References and Notes

1. J. H. Trainor, B. J. Teegarden, D. E. Stilwell, F. B. McDonald, E. C. Roelof, W. R. Webber, *Science* **183**, 311 (1974); D. E. Stilwell, R. M. Joyce, J. H. Trainor, H. P. White, Jr., G. Streeter, J. Bernstein, *Inst. Electr. Electron. Eng. Trans. Nucl. Sci.* **22** (No. 1), 1 (1975).
2. J. H. Trainor, F. B. McDonald, B. J. Teegarden, W. R. Webber, E. C. Roelof, *J. Geophys. Res.* **79**, 3600 (1974).
3. J. A. Simpson, D. C. Hamilton, R. B. McKibben, A. Mogro-Campero, K. R. Pyle, A. J. Tuzzolino, *ibid.*, p. 3522; R. B. McKibben and J. A. Simpson, *ibid.*, p. 3545; J. A. Van Allen, D. N. Baker, B. A. Randall, D. D. Sentman, *ibid.*, p. 3559; T. G. Northrop, C. K. Goertz, M. F. Thomsen, *ibid.*, p. 3579; R. W. Fillius and C. E. McIlwain, *ibid.*, p. 3589.
4. E. J. Smith, L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonett, A. M. A. Frandsen, *ibid.*, p. 3501.
5. J. H. Wolfe, J. D. Mihalov, H. R. Collard, D. D. McKibbin, L. A. Frank, D. S. Intriligator, *J. Geophys. Res.* **79**, 3489 (1974).
6. B. J. Teegarden, F. B. McDonald, J. H. Trainor, W. R. Webber, E. C. Roelof, *ibid.*, p. 3615; D. L. Chenette, T. F. Conlon, J. A. Simpson, *ibid.*, p. 3551.
7. C. F. Hall, *Science* **188**, 445 (1975).
8. G. D. Mead, *J. Geophys. Res.* **79**, 3487 (1974); ——— and R. E. Sweeney, *Goddard Space Flight Center Doc. No. X-922-74-339* (November 1974).
9. M. Acuna and N. Ness, personal communication.
10. G. D. Mead and W. N. Hess, *J. Geophys. Res.* **78**, 2793 (1973); W. N. Hess, T. J. Birmingham, G. D. Mead, *ibid.* **79**, 2877 (1974).
11. M. Acuna and N. Ness, personal communication.
12. J. H. Wolfe, personal communication.

13. We thank E. J. Smith and his coinvestigators for supplying the magnetic field data for Pioneer 10 and Pioneer 11 from the helium vector magnetometer and M. Acuna and N. Ness for supplying data from the Pioneer 11 high-field, flux-gate magnetometer.

14 March 1975

Radiation Belts of Jupiter: A Second Look

Abstract. *The outbound leg of the Pioneer 11 Jupiter flyby explored a region farther from the equator than that traversed by Pioneer 10, and the new data require modification or augmentation of the magnetodisk model based on the Pioneer 10 flyby. The inner moons of Jupiter are sinks of energetic particles and sometimes sources. A large spike of particles was found near Io. Multiple peaks occurred in the particle fluxes near closest approach to the planet; this structure may be accounted for by a complex magnetic field configuration. The decrease in proton flux observed near minimum altitude on the Pioneer 10 flyby appears attributable to particle absorption by Amalthea.*

Pioneer 11 traversed Jupiter's magnetosphere almost exactly 1 year after its predecessor, Pioneer 10 (*1*). The outbound trajectory was farther from the equator than previous passes, and high particle fluxes encountered here challenge the original magnetodisk model of the outer radiation belts.

Figure 1a illustrates the observations. The large peak spans the closest approach to the planet at 0523 on 3 December with the inbound leg to the left and the outbound leg to the right. The low latitude data inbound exhibit modulation at the Jovian rotation rate with intensity maxima near the expected position of the magnetic equator. Crossings of the current sheet, identified by the magnetometer experiment (*2*), were found to be in coincidence with some of the maxima. These observations are similar to those from Pioneer 10 and are consistent with the magnetodisk model. The outbound pattern is deceptively similar to that near the equator, with strong modulation at the planetary rotation frequency and comparable intensities. However, there were no current sheet crossings (*2*), and the maxima were higher even than recorded inbound. Such high intensities were not visualized in the original magnetodisk model.

