periodicities out to 90 R_J. As the radial distance increased, the field again became strongly extended, principally in a radial direction so that it tended to lie parallel to the equatorial plane. Dips in the field strength continued to occur at 10-hour intervals and were correlated with Pioneer locations near the magnetic equator. The field lay nearly in the local meridian plane in the inner magnetosphere but a systematic deviation of tens of degrees developed as the radial distance increased. The deviation was toward the antisolar direction, again consistent with the apparent spiraling of the field seen inbound.

Pioneer crossed the magnetopause at 98 R_J, a location consistent with a cylindrically symmetric disklike shape for the magnetosphere near the equatorial region. Alternatively, if temporal variations were occurring during the inbound measurements, the Jovian magnetosphere could flare out at the sides as at the earth.

Our understanding of the observed distortions of the planetary field in the outer magnetosphere is tentative and incomplete. However, the frequent dips in field magnitude at irregular intervals argue for substantial plasma effects on a small scale or for large-amplitude propagating disturbances. Furthermore, the systematic large-scale, spiral deviation of the field from meridian planes must be the consequence of meridional currents or, equivalently, azimuthal stresses. The latter could be associated with magnetospheric plasma that is not corotating with the inner region, with a viscous-type solar wind drag, or with a combination of both. The outward stetching of field lines may be due to centrifugal effects of the rotating plasma or to the pressure of thermal and energetic particles mirroring near the magnetic equatorial plane, either of which would give rise to azimuthal currents. This stretching suggests that the magnetosphere may be flattened into a disklike shape. It could be argued that in order for the standoff distance of the shock to be as small as observed, the magnetic field must conform to a moderately thin disk. On the other hand, the observations are also consistent with a thick magnetosphere, if the boundaries are allowed to be in motion during the encounter.

The observations of Jupiter's magnetic field over the radial range 2.84 to 6 R_J and the system III latitude range $-13°$ to $+13°$ and longitude range 180° to 320° were used to model the planetary dipole. The best least squares fit of the data, in a right-handed Cartesian coordinate system whose z-axis is the rotation axis and whose x-axis is toward system III zero longitude, gives a source location at $(-0.19, -0.04, 0.12)$ R_J and a vector dipole moment of 4.0 gauss R_J^3 whose components are $(-0.63, 0.78, 3.83)$. Estimates of the errors in position and dipole moment are roughly ± 0.03 R_J and ± 0.1 gauss R_J^3, respectively, for each component. In spherical coordinates, the dipole is inclined $\sim 15°$ to Jupiter's rotation axis and lies in a meridian plane corresponding to a system III longitude of $\sim 230°$.

Thus, the observed dipole has the same polarity but roughly half the strength and twice the tilt of the dipole usually inferred from the analysis of radio astronomy data. Surface fields should range from ~ 2.3 to ~ 11.7 gauss unless quadrupole terms are important near the surface. The dipole moment is approximately parallel to the rotation axis of Jupiter rather than antiparallel as for the earth. Because of the tilt, Pioneer 10 crossed the magnetic equator about an hour before closest approach, which explains why the maximum flux of energetic particles was observed at this time. The eccentric location of the dipole will affect the distribution of energetic particles close to Jupiter by enlarging the volume in which they cannot be trapped.

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Notes

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Protons and Electrons in Jupiter's Magnetic Field: Results from the University of Chicago Experiment on Pioneer 10

Abstract. *Fluxes of high energy electrons and protons are found to be highly concentrated near the magnetic equatorial plane from distances of ~ 30 to ~ 100 Jovian radii (R_J). The 10-hour period of planetary rotation is observed as an intensity variation, which indicates that the equatorial zone of high particle fluxes is inclined with respect to the rotation axis of the planet. At radial distances $\lesssim 20$ R_J the synchrotron-radiation-producing electrons with energies $\gtrsim 3$ million electron volts rise steeply to a maximum intensity of $\sim 5 \times 10^8$ electrons per square centimeter per second near the periapsis at 2.8 R_J. The flux of protons with energies $\gtrsim 30$ million electron volts reaches a maximum intensity of $\sim 4 \times 10^6$ protons per square centimeter per second at ~ 3.5 R_J with the intensity decreasing inside this radial distance. Only for radial distances $\lesssim 20$ R_J does the radiation behave in a manner which is similar to that at the earth. Burst of electrons with energies up to 30 million electron volts, each lasting about 2 days, were observed in interplanetary space beginning approximately 1 month before encounter. This radiation appears to have escaped from the Jovian bow shock or magnetosphere.*

