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Gerhard E. Aichinger
Project Officer

FOR THE COMMANDER

Frank J. Bane

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The recent close encounters of Pioneer 10 (December 1973) and Pioneer 11 (December 1974) with the planet Jupiter provided the first in situ observations of zenomagnetically trapped particle radiation. Such observations represented a major advance in planetary research. Prior estimates of radiation intensities (particle fluxes) at Jupiter had necessarily relied (in the case of electrons) upon inferences from Jovian decimetric radio emission observed at the earth and (in the case of protons) upon postulates for the numerical scaling from terrestrial proton intensities. The Pioneer 10 and Pioneer 11

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19. KEY WORDS *(Continued)*

20. ABSTRACT *(Continued)*

These observations have stimulated continuing theoretical efforts to understand the reported findings and to extrapolate from them to other planets and other epochs. While the analysis of trapped-radiation data from the Pioneer spacecraft is far from being completed, a consensus has developed with respect to the physical mechanisms that must be considered. The observed radiation belts seem to be populated by radial diffusion from an external source. The diffusion coefficient seems to be that derived from fluctuations in the polarization electric field produced by neutral winds in the Jovian ionosphere, which is coupled to the magnetosphere by equipotential B-field lines. Radiation-belt electrons lose energy and change their equatorial pitch angles by virture of synchrotron emission. Radiation-belt ions and electrons both may be subject to pitch-angle diffusion caused by waves that the respective particle anisotropies have created through plasma instabilities. Finally, radiation-belt ions and electrons seem to experience absorption by the inner Jovian satellites (moons) in a manner that may depend upon the species and energy of the incident radiation-belt particle. It is not yet known whether satellite-associated clouds of sodium and sulfur contribute substantially to the inferred particle absorption. Also still open is the question of whether the satellites provide a substantial source of radiation-belt particles. Moreover, there remains doubt concerning the configuration of the outer Jovian magnetosphere and the influence of this configuration on the zenomagnetic trapping of energetic charged particles.

PREFACE

This work is based on (and represents a substantial elaboration of) an invited review paper presented 30 May 1978 at the International Symposium on Solar-Terrestrial Physics, which was held 29 May 1978 through 3 June 1978 at Innsbruck, Austria. The author is pleased to thank Dr. E. R. Dyer, Jr., secretary of the Special Committee on Solar-Terrestrial Physics (SCOSTEP) for issuing the invitation. The author is also pleased to thank the International Astronomical Union for partial travel support. Finally, the author is pleased to thank Frances Wainwright and Joanne B. Kari for their careful typing of the manuscript.

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1. INTRODUCTION

The radiation belts of Earth were discovered by in situ observation in 1958 (Van Allen et al., 1958; Vernov et al., 1959). Non-thermal decimetric (3-GHz) radio emission from the vicinity of Jupiter was discovered in the same year (Sloanaker, 1959) by remote observation. It was soon realized (Field, 1959; 1960; 1961) that the decimetric radiation arose from electrons trapped in Jupiter's magnetic field. The radiation mechanism remained uncertain for only a few years. The presence of a linearly polarized component at the 31-cm wavelength (Radhakrishnan and Roberts, 1960), a polarization subsequently confirmed over a broad spectrum of wavelengths (e. g., Michaux,1967), convinced Chang and Davis (1962) that the responsible mechanism was synchrotron radiation by highly relativistic electrons having mirror points very near the zenomagnetic equator. Thus, it can be said that the radiation belts of Jupiter were positively identified within five years of the discovery of radiation belts around the Earth.

A further decade of remote observation and theoretical activity set the stage for the first in situ observations of Jupiter's radiation belts by Pioneer 10 in December 1973 and Pioneer 11 in December 1974. It is fortunate for the interested reader that much of the work on Jupiter's radiation belts during this period and following the Pioneer encounters has been reported and reviewed in certain major collections of articles (see Table 1) rather than being scattered through the literature. Indeed, the subject of Jupiter's radiation belts has already been extensively reviewed in recent years (e. g., Coroniti, 1975; Goertz, 1976b; Simpson and McKibben, 1976; Fillius, 1976; Van Allen, 1976; McDonald and

Table 1. Major Collections of Papers on Jupiter, Pioneer 10, and Pioneer 11

Proceedings of the Jupiter Radiation Belt Workshop (held at Pasadena, 13-15 July 1971), A. J. Beck (ed.), JPL Tech. Memo. 33-543, Pasadena (1 July 1972): 542 pp., 25 articles on radiation-belt models, including 23 workshop papers and 2 post-workshop papers.

Science, 183 (4122), 301-324 (25 January 1974): P. H. Abelson (ed.), 24 pp., 15 articles based on data from Pioneer 10.

Journal of Geophysical Research, 79 (25), 3487-3694 (1 September 1974): G. D. Mead (special ed.), 208 pp., 21 articles based on data from Pioneer 10.

The Magnetospheres of the Earth and Jupiter (proceedings of the Neil Brice Memorial Symposium held at Frascati, 28 May 1 June 1974), V. Formisano (ed.), Reidel, Dordrecht (1975): 485 pp., 20 articles plus one abstract on Jupiter, 15 articles on the Earth's magnetosphere.

Science, 188 (4187), 445-477 (2 May 1975): P. H. Abelson (ed.), 33 pp., 13 articles based on data from Pioneer 11.

Icarus, 27 (3), 335-459 (March 1976): T. Gehrels (guest ed.), partial proceedings of IAU Colloquium 30 (held at Tucson, 18-23 May 1975), 125 pp., 12 articles, mostly on radio science and aeronomy of Jupiter.

Journal of Geophysical Research, 81 (19), 3373-3422 (1 July 1976): G. C. Reid (ed.), partial proceedings of IAU Colloquium 30 (held at Tucson, 18-23 May 1975), 50 pp., 11 articles, mostly on the magnetosphere.

Icarus, 29 (2), 165-328 (October 1976): C. Sagan (ed.), partial proceedings of IAU Colloquium 30 (held at Tucson, 18-23 May 1975), 164 pp., 21 articles (including 16 actually presented at the symposium), mostly on the Jovian atmosphere.

Jupiter, T. Gehrels (ed.), University of Arizona Press, Tucson (1976): 1254 pp., 44 invited review papers from IAU Colloquium 30 (held at Tucson, 18-23 May 1975) on various aspects of Jovian research.

Trainor, 1976; Mogro-Campero, 1976; Kennel and Coroniti, 1978), and there is hardly need at present for yet another comprehensive review of the subject. Accordingly, the present work will offer a broad overview of principles together with a detailed coverage of certain specific issues that seem to have escaped proper attention in past reviews.

Theoretical analysis of Jupiter's radiation belts has proceeded largely along lines established by terrestrial analogy. People have invoked the radial diffusion of particles injected from the solar wind at the outer boundary of trapping. They have invoked strong pitch-angle diffusion where the resulting particle flux exceeded the limit calculated by analogy with Kennel and Petscheck (1966). Some have considered the effects of albedo-neutron decay (Thomas and Doherty, 1972), a known source of geomagnetically trapped protons.

There are perhaps three major conceptual differences between Jupiter's radiation belts and the Earth's. One is the importance of synchrotron radiation as a loss mechanism for Jovian electrons. Another is the unimportance of terrestrial radial-diffusion mechanisms at Jupiter. The third is the presence of Jovian satellites (moons) in the radiation belts. Synchrotron loss is rather well defined. Its consequences for the evolution of electron energies and equatorial pitch angles are essentially expressible in closed form (Schulz, 1977). Jovian radial diffusion, it seems, must be caused by the mechansim of Brice and McDonough (1973): fluctuations in the polarization electric field produced by neutral winds in the Jovian ionosphere, which is coupled to the magnetosphere by equipotential $\mathbf{B}$-field lines. The radial-diffusion coefficient for Jupiter must therefore vary as L^3, rather than as the L^6 or L^{10} characteristic of terrestrial mechanisms. The presence of Jovian satellites in the radiation belts can represent either an additional source of zenomagnetically trapped radiation (e.g., Neubauer, 1974) or an additional sink for it (Mead and Hess, 1973), or perhaps both.

Whereas the existence of a Jovian electron radiation belt was well established by Chang and Davis (1962) from their analysis of the decimetric radio emission, the existence of a proton radiation belt around Jupiter could never be firmly established by remote observation. The existence of such a proton belt was largely taken for granted on the basis of terrestrial analogy, but estimation of its intensity remained a subject for theoretical conjecture until the encounter of Pioneer 10 with Jupiter in December 1973.

The encounters of Pioneer 10 and Pioneer 11 with Jupiter's magnetosphere are illustrated in Figures 1-3, taken from the papers by Fillius (1976) and Van Allen (1976). The coordinates in Figures 2-3 are magnetic (R, λ), and the 10° inclination of the dipole axis to Jupiter's rotation axis modulates the magnetic latitude of the spacecraft at a 10-hour period. The outbound pass of Pioneer 11 (Figure 3) represented the beginning of an out-of-ecliptic excursion, and so provided data from fairly high zenomagnetic latitudes λ. The cross-hatched regions in Figures 2-3 correspond to the inner Jovian satellites Io (JI), Europa (JII), Ganymede (JIII), Callisto (JIV), and Amalthea (JV, the innermost). The Pioneer spacecraft provided a wealth of data on Jupiter's radiation belts, and the analysis of the Pioneer results continues to occupy the attention of

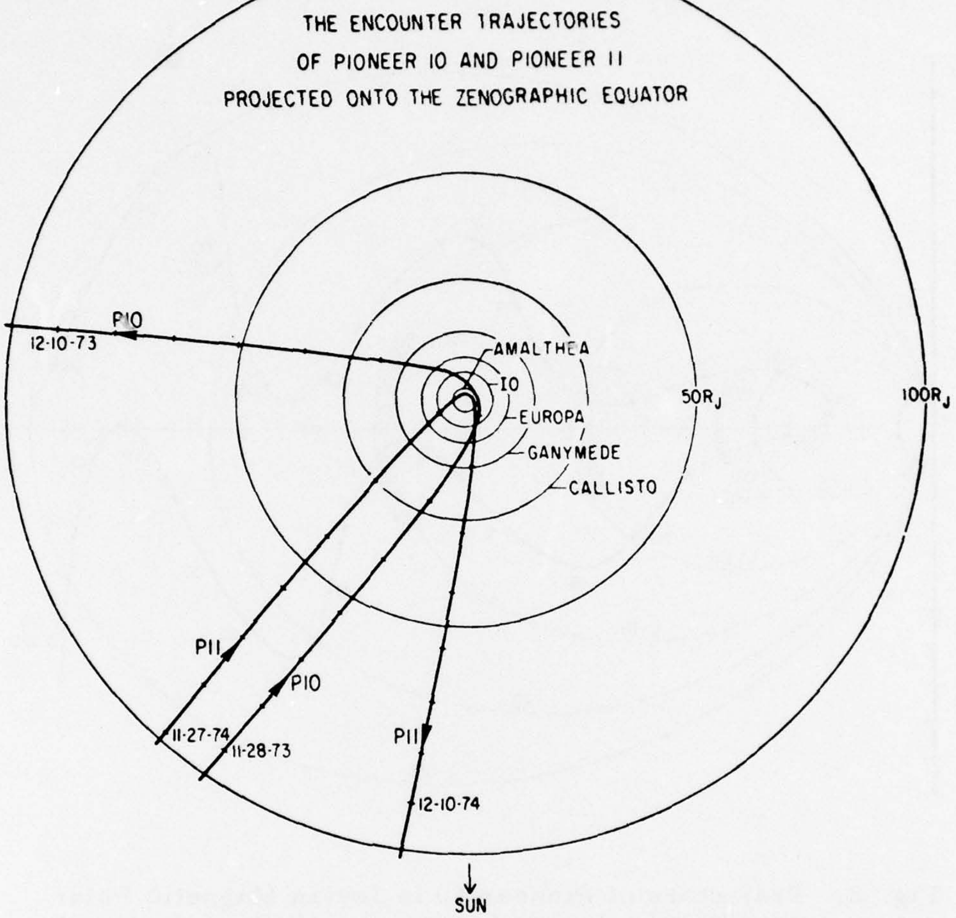

Fig. 1. Projection of Pioneer 10 and Pioneer 11 Trajectories on the Equatorial Plane of Jupiter

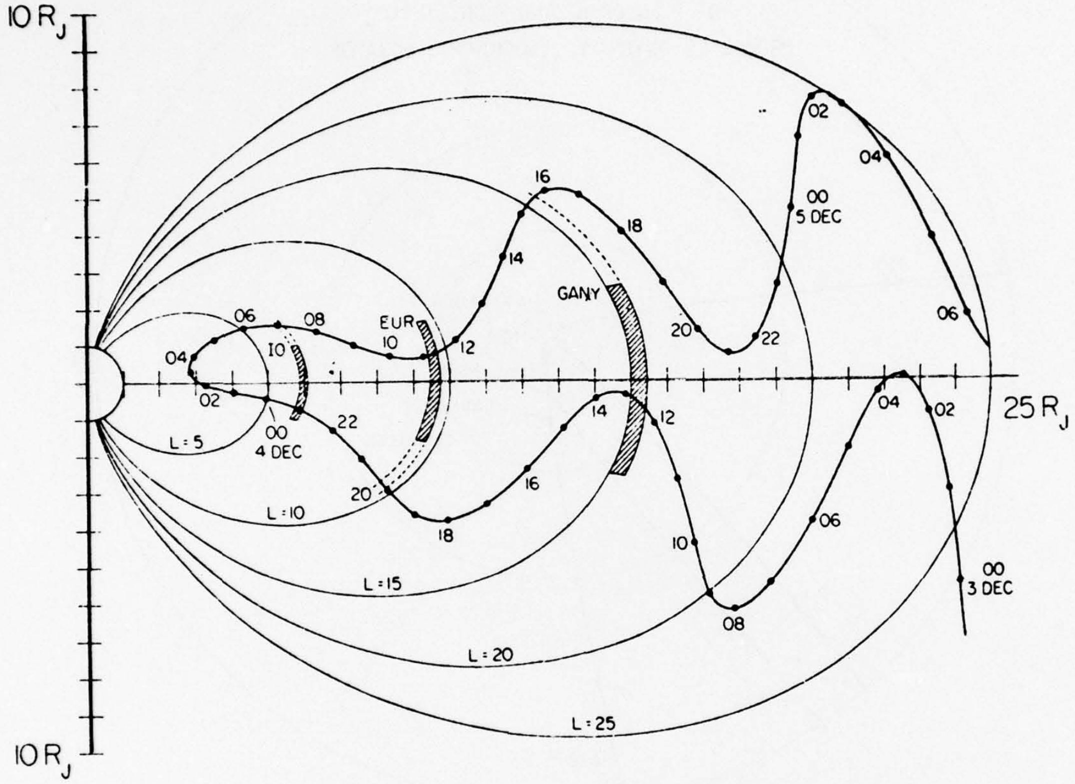

Fig. 2. Trajectory of Pioneer 10 in Jovian Magnetic Polar Coordinates (longitude suppressed) for a Centered Dipole Tilted 9.5° Toward $\lambda_{III}(1957) = 230°$

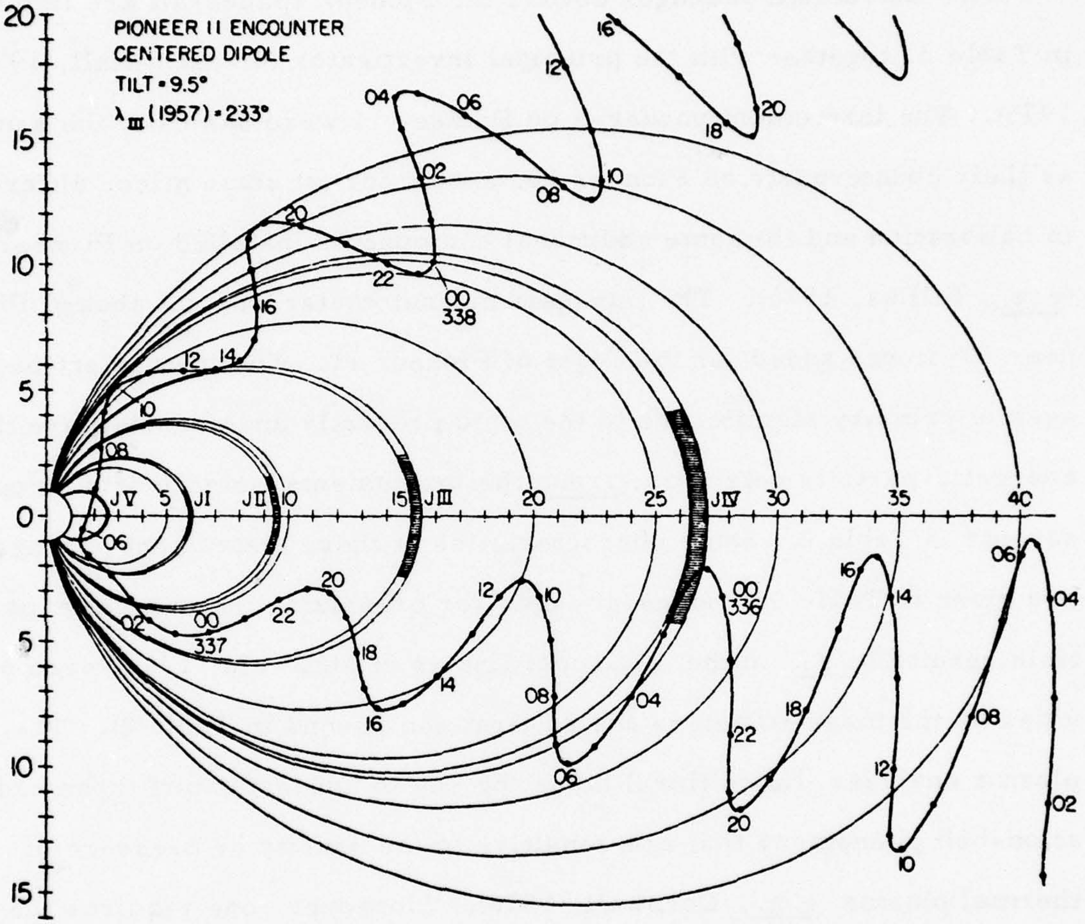

Fig. 3. Trajectory of Pioneer 11 in Jovian Magnetic Polar Coordinates for a Centered Dipole Tilted 9.5° Toward λ_{III}(1957) = 233° (Van Allen, 1976)

numerous investigators. Some of the major preliminary scientific results from the two spacecraft are summarized by Mead (1974a) and Opp (1974, 1975).