According to the original model, the energetic radiation is contained in a disklike volume defined by nearly radial lines of force stretched outward by a current sheet at the equator. The tilt of the internal planetary field imparts an up-and-down motion to the current sheet at the planetary rotation frequency, and the modulation of the trapped radiation is caused by this up-and-down motion in conjunction with a very sharp vertical gradient of the trapped radiation. Because the intensity was already reduced by one or two orders of magnitude only 10° from the equator, we had expected very little radiation at higher latitudes.

It may be that the configuration is altered by a local time difference. If so, however, the change must take place across only 45° in rotation from midmorning to noon. Alternatively, if the high outbound fluxes are caused by a real time change, it would have to be synchronized coincidentally with closest planetary approach, and no such changes were recorded at other times when the spacecraft was in the magnetosphere. If these possibilities are ruled out, it is still not clear that the magnetodisk model must be abandoned, for this model and the higher latitude phenomena may exist side by side. If this is the case, the Pioneer 11 data imply a latitude profile that initially decreases from a maximum at the equator, goes through a minimum, and then increases to a greater maximum at higher latitudes before dropping off again. The physical processes responsible for this latitude stratification and the interaction between these radiation zones are open questions. However this problem is resolved, it is clear that the new measurements at high latitude provide indispensable information regarding the dynamics and configuration of the vast Jovian magnetosphere.

It is natural to investigate the phase of the modulation for clues regarding the magnetospheric model and internal physical processes. The data in Fig. 1b have been filtered to display frequencies near the planetary rotation cycle, and we have included tic marks synchronized to Jupiter's rotation. The tics on the lower border occur at intervals of one Jovian day (9 hours, 55 minutes, 29.37 seconds); the marks on the bottom line indicate when the spacecraft is aligned and antialigned with

Table 1. Zenocentric and magnetic coordinates for particle features in Fig. 3; *L*, magnetic shell parameter.

Feature in Fig. 3	Zenocentric coordinates			Magnetic cordinates		
				Model D_4*		Model O_3†
	R (R_J)	Latitude (deg)	Longitude III (deg)	L	Magnetic latitude	L
N1	1.76	− 38.6	315	2.79	− 36.2	2.48
X1	1.62	− 24.3	342	2.15	− 27.0	1.72
N2	1.60	− 18.0	352	1.99	− 22.7	1.61
X2	1.63	1.0	18.0	1.77	− 8.3	1.61
N3	1.75	13.2	35.1	1.84	2.0	1.79
X3	1.82	18.5	43.3	1.92	6.8	1.93
N4	2.13	31.8	68.7	2.47	20.5	2.56

* See (*8*). † See (*7*).

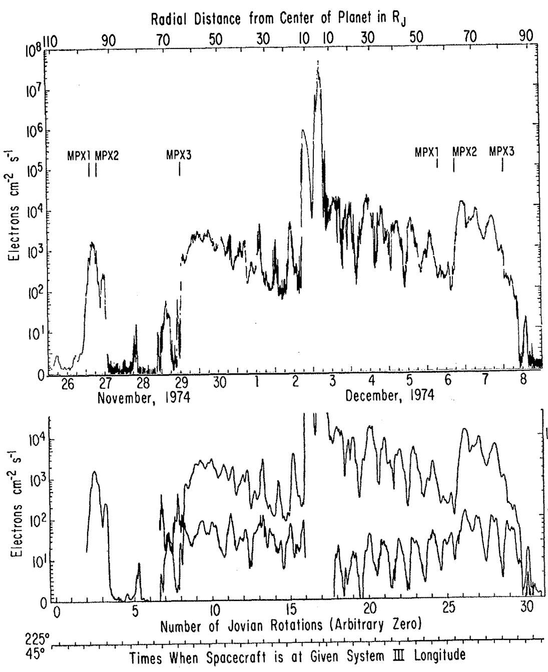


Fig. 1. (a) The flux of electrons of energy > 5 Mev recorded by the UCSD trapped radiation detector along the Pioneer 11 trajectory through the Jovian radiation belts. The labels MPX-1, MPX-2, and MPX-3 mark the times when the spacecraft entered or left the magnetosphere (*10*). (b) **Running averages (1 hour) of flux and a spectral ratio for electrons of energy near 5 Mev. The middle trace is identical to the top trace except for the 1-hour filter. The bottom trace is the ratio of two channels with energy thresholds above and below 5 Mev. Higher ratios indicate harder spectra.**

