As can be seen in Fig. 4, the data points fall close to a straight line, indicating Maxwellian thermal characteristics. An unweighted least-squares straight line fit to the data points is also given in Fig. 4. Under the assumption that the velocity distribution is Maxwellian, the proton temperature in terms of the slope b of the straight line fit is

$$T_{\text{Maxw.}} = \frac{m}{2kb} = 730{,}000 \text{ K}$$

where m is the proton mass and k is Boltzmann's constant. Many of the Pioneer 11 proton speed distributions for the Jupiter magnetosheath (and those from Pioneer 10) have these Maxwellian characteristics.

In summary, the preliminary Pioneer 11 observations from the Ames Research Center plasma analyzer experiment provide a direct measurement that suggests that the half-thickness of Jupiter's magnetosphere is, at a minimum, comparable to the sunward distance to the nose. Pioneer 10 results for the size and variability of Jupiter's outer magnetosphere, and the nature of Jupiter's magnetopause and bow shock plasma transitions in the sunward direction, have been confirmed.

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14 March 1975

Jupiter's Magnetic Field, Magnetosphere, and Interaction with the Solar Wind: Pioneer 11

Abstract. *The Pioneer 11 vector helium magnetometer provided precise, continuous measurements of the magnetic fields in interplanetary space, inside Jupiter's magnetosphere, and in the near vicinity of Jupiter. As with the Pioneer 10 data, evidence was seen of the dynamic interaction of Jupiter with the solar wind which leads to a variety of phenomena (bow shock, upstream waves, nonlinear magnetosheath impulses) and to changes in the dimension of the dayside magnetosphere by as much as a factor of 2. The magnetosphere clearly appears to be blunt, not disk-shaped, with a well-defined outer boundary. In the outer magnetosphere, the magnetic field is irregular but exhibits a persistent southward component indicative of a closed magnetosphere. The data contain the first clear evidence in the dayside magnetosphere of the current sheet, apparently associated with centrifugal forces, that was a dominant feature of the outbound Pioneer 10 data. A modest westward spiraling of the field was again evident inbound but not outbound at higher latitudes and nearer the Sun-Jupiter direction. Measurements near periapsis, which were nearer the planet and provide better latitude and longitude coverage than Pioneer 10, have revealed a 5 percent discrepancy with the Pioneer 10 offset dipole model (D_2). A revised offset dipole (6-parameter fit) is presented as well as the results of a spherical harmonic analysis (23 parameters) consisting of an interior dipole, quadrupole, and octopole and an external dipole and quadrupole. The dipole moment and the composite field appear moderately larger than inferred from Pioneer 10. Maximum surface fields of 14 and 11 gauss in the northern and southern hemispheres are inferred. Jupiter's planetary field is found to be slightly more irregular than that of Earth.*

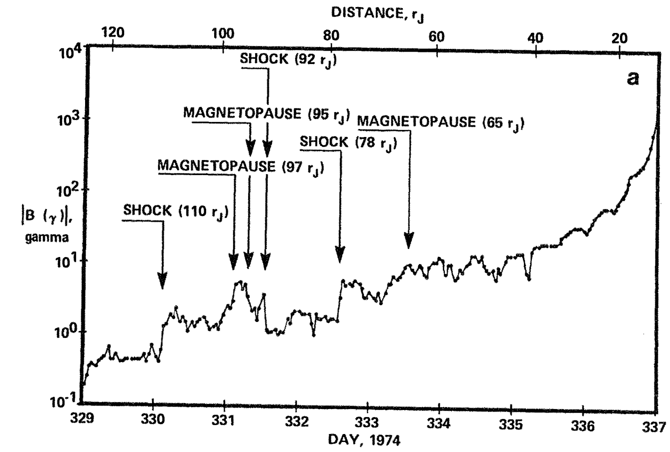
The results presented here are based on field vectors averaged over successive 5-minute intervals which were provided by the Pioneer Project in near real time (quick-look data). They were obtained with the vector helium magnetometer which is essentially identical to the Pioneer 10 instrument (*1*). As before, the magnetometer operated faultlessly and there were no anomalies of any kind associated with either the trapped radiation environment or other causes.

