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14 March 1975

Jupiter Revisited: First Results from the University of Chicago Charged Particle Experiment on Pioneer 11

Abstract. *During the December 1974 Pioneer 11 Jupiter encounter our experiment provided measurements of Jovian energetic protons and electrons both in the magnetic equatorial zone and at previously unexplored high magnetic latitudes. Many of the observations and conclusions from the Pioneer 10 encounter in 1973 were confirmed, with several important exceptions and new findings. We report evidence from Pioneer 11 for protons (~ 1 million electron volts) of Jovian origin in interplanetary space. In the outer magnetosphere particle intensities at high magnetic latitudes were comparable to those observed in the equatorial zone, and 10-hour variations in particle intensities and spectra were observed at both high and low magnetic latitudes. Therefore, confinement of particles in the outer magnetosphere to a thin equatorial magnetodisc is adequate neither as a description of the particle distribution nor as a complete explanation of the 10-hour variations. Pioneer 11 data support a model in which the intensity varies with a 10-hour period in phase throughout the sunward side of the magnetosphere and is relatively independent of position within the magnetosphere. Transient, highly anisotropic bursts of protons with energies of ~ 1 million electron volts observed near the orbit of Ganymede suggest local acceleration in some regions of the magnetosphere. In the inner core where particles are stably trapped, a maximum in the high-energy nucleonic flux was again found, corresponding to the Pioneer 10 maximum at ~ 3.4 Jupiter radii* (R_J)*, which is apparently a persistent feature of the inner radiation zone. In addition, Pioneer 11 data indicate two more local maxima in the nucleonic flux inside 3.4* R_J*, one of which may be associated with absorption by Amalthea, and a maximum intensity at 1.9* R_J *more than 20 times that at 3.4* R_J*. The flux of relativistic electrons reached a maximum on the magnetic equator at 1.8* R_J*, only slightly less than that measured by Pioneer 10 near its closest approach at 3.1* R_J.

The first investigations of the Jovian magnetosphere by Pioneer 10 in November–December 1973 yielded important new insights of general astrophysical interest concerning the acceleration, trapping, and escape of protons and electrons in a large-scale, rapidly rotating magnetic field (*1, 2*). Detailed studies of these observations (*2*) raised many new questions which could be investigated further only by measurements in regions of the magnetosphere outside the near-equatorial regions sampled by Pioneer 10. The choice of trajectory for Pioneer 11 shown in Fig. 1 was made both to explore a high-latitude region of the magnetosphere not traversed by Pioneer 10 and to provide the opportunity to direct the spacecraft toward a Saturn encounter in 1979 (*3*). This report is a preliminary account of our Pioneer 11 observations based on our first examination of the data, and many of the questions discussed here will receive more detailed treatment in later papers. The University of Chicago instrument on Pioneer 11 is essentially identical to the instrument on Pioneer 10 described elsewhere (*4, 5*). Four sensor systems provide measurements over a wide range of energies and particle species. For clarity and for direct comparison with our preliminary Pioneer 10 results (*1*) we show data from only a few channels from our instrument in this report, namely: (i) protons in the energy range from 0.5 to 1.8 Mev from the low-energy telescope (LET); (ii) electrons with energies of 6 to 30 Mev from the main telescope (MT); (iii) electrons with energies > 3 Mev measured by the electron current detector (ECD); and (iv) protons ≳ 35 Mev and high-energy heavier nuclei measured by the fission cell.

Figure 2 displays an overview of the counting rate profiles for Pioneer 11 of the ~ 1-Mev protons and the 6- to 30-Mev electrons from before the first bow shock crossing until after the last bow shock crossing. There are several important large-scale features which confirm observations of Pioneer 10.

1) In the nearby interplanetary medium, there are occasional sharp increases in the proton and electron flux which are associated with the planet.

2) The magnetopause is a sharp boundary for confinement of energetic particles independent of its radial position. As in the case of Pioneer 10, the magnetopause was observed at radial positions from about 50 R_J to 100 R_J at various times as a result of compression and relaxation in response to changes in solar wind pressure.