The instrument packages aboard the Pioneer spacecraft are listed in Table 2, together with the principal investigator for each (Hall, 1974; 1975). The instrument packages on Pioneer 11 were basically the same as their counterparts on Pioneer 10, except for (a) some minor differences in calibration and (b) some additional components installed on Pioneer 11 (*e.g.*, Fillius, 1976). The flux-gate magnetometer was not aboard Pioneer 10; it was added for the flight of Pioneer 11. The instrument packages of primary significance to the topic presently under review are the energetic-particle detectors, *i.e.*, the instruments listed fourth through seventh in Table 2. Some characteristics of these instrument packages are given in Table 3. Necessary data for organizing the energetic-particle results (*e.g.*, in the B,L coordinates of McIlwain, 1966) were provided by the magnetometers (listed first and second in Table 2). The plasma analyzer (listed third) holds the key to understanding those radiation-belt phenomena that are sensitive to the density or pressure of thermal plasma (*e.g.*, Cornwall, 1976). Moreover, one requires the plasma analyzer and at least one magnetometer in order to define the configuration of Jupiter's outer magnetosphere. Without such a definition, quantitative aspects of the *origin* of Jupiter's trapped radiation can hardly be discussed at all.

Table 2. Instrumentation Aboard Pioneer 10 and Pioneer 11 (Hall, 1974; 1975)

Instrument	Principal Investigator (Institution)
Helium Vector Magnetometer	E. J. Smith (Jet Propulsion Laboratory, JPL)
Flux-Gate Magnetometer*	M. Acuña (NASA Goddard Space Flight Center, GSFC)
Plasma Analyzer	J. H. Wolfe (NASA Ames Research Center)
Charged-Particle Detector	J. A. Simpson (University of Chicago)
Geiger-Tube Telescope	J. A. Van Allen (University of Iowa)
Cosmic-Ray Telescope	F. B. McDonald (NASA Goddard Space Flight Center, GSFC)
Trapped-Radiation Detector	R. W. Fillius (University of California at San Diego, UCSD)
Ultraviolet Photometer	D. L. Judge (University of Southern California, USC)
Imaging Photopolarimeter	T. Gehrels (University of Arizona)
Infrared Radiometer	G. Münch (California Institute of Technology, Caltech)
Asteroid-Meteoroid Detector	R. K. Soberman (General Electric Company, GE)
Meteoroid Detector	W. H. Kinard (NASA Langley Research Center)

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*Flux-gate magnetometer was aboard Pioneer 11 only, not aboard Pioneer 10. The other instruments were aboard both spacecraft.

Table 3. Summary of Particle Energy Ranges Covered by Energetic-Particle Instruments Aboard Pioneer 10 and Pioneer 11

Group	Designation	Electrons	Protons	Helium Ions	Heavier Ions
Chicago	ECD	>3 MeV	>30 MeV		
Chicago	FC	dep/spectrum†	>35 MeV	dep/spectrum†	dep/spectrum†
Chicago	LET	dep/spectrum	0.54-1.85 MeV		
Chicago	LET	dep/spectrum	1.85-8.8 MeV		
Iowa	G - C	0.06-21 MeV	dep/spectrum		
Iowa	B - C	0.55-21 MeV	6.6-77.5 MeV		
Iowa	A - C	5-21 MeV	30-77.5 MeV		
Iowa	C	>21 MeV	>77.5 MeV		
Iowa	D	>31 MeV	>77.5 MeV		
GSFC	HET	2.1-8.0 MeV	20-500 MeV	80-2000 MeV	40-120 MeV/nucleon
GSFC	LET-1		← 0.43-3 MeV/nucleon →		
GSFC	LET-1		3-21 MeV	12-84 MeV	6-40 MeV/nucleon
GSFC	LET-2	0.05-2.1 MeV*	0.2-21 MeV		
UCSD	C1	>6 MeV			
UCSD	C2	>9 MeV			
UCSD	C3	>13 MeV			
UCSD	CDC	>1 MeV	(CDC was aboard Pioneer 11 only, not aboard Pioneer 10)		
UCSD	E1	>0.16 MeV			
UCSD	E2	>0.255 MeV			
UCSD	E3	>0.460 MeV			
UCSD	M1	>35 MeV			
UCSD	M2	background			
UCSD	M3		>80 MeV		
UCSD	SPDC	>0.01 MeV	>0.15 MeV	(SPDC aboard Pioneer 11 only, not 10)	
UCSD	SEDC	>0.01 MeV	>0.15 MeV	(SEDC aboard Pioneer 11 only, not 10)	

*Electrons were separated from protons at energies >0.12 MeV; †dep/spectrum = dependent on spectrum

Chicago: ECD = Electron-Current Detector, FC = Fission Cell; LET = Low-Energy Telescope (Simpson et al., 1974b)

Iowa: Geiger-Tube Telescope (Van Allen et al., 1974b)

GSFC: HET = High-Energy Telescope; LET = Low-Energy Telescope (Trainor et al., 1974b)

UCSD: C = Cherenkov Counter; CDC = Cherenkov Counter; E = Electron-Scatter Counter; M = Minimum-Ionizing Particle Counter; SPDC = SP Scintillator; SEDC = SE Scintillator (Fillius and McIlwain, 1974b; Fillius, 1976)

2. ELECTRON OBSERVATIONS

All four of the energetic-particle instrument packages (see Table 3, above) included detectors that would respond to incident electrons. Taken together, the various packages provided coverage from ~ 50 keV to > 35 MeV. Detailed results specifically addressing the radiation belts of Jupiter are given by Fillius (1976), Fillius and McIlwain (1974a, b), Fillius et al. (1975, 1976), McDonald and Trainor (1976), McIlwain and Fillius (1975), McKibben and Simpson (1974, 1975), Randall (1975), Sentman and Van Allen (1976) Simpson and McKibben (1976), Simpson et al. (1974a, b; 1975a, b), Trainor et al. (1974a, b; 1975), Van Allen (1976), and Van Allen et al. (1974a, b; 1975). Some representative findings are recounted here.

Contours of constant radiation intensity, as inferred from the counting rate in an omnidirectional channel sensitive to electrons of energy $E > 21$ MeV, are shown in Figure 4 (Van Allen et al., 1975). The maximum flux occurs at $L \sim 3$. There is no evidence here of a two-zone structure such as that found in the Earth's magnetosphere. On a given L shell the counting rate is largest at the equator. This corresponds to the usual peak at $\alpha_0 = 90^\circ$ in the distribution of equatorial pitch angles.

Representative electron spectra, in this case from the outer magnetosphere, are shown in Figure 5 (Trainor et al., 1975). Each of the spectra seems to satisfy a power law for $E \lesssim 10$ MeV, and the power-law indices (2.0, 2.0, and 1.5) are remarkably small. Transition to a steeper descent should be anticipated at some higher energy ($E \gtrsim 10$ MeV). Otherwise, the integrated energy flux would be at least logarithmically divergent.

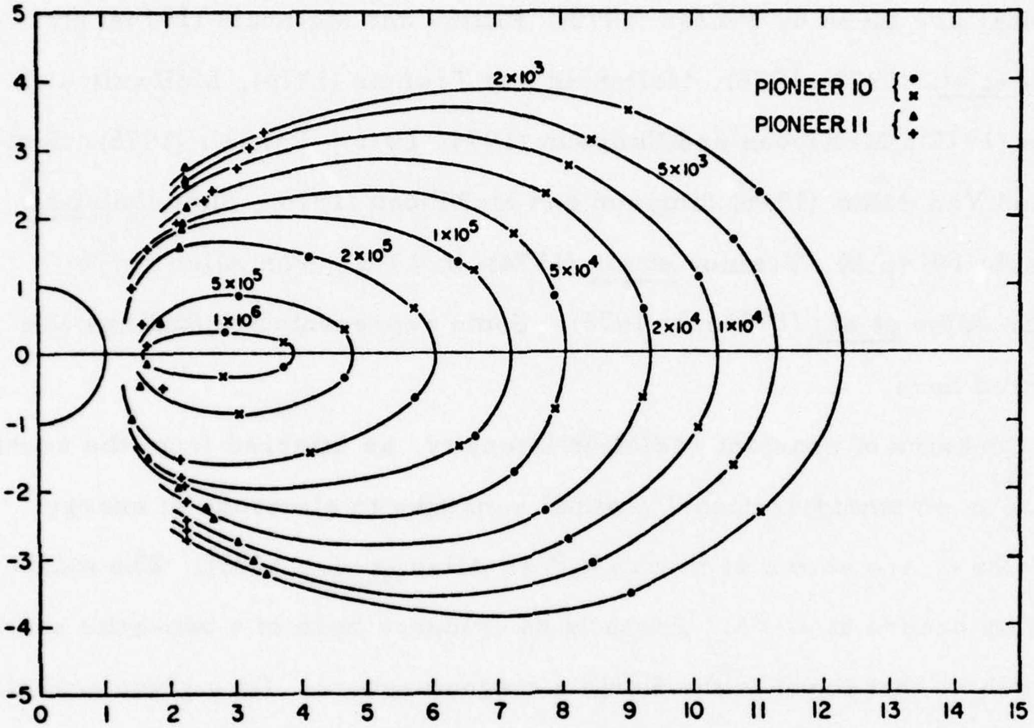

Fig. 4. Contours of Constant (specified) Omnidirectional Counting Rate ($\approx I_{4\pi}/23$, cm^{-2} sec^{-1}) for Electrons ($E > 21$ MeV) in Jovian Magnetic Polar Coordinates (see Figs. 2 and 3)

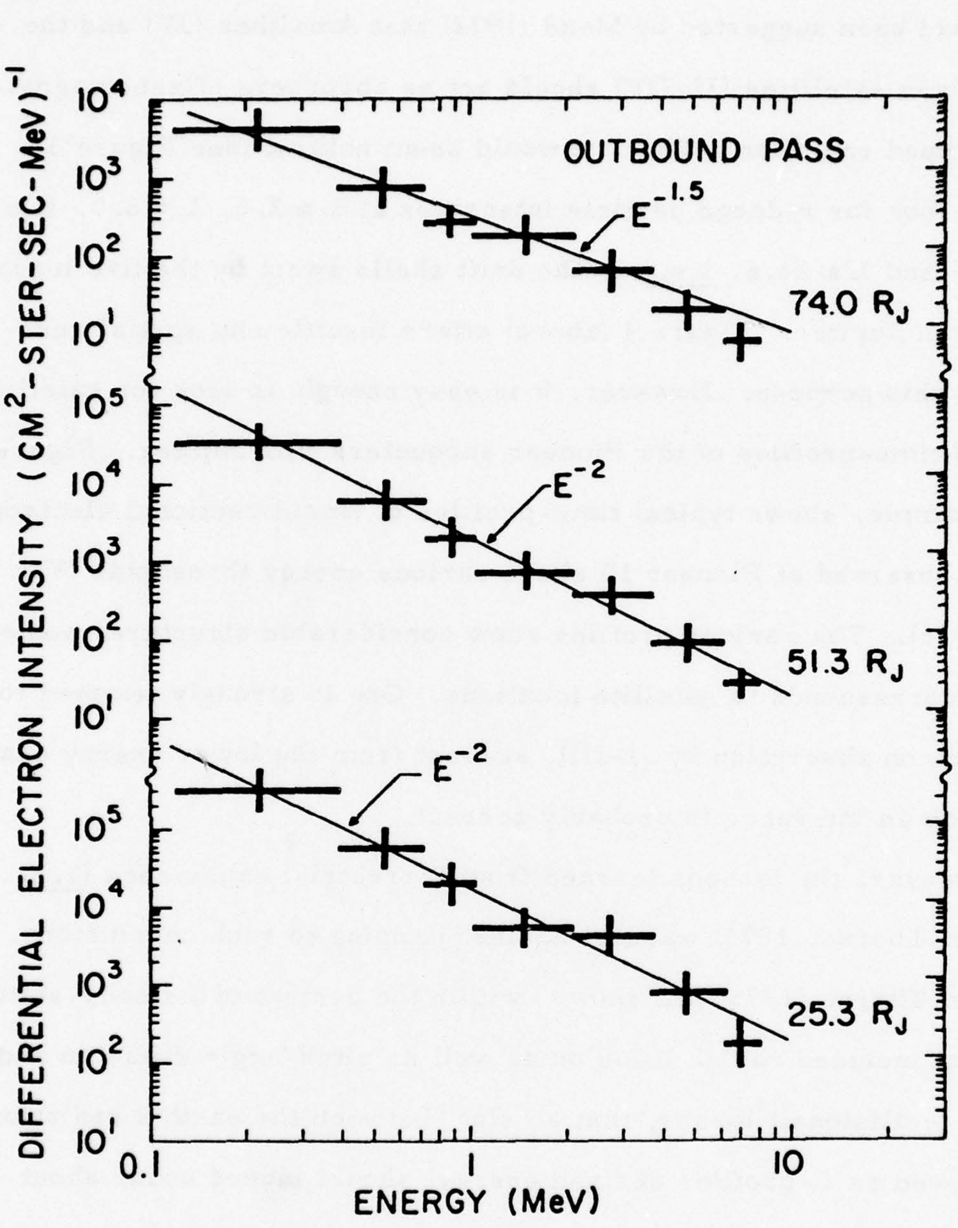

Fig. 5. Electron Energy Spectra from Pioneer 10 at Selected Zenocentric Distances R (McDonald and Trainor, 1976) In and Near the Jovian Magnetosphere

It had been suggested by Mead (1972) that Amalthea (JV) and the four Galilean satellites (JI-JIV) should act as absorbers of zenomagnetically trapped radiation. Thus, it would seem natural (see Figure 3, above) to look for reduced particle intensities at $L \approx 2.6$, $L \approx 6.0$, $L \approx 9.5$, $L \approx 15.1$, and $L \approx 26.6$, i.e., at the drift shells swept by the five inner satellites of Jupiter. Figure 4 (above) offers insufficient spatial resolution for this purpose. However, it is easy enough to look for satellite effects in time-profiles of the Pioneer encounters with Jupiter. Figure 6, for example, shows typical time-profiles of omnidirectional electron intensity observed at Pioneer 10 above various energy thresholds (Van Allen, 1976). The various profiles show considerable structure, some of which corresponds to satellite locations. One is strongly tempted to infer electron absorption by JI-JIII, at least from the lower energy channels. Such an inference is probably correct.

