra, electron-to-proton intensity ratio, and pitch angle distributions of energetic charged particles trapped in a Saturnian magnetic field outside of Ring A can potentially provide information on the existence of Ring E, on the size distribution of the particulate matter therein and on the magnitude of the radial diffusion coefficient for energetic particles.

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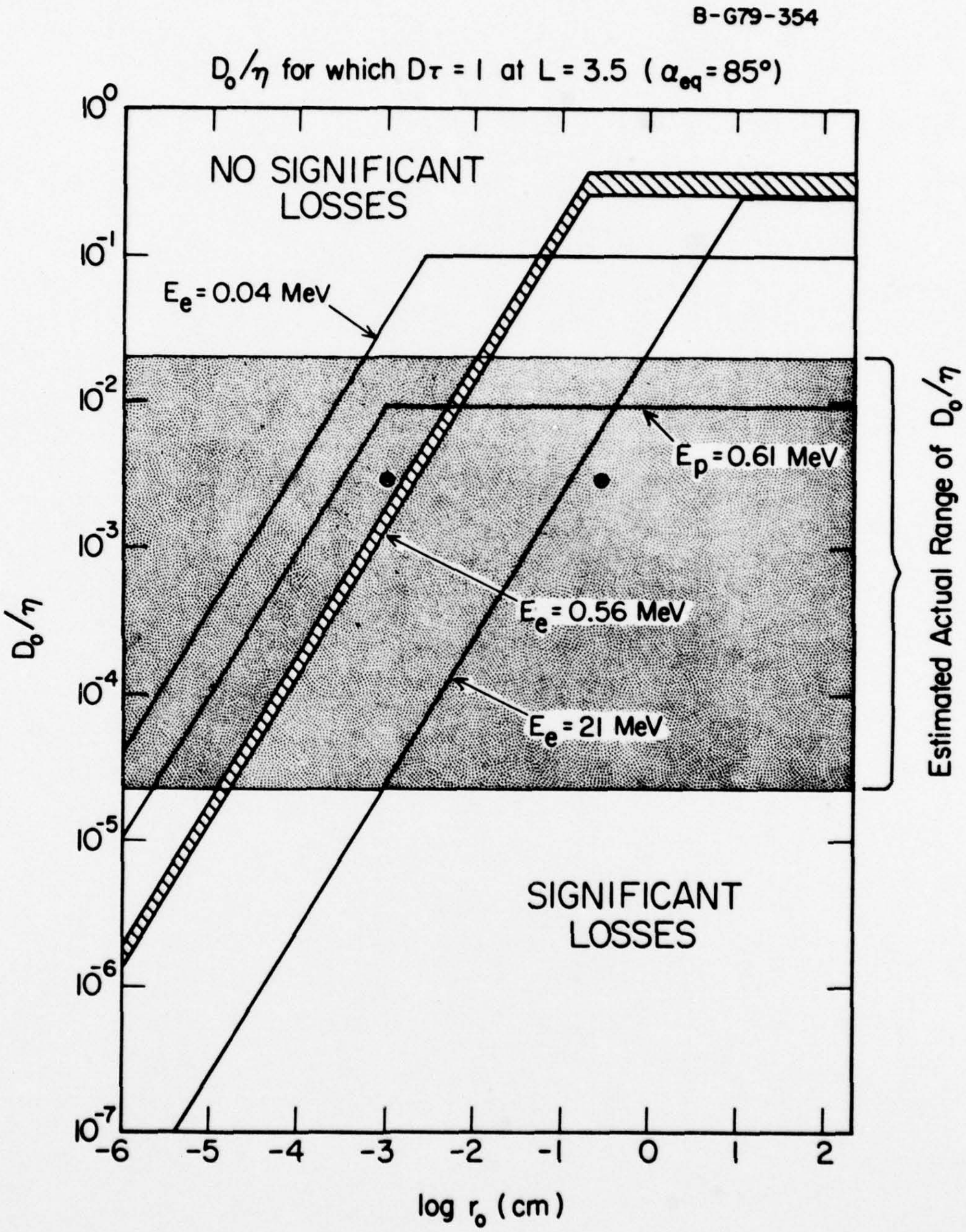
FIGURE CAPTIONS