3) Variations in the electron and proton intensity [and electron spectral index (*6*)] with a 10-hour period associated with Jupiter's 10-hour rotation period are found throughout the magnetosphere (*1, 7*).

4) Outside $R \cong 20\ R_J$, the intensities of protons or electrons averaged over a 10-hour period do not depend strongly on radial distance from the planet.

5) There is a central core region of very-high-intensity, stably trapped particles.

In addition to confirming results from Pioneer 10, our experiment on Pioneer 11 has also provided significant new information important for understanding the physics of the Jovian magnetosphere. For example, the Pioneer 10 results from all of the charged particle experiments (*1, 2*) suggested a model in which electrons were highly concentrated near a magnetic equatorial current sheet in the outer magnetosphere. The Pioneer 11 outbound trajectory was at high magnetic latitudes, however, where we found that the electron intensity averaged over a Jovian rotation was at least as high as the average equatorial zone intensity observed both on Pioneer 10 and on Pioneer 11 on

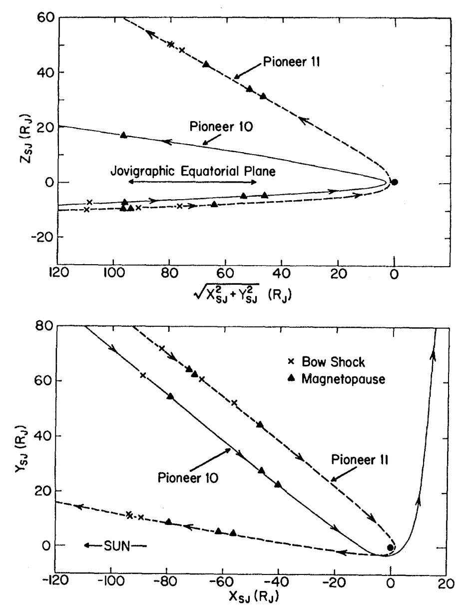

Fig. 1. The trajectories of Pioneer 10 and Pioneer 11 in the Sun-Jupiter (SJ) system; X_{SJ} is in the ecliptic plane and is positive radially away from the Sun along the Sun-Jupiter line, Z_{SJ} is positive toward the north pole and is perpendicular to the ecliptic, and Y_{SJ} completes a right-handed coordinate system. Magnetopause and bow shock crossings have been indicated, based on the data of Wolfe *et al.* (*15*) for Pioneer 10 and Smith (*12*) for Pioneer 11. The unit of distance is the Jovian equatorial radius (1 $R_J = 71{,}372$ km), and distances are measured from the center of the planet.

their inbound trajectories. The proton intensity at high altitudes also was found to be comparable to that measured near the equator. As is apparent from Fig. 2, the particle intensity was high at high latitudes both for a compressed and for an expanded state of the magnetosphere.

As a further example, the 1-Mev proton flux varied by approximately three to four orders of magnitude with a 10-hour period during the Pioneer 10 outbound or "dawn side" pass [see figure 2 of (*1*)]. The intensity maxima were identified as being associated with the entry into the equatorial current sheet (*8*), but this effect was not discernible in the Pioneer 10 inbound pass. We see, however, that on Pioneer 11 this behavior in the particle flux emerged in the radial range 15 R_J to 40 R_J for the inbound pass, on the sunward side of the planet, where a well-developed current sheet was not found on Pioneer 10. From this general comparison of observations alone it is clear both that the concentration of particles in a thin "magnetodisc" is not an adequate description of the particle distribution in the outer magnetosphere and that the spatial distribution of particles changes with time over a period of many days.