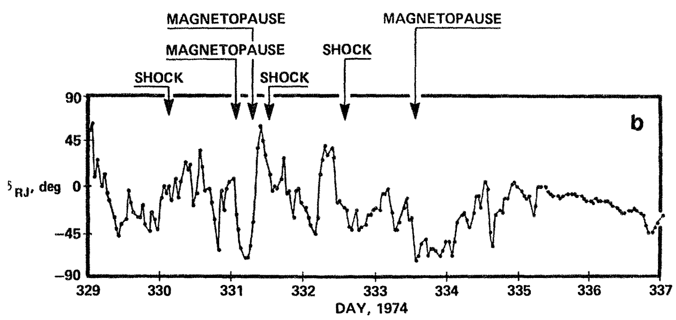
The magnetometer measures field components between 0.01 γ (10^{-5} gauss) and 1.4 gauss by automatically selecting one of eight ranges, all of which are linear to within 0.01 percent. On its highest range, the magnetometer is capable of measuring components at least as large as 1.35 gauss with an uncertainty of only ± 265 γ. Since the largest measured total field strength was significantly smaller (1.135 gauss), the dynamic range of the instrument was never exceeded. The prelaunch magnetometer calibrations were checked inflight at least once every month during the transit to Jupiter without significant changes being observed, so that the measurements are known to be accurate to within 1 percent. The magnetometer sensor is located at the end of a 5-m boom outside the influence of permanent, induced, or current-associated spacecraft magnetic fields. Vector measurements were obtained continuously throughout the encounter, including Earth occultation during which several hundred triaxial samples were stored in an on-board memory.

The effect of Jupiter on the solar wind observed farthest from the planet, as on Pioneer 10 (*2*), was the presence of hydromagnetic waves upstream of the Jovian bow shock. These waves were again associated with bursts of relativistic electrons escaping from Jupiter's magnetosphere detected simultaneously by the cosmic ray experiments (*3*). Six crossings of the Jovian bow shock were observed: three inbound (Fig. 1) at 110, 92, and 78 Jupiter radii (R_J), at $\simeq$ 0900 local time (L.T.) and a Jovigraphic latitude of $\simeq 7°$, and three outbound (Fig. 2) at 91, 94.5, and 95 R_J at 1130 L.T. and at a latitude of $\simeq 32°$. The shocks were typically perpendicular (flow perpendicular to the field) rather than parallel (or "pulsating"). The velocity of the moving bow shock in Jupiter's reference frame was estimated from the conservation of magnetic flux across a perpendicular shock,

$$V = \frac{(B_2V_2 - B_1V_1)}{(B_2 - B_1)}$$

where B is the field strength and V is the solar wind speed; the subscript "2"





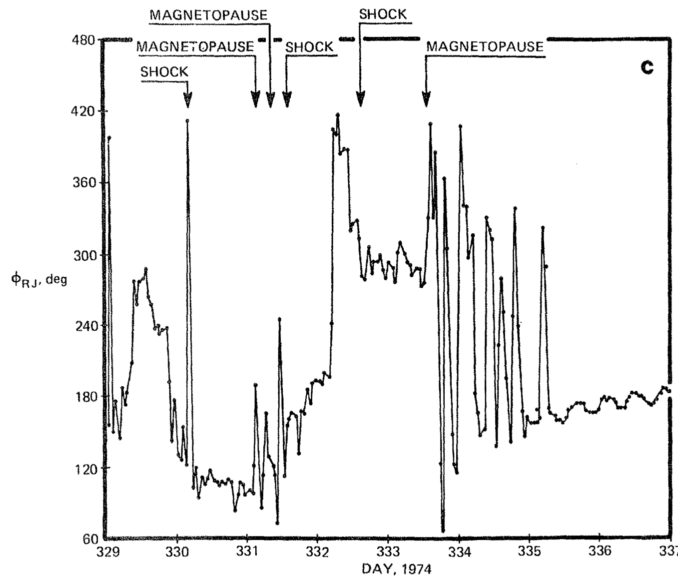
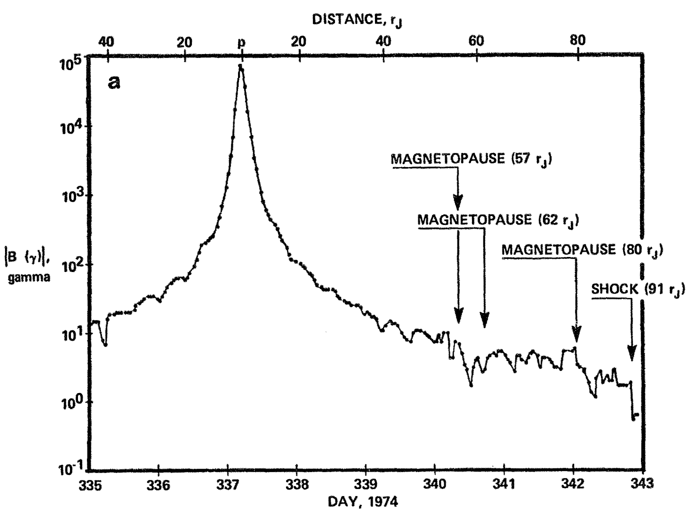
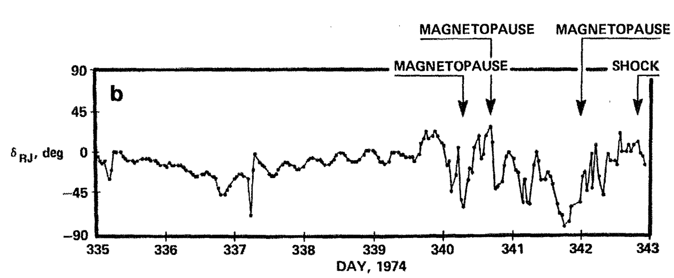