However, the lessons learned from terrestrial experience (e.g., Lyons and Thorne, 1973) warn us against jumping to such conclusions. Lyons and Thorne (1973) had shown, within the context of a steady-state model that included radial diffusion as well as pitch-angle diffusion and Coulomb (collisional) losses, that a "slot" between the earth's radiation belts (viewed as L-profiles at fixed energy) should indeed occur about where the particle lifetime is least. Along the way, however, they also had found that the phase-space density $\bar{f}$ was monotonic with L when plotted at fixed M and J, the two adiabatic invariants conserved by the radial-diffusion process that was postulated. The L-profiles of electron

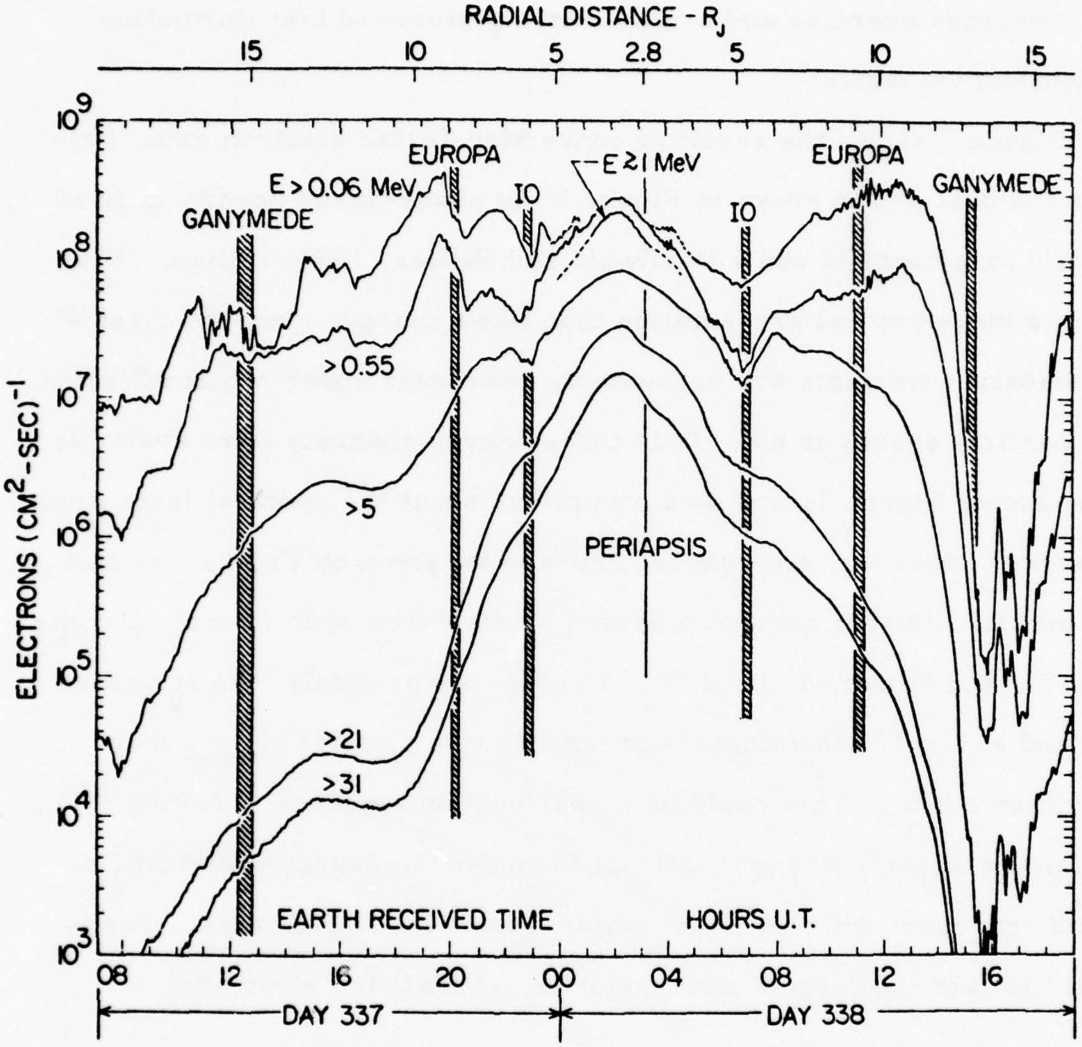

Fig. 6. Omnidirectional Electron Intensities $I_{4\pi}$ from Pioneer 10

flux at fixed energy, which showed the distinct "slot" between zones of intense particle radiation, thus emerged only after a rather formidable computer exercise and a rather straightforward transformation of kinematic variables.

Figure 7 shows the result of converting Jovian electron data, similar to the data shown above in Figure 6, to phase-space density at fixed adiabatic invariants M and J (McIlwain and Fillius, 1975; Fillius, 1976). This is a more natural presentation than fixed energy, since the first two adiabatic invariants are presumably conserved under radial diffusion, while particle energy is not. Only three energy channels were available for producing Figure 7, and so assumptions about the spectral form were necessary. However, the general impression given by Figure 7 is that of an inward diffusion current modified by structure at Io ($L \approx 6$), Europa ($L \approx 9.5$), and Ganymede ($L \approx 15$). Perhaps surprisingly, the structure at Io (and at $L \approx 12$) seemingly corresponds to a particle source there, rather than a sink. This could be a spurious consequence of having postulated a slightly wrong functional form for the energy spectrum, or it could represent a discovery of major dynamical significance. One is inclined toward the former interpretation, at least for electrons.

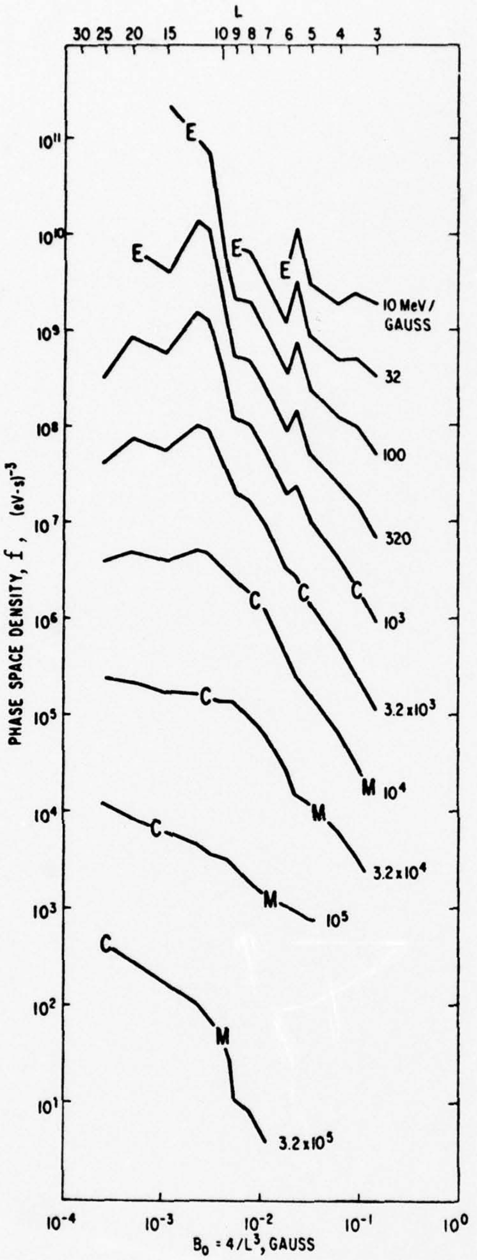

Fig. 7. Profiles of Phase-Space Density f Deduced from Pioneer 10 Data (Fillius, 1976) at Fixed Adiabatic Invariants M (specified) and J (≈0)

3. PROTON OBSERVATIONS

All four of the energetic-particle instrument packages on Pioneer 10 and Pioneer 11 (see Table 3, above) included detectors that would respond to incident protons. Taken together, the various packages provided coverage from ~ 120 keV to > 80 MeV. Detailed results specifically pertaining to protons in the radiation belts of Jupiter are given by Fillius (1976), Fillius and McIlwain (1974a, b), Fillius et al. (1975), McDonald and Trainor (1976), McKibben and Simpson (1974, 1975), Simpson and McKibben (1976), Simpson et al. (1974a, b; 1975a, b), Trainor et al. (1974a, b; 1975), Van Allen (1976), and Van Allen et al. (1974b, 1975). Some representative findings are recounted here.

An outstanding feature of Jovian energetic ions is the great magnitude of their intensity variation with L. This is illustrated in Figure 8 (Simpson and McKibben, 1976). The L value for this illustration was derived, by the methods of McIlwain (1966) and Mead (1974b), from a set of spherical-harmonic coefficients (called Model D4) that had been fitted by Smith et al. (1975) to their Pioneer-11 magnetometer data. Intensities at the inbound and outbound traversals of the same L shell agree remarkably well. Simpson and McKibben (1976) take this agreement as a testament to the accuracy of the magnetic-field model, as it undoubtedly is.

However, one should view with caution the pronounced variation of ion flux with L in Figure 8, since the magnetic latitude of the spacecraft varies strongly with L. It can be seen from Figure 3 that the inbound and outbound traversals of the L = 5 drift shell occurred at about the same ($\sim 45^\circ$) magnetic latitude. Actually the magnetic latitude was slightly

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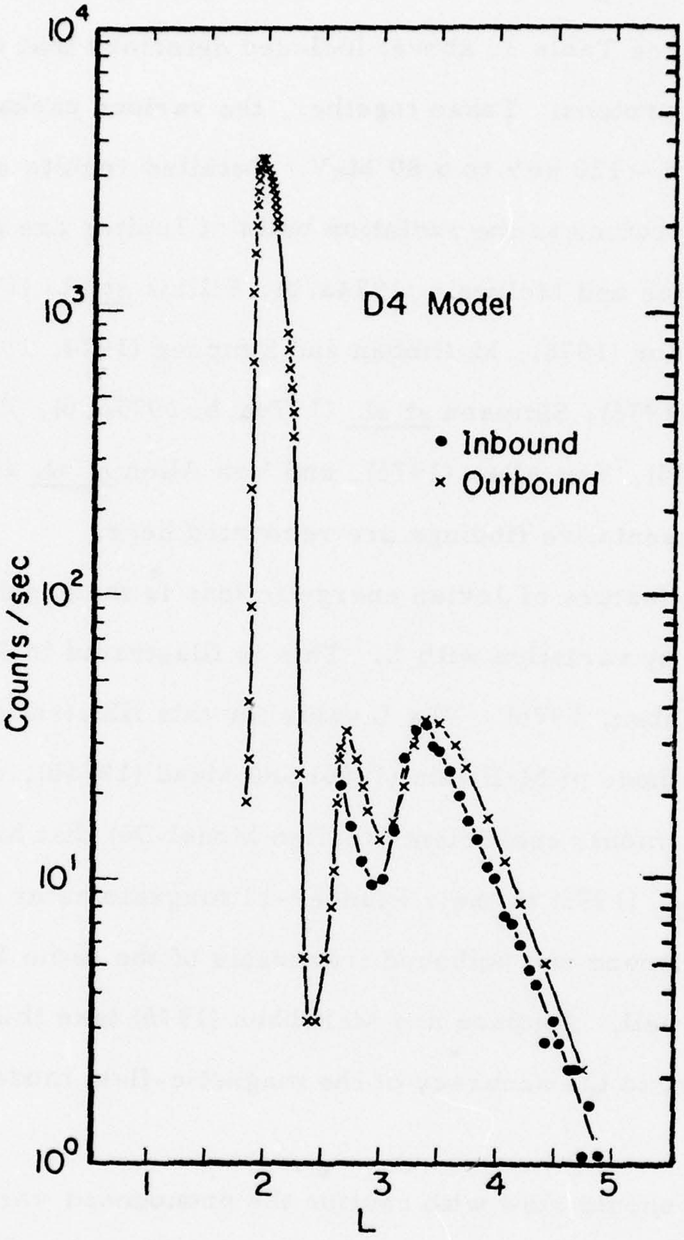

Fig. 8. Intensity of Trapped Protons (E > 35 MeV) from Pioneer 11 Data, as Organized (Simpson and McKibben, 1976) by Calculating L at the Spacecraft from the B-Field Model of Smith <u>et al.</u> (1975)

higher on the inbound pass than on the outbound. Traversal of the lowest L shells is accompanied by a very rapid change in magnetic latitude. If the directional intensity were to vary as some large power 2n of sin α_0 (where α_0 is the equatorial pitch angle), then the omnidirectional intensity would vary as $(B_0/B)^n$ along the field line. The flux would be maximal at the equator, i.e., at $B/B_0 = 1$. Thus, the variation of equatorial intensity with L is folded inextricably with latitudinal variation of ion flux on a given drift shell in the construction of Figure 8. Experience with the Earth's radiation belts (e.g., Schulz, 1975b), where $n > 3$ for protons and $n > 5$ for alpha particles (helium nuclei) at $L \sim 2$, provides a clear warning on the interpretation of Figure 8 for Jupiter. The spatial structure identified by Fillius (1976) for protons having $E > 80$ MeV must be viewed with similar caution. Geomagnetically trapped ions acquire their considerable anisotropy (which increases somewhat with energy, at least for protons) by diffusing from $L \sim 10$ to $L \sim 2$ under conservation of M and J. One should expect the source of Jovian protons to lie well beyond $L \sim 10$, which is to say that the anisotropy of Jovian protons at $L \sim 2$ should be even larger than in the terrestrial case (see also Cornwall and Schulz, 1978). Of course, particle absorption by Amalthea (Fillius, 1976) may well be responsible for some of the structure seen in Figure 8, but probably not for all of it.

The particle data for Figure 8 were derived from a fission cell, which can respond to heavier ions in addition to protons (Simpson et al., 1974b). However, it seems that the contribution from heavier ions would have been rather small. The intensity ratio of alpha particles to protons, at least at fixed energy/nucleon, has been found to decrease quite strongly with L (Trainor et al., 1974b; 1975). This is illustrated in Figure 9. Extrapolation of these results would suggest that J_α/J_p 10^{-4} at $L \lesssim 10$. To this remark must be added the usual caution that geomagnetically trapped alpha particles and protons have very different anisotropies on the same L shell, which is to say that the α/p ratio is a strong function of magnetic latitude (e.g., Schulz, 1975b). The same might well be true at Jupiter.

A representative energy spectrum for zenomagnetically trapped protons is shown in Figure 10 (Trainor et al., 1974b; 1975). It seems clear that a power law fits very well, and that the index (3.5 in this case) is significantly larger for protons than for electrons (cf. Figure 5). In other words, Jovian protons seem to have softer (i.e., steeper) spectra than Jovian electrons in the 0.1-10 MeV range. Quite the opposite is true in the Earth's magnetosphere.

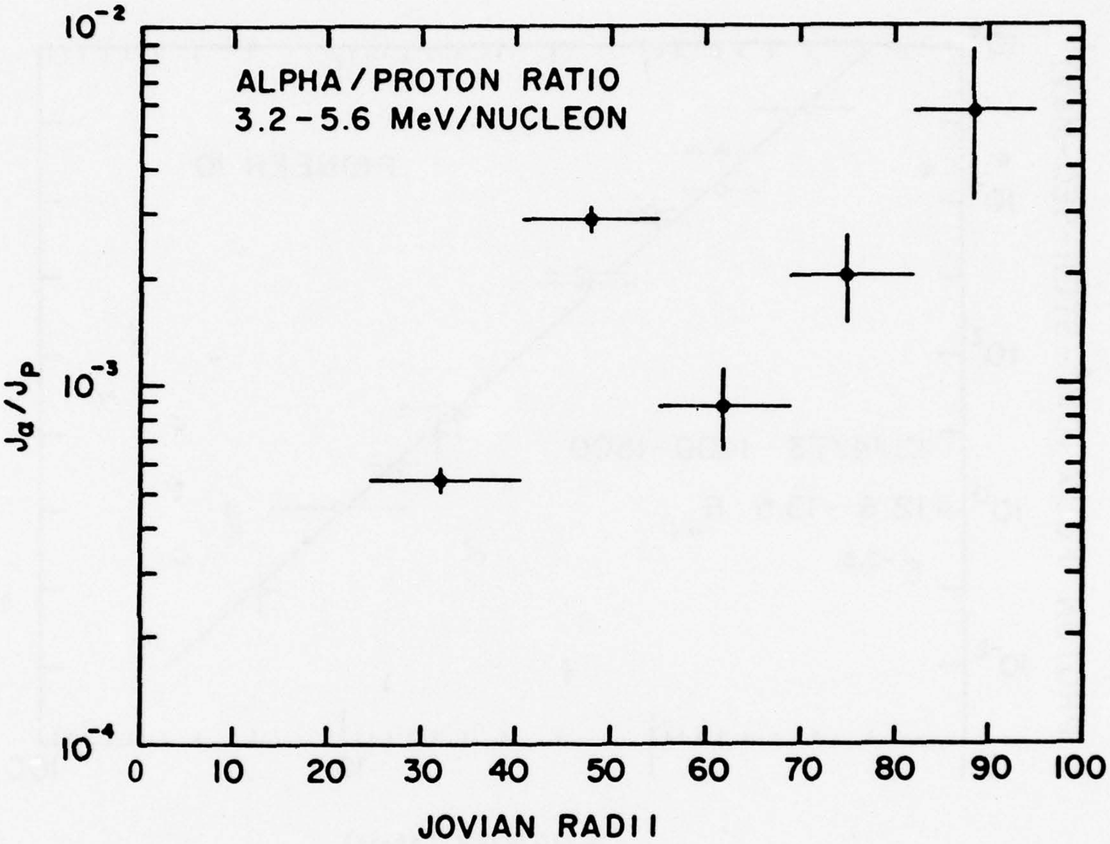

Fig. 9. Alpha/Proton Flux Ratios (at fixed energy/nucleon) from Pioneer 10 Data at Selected Zenocentric Distances (Trainor et al., 1975)