Two fundamentally different models have been proposed to account for the variations in the electron flux observed in Jupiter's outer magnetosphere ($R \gtrsim 15\ R_J$). In the first, whose most extreme form is the "magnetodisc" model, particles are confined primarily to the equatorial zone of Jupiter's magnetic field, highly distended in the outer magnetosphere by centrifugal stresses from rapidly rotating magnetospheric plasma. As Jupiter rotates with its magnetic dipole, which is inclined 11° to the rotation axis, the magnetic equatorial zone alternately approaches and recedes from the spacecraft, so that the observed intensity variations are the result of the latitude dependence of the particle flux. Strong support for this model was found in the association of particle intensity maxima with magnetic field minima, especially on the outbound pass of Pioneer 10 (*8, 9*). Several authors have discussed this model and found that, for consistency with the observations, large distortions in the equatorial zone were required (*9, 10*).

Chenette *et al.* (*7*), on the other hand, argued that the intensity variations observed in the outer magnetosphere could be interpreted as time variations, the phase of which was approximately independent of position in the outer magnetosphere. Support for this model came from the fact that (i) near the outer boundary of the magnetosphere the 10-hour variations observed inbound and outbound on Pioneer 10 were approximately in phase and (ii) variations in the intensity and spectral index of electrons from Jupiter in interplanetary space were in time phase with the variations observed near the magnetopause. A conclusive choice between these interpretations was not possible with the data from Pioneer 10.

On the basis of the trajectory shown in Fig. 1, the latitude-dependent model with maximum particle flux in the equatorial zone predicts for the relative phase of the intensity variation inbound and outbound a phase shift of 180° (5 hours) as a result of changing hemispheres, plus $\sim 40°$ (~ 1 hour) as a result of the different Sun-Jupiter-probe angles in the ecliptic inbound and outbound, so that the phase of the variations observed outbound should lead the inbound phase by about 4 hours. In contrast, the time-dependent model predicts no phase change for inbound as opposed to outbound variations.

The observations made with Pioneer 11 are presented in Fig. 3, in which the times of observed flux minima and spectral index maxima have been related to the times expected near the magnetopause based on Pioneer 10 observations, Chenette *et al.* (*7*) showed that spectral index maxima are associated with flux minima for Pioneer 10 near the magnetopause. The heavy line indicates the times expected for inten-

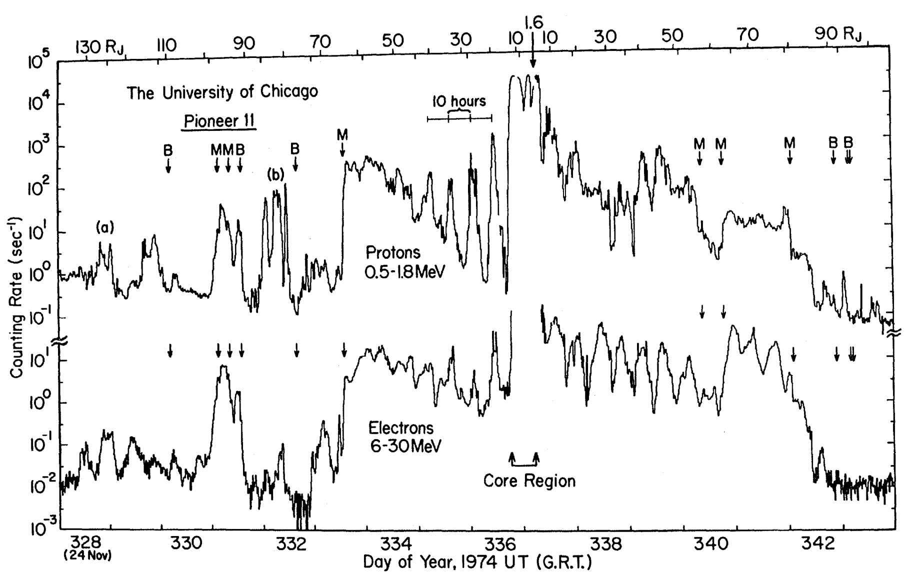

Fig. 2. An overview of the 0.5- to 1.8-Mev proton and 6- to 30-Mev electron intensity profiles near Jupiter measured by Pioneer 11. Magnetopause crossings (*M*) and bow shock crossings (*B*) have been indicated. For $R \lesssim 10\ R_J$, the logic of the MT was saturated and no useful information concerning the flux of 6- to 30-Mev electrons was returned. The profiles are plotted as a function of the universal time (U.T.) of receipt of data on the ground (G.R.T.).