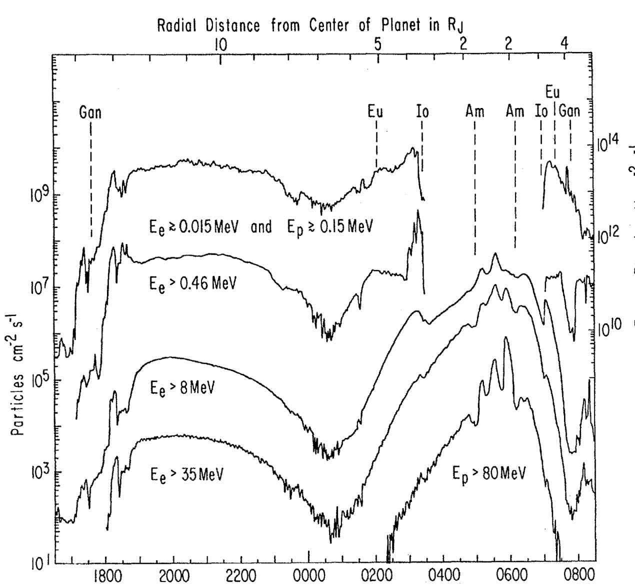
the internal magnetic dipole. These would be the times of highest and lowest latitudes in a coordinate system fixed to a wobbly magnetodisk that was rigid and unwarped. Phase shifts between this and the diurnal clock are caused by the angular swing of the spacecraft around the planet. For an unwarped wobbly magnetodisk the closest approach to the equator would be at 225° inbound, would change phase when the spacecraft crosses the equator, and would be at 45° outbound. The phase change is the difference between this model and one in which the maxima occur at a single longitude in both hemispheres.

None of these timing marks predict the maxima with any precision. A phase change seems called for to describe the intensity modulation; however, the ratio is in phase with the intensity after closest approach although it is not in phase for several cycles before.

Differences in phase between a model and the observed peaks can be explained in terms of spiraling of field lines caused by the angular momentum lag of an outward moving plasma, or warping of field lines from viscous interactions with the solar wind, or other mechanisms. Although these differences contain important information, unfortunately they allow different models enough freedom to be brought into agreement with the data.

A comparison of Fig. 1a with Fig. 1b emphasizes the abruptness of the fluctuations. Without filtering, the data are very spiky and suggest large temporal changes. The prevalent angular distribution is isotropic. In these respects the Pioneer 11 data are similar to the Pioneer 10 data.

The Pioneer 11 data confirm the major findings of Pioneer 10 in the high-intensity inner magnetosphere. Figure 2 shows five channels of the University of California at San Diego (UCSD) instrument plotted versus time. If these data were plotted versus