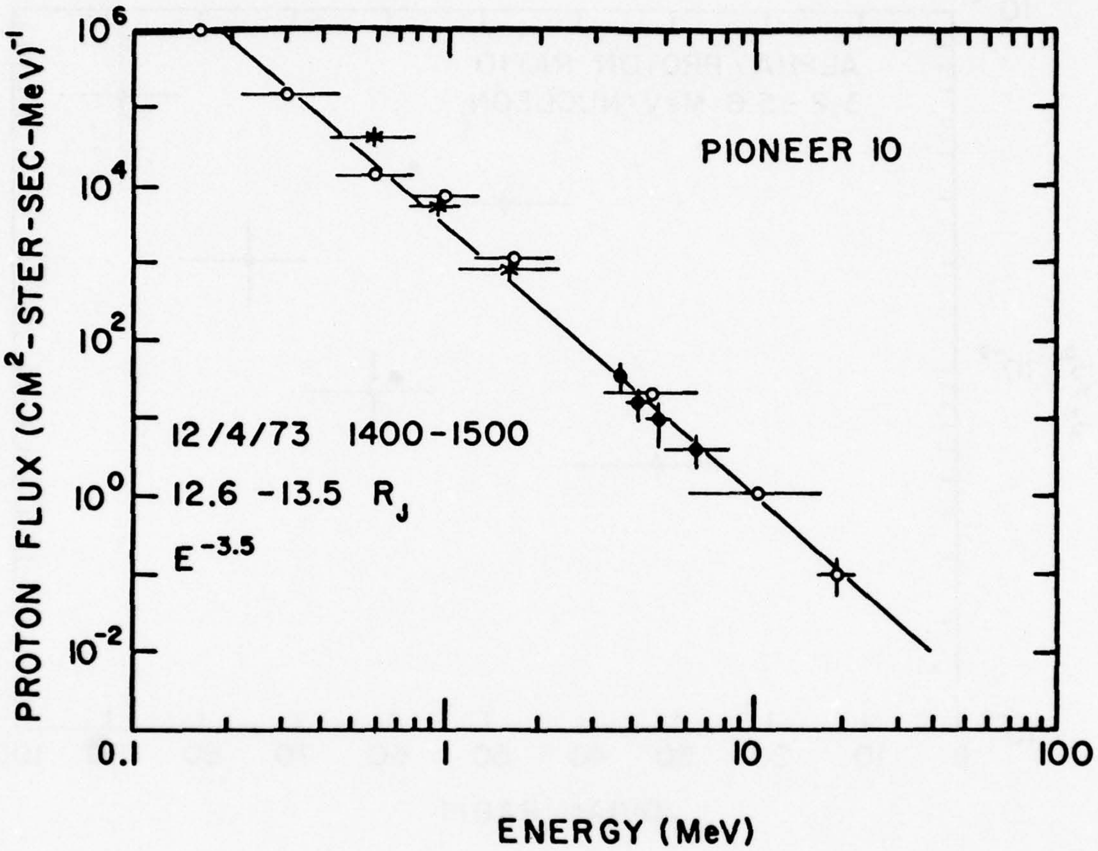

Fig. 10. Representative Proton Energy Spectrum from Pioneer 10 (Trainor et al., 1975) at Magnetic Latitude 18.5° ± 2.0° and L ≈ 13.7 ± 0.7 in Centered-Dipole Model

4. SATELLITE EFFECTS

Following the suggestion by Mead (1972) that the five inner satellites of Jupiter would tend to sweep the radiation belts of their energetic particles, Mead and Hess (1973) undertook a detailed study of the effect. They found, for example, that the 10° tilt between Jupiter's magnetic and rotation axes (and hence, the 10° tilt between Jupiter's magnetic equator and the plane of the satellite orbits) would enable particles having mirror latitudes $< 10^\circ$ to escape absorption much of the time. Particles mirroring at higher latitudes than 10°, but having energies either sufficiently low or sufficiently high, might avoid absorption if their drift motion advanced the guiding center at least one satellite diameter in longitude during half a bounce period. Still other particles might escape absorption if the drift shells swept by the satellite were traversed via radial diffusion in less than a drift period. Mogro-Campero and Fillius (1976) considered such effects and thereby estimated an effective lifetime (to be inserted in the Fokker-Planck equation) for particles at L values in the vicinity of the satellites.

In the above-described analysis, it had been assumed that the satellites did not otherwise (apart from absorption) perturb the adiabatic trajectory of a charged particle. Schulz and Eviatar (1977) reconsidered the problem of charged-particle absorption for the case of a perfectly conducting satellite. This study was motivated by certain models of Jovian decametric radio emission (e.g., Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969; Smith, 1976) that require the satellite Io to be a good conductor. However, substantially similar effects on particle absorption should occur for satellites (such as Ganymede) that have a very large dielectric constant (Cornwall and Schulz, 1978). If, as Piddington and Drake (1968) propose, the satellite Io is a good electrical conductor, then the equipotentials of Jupiter's corotation electric field (as observed in Io's frame) would be distorted somewhat as in Figure 11a. The 10° tilt of Jupiter's magnetic axis is neglected here, as is any offset of Jupiter's dipole from the center of the planet, so as to make $\partial \mathbf{B}/\partial t = \mathbf{0}$. The distortion of the cold-plasma drift paths (*i.e.*, of the electrostatic equipotentials) in Figure 11a would not only (a) preclude the absorption of cold plasma by Io, but would also modify the absorption of energetic trapped radiation as follows (see Figure 11): (b) 20-MeV protons, reduced absorption; (c) 28-MeV electrons, no absorption; (d-f) $E > 31$-MeV electrons, enhanced absorption (Schulz and Eviatar, 1977).

The observational data shown in Figure 6 (above) do not seem to support the above conclusions based on Figure 11. Indeed, from Figure 6 one infers much absorption at the *lower* energies and little absorption (if any) at the higher. Thus, it seems that the absorption probability predicted by Figure 11 depends in the wrong way on electron energy (Thomsen *et al.*, 1977b). It is possible, of course, that the energetic electrons are being absorbed not by the satellite itself but by Io-associated clouds of sodium and/or sulfur, such as have been observed by Trafton *et al.* (1974), Matson *et al.* (1974, 1978), Trafton (1976), Eviatar *et al.* (1976), Mekler and Eviatar (1976), Mekler *et al.* (1976, 1977), and

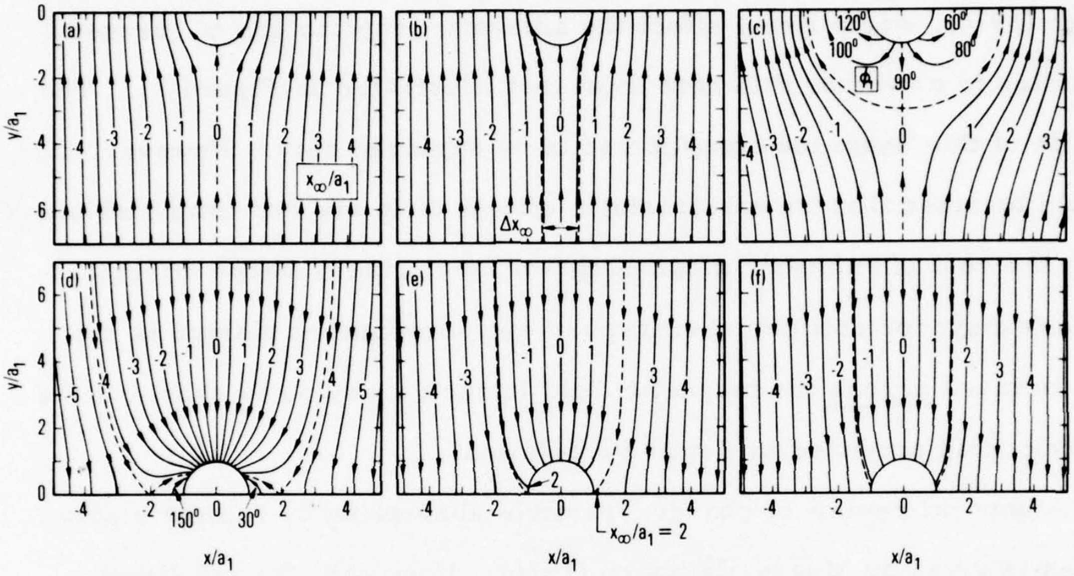

Fig. 11. Drift Paths of Representative Equatorial Guiding Centers (of particles having J = 0) in the Vicinity of Conducting Io's Magnetic Flux Tube: (a) particles having M = 0; (b) protons, M = 1 GeV/G; (c) electrons, M = 40 GeV/G; (d) electrons, M = 80 GeV/G; (e) electrons, M = 200 GeV/G; (f) electrons, M = 400 GeV/G.

Wehinger et al. (1976). Such clouds extend to considerable distances from Io itself. Another possiblity is that the electric-field configuration surrounding Io's magnetic flux tube is more complicated than that postulated by Schulz and Eviatar (1977). For example, Hubbard et al. (1974) and Shawhan et al. (1975) have proposed the configuration illustrated in Figure 12 (Shawhan, 1976). This model, among others discussed by Smith (1976), would likely affect the adiabatic trajectories of energetic particles in a manner different from that illustrated in Figure 11. The details of this seem too complicated to be explored here. However, it should be noted that the electrostatic effects of Io are not simply shielded from the rest of Jupiter's magnetosphere by ordinary Debye effects, since (except for collisional transport) the surrounding plasma is not free to move across the magnetic field in such a way as to short out the electric field produced by Jupiter's rotation.

A general review of charged-particle absorption by Jupiter's satellites is given by Mogro-Campero (1976). However, the satellites have also been proposed as sources of charged particles for the Jovian magnetosphere (e.g., Neubauer, 1974). Carlson et al. (1975) and Eviatar et al. (1976) have noted the importance of electron-impact ionization (a faster process there than photo-ionization) of Io's sodium cloud (see above). Eviatar et al. (1978) have emphasized the energy gain ($\sim$1 keV) imparted to a sodium ion by virtue of its corotation with Jupiter, a motion not characteristic of the neutral sodium atoms that orbit Jupiter (along with Io) well beyond the synchronous altitude.

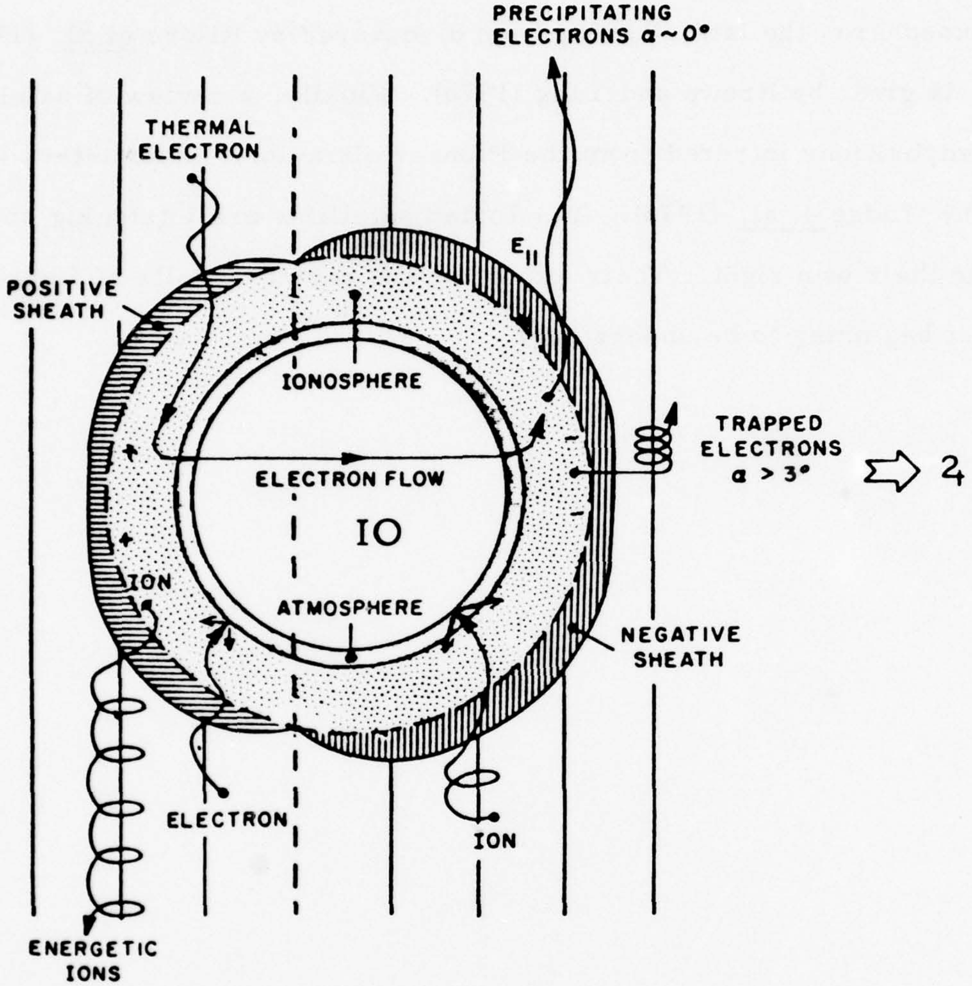

Fig. 12. Current Flow, Electric Fields, Sheath Formation, and Particle Acceleration Near Io (Shawhan et al., 1975)

Various properties of Io and the other Jovian satellites are described in reviews by Consolmagno and Lewis (1976) and by Morrison and Burns (1976). A review of Io's atmosphere (cf. Fink et al., 1976) and ionosphere, the latter having been discovered by Kliore et al. (1974, 1975), is given by Brown and Yung (1976). Finally, a review of satellite compositions inferred from the Pioneer ultraviolet photometers is given by Judge et al. (1976). The Jovian satellites are intriguing objects in their own right. Their effects on the radiation belts of Jupiter are just beginning to be understood.

5. SYNCHROTRON RADIATION

The idea that Jupiter's decimetric radiation (Sloanaker, 1959) is the result of synchrotron radiation by trapped relativistic electrons seems to have originated with Drake and Hvatum (1959). The subsequent quantitative work of Chang and Davis (1962) confirmed this idea beyond reasonable doubt. A representative contour plot of brightness temperature at decimeter wavelengths is shown in Figure 13 (Berge, 1966). The contours (except the outer dashed one) occur at 20° intervals from 20°K to 160°K. Methods for inferring charged-particle distributions from the observed radio spectrum were developed by Chang and Davis (1962), Thorne (1963), Beard and Luthey (1973), Luthey and Beard (1973), and Peng _et al._ (1974).

The other side of the coin is that synchrotron emission must represent a significant loss mechanism for the energetic electrons in Jupiter's radiation belt. The effect of synchrotron emission is to reduce the kinetic energy $(\gamma - 1)m_0c^2$ of a trapped electron and also to reduce its value of $y \equiv \sin \alpha_0$, where α_0 is the equatorial pitch angle. For particles that mirror off the equator (_i.e._, for $\alpha_0 \neq 90^\circ$), one must _average_ the local contributions to $\dot{\gamma}$ and $\dot{y}$ over the bounce motion of the particle in order to obtain transport coefficients that can be used in the Fokker-Planck equation. Luthey (1970) and Baker (1974) have undertaken largely numerical investigations of this problem, and Coroniti (1974) has attempted to expand the bounce averages of $\dot{M}$ and $\dot{J}$ in powers of $\mathrm{ctn}^2\alpha_0$, which he assumes to be small. More recently Schulz (1977) has

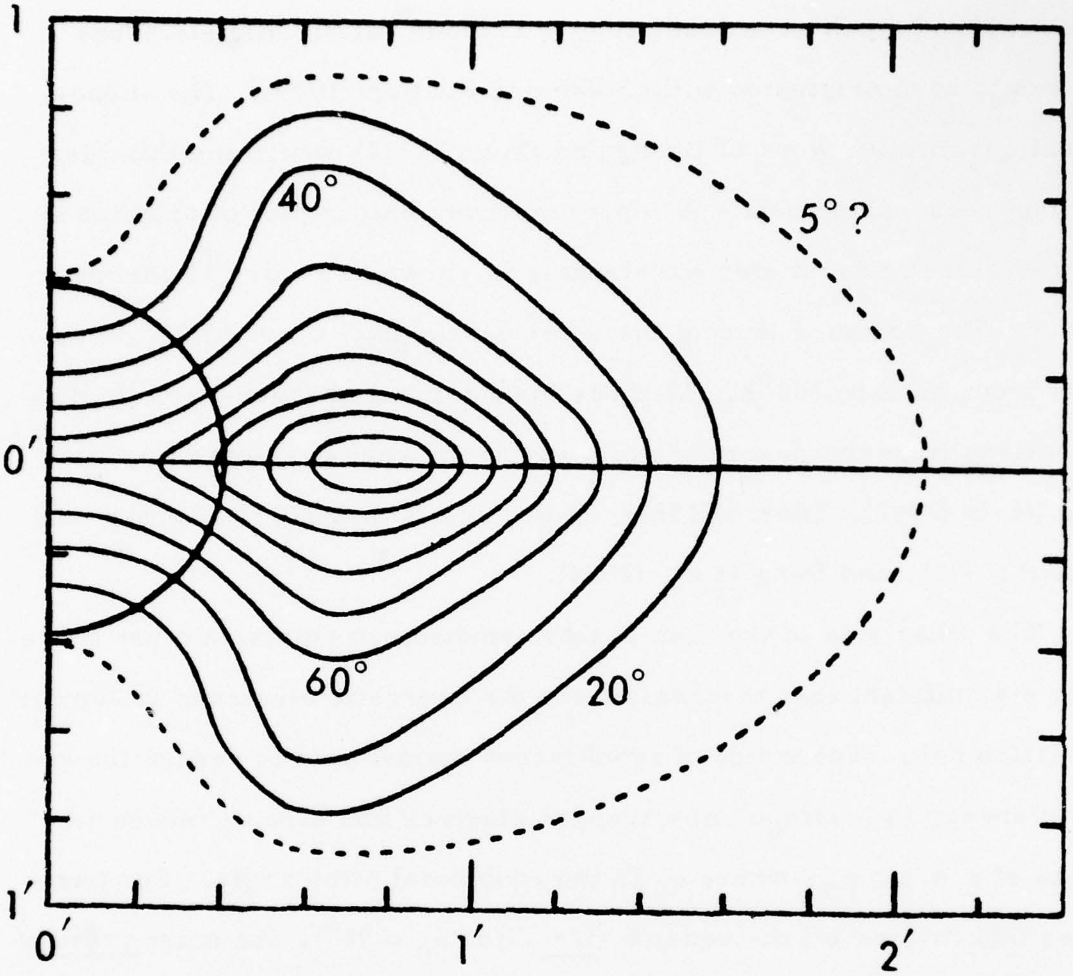

Fig. 13. The 10.4-cm Radio Brightness Distribution of Jupiter, as Measured by a Two-Antenna Interferometer (Berge, 1966)

obtained (with no such assumption about ctn^2 α_0) analytical representations of $\langle\dot{\gamma}\rangle$ and $\langle\dot{y}\rangle$, namely

$$\begin{aligned}\langle\dot{\gamma}\rangle \approx\ & -(2q^4B_0^2/3m_0^3c^5)(\gamma^2 - 1)\\ & \times (0.8153y^{-13/4} - 0.4420y^{-3}\\ & + 0.1318y^{-1} + 0.2354y)\\ & \div (1.3802 - 0.6397y^{3/4})\end{aligned} \tag{1}$$

$$\begin{aligned}\langle\dot{y}\rangle \approx\ & -(2q^4B_0^2 / 3\gamma m_0^3c^5)\\ & \times (0.2509y^{-9/4} - 0.1473y^{-2}\\ & + 0.1318 - 0.2354y^2)\\ & \div (1.3802 - 0.6397y^{3/4})\end{aligned} \tag{2}$$

by invoking a very accurate approximation (Davidson, 1976) to the bounce frequency of a particle (having charge q, rest mass m_0, and relativistic mass γm_0) in a dipole field. As usual, the factor B_0 in (1) and (2) represents the minimum (*i.e.*, equatorial) field insensity seen by the particle during its bounce period between mirror points. The field at the mirror points is denoted B_m ($= y^{-2}B_0$). The dependence of the loss rates $\langle\dot{\gamma}\rangle$ and $\langle\dot{y}\rangle$ on y is shown by the dashed and solid curves in Figure 14 (Schulz, 1977).