sity minima if minima were associated with maximum magnetic latitude. The data clearly favor the time-dependent model, in view of both (i) the maintenance of approximate phase coherence over a period of 1 year and (ii) the absence of a 4-hour phase change between the inbound and outbound passes. It appears, therefore, that the 10-hour variations in intensity and spectral index have the same phase in both hemispheres of the sunward side of Jupiter's magnetosphere. However, since the correlation between high particle fluxes and magnetic field minima appears to be well established for the outbound pass of Pioneer 10, it is likely that neither model is completely adequate to account for all the observations and that both mechanisms may exist in the Jovian magnetosphere.

On Pioneer 10, in the neighborhood of $L = 40$ [L is the magnetic shell parameter (*11*)] large transient bursts of $\sim$ 1-Mev protons were observed (*1*). On Pioneer 11, both inbound and outbound LET data in the range $10 \lesssim L \lesssim 30$ show the existence of numerous bursts of $\sim$ 1-Mev protons with large anisotropies, both unidirectional and bidirectional, usually directed parallel to the magnetic field (*12*). In some ranges of L, bursts, each of which typically lasted less than 1 minute, were observed to occur continually over a span of several hours. For example, at $L \cong 15.5$, near the orbit of Ganymede, bursts were observed at four separate crossings of the L shell at various magnetic latitudes over a period of $\sim$ 20 hours. Similar behavior was not observed in this L range by Pioneer 10. This behavior is strongly suggestive of nearby acceleration or injection for these particles.

The discovery of relativistic electrons from Jupiter in interplanetary space (*7*, *13*) and the proof of their Jovian origin (*7*) suggested a search for protons escaping from Jupiter's magnetosphere. Since the highly variable nature of the low-energy (~1-Mev) proton flux in interplanetary space makes it difficult to identify Jovian protons with the use of the time intensity profile alone, another criterion is required. On Pioneer 10, near the bow shock and magnetopause, proton fluxes with extraordinarily steep energy spectra were observed (*1*), a result which suggests that the steepness of the energy spectrum might be a useful criterion.

Preliminary analysis of both our Pioneer 10 and Pioneer 11 data has shown the existence of a number of $\sim$ 1-Mev proton events in interplanetary space characterized by steep energy spectra, many, but not all, of which occurred in association with interplanetary electron events of Jovian origin. The proton energy spectra were significantly steeper than those observed in quiet or solar active periods, and the proton flux was often highly anisotropic, with the direction of arrival more consistent with a Jovian than a solar origin.