Fig. 1. Pioneer 11 magnetic measurements inbound; 1-hour averages of the field magnitude (a), the latitude (b), and the longitude (c) are shown. In the *RJ*, coordinates which were used, the *X* axis (*R*) points from Jupiter to the spacecraft, and Jupiter's rotation axis (*J*) defines the *XZ* plane or prime meridian. Latitudes are measured from the *XY* plane with positive northward; longitudes are measured from *R* and are positive eastward. The multiple shock and magnetopause crossings are indicated. Jovicentric distances are shown above the magnitude plot.





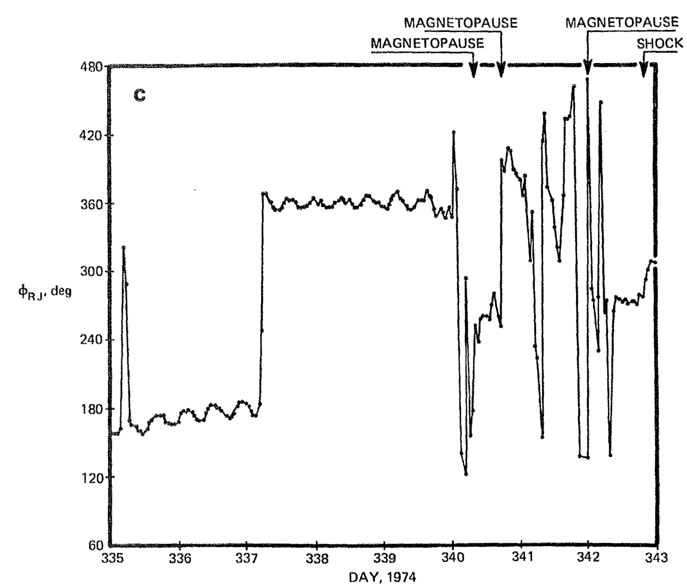


Fig. 2. Pioneer 11 magnetic measurements near periapsis and outbound. The format and coordinates are the same as in Fig. 1. Data from the last 2 days covered by Fig. 1 are repeated at the beginning of Fig. 2 for convenient reference. The hourly average of the magnitude near periapsis (*p*) is slightly less than 1 gauss. The maximum instantaneous measured value was 1.14 gauss.

refers to downstream and the subscript "1" refers to upstream. The estimates, carried out with D. Intriligator, who provided preliminary solar wind velocities adjacent to the shock, led to $V \simeq 100$ km per second. In the magnetosheath, average field directions appear consistent with expectations based on a configuration in which the fields are draped around a blunt magnetosphere. During several intervals when the field direction was unusually steady, nonlinear large-amplitude compressional waves were observed having an impulsive shape reminiscent of solitary waves.