The close encounter of Pioneer 10 with Jupiter offers the first opportunity for investigating by direct measurements the interaction of charged particles and a rapidly rotating magnetic field on an interesting astrophysical scale. For example, it is now possible to compare a direct observation of the electrons which are the source of Jupiter's decimetric radio emission (*1*) with

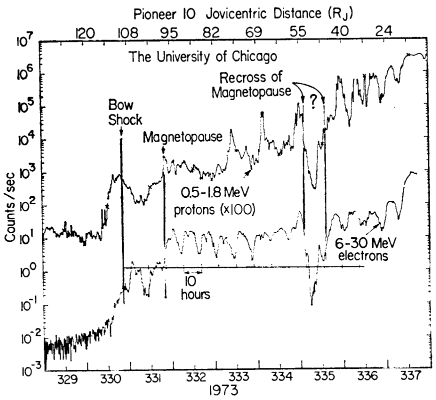

Fig. 1. Counting rate profile of energetic particles measured on the inbound pass of Pioneer 10. The bow shock and magnetopause crossings have been identified by magnetic field and plasma measurements (*4, 8*).

the predictions based on radio astronomical observations. The University of Chicago's experiment on Pioneer 10 measured not only this relativistic electron flux but also the high energy proton flux about which nothing was previously known. The unambiguous measurement of proton fluxes was one of the main objectives of the mission. In this brief report, we present some of the most immediate results and conclusions from our first examination of the data.

Our instrument consists of four separate sensor systems covering a wide range of energies and particle types. However, for simplicity we have restricted our report to one particle energy interval from each of these devices. Two of the sensors, the main telescope (MT) and the low energy telescope (LET), have been described in publications reporting our interplanetary studies (*2*). We report here the fluxes of electrons with energies of 6 to 30 Mev and of protons with energies of 0.5 to 1.8 Mev measured by these telescopes during the inbound and outbound passes of Pioneer 10. These data are presented in Figs. 1 and 2.

Inside approximately 20 R_J ($R_J \equiv 1$ Jovian equatorial radius $= 7.16 \times 10^4$ km), the LET and MT were saturated and two additional sensors, especially developed for the high intensity region close to Jupiter, were employed. The electron current detector (ECD) responds to electrons $\gtrsim 3$ Mev and excludes protons $\lesssim 30$ Mev. For the fluxes encountered at Jupiter, electrons dominated at all times. The fission cell detector measures high fluxes of protons $\gtrsim 30$ Mev by detecting fragments from proton-induced fission of ^{232}Th and is, therefore, extremely insensitive to electron fluxes.

We first detected energetic particles which we associate with Jupiter when the spacecraft was about 360 R_J from the planet, or about 1 month before encounter. These particles appeared in the form of sharp increases in the fluxes of electrons with energies ranging from about 1 to 30 Mev and in proton fluxes at about 1 Mev. Peak intensities were $\gtrsim 100$ times interplanetary quiet time levels and the events lasted about 2 days. We believe that these particles escaped into the interplanetary medium from the bow shock or magnetosphere of Jupiter.

As shown in Fig. 1, about 10 hours before the bow shock was passed we observed strong increases in the flux of electrons and protons. The proton spectrum steepened dramatically in the shock, suggesting that these particles may have been locally accelerated.