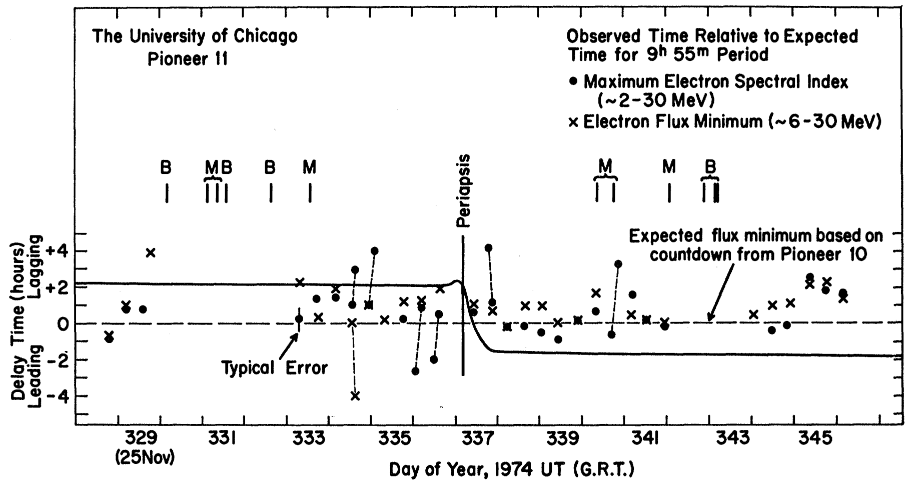

Fig. 3. Times of occurrence of electron spectral index maxima and electron flux minima relative to the time expected based on the assumption of a strict periodicity of 9 hours, 55 minutes, 33.1 seconds [Jupiter's synodic system III rotation period (*16*)] for the variations. The spectral index maximum observed by Pioneer 10 at about 0545 U.T. (G.R.T.) on day 332, 1973, has been used as the reference, consistent with the analysis of Chenette *et al.* (*7*). In cases where two flux minima or spectral index maxima were observed within one 10-hour period, both have been plotted and are joined by a light dashed line.

In Fig. 4, we have plotted the spectral index of protons with energies of 0.5 to 1.8 Mev for successive 2-hour intervals during a portion of the Pioneer 11 inbound and outbound trajectory. Of the four interplanetary proton events (labeled *a* through *d*), events a and d were associated with Jovian interplanetary electron events. Note that the event d occurred approximately 70 R_J beyond the last reported bow shock crossing (*12*). Proton spectra within the magnetosphere do not show the large

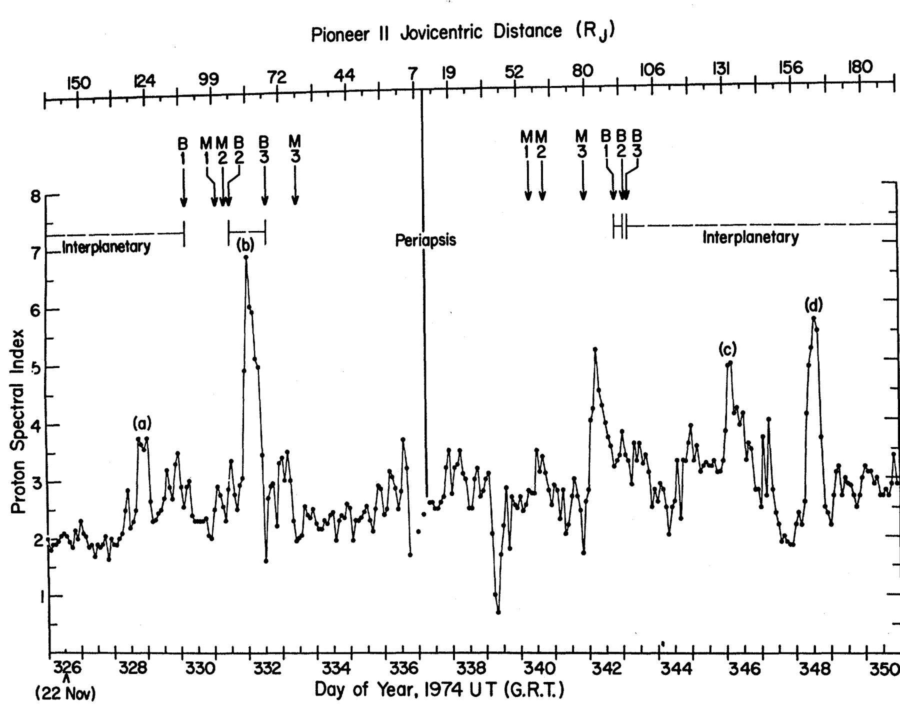

Fig. 4. Spectral index of protons with energies between 0.5 and 1.8 Mev as a function of time. Interplanetary Jovian proton events are labeled *a* through *d*. [Events a and b are also identified in Fig. 2.]

spectral index characteristic of the interplanetary protons identified as being of Jovian origin. For this reason it remains an open question whether the protons observed in these events are escaping from the magnetosphere via a highly energy-dependent escape mechanism or are accelerated in the region of the bow shock or magnetopause.