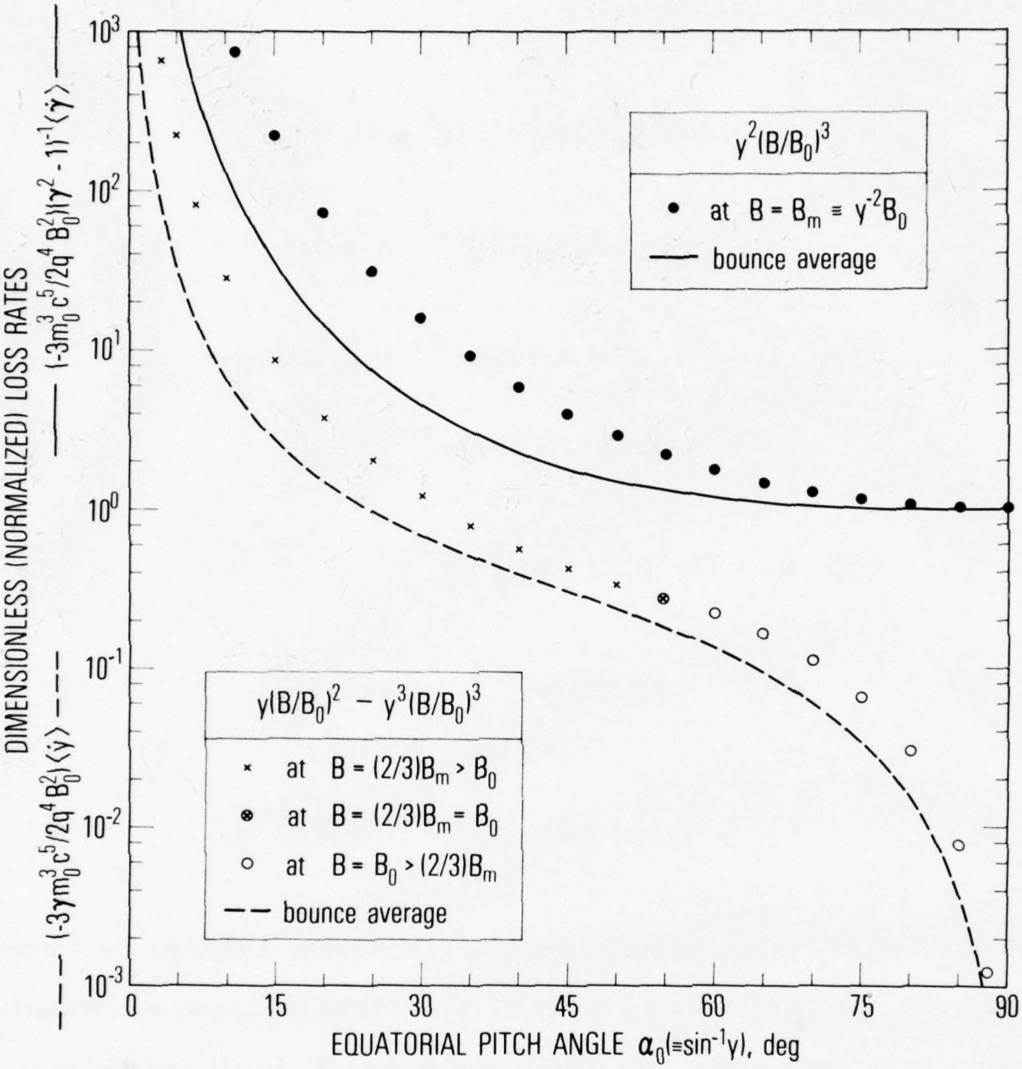

Fig. 14. Maximal Values ("data" points) and Bounce Averages (dashed and solid curves) of the Quantities $y(B/B_0)^2 - y^3(B/B_0)^3$ and $y^2(B/B_0)^3$, Which Are Proportional to the Loss Rates $\dot{y}$ and $\dot{\gamma}$, Respectively, Due to Synchrotron Radiation by Particles Trapped in a Dipolar Magnetic Field (Schulz, 1977)

In the absence of processes other than synchrotron emission, it is possible to derive from (1) and (2) a trajectory for γ as a function of y. If, for example, an electron had passed through $(\gamma, y) = (\gamma_0, y_0)$ at some (unspecified) time t, then its values of γ and y would be related at all other times by the formula

$$\gamma = \left\{1 - \left[(\gamma_0^2 - 1)/\gamma_0^2\right]\left[F(y_0)/F(y)\right]^2\right\}^{-1/2} \qquad (3)$$

where

$$F(y) \approx 0.2509y^{-13/4} - 0.1473y^{-3} + 0.1318y^{-1} - 0.2354y \qquad (4)$$

The function $F(y)$ is monotonic for $0 \le y \le 1$ and vanishes at $y = 1$. Thus, the value of y decreases monotonically with decreasing γ, and the end-point of the trajectory occurs at $y = 0$, $\gamma = 1$. Letting time run backwards indefinitely, one obtains an asymptotic (limiting) value of y ($= y_\infty$) as γ approaches infinity. Thus, the value of y_∞ serves to label the trajectory (γ versus y), and the equation of the trajectory can be written

$$\gamma = \left\{1 - \left[F(y_\infty)/F(y)\right]^2\right\}^{-1/2} \qquad (5)$$

Numerical evaluation of (5) reveals a change in α_0, *i.e.*, a difference between $\sin^{-1} y_\infty$ and $\sin^{-1} y$, of $< 0.2°$ between $\gamma = \infty$ and $\gamma = 6$, $< 0.5°$ between $\gamma = \infty$ and $\gamma = 4$, $< 1°$ between $\gamma = \infty$ and $\gamma = 3$, and $\leq 2°$ between $\gamma = \infty$ and $\gamma = 2$. Thus, it is approximately true that synchrotron radiation leaves α_0 unchanged for electron energies $E \gtrsim 3$ MeV. However, it follows from (1) that $\langle \dot{\gamma} \rangle$ is much larger (in absolute value) for small α_0 than for large α_0 (see Figure 14). Consequently, an isotropic Maxwellian electron distribution would develop a temporally increasing pitch-angle anisotropy as conventionally defined, i. e., when one scans the pitch-angle distribution at some specified (instantaneous) particle energy. Particles having $\alpha_0 = 30°$, for example, must have started with a higher energy in the initial distribution than particles now having the same energy but having $\alpha_0 = 90°$. The anisotropy created by synchrotron radiation thus resembles that created by inward radial diffusion (e. g., Schulz, 1975b). Both processes lead to a distribution that is strongly peaked at $\alpha_0 = 90°$ when particles of the same energy are compared.

Various observational aspects of Jovian decimetric radiation are described by Berge (1966, 1972), Berge and Gulkis (1976), Gerard (1975), Hide and Stannard (1976), Klein (1976), Stannard (1975), and Stannard and Conway (1976). Jupiter's decimetric emission offered a means of remotely observing the relativistic electron belt long before the arrival of Pioneer 10 and 11, but the importance of Jovian synchrotron radiation transcends our convenience. As an energy-loss mechanism for zenomagnetically trapped electrons, synchrotron radiation plays an essential role in the dynamics of the radiation belt itself.

6. RADIAL DIFFUSION

Radial diffusion (*i.e.*, diffusion across L) in the Earth's radiation belts is commonly attributed to a superposition of two processes: magnetic impulses and electrostatic impulses, both of magnetospheric extent. The respective diffusion coefficients are given in a certain model (*e.g.*, Schulz and Lanzerotti, 1974) by

$$D_{LL}^{(m)} \approx 2\,(\Omega_3/25)^2\, L^{10}\, (a/b)^2\, [Q(y)/180D(y)]^2 \times (G_1^0)^{-2}\, \mathcal{B}_z(\Omega_3/2\pi) \tag{6}$$

and

$$D_{LL}^{(e)} \approx 2(c/4aG_1^0)^2\, L^6\, \mathcal{E}_c(\Omega_3/2\pi) \tag{7}$$

where *a* is the planetary radius, *b* is the equatorial stand-off distance of the magnetopause from the center of the planet in the noon meridian, $a^3G_1^0$ is the magnetic dipole moment of the planet, $\Omega_3/2\pi$ is the (azimuthal) drift frequency of the particles under consideration, and c is the speed of light. The factor $[Q(y)/180D(y)]^2$ represents a function of the equatorial pitch angle $\alpha_0 \equiv \sin^{-1}y$ that varies monotonically from ~0.1 to 1.0 as y varies from 0 to 1 (*e.g.*, Schulz and Lanzerotti, 1974). The spectral densities $\mathcal{B}_z(\omega/2\pi)$ and $\mathcal{E}_c(\omega/2\pi)$ correspond to a uniform axial magnetic-field perturbation and an equatorially uniform electrostatic-field perturbation, respectively. Both are supposed to be evaluated at the particle drift frequency $\Omega_3/2\pi$. Both are commonly considered to vary as ω^{-2}, which is to say that the corresponding impulses are distributed randomly in time and resemble step functions on the drift time scale. In such a model the coefficient $D_{LL}^{(m)}$ is energy-independent and varies as L^{10}; the coefficient $D_{LL}^{(e)}$ bears the energy and L dependence of Ω_3^{-2}, along with the factor L^6. Thus, $D_{LL}^{(e)}$ varies roughly as $\gamma^2 y^4 L^{10}/M^2$ for particles in the Earth's magnetosphere under the assumptions described above, provided that $2\pi/\Omega_3 \ll 1$ day.

The Earth's rotation rate is inconsequential in (6) and (7) for particles of radiation-belt energy ($E \gtrsim L^{-1}$ MeV). Quite the opposite is true in the case of Jupiter, at which particles having $E \lesssim 0.1\ L^{-1}$ GeV all drift at approximately the rotation rate of the planet. For such particles one would expect $D_{LL}^{(e)}$ to vary as L^6 and bear no energy dependence at all. The energy dependence of $D_{LL}^{(e)}$ for $E \gtrsim 0.1\ L^{-1}$ GeV is complicated and species-dependent, since the gradient-curvature drift either augments (as in the case of positive ions) or opposes (as in the case of electrons) the angular velocity associated with Jupiter's rotation. (Gradient-curvature drifts at Jupiter are opposite to those at the Earth because the magnetic dipole moments of the two planets are roughly anti-parallel at the present epoch). An illustration of the complexity of particle drift motion (even at radiation-belt energies) in Jupiter's magnetosphere has been provided in Figure 11, above.

It turns out, when all is said and done, that neither $D_{LL}^{(m)}$ nor $D_{LL}^{(e)}$ is very important for $L \lesssim 10$ at Jupiter. Various methods have been tried for scaling $\mathcal{B}_z(\omega/2\pi)$ and $\mathcal{E}_c(\omega/2\pi)$ from the Earth to Jupiter, and in each case the magnitudes of $D_{LL}^{(m)}$ and $D_{LL}^{(e)}$ have been found wanting (Brice, 1972); diffusion caused by magnetospheric impulses is inadequate to account for the intensity and the spectrum of the observed decimetric radiation.

The alternative radial diffusion mechanism proposed by Brice (1972) involves the polarization electric field produced by neutral winds in Jupiter's ionosphere and mapped into the magnetosphere along equipotential magnetic field lines. It is the azimuthal (φ) component of such an electric field that would be important for radial diffusion. The rate-of-change of L seen by a radiation-belt particle would be given by

$$dL/dt = -(c/a^2 G_1^0)\, L^2 (\partial V/\partial \varphi) \tag{8}$$

where $V(L,\varphi;t)$ is the scalar potential from which the polarization electric field can be derived. If one assumes that E_φ ($\equiv -\underset{\sim}{\hat{\varphi}} \cdot \underset{\sim}{\nabla} V$) is substantially independent of θ (colatitude) in the ionosphere ($r \approx a$), then one concludes that $\partial V/\partial\varphi$ in (8) will vary as $\sin\theta$ there, i.e., as $L^{-1/2}$ everywhere. It would follow from this consideration that

$$D_{LL} \sim (c/aG_1^0)^2\, L^3\, \mathcal{E}_\varphi(\Omega_3/2\pi) \tag{9}$$

where $\mathcal{E}_\varphi(\omega/2\pi)$ is the spectrum of E_φ at ionospheric altitudes. For particles having kinetic energy $E \lesssim 0.1\ L^{-1}$ GeV this diffusion coefficient is proportional to L^3 and independent of particle energy (Brice and

McDonough, 1973; Coroniti, 1974; Jacques and Davis, 1972). For particles of higher energy, such as those represented in Figure 11 (b-f), the dependence of D_{LL} on energy, species, and L value would be more complicated than this.

It is especially important to recognize that a static polarization electric field (such as would be produced by a global atmospheric circulation pattern showing only the usual diurnal variation at any given zenographic coordinate corotating with Jupiter) would produce no radial diffusion. Such a configuration would yield no spectral intensity at the drift frequency, i. e., would yield $\mathcal{E}_{\varphi}(\Omega_3/2\pi) = 0$ in (9). One is relying on spatially correlated temporal fluctuations in the circulation pattern to produce D_{LL}. It is understandably difficult to estimate the magnitude of such a phenomenon. The best that one can do is postulate that the circulation velocity fluctuates globally by a certain percentage of itself every so often (e.g., by 100% of itself every Jovian day, on the average). This procedure enables one to estimate $\mathcal{E}_{\varphi}(\omega/2\pi)$ in terms of a model for the ionosphere and a model for the mean circulation. Coroniti (1974), for example, obtains $D_{LL} \sim 2 \times 10^{-10} L^3 \text{ sec}^{-1}$ as a reasonable estimate.

However the diffusion coefficient is ultimately determined, it must be inserted in the appropriate Fokker-Planck equation if one is to describe the consequences of radial diffusion quantitatively. The Fokker-Planck equation describes the evolution of $\bar{f}$, which is the canonical phase-space density averaged over gyration, bounce, and drift:

$$\frac{\partial \bar{f}}{\partial t} + \frac{1}{\gamma p}\frac{\partial}{\partial \gamma}\Big[\gamma p \langle \dot{\gamma} \rangle \bar{f}\Big]_{y,L} + \frac{1}{yT(y)}\frac{\partial}{\partial y}\Big[y\,T(y)\langle \dot{y} \rangle \bar{f}\Big]_{\gamma,L}$$

$$= L^2 \frac{\partial}{\partial L}\Big[L^{-2} D_{LL} \frac{\partial \bar{f}}{\partial L}\Big]_{M,J} + \frac{1}{y\,T(y)}\frac{\partial}{\partial y}\Big[y\,T(y)\, D_{yy} \frac{\partial \bar{f}}{\partial y}\Big]_{\gamma,L}$$

$$+ \bar{S} - \frac{\bar{f}}{\tau} \qquad (10)$$

where $T(y) \approx 1.3802 - 0.6397y^{3/4}$ (Davidson, 1976), where $p = (\gamma^2 - 1)^{1/2} m_0 c^2$ is the scalar momentum of the particle, and where τ is the lifetime against processes such as absorption by satellites and neutralization by charge exchange. The term involving $\langle \dot{\gamma} \rangle$ corresponds to synchrotron loss for electrons and Coulomb loss for both ions and electrons. The term involving D_{yy} corresponds to pitch-angle diffusion. The source term $\bar{S}$ corresponds to processes such as the radioactive decay of cosmic-ray-albedo neutrons (e.g., Thomas and Doherty, 1972) or the ionization of neutral sodium (e.g., Eviatar et al., 1978; Siscoe, 1977).