As is apparent from Figs. 1 and 2, everywhere within the magnetopause the electron flux showed pronounced variations with the Jovian rotational period of about 10 hours. Given the trajectory of Pioneer 10 (*3*), such oscillations are consistent with what would be expected if the particle flux were strongly peaked at the magnetic equator of a field tipped with respect to the rotational axis of the planet. The electron spectral slope varied in phase with the intensity modulation on both the inbound and outbound passes. Within the magnetopause on the inbound pass, the electron flux was a factor of about 10^3 above quiet time interplanetary levels at

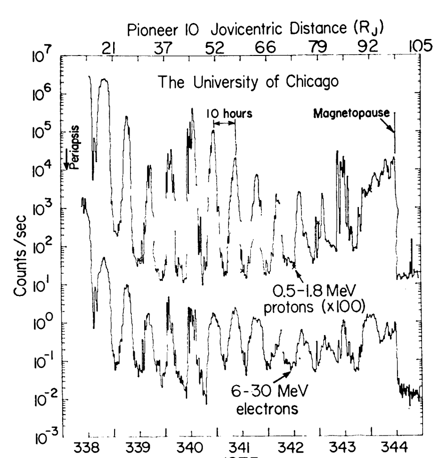

Fig. 2. Counting rate profiles for the outbound pass of Pioneer 10.

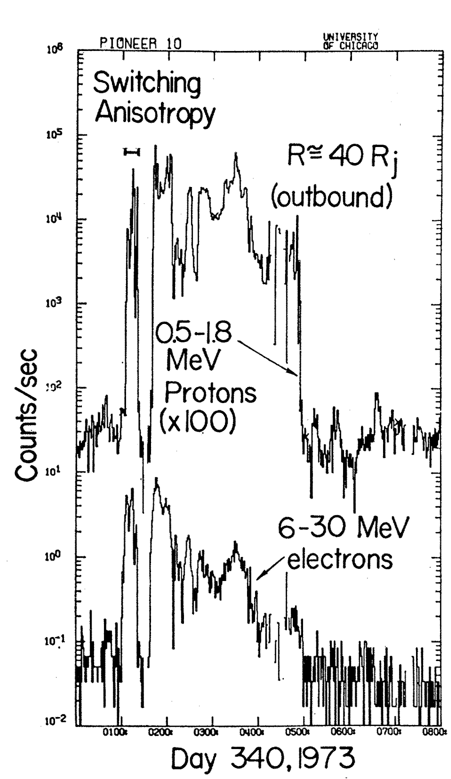

Fig. 3. Counting rate profiles averaged over 1-minute intervals for the first maximum on day 340. Note the significant time structure on a scale of 1 minute and the simultaneity of proton and electron features.

all times. However, on the outbound pass, the intensity minima were only a factor of about 10 above quiet time interplanetary levels. The variations of the 1-Mev proton fluxes were in phase with the electron fluxes on both the outbound pass and after day 335 on the inbound pass. However, for the first 3 days after the magnetopause was passed there was no apparent correlation between the electron and proton fluxes. The reasons for these differences between the proton and electron flux variations and the differences in flux levels for the two passes are not yet clear, but we note that the inbound pass was primarily through the front side of the magnetosphere [Sun-Jupiter-probe (SJP) angle $\theta_{SJP} \simeq 40°$] whereas the outbound pass was behind the dawn meridian ($\theta_{SJP} \simeq 105°$).

The strong concentration of protons and electrons in the magnetic equatorial plane can best be seen in the outbound pass. For example, on day 339 the proton flux changed by a factor of about 10^4 over a latitude range of less than 20° with the flux dropping to only about ten times the interplanetary level within this latitude range.

The proton and electron fluxes dropped by more than 90 percent within a distance of $\pm 6\ R_J$ from the magnetic equator for the electrons and $\pm 3\ R_J$ for the protons as far out as about 50 R_J.