The intensity profiles of energetic particles stably trapped in the dipole region of Jupiter's magnetic field ($L \lesssim 10$) are shown as a function of L (*11*) in Fig. 5. For LET counting rates $> 2 \times 10^4$ sec^{-1}, the response of the LET counting rate to changes in flux is nonlinear. Nevertheless, the counting rate continues to give a qualitatively correct indication of the behavior of the particle flux in spite of the nonlinearity (*5*).

For the fission cell, whose nominal response is to protons $\gtrsim 35$ Mev, we find a peak proton flux at $L \cong 1.9$ of 1.3×10^8 cm^{-2} sec^{-1}. The ECD current measured in the sharp maximum at $L \cong 1.9$ provides an upper limit of 1.4×10^7 cm^{-2} sec^{-1} for protons $\gtrsim 30$ Mev, however. The source of this discrepancy is most likely background in the fission cell counting rate due either to detection by direct energy loss in the fission cell detectors of nuclei with atomic number $Z > 1$, as discussed by Simpson *et al.* (*5*), or, in the immediate vicinity of $L = 1.9$, possible pileup of pulses from direct energy loss by high-energy protons in the detectors. We are quite confident that there is no appreciable contribution to the fission cell counting rate from electrons, so that the profile measured is that of high-energy trapped nuclei.

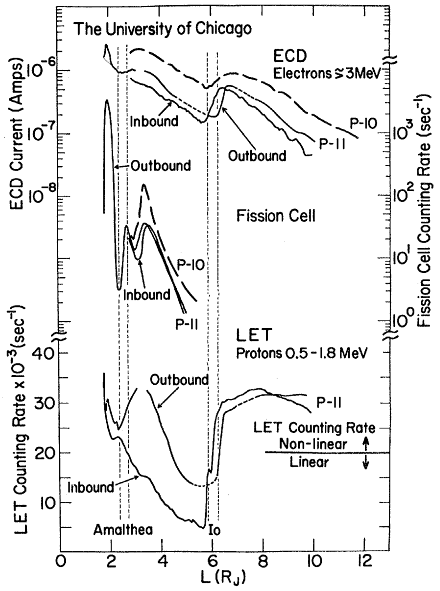

Fig. 5. The intensity profiles of $\gtrsim$ 3-Mev electrons, high-energy nuclei, and $\sim$ 1-Mev protons measured by Pioneer 11 as a function of magnetic shell parameter L in the dipole region of Jupiter's magnetosphere. For comparison, inbound data from the Pioneer 10 ECD and fission cell have also been plotted as the dashed curves. The D_2 magnetic field model of Smith *et al.* (*8*) has been used to compute L (*11*). The differential flux of 0.5- to 1.8-Mev protons (per square centimeter per second per million electron volts) may be obtained by multiplying the LET counting rate by 20 for counting rates $\lesssim 2 \times 10^4$. For the ECD, multiplying the observed current by 10^{14} yields the integral flux of electrons $\gtrsim 3$ Mev (per square centimeter per second). For the fission cell, the integral flux of protons $\gtrsim 35$ Mev (per square centimeter per second) is found by multiplying the counting rate by 4×10^4. See also the discussion in the text, however, concerning possible fission cell background.

A major discovery made during the Pioneer 10 encounter was the existence of a local maximum in the flux of high-energy nuclei at $L \cong 3.4$ (*5*). As can be seen in Fig. 5, data from Pioneer 11 confirm the existence of this maximum as a persistent feature of the trapped radiation. It is also clear from the behavior of the flux profile inside $L \cong 3$ that absorption by Amalthea (at $L =$ 2.4 to 2.7) is not the cause of the flux decrease extending from $L = 3$ to 3.4.