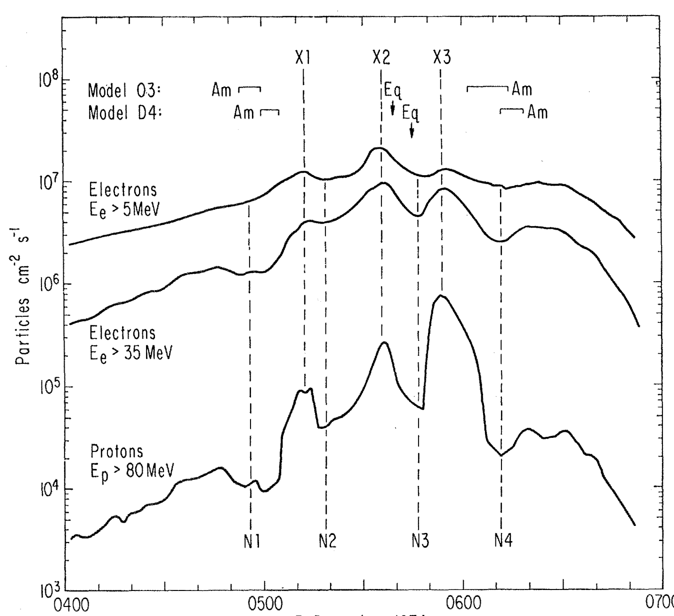


Fig. 2 (left). Integral fluxes of protons and electrons of kinetic energies greater than the values indicated. The uppermost trace shows the combined energy flux for electrons and protons above the threshold and below ~ 0.1 Mev (electrons) and several Mev (protons). The right scale refers to the uppermost trace only; all other profiles should be measured with the left scale. The average positions of the orbits of the inner Jovian satellites are indicated by dashed lines as calculated with the use of the D_2 magnetic field model (*5*). Particle fluxes corresponding to the two top profiles are not shown near closest approach to the planet because they are too low to be distinguished from the energetic particle background. Fig. 3 (right). Electron and proton fluxes measured near the closest approach of Pioneer 11 to Jupiter (1.6 R_J from the center of the planet at 0523). The multiple peak structure may be accounted for by a higher-order spherical harmonic expansion of the magnetic field.

magnetic coordinates, the broad peak on 2 December and the minimum at 0100 on 3 December would emerge as spatial effects associated with magnetic latitude. As with Pioneer 10, the largest numbers of high-energy particles are found nearest the planet and there is a cavity of low-energy particles inside the moons Europa and Io. With the Pioneer 10 data we demonstrated that these features are consistent with inward radial diffusion (*3*), and we derived diffusion coefficients from the loss rate at the moons (*4*).

The peak fluxes of electrons experienced by the Pioneer 11 spacecraft were comparable to those experienced by the Pioneer 10 spacecraft. Since Pioneer 11 approached the planet more than 1 Jupiter radii (R_J) closer than Pioneer 10, this comparison shows that the radial gradient levels off.

The Pioneer 11 electron fluxes at high latitude are significantly higher than those which would be extrapolated from the Pioneer 10 latitude dependence near the equator. This may be another manifestation of the same phenomenon discussed above for the outer magnetosphere. The Pioneer 10 and Pioneer 11 magnetic coordinates crossed each other in the inner region only between 10 and 13 R_J. At three crossover points the ratios of electron fluxes were near unity for energies from 0.2 to > 35 Mev, and we believe that the radiation belts are stable over the time period of a year.

On 3 December Pioneer 11 had a near encounter with the magnetic flux tube containing Io. Between 0300 and 0330 the spacecraft passed within probably 6000 km of the flux tube. [This distance is based on the D_2 magnetic field model (*5*) and will differ for other models.] The flux of electrons of energy $E > 0.46$ Mev jumped suddenly by an order of magnitude to the highest level encountered by either spacecraft (see Fig. 2). Just past the magnetic coordinate of Io these particles disappeared below the minimum we can accurately extract from the high-energy background. Particle acceleration on this flux tube had been predicted (*6*) because of Io's remarkable control over the decametric radio noise from Jupiter. In the context of these models, a conservative estimate for the power in the particles near Io is $\sim 10^{13}$ watts, and this can easily supply the 10^8 watts of radio power observed.

During its closest approach to the planet, Pioneer 11 passed through multiple peaks in the trapped particle fluxes at all energies. This region is shown in detail in Fig. 3. Three maxima and four minima are indicative of the time profile, and position coordinates for these features are given in Table 1. Minima N1 and N4 may reasonably be attributed to particle absorption by Amalthea. However, since there are no more moons nearby, the other features require another explanation.