The magnetopause at both low and intermediate latitudes again appears typically to be a thin ($\ll 1$ R_J) well-defined boundary. The normal to the magnetopause, based on a preliminary analysis, is generally radial as anticipated for a blunt magnetosphere. Six magnetopause crossings were observed: three inbound at 97, 95, and 65 R_J at a latitude of $\simeq -7°$ and three outbound at 57, 62, and 80 R_J at a latitude of $\simeq 32°$. The distance to the magnetopause outbound implies a relatively thick magnetosphere. Although, as a result of the current sheet and its elongation of equatorial field lines, the trapped energetic particles inside the magnetosphere tend to be confined to a disk, this shape does not characterize the magnetosphere as a whole. The multiple bow shock and magnetopause crossings imply a very dynamic interaction of Jupiter's magnetosphere with the solar wind. Changes in dimension of the dayside magnetosphere by factors of 2 are apparently common.

On the basis of Pioneer 11, as well as Pioneer 10, there are three basic regions within the magnetosphere (Figs. 1 and 2). In the inner magnetosphere, within perhaps 20 R_J, the planetary field of Jupiter is dominant and the perturbation magnetic field attributable to ring currents and other sources is significantly smaller. Rotation of the planetary dipole is clearly evident, and the observed field is generally relatively smooth without major small-scale deviations. Exceptions to the latter were noted in the vicinity of two satellite L shells (Europa and Ganymede). Significant perturbations in field direction are possible in these regions, perhaps attributable to field-aligned currents.

In the middle magnetosphere, between 20 and 50 R_J and relatively near the equator, currents associated with trapped low-energy plasma severely distort the planetary field. The field strength is approximately constant at 10 γ, the field tends to be parallel to the equator rather than dipole-like, and there is little variation in field latitude and longitude anticipated for a rotating dipole field. The Pioneer 11 observations inbound (Fig. 1 at $\simeq 40$ R_J) contain the first clear evidence in the dayside magnetosphere of the current sheet that was such a dominant feature of the Pioneer 10 data outbound (*1*). The Pioneer 11 current sheet crossing exhibits the same features as seen by Pioneer 10: a reduction in field magnitude from 10 to $\simeq 1$ γ, a southward field within the current, and a reversal of field longitude by 180° on opposite sides of the current sheet. The major 10-hour periodicity appears to consist of a motion of the current sheet toward and away from the spacecraft. A good correlation exists between this periodic field variation and periodic changes in the flux of trapped radiation (*4*). A modest spiraling of the field, up to a few tens of degrees, was again evident inbound.

In the middle magnetosphere at higher latitudes, the outbound Pioneer 11 data contain a 10-hour periodicity but, as anticipated, without any current sheet crossings. The field generally appears to be more characteristic of a dipole field than at lower latitudes inbound. In particular, the longitude angle is well defined and regular and there is no evidence of the westward spiral seen in the Pioneer 11 data inbound and on Pioneer 10 both inbound and outbound. As the magnetic latitude of Pioneer 11 decreased, the field diminished in strength and became more southward and the particle fluxes simultaneously increased.

The outer magnetosphere, as with Pioneer 10, was characterized by much less obvious periodicities and by significant irregularities in the field magnitude and direction. Pioneer 11 observations at higher latitude outbound closely resemble those observed inbound a low latitudes on both Pioneer 10 and Pioneer 11 between the middle magnetosphere (current sheet) and the magnetopause. The field exhibits a strong tendency to point southward, especially near the magnetopause. Thus, there is no direct evidence of open field lines. Furthermore, the energetic particle fluxes remain well above interplanetary levels and the particles in this region appear to be trapped (*4*).

The most significant Pioneer 10 results regarding the planetary field of Jupiter were a reasonably accurate measurement of the magnetic dipole moment and field strength and incontrovertible evidence that the planetary field could not be represented by a simple centered dipole (*1*). A 6-parameter fit to the Pioneer 10 data was derived corresponding to an offset dipole. A spherical harmonic analysis of the Pioneer 10 data was also carried out to yield a centered dipole plus quadrupole (an 8-parameter fit). The inclusion of higher-order terms did not appear justified, considering the likely uncertainties associated with the leading terms of the series.

The Pioneer 11 encounter had an advantageous trajectory which went nearer the planet (within 1.6 R_J) and gave significantly better latitude and longitude coverage. Consequently, Pioneer 11 data were expected to test the validity of the models away from the Pioneer 10 trajectory and to lead to improved models of the planetary field, including reasonably accurate estimates of the next higher order (octopole) term. As Pioneer 11 data were received, they were compared with field values predicted by the Pioneer 10 (D_2) model. Although the agreement was generally good, significant discrepancies at a level of $\simeq 5$ percent were evident, the principal difference being a measured field strength that was somewhat larger than predicted.