The Fokker-Planck equation is ordinarily solved in some model situation by setting $\partial\bar{f}/\partial t = 0$ and imposing appropriate boundary conditions. For example, Birmingham et al. (1974) set $D_{yy} = 0$, $\bar{S} = 0$, and $\tau = \infty$, imposed a phase-space density $\bar{f} = \delta(J)\delta(M - 769 \text{ MeV/G})$ at $L = 15$, and adjusted the two parameters D_1 and k in the postulated radial-diffusion coefficient $D_{LL} = D_1 L^k$. Their objective was to obtain a nonlinear least-squares fit between the observed equatorial decimetric radio emissivity distribution I at 10.4 cm (Berge, 1966) and that which would result (e.g., Beard and Luthey, 1973; Northrop and Birmingham, 1974) from the calculated $\bar{f}$ (without regard for overall normalization). The best fit was obtained for $D_1 = 1.7 \times 10^{-9}$ sec^{-1} and k = 1.95, i.e., for $D_{LL} = 1.7 \times 10^{-9} L^{1.95}$ sec^{-1}. The comparison between the observed and calculated emissivities in this case is shown in Figure 15 (Birmingham et al., 1974), and the corresponding forms of $\bar{f}$ at four selected values of M are shown in Figure 16. The curve for M = 769 MeV/G is monotonic for the usual reason, i.e., the model provides no source of particles (other than radial diffusion) for this contour at $L < 15$. The three contours representing $M \leq 432$ MeV/G need not be monotonic (and indeed, they are not) since these are continuously populated by the deceleration of electrons having larger values of M.

Stansberry and White (1974) carried out a similar study, using a Gaussian spectrum of first invariants at their outer boundary (L = 5) and comparing their results with observation at an additional wavelength (21.3 cm). By imposing k = 3, they found $D_{LL} \sim 10^{-9} L^3$ sec^{-1} as an optimal, but somewhat unsatisfactory, fit. They obtained a better fit by taking $D_{LL} \approx 1.2 \times 10^{-8} L^3$ sec^{-1} with $\tau = 3 \times 10^4 L^3$ sec in (10), and by depleting the source spectrum at very high and very low values of M.

A subsequent study by Hess et al. (1974) took explicit account of charged-particle absorption by Jupiter's moons as discrete entities. Using various forms of D_{LL} with $1.45 \leq k \leq 2.45$ and $D_1 = 1.2\text{-}2.2 \times 10^{-9}$

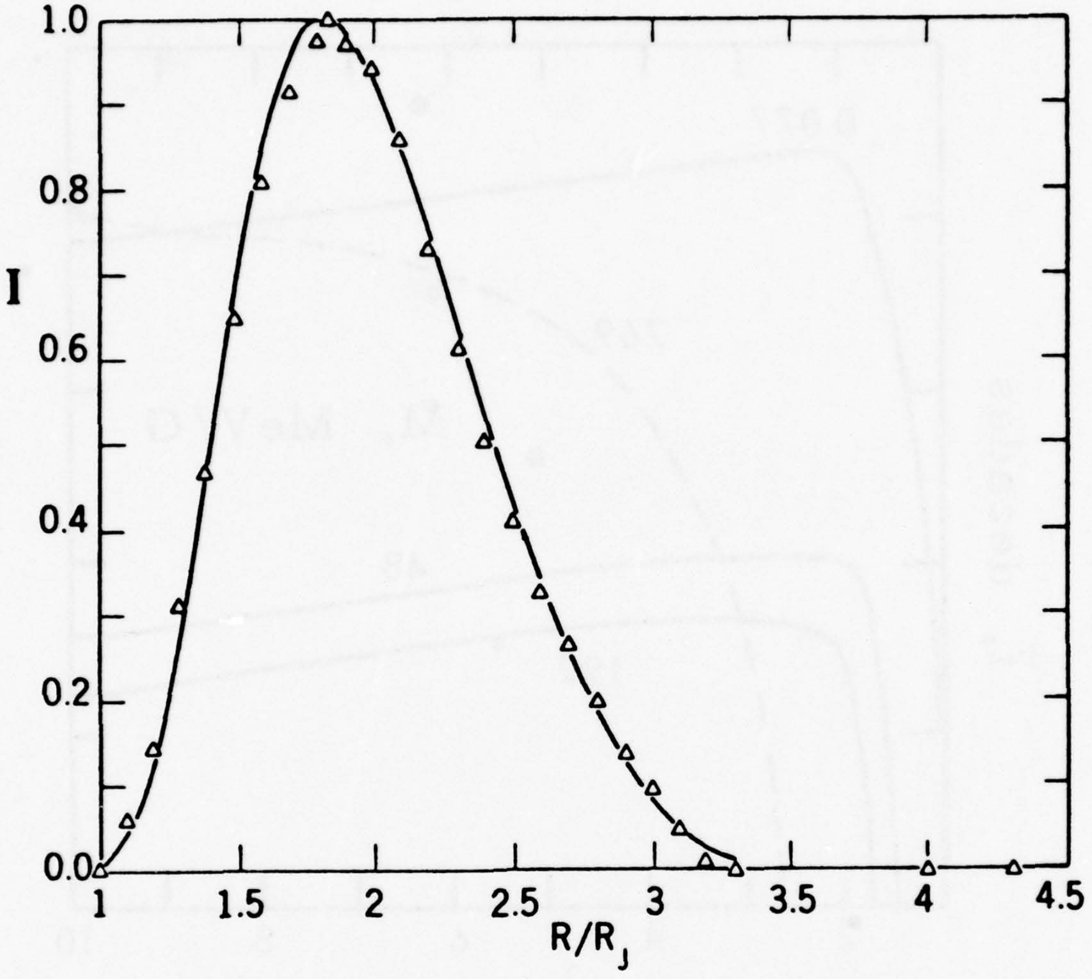

Fig. 15. Optimal Fit (Birmingham et al., 1974) of the Equatorial 10.4-cm Emissivity Profile (triangles) Obtained by Berge (1966)

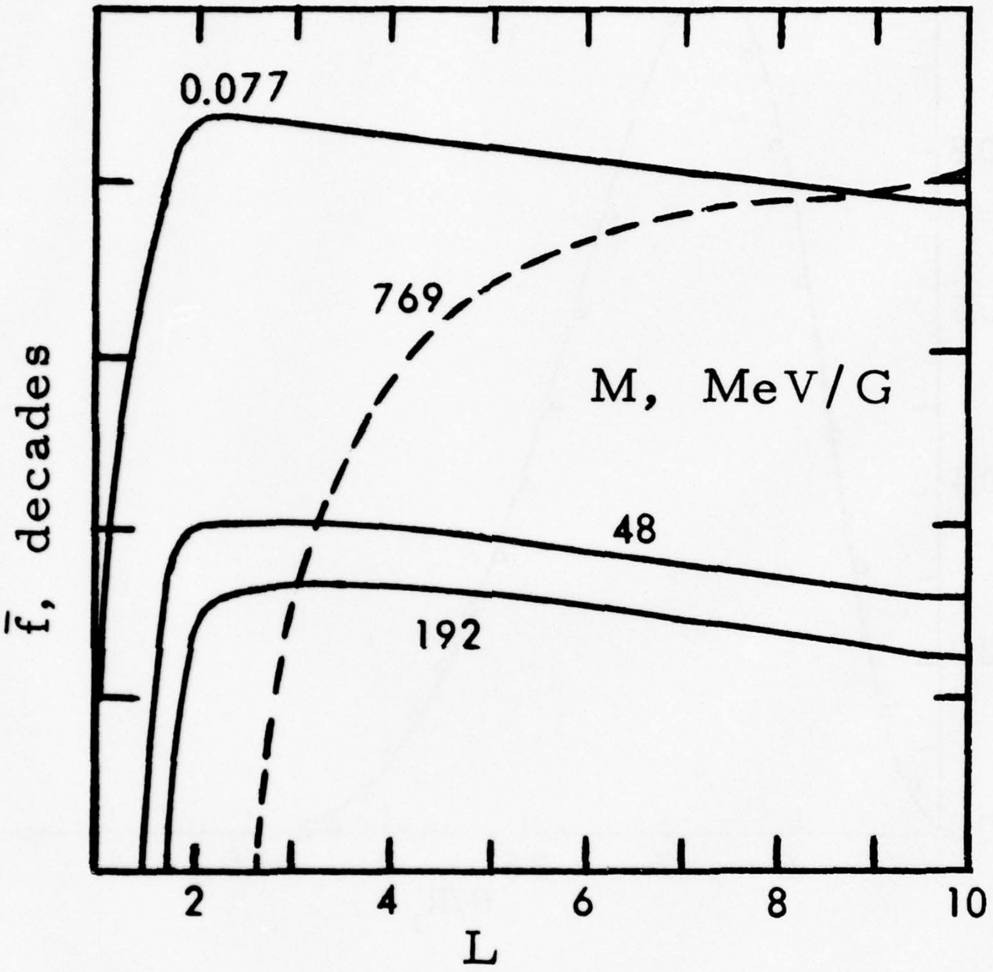

Fig. 16. Canonical Phase-Space Densities $\bar{f}$ (having units of $erg^{-3}\ sec^{-3}$) Derived from Results of Birmingham et al. (1974) That Optimally Fitted the Equatorial 10.4-cm Emissivity Profile (see Fig. 15)

$\sec^{-1}$, they found major reductions in $\bar{f}$ (about 1.5 orders of magnitude per encountered moon for $\alpha_0 < 69^\circ$) as compared with the case in which $\tau = \infty$. It seems that a much larger value of D_{LL} (perhaps $D_{LL} \sim 10^{-8} L^3 \sec^{-1}$) would have been required in order to account for the decimetric profile (Figure 15) in the face of particle absorption by Jupiter's moons (cf. Stansberry and White, 1974).

In analyzing the absorption of charged particles by Jovian satellites, it is essential to take literally the drift average that is implied in the writing of (10). Since the Pioneer data provide only isolated passes, one must discount any data obtained from the swath of the satellite itself (e.g., Thomsen et al., 1977b). One would expect the phase-space density to vary with φ (the azimuthal separation between the observer and the absorbing satellite) by virtue of the elementary processes that contribute to radial diffusion. However, one cannot calculate D_{LL} correctly without averaging the particle trajectory over many drift periods. Thus, the ability of particles to escape absorption may not be describable in terms of a diffusion coefficient and may (for example) depend somewhat on the phase of the moon relative to the general pattern of atmospheric circulation, as well as on the elementary step size characteristic of the random-walk process. In any event, the phase-space density inferred from an inbound or outbound pass of Pioneer 10 or 11 is not likely to agree with the drift-averaged value ($\bar{f}$) that is required in (10), except on adiabatic trajectories that have not intersected a satellite within the past drift period. These considerations cast doubt on estimates of D_{LL} (e.g., Mogro-Campero and Fillius, 1976) that rely on Pioneer data from drift shells that intersect the satellite. However, Thomsen et al. (1977a, b) have obtained $D_{LL} \sim 3 \times 10^{-8}$ sec^{-1} at L = 6 (assuming no pitch-angle diffusion) and $D_{LL} \leq 7 \times 10^{-7}$ sec^{-1} at L = 6 (assuming strong pitch-angle diffusion) solely from Pioneer data taken outside the swath of the satellite Io (which, in contrast to Figure 11, they model as a geometrical absorber that does not distort the adiabatic trajectories electrostatically). These values are compatible with having $D_{LL} = 2\text{-}40 \times 10^{-10} L^3$ sec^{-1}, the lower limit being in good agreement with the magnitude of D_{LL} proposed by Coroniti (1974) on the basis of totally different considerations.

It is necessary to mention at this point a radial-diffusion mechanism proposed by Nishida (1976), who argues that electric fields fluctuating at the bounce frequency of a particle and localized near its mirror point might violate the adiabatic invariance of both J and L while largely preserving the kinetic energy (E) of the particle. This might produce an outward diffusion current at $L \geq 3$, since (according to Figure 4, above) the quantity $-D_{LL}(\partial \bar{f}/\partial L)_{E,M}$ would seem to be postive there. Sentman et al. (1975) report having observed such a diffusion current, but the overall significance of this idea for the dynamics of Jupiter's radiation belts remains unclear.

It is interesting that the radial-diffusion mechanism of Brice and McDonough (1973), which seems to be the dominant one at Jupiter, may also be important in the Earth's magnetosphere at epochs of very small magnetic moment $G_1^0 a^3$ (Cornwall and Schulz, 1978) such as that which occurred ~6000 years ago. Using a certain model to scale $D_{\Phi\Phi}^{(m)}$ and $D_{\Phi\Phi}^{(e)}$, Schulz (1975a) found that both vary as $(G_1^0)^k$, where Φ is the third adiabatic invariant ($= 2\pi G_1^0 a^2/L$) and $5 < k < 6$. With a magnetic moment half as large as the present one, the Earth would see $D_{\Phi\Phi}^{(m)}$ and $D_{\Phi\Phi}^{(e)}$ reduced by factors ~50 for particles on a given drift shell (as identified by Φ). Other scaling laws, applicable either to interplanetary or to paleomagnetospheric considerations, are described by Siscoe (1978). The concept of paleomagnetospheric scaling is due to Siscoe and Chen (1975).

7. PITCH-ANGLE DIFFUSION

The term containing D_{yy} in (10) has played a rather uncertain role in Jovian radiation-belt theory because the magnitude of D_{yy} itself is so difficult to estimate from the available data. However, Fillius et al. (1976) have cleverly inverted the problem by using the observational data on $\bar{f}$, together with an estimate for D_{LL}, to evaluate all the other major terms in (10). They assumed, as usual, that $\partial\bar{f}/\partial t = \bar{S} = \bar{f}/\tau = 0$ for the energetic electrons and concluded that, since the synchrotron terms are insufficient to balance the radial-diffusion term on drift shells that are not swept by the satellites, the pitch-angle diffusion term must be very important. However, they found that the particle lifetimes associated with pitch-angle diffusion are far longer than the minimal "strong-diffusion" lifetimes that would apply if D_{yy} were large enough to transport the average particle across the entire loss cone in half a bounce period. The term that represents pitch-angle diffusion in (10) would have to be modified in the case of strong diffusion, since the underlying concept of a bounce-averaged $\bar{f}$ would have been violated.

Using a very similar method, Baker and Goertz (1976) concluded that pitch-angle diffusion is very significant for electrons in regions where neither synchrotron loss nor particle absorption by satellites is at all important. In other words, Baker and Goertz (1976) found that the radial diffusion current had a nonvanishing divergence with respect to L for reasonable values of k in the coefficient $D_{LL} = D_1 L^k$. They favored cyclotron resonance with whistler-mode waves as a likely mechanism for pitch-angle diffusion. Various authors (Scarf, 1976; Scarf and Sanders, 1976; Sentman and Van Allen, 1976; Van Allen, 1976) have shown that the pitch-angle distributions of electrons having $E > 21$ MeV at $L < 7$ were compatible with such a concept.

Other approaches to pitch-angle diffusion at Jupiter have been largely theoretical. Brice (1972) immediately recognized that zenomagnetically trapped protons are susceptible to the electromagnetic ion-cyclotron instability that is associated with pitch-angle anisotropy. Since this is a convective instability in a bounded medium with imperfect wave reflection from the boundaries, it has the effect of limiting the Jovian energetic proton flux to a certain value, viz., $\sim 3 \times 10^9/L^4$ cm^{-2} sec^{-1} (Kennel, 1972) at energies above the usual threshold $\sim B^2/8\pi N$, where N is the cold-plasma density. These considerations are fully analogous to those that led Kennel and Petschek (1966) to propose a limit $\sim 7 \times 10^{10}/L^4$ cm^{-2} sec^{-1} on the flux of geomagnetically trapped electrons.

The instability calculation of Kennel and Petschek (1966) was non-relativistic). Barbosa and Coroniti (1976) performed an analogous (but relativistic) calculation of the stable-trapping limit for a spectrum typical of Jovian radiation-belt electrons. They obtained a limit $\sim 4 \times 10^{10}/L^4$ cm^{-2} sec^{-1}, which is surprisingly similar to the nonrelativistic result.

One expects strong pitch-angle diffusion to occur whenever the actual flux exceeds the limiting flux by a factor $\gtrsim 2$. In this limit the particle lifetime becomes independent of D_{yy} and approaches a value

$\sim (\pi/\alpha_c^2)\tau_B$, where α_c is the half-angle of the equatorial loss cone and τ_B is the full bounce period of the particle having α_c as its equatorial pitch angle. However, the strong-diffusion lifetime is so short that the actual flux can hardly ever exceed twice the stable-trapping limit. Pitch-angle diffusion inferred from the stable-trapping limit plays an essential role in the Jovian radiation-belt model of Thorne and Coroniti (1972) and in the various refinements thereof (Coroniti, 1974; 1975).

8. PARTICLE PRECIPITATION AND RELATED PHENOMENA

Pitch-angle diffusion results in a net transport of particles from trapped trajectories into the loss cone, and particles in the loss cone are doomed to deposit their energy in Jupiter's ionosphere or atmosphere within half a bounce period. Heaps (1976) has determined that such precipitation of already energetic particles into Jupiter's atmosphere may contribute significantly to the heating of the atmosphere. This would be in addition to the atmospheric heating produced by the absorption of solar EUV (extreme ultraviolet) radiation and by the upward convection of heat from Jupiter's interior. One heating mechanism that seems to have major global significance for the Earth but not for Jupiter is the Joule dissipation of ionospheric currents driven by magnetospheric electric fields (Heaps, 1976). However, one must also consider (for both planets) the currents driven by neutral winds transverse to $\mathbf{B}$ in a collisional ionosphere. As has been noted above, the polarization resulting from such currents ultimately provides the dominant mechanism for radial diffusion in Jupiter's magnetospheric radiation belts.