The profiles of the LET protons and ECD electrons show, as did similar profiles for Pioneer 10, the importance of absorption by Io in limiting fluxes of these particles for $L < 6$, and thus provide further conclusive evidence that the trapped radiation in Jupiter's inner magnetosphere is supplied and maintained by inward diffusion from the outer regions. The intensity profiles also indicate a possible role for absorption by Amalthea in determining the flux inside $L \cong 2.4$, although this is not proved at the present time. The flux of $\gtrsim$ 3-Mev electrons measured on the magnetic equator at $L \cong 1.8$ was 1.6×10^8 cm^{-2} sec^{-1}, somewhat less than the flux of 2.5×10^8 cm^{-2} sec^{-1} measured on the Pioneer 10 mission on the magnetic equator at $L \cong 3.1$, indicating a maximum in the electron flux as a function of L between $L = 3.1$ and $L = 1.8$. The fact that a generally higher flux was measured by Pioneer 10 than by Pioneer 11 for $L < 10$ is most reasonably attributed to a latitude dependence of the flux, since in this region the Pioneer 11 trajectory was, for the most part, at high magnetic latitudes. Present evidence indicates that changes in the stably trapped flux with time were small in the interval between the Pioneer 10 and Pioneer 11 encounters. The correct determination of the electron flux profile as a function of L and magnetic latitude has great significance for astrophysics because of the possibility of comparing for the first time observed synchrotron emission with that predicted by theory for a measured population of electrons.

Although we have presented our data in this report in terms of the D_2 magnetic field model of Smith *et al.* (*8*), we have also analyzed our data in terms of the O_3 magnetic field model of Acuna and Ness (*14*), which differs significantly from the D_2 model. Neither model organizes all of the particle data for $L \lesssim 10$ in a fully satisfactory manner, and the basic conclusions in this report are unaffected by our choice of model. More detailed discussion will be given this question in a later paper.

Our experiment on Pioneer 11 suffered no detectable damage or degradation as a result of passage through Jupiter's radiation belts.

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17. We are especially grateful for the exceptional assistance of those associated with the Pioneer Project Office, including C. F. Hall, A. Wilhelmi, J. Lepetich, R. Fimmel, and A. Natwick. Our experiment was fabricated and prepared for space flight in the Laboratory for Astrophysics and Space Research of the Enrico Fermi Institute for which we thank the staff, particularly R. M. Jacquet and J. E. Lamport. We thank W. D. Schroeder and C. W. Barnes who assisted in the data-processing. In the analysis of the Pioneer 11 data we benefited from the assistance of T. F. Conlon and D. L. Chenette, especially in determining the phase of the variations between Pioneer 10 and Pioneer 11. This work was supported in part by NASA contract NAS 2-5601 and NAS 2-6551 with the Ames Research Center, NASA grant NGL 14-001-006, and NSF grant GA-38913X.

14 March 1975

Pioneer 11 Observations of Energetic Particles in the Jovian Magnetosphere

Abstract. *Knowledge of the positional distributions, absolute intensities, energy spectra, and angular distributions of energetic electrons and protons in the Jovian magnetosphere has been considerably advanced by the planetary flyby of Pioneer 11 in November–December 1974 along a quite different trajectory from that of Pioneer 10 a year earlier. (i) The previously reported magnetodisc is shown to be blunted and much more extended in latitude on the sunward side than on the dawn side. (ii) Rigid corotation of the population of protons* $E_p \approx 1$ *million electron volts in the magnetodisc is confirmed. (iii) Angular distributions of energetic electrons* $E_e > 21$ *million electron volts in the inner magnetosphere are shown to be compatible with the Kennel-Petschek whistler-mode instability. (iv) A diverse body of magnetospheric effects by the Jovian satellites is found. (v) Observations of energetic electrons in to a radial distance of 1.59 Jovian radii provide a fresh basis for the interpretation of decimetric radio noise emission.*

A second body of in situ observations of the Jovian magnetosphere was obtained by instruments on the Pioneer 11 spacecraft of the Ames Research Center of the National Aeronautics and Space Adminstration during November–December 1974. Results of the predecessor mission of Pioneer 10, which flew by Jupiter 1 year earlier, have been reported in the 25 January 1974 issue of *Science* and in the 1 September 1974 issue of the *Journal of Geophysical Research.*

We present here a preliminary report of observations of energetic electrons and protons with the University of Iowa instrument on Pioneer 11.