It might be that the field is convoluted in such a way that the trajectory passed through the same features more than once; or it might be that asymmetries in the field cause certain particle drift surfaces to dip into the planetary atmosphere where the particles would be absorbed. Such effects would not be predicted by a dipole representation of the field, but higher-order terms in the magnetic field expansion are likely to become important at these close distances. One might then expect a magnetic field model which contains higher-order terms to be necessary to organize the particle data. It is not assured that the field mapping by Pioneer 10 and Pioneer 11 covered a sufficient range to determine all the possibly complex radial, longitudinal, and latitudinal irregularities near the planet. However, we do have the opportunity to compare a preliminary octopole model with what is probably the best dipole representation possible (*7, 8*). Magnetic coordinates from these models are listed in Table 1, and times when the spacecraft crossed the magnetic equator and when it passed through the range of particle drift shells traversed by Amalthea are marked for each model in Fig. 3. As we expect minima at Amalthea and maxima on or near the equator, it is clear that a better correspondence is obtained with the octopole model. Further work is required to explain the multiple peaks, but it is encouraging that the first attempt at a higher-order field expansion brings about this much improvement. We believe that further work in this direction will be fruitful.

With regard to the absorption of particles by Amalthea, it may be recalled that for Pioneer 10 there was a decrease in the proton flux near its closest approach, but the reason for this behavior was not determined. The peaks observed for Pioneer 10 correspond closely to the relative maxima outside minima N1 and N4 in Fig. 3, and those minima can be identified with the decrease in the Pioneer 10 mission. The Pioneer 11 flux recovered inside this position and climbed by a factor of ~ 15 higher than the maximum of Pioneer 10. It is now safe to conclude that, of the possibilities discussed for Pioneer 10, the absorption effect of Amalthea is dominant.

Since absorption losses depend upon the radial diffusion velocity of the particles, we can estimate the diffusion coefficient from the observed decrease in the particle fluxes across the region of Amalthea. We deduce the following preliminary values of the diffusion coefficient D: for protons of ~ 100 Mev, $D \sim 3 \times 10^{-9}$ sec^{-1} and for electrons of ~ 90 Mev, $D \sim 2 \times 10^{-9}$ sec^{-1}. These values are ~1/20 of the value we derived for 14-Mev electrons at the orbit of Io based on Pioneer 10 data. However, spatial and energy dependences of the diffusion coefficient are expected (*9*).

In conclusion, we note that the integrated radiation dose received by Pioneer 11 was considerably smaller than that received by Pioneer 10, and there was no permanent radiation damage to the UCSD instrument.

R. WALKER FILLIUS
CARL E. MCILWAIN
ANTONIO MOGRO-CAMPERO
Physics Department, University of California, San Diego, La Jolla 92037

References and Notes

1. Preliminary reports by Pioneer 10 experimenters appeared in *Science* **183**, 301–324 (1974); more extensive articles were published in *J. Geophys. Res.* **79**, 3489–3694 (1974).
2. E. J. Smith, personal communication.
3. C. E. McIlwain and R. W. Fillius, *J. Geophys. Res.*, in press.
4. A. Mogro-Campero and R. W. Fillius, *EOS Trans. Assoc. Geophys. Union* **56**, 1172 (1974); in preparation. Diffusion coefficients for protons and electrons were also derived J. A. Simpson, D. C. Hamilton, R. B. McKibben, A. Mogro-Campero, K. R. Pyle, and A. J. Tuzzolino [*J. Geophys. Res.* **79**, 3522 (1974)].
5. E. J. Smith, L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonett, A. M. A. Frandsen, *J. Geophys. Res.* **79**, 3501 (1974).
6. P. Goldreich and D. Lynden-Bell, *Astrophys. J.* **156**, 55 (1969); D. Shawhan, D. A. Gurnett, R. F. Hubbard, G. Joyce, *Science* **182**, 1348 (1973).
7. M. H. Acuna and N. F. Ness, personal communication. The spherical harmonic analysis model of Smith *et al.* (*8*) was not available before the deadline for this report.
8. E. J. Smith, L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonett, *Science* **188**, 451 (1975).
9. A. Mogro-Campero, R. W. Fillius, C. E. McIlwain, in *Space Research XV*, in press.
10. J. D. Mihalov, H. R. Collard, D. D. McKibben, J. H. Wolfe, *Science* **188**, 448 (1975).
11. We thank the staffs of the Pioneer Project Office and the Deep Space Network for another well-organized and highly successful encounter with Jupiter. We also thank the programming staff at UCSD, and J. Peters in particular, for their help. This work was supported by NASA contract NAS2-6552.

14 March 1975