Figure 1. Values of D_o/η for which the diffusion time ($\sim 1/D$) is roughly equal to the lifetime against ring-particle loss (τ) at $L = 3.5$ for the various species and energies observable by the Pioneer 11 University of Iowa detector complement. For $E_e = 0.56$ MeV neither the non-relativistic limit nor the ultra-relativistic limit for the lifetime (eqs. 8-11) is appropriate, so the lifetime (and the value of D_o/η plotted here) has been calculated using both limits, and the area between the two results has been shaded. If D_o/η lies much above the curve for particles of a given species and energy, those particles will suffer very few losses from ring absorption. If D_o/η lies much below the curve, they will suffer significant losses. Points marked by x correspond to parameter sets investigated in subsequent figures, and the shaded region shows the predicted ranged of D_o/η obtained by combining the estimated opacity of Ring E [Smith, 1978] and the radial diffusion coefficient scaled from its range of values at Jupiter [e.g., Thomsen et al., 1977] according to the scaling relation described by Siscoe [1978a].

Figure 2. Radial profiles of unidirectional (local pitch angle = 85°) integral intensities observable by University of Iowa detectors as predicted for loss-free radial diffusion and for radial diffusion with Ring E absorption for the two sets of ring parameters marked by an x on Figure 1.

Figure 3. Ratios of unidirectional integral intensities observable by various University of Iowa detectors as predicted for ring absorption assuming two different sets of Ring E parameters.

Figure 4. Ratios of predicted observable unidirectional integral intensities at pitch angles of 85° and 45° for two different sets of Ring E parameters.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D_o/η for which $D\tau = 1$ at $L = 3.5$ ($\alpha_{eq} = 85°$)
NO SIGNIFICANT LOSSES
SIGNIFICANT LOSSES
$E_e = 0.04$ MeV
$E_p = 0.61$ MeV
$E_e = 0.56$ MeV
$E_e = 21$ MeV
Estimated Actual Range of D_o/η
D_o/η
log r_o (cm)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
-6
-5
-4
-3
-2
-1
0
1
2

Figure 1

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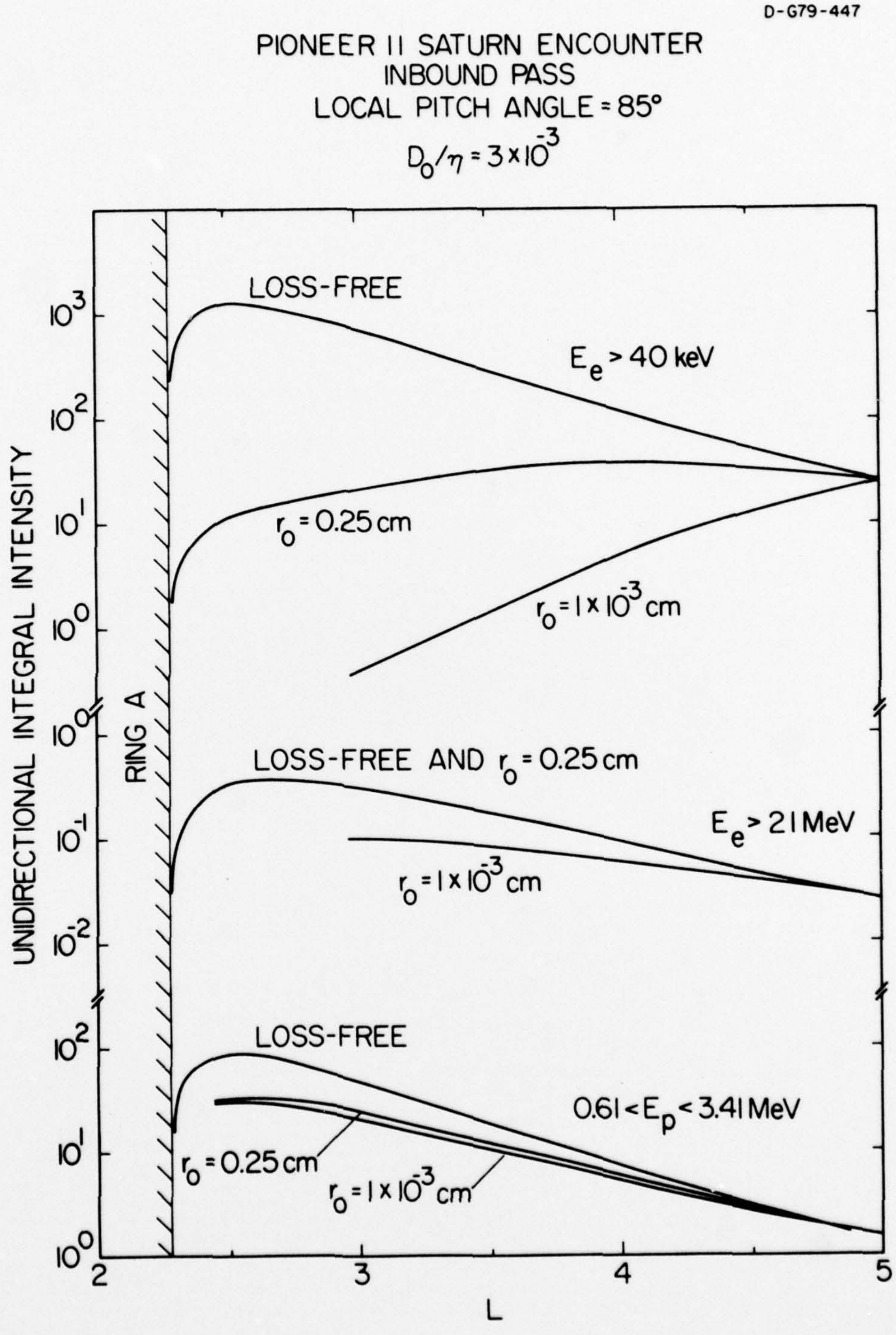