The analysis used to derive D_2 has been carried out on the Pioneer 11 data to develop an independent model which we henceforth call D_4. The dipole moment of D_4 has a magnitude of 4.225 gauss $R_J{}^3$, a tilt angle of 10.77°, and a system III longitude (epoch 1974.9) of 230.9°. The D_4 offset vector has a magnitude of 0.101 R_J, a latitude of 5.12°, and a system III longitude of 185.7°. Comparison with D_2 shows the dipole moment of D_4 to be larger by $\simeq 6$ percent. The tilt angle is virtually unchanged, and the longitude of the north magnetic pole is in close agreement with current radio astronomy estimates after allowance has been made for the drift of the Jovian field relative to system III. The offsets in the two models are remarkably close, both D_2 and D_4 indicating a nearly equatorial displacement of 0.10 R_J. The difference in the dipole moments presumably represents an improvement that is possible because of the Pioneer 11 trajectory; however, the possibility of a secular change probably cannot be dismissed.

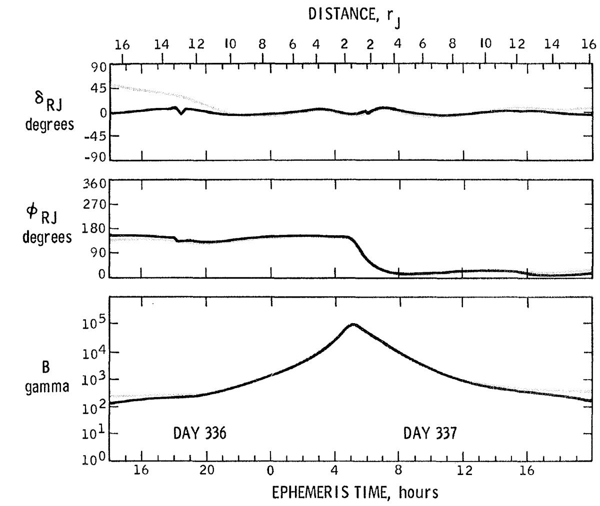


Fig. 3. Comparison of planetary field observations and model. The measured magnitude and latitude and longitude in R_J coordinates are plotted for 30 hours centered on periapsis. Jovigraphic distance varied between $+16\ R_J$ and $-16\ R_J$ as given at the top of the figure. The dark curve passes through 5-minute averages of the data. The gray curve is drawn through fields corresponding to the 23-parameter SHA described in the text. Over much of the interval, the two agree so closely that they are difficult to distinguish. The irregular changes in field direction near 336/1630 may be an effect associated with passage through the Ganymede *L* shell.

A spherical harmonic analysis (SHA) of the Pioneer 11 measurements of the type conventionally used to describe the geomagnetic field (*5*) has also been carried out. We obtained the basic fit by using 15 parameters corresponding to an internal dipole, quadrupole, and octopole and 8 parameters representing fields due to ring currents and other sources external to the region of observation. The coefficients are as follows: dipole, $g_1^0 = 4.129$, $g_1^1 = -0.492$, $h_1^1 = 0.531$; quadrupole, $g_2^0 = 0.042$, $g_2^1 = -0.738$, $h_2^1 = -0.050$, $g_2^2 = 0.324$, $h_2^2 = -0.381$; octopole, $g_3^0 = 0.092$, $g_3^1 = -0.413$, $h_3^1 = -0.084$, $g_3^2 = 0.335$, $h_3^2 = 0.002$, $g_3^3 = -0.239$, $h_3^3 = 0.118$; exterior (the bar designates exterior) dipole $\bar{g}_1^0 = -0.00129$, $\bar{g}_1^1 = 0.00044$, $\bar{h}_1^1 = 0.00065$; exterior quadrupole, $\bar{g}_2^0 = 0.000042$, $\bar{g}_2^1 = 0.000057$, $\bar{h}_2^1 = -0.000051$, $\bar{g}_2^2 = 0.000009$, $\bar{h}_2^2 = -0.000124$. The distance factor, *a*, has been set equal to 1 R_J (71,372 km); therefore, all coefficients have the units of gauss. A direct comparison of the observed fields and those predicted by the 23-parameter model is presented in Fig. 3, and the two are in excellent agreement.