The hyperbolic encounter trajectory of Pioneer 10 with Jupiter was prograde in a plane inclined 13.8° to the planet's equatorial plane and had periapsis at a radial distance of 2.85 R_J ($1\ R_J = 71{,}372$ km, the adopted value of the equatorial radius of the planet). The encounter trajectory of Pioneer 11 was retrograde in a plane inclined at 51.8° and had periapsis at a radial distance of 1.60 R_J (Fig. 1). Thus the new observations spanned a considerably greater range of latitude and longitude; extended inward much closer to the planet; and were obtained, of course, at a different epoch.

Pioneer 11 passed through periapsis at 0603 ERT (Earth received time) on DOY (day of the year) 337/1974 (3 December 1974). Relative to a plane containing the Sun and the poles of the ecliptic plane, the local time of the spacecraft at a radial distance r of 100 R_J was 9.2 hours inbound and 11.6 hours outbound. The spacecraft crossed the reference plane of the sunward side of the planet at 0025 ERT/DOY 339 at a radial distance of 36.4 R_J.

The spin period of Pioneer 11 was 11.89 seconds during Jovian encounter, and, as with Pioneer 10, the spin axis was pointed continuously at Earth to an accuracy of better than 1°.

Our instrument on Pioneer 11 was considerably improved over that on Pioneer 10 by the replacement of one of the original Geiger-Müller tube detectors with a thin (29-μm) single-element, solid-state detector for unambiguous detection of protons $0.61 < E_p < 3.41$ Mev and by modification of another detector so as to increase our sensitivity to low-energy electrons by increasing the geometric factor fourfold and by lowering the detection threshold from 60 to 40 kev. General characteristics of the instrument and other experimental details have been described in detail by Van Allen *et al.* (*1*).

The first crossing of the bow shock was identified by the magnetometer and plasma analyzer experimenters at 109.7 R_J on DOY 330 (26 November 1974) at 0420 ± 05 ERT. After this event there were a miscellany of magnetopause and bow shock crossings until a "final" durable crossing of the magnetopause at about 65 R_J on DOY 333 at 1345 ERT. Particle intensities on the inbound traversal of the magnetodisc were generally similar to those

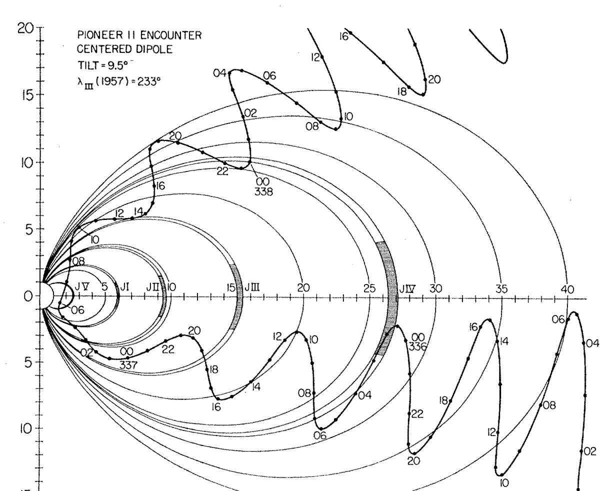

Fig. 1. Trace of the Jovian encounter trajectory of Pioneer 11 on a magnetic meridian plane for the centered dipole model of Randall [see (*1*)] updated to December 1974. Cross-hatched regions are those swept out by satellites JI through JV. The unit of distance is the equatorial radius of Jupiter, 71,372 km.