Figure 2

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RADIAL DEPENDENCE OF INTENSITY RATIOS FOR $D_0/\eta = 3 \times 10^{-3}$

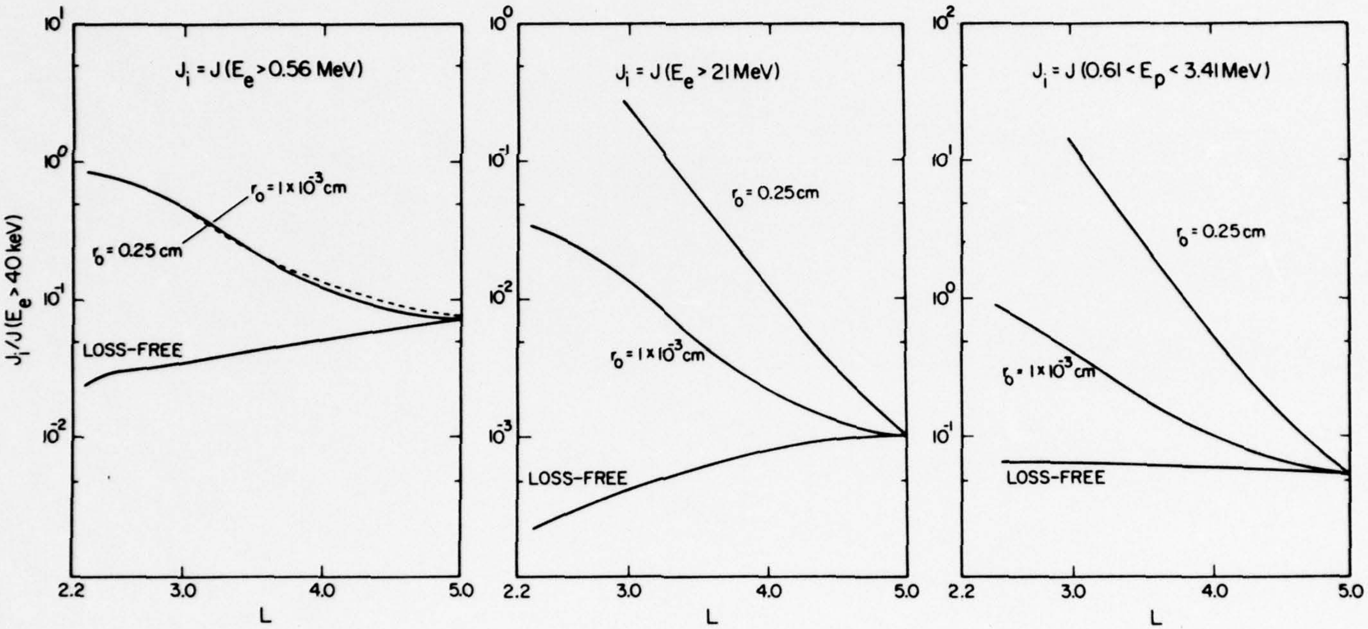
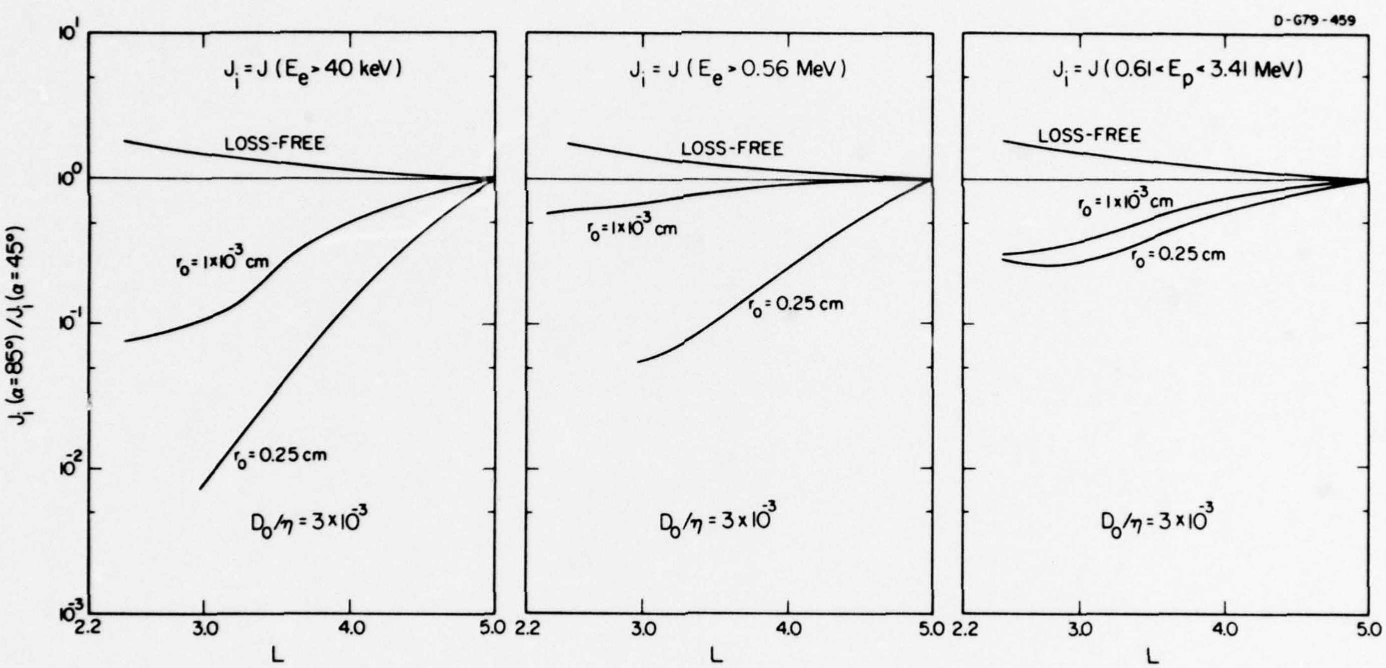


Figure 3



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$J_i = J\,(E_e > 40$ keV)
LOSS-FREE
$r_o = 1\times10^{-3}$ cm
$r_o = 0.25$ cm
$D_0/\eta = 3\times10^{-3}$
$J_i = J\,(E_e > 0.56$ MeV)
LOSS-FREE
$r_o = 1\times10^{-3}$ cm
$r_o = 0.25$ cm
$D_0/\eta = 3\times10^{-3}$
$J_i = J\,(0.61 < E_p < 3.41$ MeV)
LOSS-FREE
$r_o = 1\times10^{-3}$ cm
$r_o = 0.25$ cm
$D_0/\eta = 3\times10^{-3}$
$J_i\,(\alpha=85°)\,/\,J_i\,(\alpha=45°)$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
2.2
3.0
4.0
5.0
L

Figure 4