As an indication of the sensitivity of the fit to changes within the model, various cases were tested over differing radial ranges and with 8 to 23 parameters. Generally, the variation in the low-order terms (dipole, quadrupole, and external dipole field) was modest. The octopole terms appear clearly to be significant but, as anticipated, are probably determined with a lesser accuracy. The largest residuals for the spherical harmonic analysis, as well as D_4, occur during occultation (periapsis ± 20 minutes). Subsequent analysis has shown that most of the contribution comes from an error in the roll attitude of the spacecraft that appeared to be present during occultation. Hence, in the preliminary analysis presented here, the models were fitted to the data excluding the occultation data, although the latter are included in Fig. 3 for the purpose of comparison.

The offset dipole and the SHA models may be compared in terms of their root-mean-square residuals, which are 311 and 57 γ, respectively. A direct comparison of the fields predicted by the two models inside 8 R_J shows that the magnitude based on D_4 agrees with the other model to within 5 percent. The angle between the field directions predicted by the two models is less than a few degrees. Thus, for many purposes, D_4 is a reasonably accurate representation of the planetary field.

The spherical harmonic representation has been used to derive contours of the magnetic field strength at the surface of Jupiter (Fig. 4). The maximum field strengths at the north and south poles are 14 and 11 gauss, respectively. These values are slightly larger than has previously been inferred from D_2 (*6*) and presumably reflects the increase in the dipole moments mentioned above as well as a modest contribution of the octopole terms. By comparison, the maximum surface fields in the northern and southern hemispheres based on D_4 are 11 and 10 gauss, respectively. At the approximate location of the foot of the Io flux tube (*6*) the values range between 7 and 14 gauss in the northern hemisphere and between 8 and 10 gauss in the southern hemisphere. The upper limit of 14 gauss, corresponding to an electron gyro frequency of 40 Mhz, appears reasonably compatible with the observed high-frequency cutoff in the decametric radiation.

On the basis of the Pioneer 10 and Pioneer 11 data, the planetary field of Jupiter is evidently only slightly more irregular than that of Earth. The respective offsets are 0.10 R_J and 0.05 R_E, and both are principally equatorial. For Jupiter, the ratios of the quadrupole and octopole moment to the dipole moment are 20 and 15 percent. The corresponding ratios for Earth are 13 and 9 percent.

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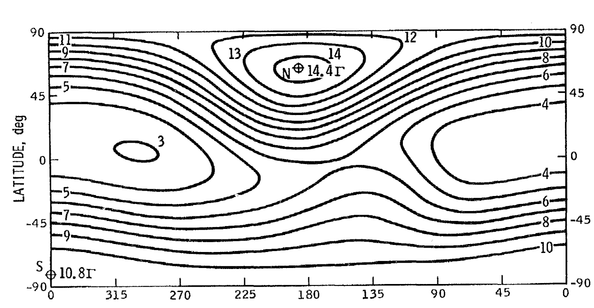

Fig. 4. Surface magnetic field contours. The isointensity contours of field magnitude at Jupiter's surface, which are shown as a function of Jovigraphic latitude and longitude, are based on the 23-coefficient SHA. The maximum values in the northern and southern hemisphere are 14.4 and 10.8 gauss, respectively.

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7. We were assisted in the reduction and analysis of the data during and following encounter by A. M. A. Frandsen, B. T. Tsurutani, J. Mannan, E. Parker, G. T. Foster, J. Van Amersfoort, E. J. Rhodes, J. Hull, C. Stanley, L. Shaw, and J. Davis, all of the Jet Propulsion Laboratory, and by J. Melville of Brigham Young University. We benefited from close contact with the particle investigators, especially J. Wolfe and his collaborators in the plasma experiment. As before, the Pioneer Project staff performed an outstanding job of processing the data in near real time. We appreciate the special assistance provided by J. Dyer, R. Fimmel, T. Bridges, and A. Wilhelmi. The vector helium magnetometer was fabricated by Time Zero Corporation of Gardena, California, under the direction of the Jet Propulsion Laboratory (Space Flight Instruments Section). This paper represents one aspect of research carried out by the Jet Propulsion Laboratory under NASA contract NAS-7.

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