After Pioneer 10 entered the magnetosphere on the inbound pass the electron fluxes averaged over a Jovian rotation remained essentially constant for about 3 days and the proton fluxes for about 1.5 days. In addition, the spectral form for each species did not depend strongly on radial distance from the planet and the fluxes were generally isotropic. These facts demonstrate that the particle behavior in the region 50 to 95 R_J is substantially different from what would be expected to result from L-shell diffusion in a dipole magnetic field. This is consistent with the preliminary results of the magnetometer experiment (*4*), which indicate that the field lines were drawn out in the equatorial plane and were somewhat disordered throughout this region.

Evidence for the importance of local acceleration processes is found in the existence of sharp intensity spikes occurring during individual intensity maxima on the outbound pass, as shown in Fig. 3. These spikes lasted a few minutes and appeared simultaneously for electrons and protons. They occurred typically as the spacecraft approached the magnetic equator and exhibited large directional anisotropies in the magnetic equatorial plane (maximum/minimum ratios of about 100/1) with the direction of maximum flux occasionally changing by 180° in less than 1 minute. The simultaneity of the proton and electron spikes argues strongly for local acceleration. A similar behavior has been observed near the neutral and plasma sheet boundaries in the earth's magnetotail (*5*).

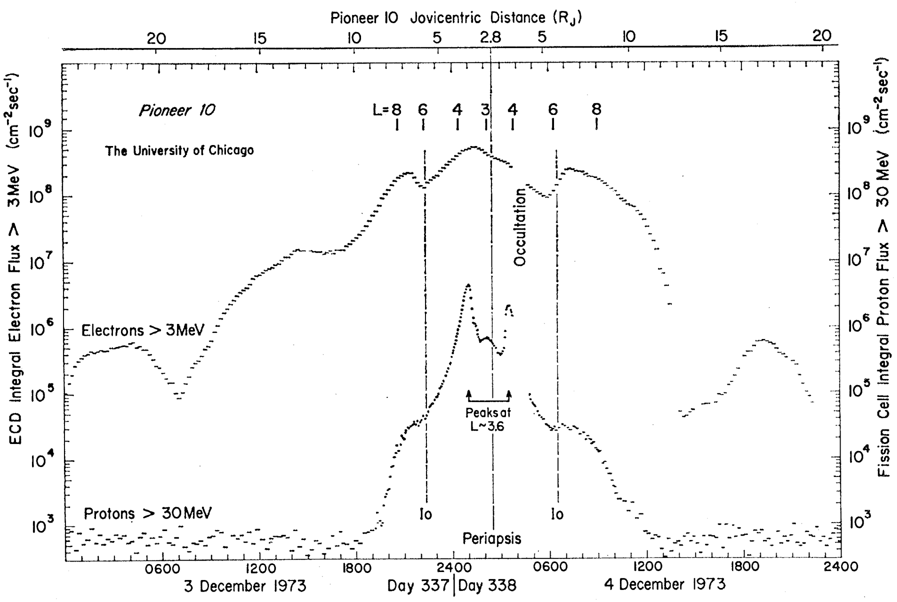

Fig. 4. Flux profiles of energetic particles within $\sim 20\ R_J$. The structure in the ECD profile, except for the decreases associated with Io, results from magnetic latitude variations. Before about 1800 on day 337 and after 1200 on day 338, the fission cell was essentially at background. The maximum flux of $\gtrsim$ 3-Mev electrons is $\sim 5 \times 10^8$ cm^{-2} sec^{-1}, which is, for example, $\sim 8 \times 10^5$ times greater than the flux of 6- to 30-Mev electrons observed during the first peak flux period on day 339 (~ 600 cm^{-2} sec^{-1}), shown in Fig. 2. The maximum flux for $\gtrsim$ 30-Mev protons is $\sim 4 \times 10^6$ cm^{-2} sec^{-1}, which is ~ 80 times greater than the flux of 0.5- to 1.8-Mev protons observed during the first peak flux period on day 339 (5×10^4 cm^{-2} sec^{-1}), shown in Fig. 2.