In addition to the diffuse precipitation attributed to pitch-angle scattering (e.g., by electromagnetic waves resonant with trapped particles), one must consider the very localized acceleration of particles along magnetic-field lines by the parallel (to $\mathbf{B}$) component of a magnetospheric electric field. In the Earth's magnetosphere one finds $\mathbf{E}\cdot\hat{\mathbf{B}}$ to be significant only in auroral arcs, where the resulting electron acceleration and precipitation can lead to significant x-ray production. X-ray data from

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the Uhuru (Hurley, 1975) and Copernicus (Vesecky *et al.*, 1975) satellites in Earth orbit fail to show an analogous x-ray flux that ought to be emitted from Jupiter; perhaps the instrumental sensitivity on Uhuru and Copernicus is insufficient, or perhaps Jupiter does not emit as large an x-ray flux as one might expect.

However, Jupiter is known to be a strong emitter of decametric (~30-MHz) radiation (*e.g.*, Carr and Desch, 1976), and much of this emission seems to be a consequence of the electrodynamic properties of Jupiter's satellite Io (Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969; Smith, 1976). Most theories of the Io-associated decametric radiation entail the flow of current parallel to $\mathbf{B}$ along the surface of Io's magnetic flux tube and through the Jovian ionosphere. The "sheath" model of Shawhan *et al.* (1975) leads to a substantial component of electric field parallel to $\mathbf{B}$ along the surface of Io's flux tube, and hence to an acceleration of particles somewhat analogous to that which accurs in terrestrial auroral arcs (see Figure 12, above). However, the Io-associated Jovian decametric radiation is confined not only in latitude (as is the aurora) but also in longitude, *i.e.*, is confined to the feet of the flux tube that contains Io.

In addition to the Io-associated decametric emission, there exists an Io-independent decametric emission that seems to be associated with specific locations on the planet Jupiter (*e.g.*, Michaux, 1967; Bozyan and Douglas, 1976; Carr and Desch, 1976). This latter emission shows a very consistent period of about 595.495 min (irrespective of Jovian latitude) and forms the basis for defining that which is known as

System III longitude (λ_{III}). Magnetospheric physicists must make a special effort to remember that λ_{III} is measured westward from its origin. Secular variations of Jupiter's apparent magnetic rotation rate and/or improvements in the observational data require that the definition of System III be updated from time to time (Riddle and Warwick, 1976).

It is interesting to note that System III longitude, which is based on radio observations and hence (implicitly) on magnetic geometry, shows no evidence of the differential (latitude-dependent) rotation that is inferred from visual observations of Jupiter. Similarly, one might say, the interplanetary magnetic field and its "sector" structure (being derived from the large-scale magnetic field of the Sun) show no evidence of the differential rotation that is seen in visual observations of sunspots (which correspond to small-scale magnetic features on the Sun). By the same token, those who observe only the clouds would infer differential rotation for the Earth and Venus, whereas radio observers would contradict such a finding. The point of this digression is to emphasize that an object in the solar system may show differential rotation in certain physical features, but not necessarily in others.

9. MAGNETOSPHERIC CONFIGURATION

Much has been written about the shape and the interior structure of the Jovian magnetosphere. A review is given by Goertz (1976b). On the basis of Pioneer-11 data, it now seems clear that the nose of Jupiter's magnetospause is blunt, like the nose of the Earth's. However, the magnetosphere of Jupiter seems to contain a discus-shaped substructure of closed field lines (*e.g.*, Van Allen *et al.*, 1974a) known as the magnetodisk. Barish and Smith (1975) and Beard and Jackson (1976) have constructed semi-empirical models of such a magnetospheric configuration. The magnetodisk differs conceptually from the Earth's ring-current zone, which is likewise a region of distended field lines (reduced component of $\mathbf{B}$ normal to the magnetic equator; enhanced component of $\mathbf{B}$ parallel to the magnetic equator). The terrestrial case corresponds to a diamagnetic hot-plasma effect. The Jovian case possibly corresponds to the effects of a centrifugal force, *i.e.*, to a current density

$$\mathbf{J} = (\rho c/B^2)\,[(\boldsymbol{\Omega}\cdot\mathbf{B})\,(\boldsymbol{\Omega}\times\mathbf{r}) - \boldsymbol{\Omega}\,(\boldsymbol{\Omega}\times\mathbf{r})\cdot\mathbf{B}], \qquad (11)$$

where ρ is the mass density of the plasma, $\boldsymbol{\Omega}$ is the angular velocity of Jupiter, and c is the speed of light. Gleeson and Axford (1976) have augmented (11) with currents resulting from gravitational and pressure-gradient drifts and have thereby obtained an analytical model for $\mathbf{B}$ in the axisymmetric case. Goertz (1976a) has conducted a similar study of the tilted-dipole case (which is not axisymmetric) and has thereby illustrated a major distinction between diamagnetic (hot-plasma) and centrifugal (cold-plasma) effects. If one defines the magnetic equator as the minimum-B surface, *i. e.*, as the set of points where $\hat{\mathbf{B}} \cdot \boldsymbol{\nabla} B = 0$ and $\hat{\mathbf{B}} \cdot \boldsymbol{\nabla}(\hat{\mathbf{B}} \cdot \boldsymbol{\nabla} B) > 0$, then one finds the magnetic equator asymptotically perpendicular to the dipole axis in the diamagnetic case but asymptotically perpendicular to the rotation axis in the centrifugal case. Of course, the magnetic equator essentially coincides with the dipole equator in the inner magnetosphere, and the consequence of the possible asymptotic distinction for Jupiter is a corotating warp in the magnetic equator (Smith *et al.*, 1974b; Hill *et al.*, 1974a).

Some observational evidence for the Jovian magnetodisk is shown in Figure 17 (McKibben and Simpson, 1974). Very obvious minima in the magnetic field recur with about a 10-hour periodicity (especially on Days 339-342), and these are coincident with *maxima* in the energetic electron flux. The other Pioneer-10 investigators found the same anti-correlation between B and particle flux in Jupiter's outer magnetosphere and the same dominant periodicity ~ 10 hr (Fillius and McIlwain, 1974a; Simpson *et al.*, 1974a; Trainor *et al.*, 1974a; Van Allen *et al.*, 1974a). This does not mean that the energetic electrons are responsible for creating the minimum in B (as by diamagnetic effects), but only that they have the customary form of equatorial pitch-angle distribution (*i. e.*, peaked at $\alpha_0 = 90^\circ$. For example, an equatorial pitch-angle distribution of the form $\sin^{2n} \alpha_0$ corresponds to an off-equatorial intensity proportional

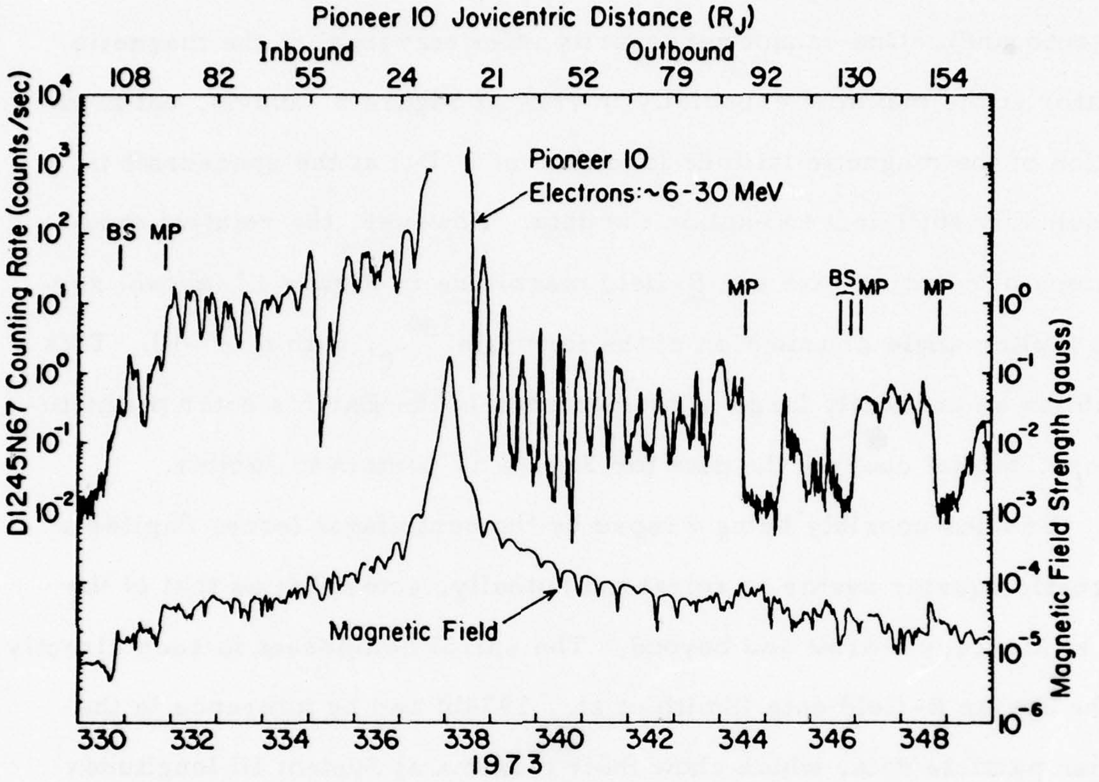

Fig. 17. Comparison (McKibben and Simpson, 1974) of Electron Intensity (Simpson et al., 1974a) with Magnetic-Field Magnitude (Smith et al., 1974a) from Pioneer 10 Data

to $(B_0/B)^n$, where B_0 is the equatorial field strength. Proton and electron data from Pioneer 11 are shown in Figure 18 (Simpson et al., 1975a). Both intensities are modulated (in phase with each other) at the Jovian rotation period ~ 10 hr (Days 335-336 inbound and Days 338-339 outbound). One cannot necessarily infer traversal of the magnetic equator at the maxima (especially in view of Figure 3, above), but modulation of the magnetic latitude (and thus of B/B_0) at the spacecraft is presumably sufficient to explain the data. However, the relative modulations of counting rate and $\mathbf{B}$-field magnitude in Figure 17 (above) suggest a pitch-angle distribution of the form $\sin^{2n} \alpha_0$, with n ~ 5-10. This would be an unusually large n for electrons in the Earth's outer magnetosphere, but (of course) the data for Figure 17 pertain to Jupiter.

Besides possibly being wraped by the centrifugal force, Jupiter's magnetic equator seems to spiral azimuthally, somewhat as that of the Sun at Mercury's orbit and beyond. The spiral component is seen directly in the Jovian $\mathbf{B}$-field data (Smith et al., 1974b) and by inference in the Jovian particle data, which show their maxima at System III longitudes λ_{III} (see above) substantially different from those of Jupiter's magnetic poles (Van Allen et al., 1974b). The observed spiral has generally been attributed to the radial outflow of plasma (analogous to the stellar wind of a pulsar), to a propagating MHD disturbance emitted by the oblique rotation of Jupiter's magnetodisk, to rotational dissipation at the Jovian magnetopause or ionosphere, or to a combination of the above phenomena (e.g., Northrop et al., 1974; Kennel and Coroniti, 1975; Kivelson et al., 1977). The current sheet and the azimuthal component of $\mathbf{B}$ would help

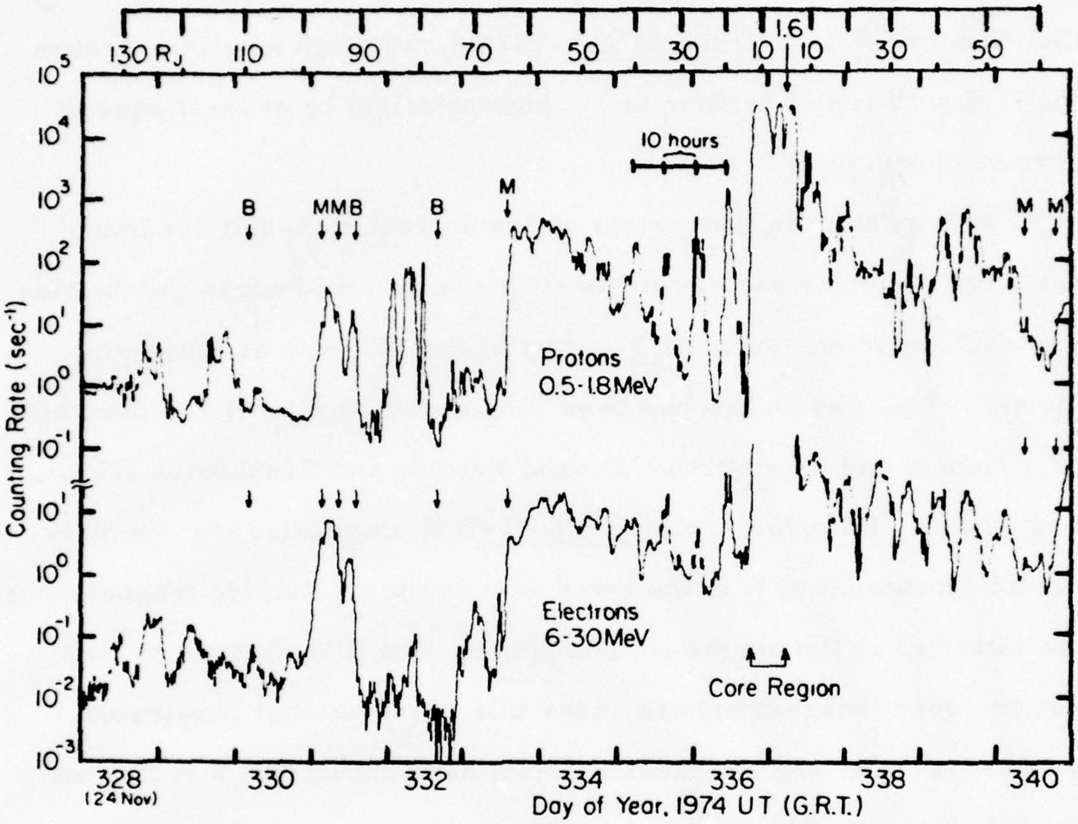

Fig. 18. Comparison of Proton and Electron Time-Intensity Profiles from Pioneer 11 Data (Simpson et al., 1975a), Showing Positive Correlation

to account for the observationally weak (Smith *et al.*, 1974b) variation of $|\mathbf{B}|$ in Jupiter's outer magnetosphere. The weakness of the variation of $|\mathbf{B}|$ with r helps to account for the identification of magnetopause crossings at such widely varying zenocentric distances ($r \sim 50\text{-}100\ R_J$) in the Pioneer-10 data (Smith *et al.*, 1974b), although kinetic pressure associated with radial outflow or hot plasma might be at least equally important (Smith *et al.*, 1974a).

It is important in the context of Jovian radiation-belt dynamics to determine whether radial outflow (if present) would cause the dayside magnetosphere to be "open" (*i.e.*, part of the tail even at equatorial latitudes). This possibility has been considered by Michel and Sturrock (1974), Kennel and Coroniti (1975), and Eviatar and Ershkovich (1976), among others. However, Smith *et al.* (1976b) emphasize that the predominant component of $\mathbf{B}$ in the outer part Jupiter's dayside magnetosphere at low latitudes is the southward component, and it is difficult to construct an "open" magnetosphere under this observational constraint. Moreover, Eviatar and Ershkovich (1976) have shown that a radial outflow faster than the Alfvén speed is not especially consistent with the plasma-density data of Wolfe *et al.* (1974b).

The above considerations, as well as the observation of zenomagnetically trapped particles in Jupiter's outer magnetosphere on the day side (see Figures 17-18), make the "closed" dayside magnetosphere (Brice and Ioannidis, 1970; Hill *et al.*, 1974a) quite appealing. Of course, it is entirely possible for such a magnetosphere to be "open" on the night side and even to have a polar wind (Hill *et al.*, 1974a). Moreover, the open field lines that carry the polar wind can extend to fairly low latitudes (but not to the equator) on the dayside before being swept back into the tail (Goertz et al., 1976). In other words, the topology of Jupiter's magnetosphere may well resemble that of the Earth's .

In constructing a theoretical model of Jupiter's radiation belts, it is important to know where in L the boundary of stable trapping (triply adiabatic motion) is. This is the boundary at which the source spectrum (perhaps that of the shocked solar wind) must be imposed. It is presumed that trapped particles can gain more energy by inward radial diffusion in a "closed" magnetosphere than in an "open" one.

It is not at all certain, however, that the topological configuration of Jupiter's magnetosphere is permanent. It has been suggested (Coroniti and Kennel, 1977; Kennel and Coroniti, 1977) that variations in either the dynamical pressure of the solar wind or the interplanetary magnetic field could lead to transitions between the "open" and "closed" topologies, or at least reverse the inequality between the velocity of radial outflow and the Alfvén speed. Eviatar et al. (1978) have suggested that similar effects might result from changes in the material composition of the toroidal cloud of gas that surrounds the orbit of Io. It seems that this nebula consists of sodium part of the time and of sulfur part of the time, but never of a sodium-sulfur mixture (e.g., Mekler et al., 1977). Hill et al. (1974b) have suggested that azimuthal asymmetries in the Jovian ionosphere or main magnetic field might propagate to the magnetopause and thereby alter the magnetospheric topology with each rotation of Jupiter.