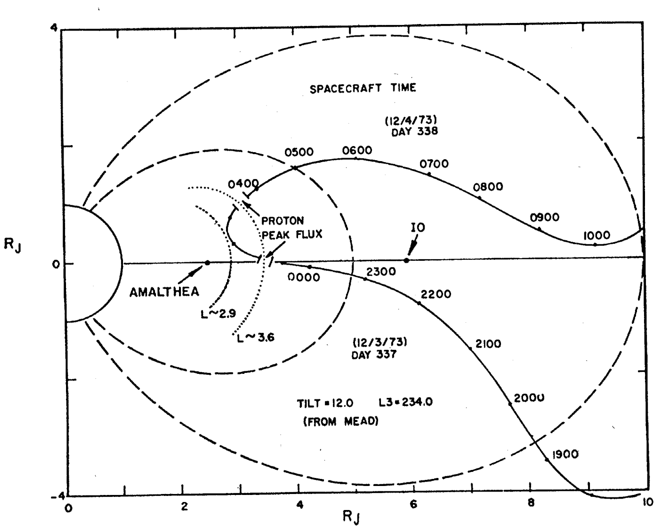

Fig. 5. Representation of the Pioneer 10 trajectory in magnetic coordinates for a centered dipole model adapted from (*6*) with tilt and orientation similar to that deduced from magnetic field observations (*4*).

We have so far measured the flux of helium nuclei with an energy of about 1 Mev per nucleon at several points on the inbound and outbound passes; within the magnetosphere the abundance ratio of protons to helium nuclei in this energy range was typically $\gtrsim 100/1$, but occasionally as low as 15/1. The ratio was highly variable.

As shown in Fig. 4, for radius $R \lesssim 20\ R_J$ the electron flux began to increase rapidly with decreasing distance from the planet, as would be expected for particles trapped in a dipole field. The radial dependence of the flux at the magnetic equator for $20 \geq L \geq 5$ was approximately L^{-5}. [The parameter $L \equiv R\cos^{-2}\lambda$ where λ is the magnetic latitude and R is measured in units of R_J. In this determination of L we have used the magnetic field model suggested by Pioneer 10 observations (*4*).] The ECD and fission cell provided measurements for the proton and electron fluxes in this region. The maximum flux of electrons $\gtrsim$ 3 Mev was about 5×10^8 cm^{-2} sec^{-1} near periapsis. This flux is somewhat higher than had been deduced from radio observations. The measured dipole moment (*4*) was weaker than had been thought, however, so a larger flux of electrons is required to produce the observed decimetric radio emissions.

For protons $\gtrsim$ 30 Mev, two maxima were observed, in contrast to the single maximum for the electrons. The highest flux was about 4×10^6 cm^{-2} sec^{-1}. These maxima occurred at $L \simeq 3.6$ on either side of periapsis, with the flux decreasing for smaller values of L. The location of these maxima with respect to the Jovian magnetic field and to the trajectory of Pioneer 10 is shown in Fig. 5. The difference in intensity between the two peaks is consistent with $\lambda_0 \simeq 22°$ for a latitude dependence of the form $\exp[-(\lambda/\lambda_0)^2]$.

The radial dependence of this proton flux at the magnetic equator is about L^{-9} for $10 \geqq L \geqq 5$.

The drop-off in the proton flux inside $L \simeq 3.6$ is not understood, but it may be the result of either a flux-limiting instability such as the ion-cyclotron instability or absorption by the satellite Amalthea, whose orbital radius is 2.55 R_J. Absorption by the Galilean satellites appears not to have been as effective as thought possible (*6*) for particles of the energies we are discussing here. Only the effect of Io appears in our data, as shown in Fig. 4.

From the foregoing results it is clear that only in the central region of the Jovian magnetic field ($R \lesssim 20$ R_J) does the radiation behave in a manner which is similar to that at the earth. In the region beyond 20 R_J extending to the magnetopause boundary both electrons and protons are highly concentrated near the magnetic equator, especially on the dawn side. For the region between 30 R_J and the magnetopause both the observed magnetic field (*4*) and the early models for the field which incorporate the effects of a strong equatorial plasma flow (*7*) are qualitatively consistent with our particle observations. In future publications we will report detailed studies of fluxes, spectra, and relative abundances of protons, electrons, and helium nuclei to test further the validity of these ideas.