The controversy over the shape of Jupiter's outer magnetosphere has no parallel in the inner magnetosphere. It is agreed (Acuña and Ness, 1976a, b, c; Smith *et al.*, 1974a, b; 1975; 1976b; Davis and Smith, 1976) that the main $\mathbf{B}$ field of Jupiter is substantially dipolar, and that the fractional surface contribution from higher multipoles is at most twice that found for the Earth. A suggestion that higher harmonics contributed far more substantially than this at the surface of Jupiter (Acuña and Ness, 1975) had been based on preliminary calibration of the fluxgate magnetometer (see Table 2). The simplicity of Jupiter's main field allows one to trace the adiabatic trajectories of charged particles by means of numerical codes commonly used for studying the Earth's radiation belts (Roederer *et al.*, 1977). One does not have to worry about isolated magnetic equators and interior neutral points (such as might occur in the solar corona) when tracing the paths of zenomagnetically trapped particles.

Jupiter's magnetic field is subject to localized distortion by field-aligned currents, such as those associated with discrete auroral arcs in the Earth's magnetosphere. Additional currents in Jupiter's magnetosphere are presumed (*e.g.*, Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969; Hubbard *et al.*, 1974; Shawhan, 1976) to flow parallel to $\mathbf{B}$ on the surface of the satellite Io's magnetic flux tube. Kivelson and Winge (1976) have reported evidence (in the form of an azimuthal perturbation of Jupiter's $\mathbf{B}$ field at the L value and longitude of Ganymede) that similar currents flow parallel to $\mathbf{B}$ along the surface of Ganymede's magnetic flux tube.

The magnetospheric configuration and certain density-sensitive instabilities (e.g., Kennel and Petschek, 1966; Barbosa and Coroniti, 1976; Cornwall, 1976) are contingent on the distribution of thermal plasma in Jupiter's magnetosphere. Results of the Pioneer 10-11 plasma analyzer, which measures the densities and energy spectra of protons (0.1-18 keV) and electrons (1-500 eV) by electrostatic deflection into collectors, have been reported by Wolfe et al. (1974a, b), Mihalov et al. (1975), Wolfe (1975), Intriligator (1975a, b), and Intriligator and Wolfe (1974, 1976, 1977). The major conclusions derived from these results are summarized by Intriligator and Wolfe (1976, 1977). It seems from the data that Jupiter has a 100-eV plasmasphere with proton densities $\sim 50\text{-}100\ \text{cm}^{-3}$ at $L \lesssim 6$. It seems to have a well-defined plasmapause at $L \approx 6$ and a 400-eV ring current ($N_p \sim 10\text{-}15\ \text{cm}^{-3}$) that extends from $L \approx 8$ to $L \approx 12$ and merges with an equatorially confined 400-eV plasma sheet ($N_p \sim 1\ \text{cm}^{-3}$) that extends in an annulus from $L \approx 12$ to the magnetopause. Moreover, the plasma-sheet particles (especially electrons) seem, on the basis of the observations, to provide most of the pressure that is required to stand off the solar wind at the magnetopause. This conclusion would be consistent with the finding of Smith et al. (1974a) that the value of $|\underset{\sim}{B}|$ just inside Jupiter's magnetosphere seemed too small (by a factor ~ 2).

Data from the Pioneer plasma analyzer are subject to more than one interpretation, however. Grard et al. (1977) suggest that the low-energy electrons observed in Jupiter's outer magnetosphere might actually have been photo-electrons and/or secondary electrons from the spacecraft surfaces. Intriligator and Wolfe (1977) doubt this, since the electrons attributed by them to the plasma sheet have the spatial distribution and spectral characteristics that would be appropriate to plasma-sheet electrons. Neugebauer and Eviatar (1976) find the occurrence of a kinematical "plasmapause" at $L \approx 6$ theoretically puzzling (as indeed it is for Jupiter), and suggest that the reported density decrease there could mean that the satellite Io is a major source of Jovian plasma. They argue that the orientation of the plasma analyzer on Pioneer 10 would have made it difficult to observe ions that had reached $L > 6$ by outward radial diffusion from an Io-associated source.

As a blunt object immersed in a high-speed plasma flow (i.e., in the solar wind), the magnetosphere of Jupiter would be expected to have a detached bow shock. This was seen in the thermal-plasma data (e.g., Wolfe et al., 1974a). It was of interest to examine in detail the plasma found in the magnetosheath, i.e., in the region between the upstream bow shock and the magnetopause, since some of this plasma might ultimately find its way into the Jovian radiation belts after capture by the outer zenomagnetic field and transport via radial diffusion. Mihalov et al. (1976) found magnetosheath proton distributions to be Maxwellian ($T \sim 150$ eV) much of the time, but not always.

10. RADIATION-BELT MODELS

A radiation-belt model is an algorithm for generating a number that corresponds to a selected point in phase space. The number is usually called the differential unidirectional flux of some particle species. If the number generated by the algorithm agrees with the actual flux at the specified point in phase space, so much the better. If not, then at least the model constituted a basis for designing the spacecraft.

Models of the Earth's radiation belts ordinarily consist of functional fits to observational data. Models of Jupiter's radiation belts preceding the Pioneer encounters were based on a variety of considerations. Many were based in some way on radio observations (*e.g.*, Chang and Davis, 1962; Warwick, 1972; Haffner, 1972; Luthey, 1972; Beard, 1972). Others were based mainly on the concept of a maximum stably trapped particle flux (*e.g.*, Klopp, 1972; Brice, 1972; Kennel, 1972; Neubauer, 1972). Still others were based on compilations of other models (*e.g.*, Divine, 1972; Beck, 1972). However, there gradually evolved a model that incorporated all the various dynamical processes believed to be important (Thorne and Coroniti, 1972; Coroniti, 1974, 1975). This is the model summarized (for electrons) in Figure 19 (Coroniti, 1975). The threshold energy above which the unstable whistler mode imposes a limit on stably trapped electron flux ($L \approx 6-20$ in Figure 19) varies inversely with the cold-plasma density (Kennel and Petschek, 1966). However, this had been modeled for Jupiter by Ioannidis and Brice (1971).

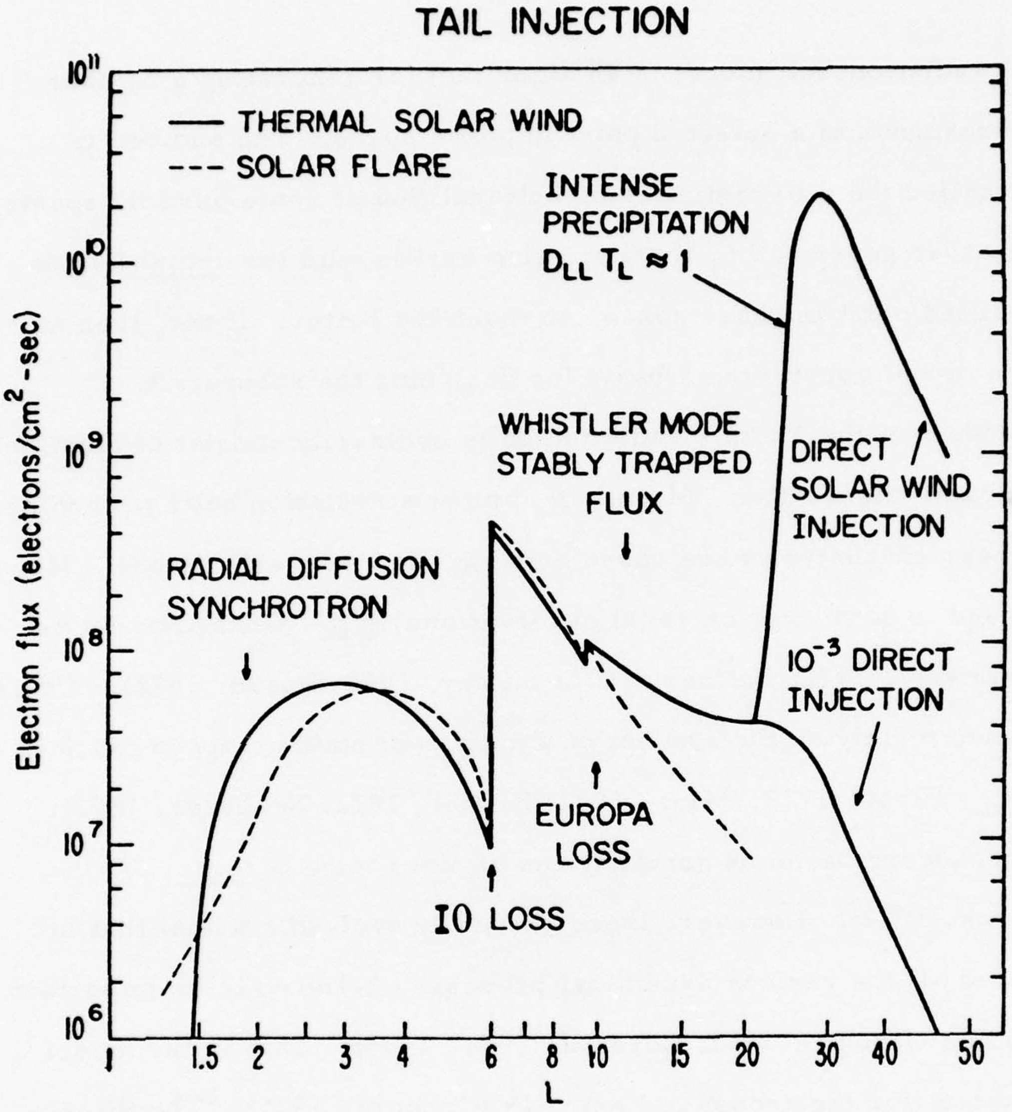

Fig. 19. Summary (Coroniti, 1975) of a Comprehensive Theoretical Model (Coroniti, 1974) of Jupiter's Electron Radiation Belt That Shows the Domains Within Which the Various Physical Processes Are Important

Figure 19 constitutes a good summary of the dynamical considerations that enter a serious analysis of Jupiter's radiation belts. One must have a source of particles, *e.g.*, the shocked solar wind. There must be radial diffusion, which for $L \leq 10$ is driven by the mechanism of Brice and McDonough (1973); radial diffusion at $L \gtrsim 10$ may well be driven by the mechanisms that dominate throughout the Earth's magnetosphere (*e.g.*, Schulz and Lanzerotti, 1974). There will be strong pitch-angle diffusion (and consequently intense precipitation) where the divergence of the diffusion current is comparable to the maximum possible (strong-diffusion) loss rate. There will be weak pitch-angle diffusion where this is sufficient to maintain the particle flux at the limit of stable trapping (Kennel and Petschek, 1966; Barbosa and Coroniti, 1976). There will be satellite effects, possibly involving depletion of the radiation belts by direct absorption. Finally, in the case of electrons, there will be energy loss via synchrotron radiation. Figure 19 illustrates these effects rather nicely. It also agrees remarkabley well with the Pioneer 10 data, except perhaps that actual absorption of radiation-belt electrons by Io and Europa is weaker than the model implies (Coroniti, 1975).

11. INTERPLANETARY PARTICLES

The Jovian magnetosphere seems to be a source for energetic particles that have long been observed in interplanetary space, even at 1 AU. The strange feature characteristic of low-energy (E ~ 1-6 MeV) electrons at 1 AU had been the recurrence of sporadic strong enhancements of their intensity about every 13 months (e.g., Mewaldt et al., 1976). The origin of this strange periodicity became evident with the approach of Pioneer 10 to Jupiter. Strong electron enhancements were found whenever the spacecraft and Jupiter's magnetosphere were most likely connected by the spiral path of an interplanetary magnetic field line (Teegarden et al., 1974). Moreover, when the spacecraft was within ~1 AU of Jupiter, such enhancements were found to be modulated at Jupiter's rotation period (Chenette et al., 1974; 1975). The same pattern held for Pioneer 11. Thus, it was natural to extrapolate the association between Jupiter's magnetosphere and interplanetary electrons to satellites in Earth orbit. Following this latter suggestion by Teegarden et al. (1974), the Jovian origin of interplanetary electron enhancements was confirmed by careful analysis of data from terrestrial satellites (Krimigis et al., 1975; Mewaldt et al., 1976). Indeed, it was found that enhancements were concentrated in those months during which Jupiter and the Earth were most probably connected by an interplanetary field line if one postulated a reasonable solar-wind velocity. Since the solar-wind velocity at 1 AU varies with time, such enhancements are necessarily sporadic (cf. Krimigis et al., 1975).

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Smith et al. (1976a) used actual B-field data from Pioneer 10 (rather than an assumed solar-wind velocity) to connect the electron bursts observed at Pioneer 10 with the Jovian magnetosphere. Moreover, they discovered that MHD waves with periods ~10 min were strongly associated with this connection to Jupiter and with the electron bursts. Since the bow shock itself is a standing MHD wave, one should not expect to find MHD waves upstream of it unless these were generated by fast particles, e.g., the upstream electrons having E ~ 1-6 MeV. This latter mechanism, i.e., the beam-cyclotron instability, is the one favored by Smith et al. (1976a) to account for their upstream observation of MHD waves.

Following the observations by Chenette et al. (1974, 1975) and Teegarden et al. (1974), attention naturally turned to finding the mechanism responsible for producing the upstream electrons. Hill et al. (1974b), Hill and Dessler (1976a), Dessler and Hill (1975), and Carbary et al. (1976) seem to favor the periodic escape of Jovian radiation-belt electrons at some preferred hour of the Jovian day, as determined by high-order magnetic multipoles in Jupiter's main field (Dessler and Hill, 1975). This view is somewhat difficult ot reconcile with the magnetometer observations (e.g., Smith et al., 1976b; Acuña and Ness, 1976b), which suggest that high-order multipoles are only slightly more important for Jupiter's magnetospheric configuration than for the Earth's (see above). The above ideas of Dessler, Hill, and Carbary produced some commentary in the literature on other grounds as well (Goertz, 1976c; Hill and Dessler, 1976b), but the issues are too complicated to be discussed here. Vasyliunas (1975), however made the interesting point that interplanetary electrons of Jovian origin have their minimum intensity and softest spectrum when the subsolar longitude λ_{III} on Jupiter is that which corresponds to the most frequent decametric radio emissions (among those not associated with Io). This suggests that a special λ_{III} may well be responsible for the emission of Jovian electrons, as Hill et al. (1974b) have proposed. Pesses and Goertz (1976) have traced the origin of interplanetary electrons specifically to the tail of Jupiter's magnetosphere, but without commenting on the 10-hour periodicity. Mewaldt et al. (1976) had reached the same conclusion independently.

It is by now widely acknowledged that, while the low-energy (E ~ 1-6 MeV) interplanetary electrons at 1 AU show the temporal variation that connects them with Jupiter via the interplanetary $\underset{\sim}{B}$ field, interplanetary electrons at least up to ~ 30 MeV also have their source at Jupiter. The higher-energy electrons presumably suffer enhanced interplanetary diffusion on account of (a) their larger gyro-radii and (b) their ability to cyclotron-resonate with longer-wavelength interplanetary disturbances. As a result, the higher-energy electrons are not well localized in heliomagnetic longitude relative to the Sun-Jupiter field line. Jokipii (1976), however, treats interplanetary diffusion as a random-walk of field lines rather than in terms of cyclotron resonance. Finally, Pizzella (1975) asks the provocative question: Is Jupiter the cosmic-ray source in our solar system?

12. DISCUSSION

The voyages of Pioneer 10 and Pioneer 11 have provided a wealth of scientific data on the radiation belts of Jupiter while leaving intact most of the major theoretical ideas that preceded the encounters. There are major similarities between terrestrial and Jovian radiation-belt dynamics, e.g., the importance of inward radial diffusion from an external source of charged particles, the importance of both weak and strong limits of pitch-angle diffusion by unstable electromagnetic waves, and the importance of the magnetospheric configuration in defining adiabatically invariant coordinates for the mapping of trapped-particle distributions. There are also major differences between terrestrial and Jovian radiation-belt dynamics, e.g., the importance of synchrotron radiation in the dynamics of Jovian radiation-belt electrons, the unimportance of terrestrial mechanisms for radial diffusion in Jupiter's magnetosphere at $L \lesssim 10$, and the presence of Jovian satellites (as sources or sinks for trapped radiation) within Jupiter's magnetosphere.

The exploration of Jupiter's magnetosphere by the Pioneer spacecraft has stimulated much thought on the topic of comparative planetary and pulsar magnetospheres (e.g., Hill and Michel, 1975; Kennel and Coroniti, 1975; Prakash and Brice, 1975; Scarf, 1975; Gold, 1976; Warwick, 1976; Siscoe, 1978) as well as on the comparative plasma environments and wave-emission characteristics of the Earth and Jupiter (e.g., Scarf, 1976; Jones, 1977) and on the origin of planetary magnetic fields (e.g., Hide, 1975; Hide and Stannard, 1976; Warwick, 1976). In this sense the great success of the Pioneer missions to

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Jupiter whets our appetite for data from Saturn and beyond.

However, there is much that also remains to be done, both observationally and theoretically, with respect to the study of Jupiter's radiation belts. The two Pioneer spacecraft each made two passes (one inbound and one outbound) through the Jovian radiation belts. Further progress would be greatly enhanced by a continuous monitoring of the Jovian radiation environment, *i.e.*, by having a satellite in a good orbit around Jupiter itself. We can expect the proposed Jupiter Orbiter/Probe (JOP) mission to help in this respect. However, the Orbiter is presently scheduled to be stationed ultimately in a nearly circular orbit out at $L \sim 15$. It seems that one purpose of stationing the Orbiter so far out is to minimize radiation damage. By the same token, however, the Orbiter will fail to report with regularity on conditions at the heart of the radiation belt. What we would need for regular monitoring is an equatorial elliptical orbit that periodically traverses the region from $L \sim 2$ to $L \sim 30$.

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Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics, chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

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Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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