Although the radiation levels encountered were near the design maximum, our instrument survived the exposure and remains in operation.

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Energetic Electrons in the Magnetosphere of Jupiter

Abstract. *Observations of energetic electrons ($\gtrsim$ 0.07 million electron volts) show that the outer magnetosphere of Jupiter consists of a thin disklike, quasi-trapping region extending from about 20 to 100 planetary radii* (R_J). *This magnetodisk is confined to the vicinity of the magnetic equatorial plane and appears to be an approximate figure of revolution about the magnetic axis of the planet. Hard trapping is observed within a radial distance of about 20* R_J. *The omnidirectional intensity* J_0 *of electrons with energy $\gtrsim$ 21 million electron volts within the region* $3 < r < 20$ R_J *is given by the following provisional expression in terms of radial distance* r *and magnetic latitude* θ: $J_0 = 2.1 \times 10^8 \exp[-(r/a) - (\theta/b)^2]$. *In this expression* J_0 *is particles per square centimeter per second*; $a = 1.52$ R_J *for* $3 \leqq r \leqq 20$ R_J; *and* $b = 15°$ *for* $3 \leqq r \leqq 10$ R_J, *diminishing gradually for larger* r. *There is tentative evidence for mild effects of the Galilean satellite Europa and possibly Io and Ganymede but not Callisto.*

This is a preliminary report of in situ observations of energetic electrons in the magnetosphere of Jupiter during the Pioneer 10 encounter 26 November to 11 December 1973. The University of Iowa experiment comprises seven miniature Geiger-Müller tubes in various physical arrangements and with various levels of shielding such as to respond to electrons in several energy ranges from 70 kev to tens of million electron volts and protons in several energy ranges from 700 kev to tens of million electron volts. No one of the individual detectors distinguishes uniquely between protons or electrons as causing its response. A full analysis of the relative responses of the entire array of detectors will provide separate energy spectra of electrons and protons by using laboratory-determined unit response functions and an identification matrix. Overall calibrations were provided by observations during the outbound pass of Pioneer 10 through the magnetosphere of the earth on 3 March 1972 and during several solar energetic particle events, especially those of July and August 1972.

Data reported herein refer only to energetic electrons. The particle identification is based on a simplified version of the above analysis and on auxiliary information provided by other Pioneer 10 experimenters which shows negligible contributions by protons to the responses of several of the detectors in our experiment.

The counting rates of all of our detectors rose discontinuously from their

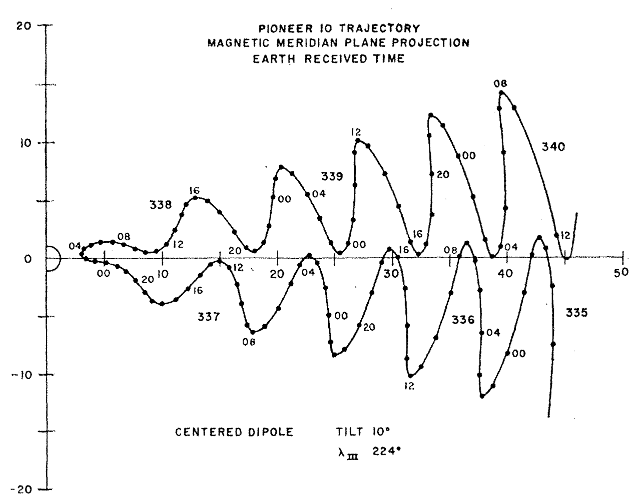

Fig. 1. Projection of the encounter trajectory of Pioneer 10 on a magnetic meridian plane of Jupiter for an assumed centered magnetic dipole having a tilt of 10° to the axis of figure with its pole at system III longitude λ_{III} = 224°. The local time of the asymptote to the inbound hyperbolic trajectory is about 10 hours and of the asymptote to the outbound trajectory, about 5 hours.