Notes

1. We thank the Pioneer Project Office at Ames Research Center for the excellent job they have done throughout this entire mission. We also thank the staff of TRW Systems, Redondo Beach, California, the main spacecraft contractor, for building a spacecraft which has operated flawlessly, and the staff of Time Zero Corporation, Torrance, California, for construction of the Ames Research Center plasma analyzer experiment which has also operated flawlessly.

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Magnetic Field of Jupiter and Its Interaction with the Solar Wind

Abstract. *Jupiter's magnetic field and its interaction with the magnetized solar wind were observed with the Pioneer 10 vector helium magnetometer. The magnetic dipole is directed opposite to that of the earth with a moment of 4.0 gauss* R_J^3 *(R_J, Jupiter radius), and an inclination of 15° lying in a system III meridian of 230°. The dipole is offset about 0.1* R_J *north of the equatorial plane and about 0.2* R_J *toward longitude 170°. There is severe stretching of the planetary field parallel to the equator throughout the outer magnetosphere, accompanied by a systematic departure from meridian planes. The field configuration implies substantial plasma effects inside the magnetosphere, such as thermal pressure, centrifugal forces, and differential rotation. As at the earth, the outer boundary is thin, not diffuse, and there is a detached bow shock.*

The following preliminary results of the Pioneer 10 vector helium magnetometer experiment are based on averages of the three field components over 5 minutes and 1 hour. The field magnitude as averaged over 1-hour intervals for the first 10 days of the encounter is shown in Fig. 1.

A single bow shock crossing was observed inbound at 108 Jupiter radii (R_J) at a Sun-Jupiter-Pioneer angle of 35°. The field jumped from 0.5 to 1.5 γ (10^{-5} gauss) and the magnetosheath fields behind the shock varied irregularly in magnitude and direction. The interplanetary field direction outside the shock was such that energetic particles could propagate upstream to the spacecraft as observed by the radiation detectors.

The magnetopause was observed shortly afterward at 96 R_J, which could imply either a standoff distance that is relatively small compared to the earth's shock and magnetopause or an outward motion of the magnetosphere. At the magnetopause the field jumped abruptly to 5 γ, indicating a relatively sharp, well-defined boundary. The magnetic energy density just inside the magnetosphere (10^{-10} erg/cm^3) would appear to be insufficient to withstand the pressure of a nominal, shocked solar wind (estimated to be 5×10^{-10} erg/cm^3). This could imply that the principal pressure came from plasma with $\beta \approx 4$ inside the magnetosphere or, alternatively, that the plasma density in the solar wind was much less than the 0.2 cm^{-3} assumed in the above estimate, a contingency consistent with the hypothesis that the outer boundary was in motion when observed.

The field inside the magnetosphere showed a persistent southward orientation, indicating that the field lines were probably closed and that the orientation of the planetary magnetic dipole is directed opposite to the earth's as inferred from radio astronomy measurements. In the outer magnetosphere the field was strongly distended such that its direction was not dipole-like but was elongated parallel to the magnetic equator. The field magnitude remained near 5 γ from 90 to about 0.50 R_J, but was very irregular with frequent dips to values near 1 γ or below. In general, the field strongly resembled that seen near the earth in the antisolar direction within the magnetotail. There was no well-defined orientation of the field into magnetic meridian planes; however, on the average, the field tended to point behind Jupiter in its motion around the sun. This direction is consistent with a spiraling of the field due to plasma effects causing the fields in the outer magnetosphere to lag behind those closer to the planet.

The magnetopause apparently moved toward and overtook the spacecraft near 50 R_J. Fields suggestive of the magnetosheath were observed for about 10 hours, after which Pioneer reentered the magnetosphere and remained inside for the remaining inbound portion of the trajectory. The apparent inward motion of the magnetopause may mean that Pioneer passed Jupiter under magnetically disturbed conditions, perhaps during a storm.

Beginning at 25 R_J, the field strength began to rise monotonically and the direction became more dipolar. Periodic variations in the field direction with a 10-hour period became clearly evident, indicating entry into the inner magnetosphere. Periodic effects then became discernible in the field magnitude and appeared to correlate well with the changing magnetic latitude of Pioneer based on the nominal radio astronomy values for the inclination and longitude of the north magnetic pole. A periodic intensification of the trapped particles was seen to correlate with intervals when the magnetic field measurements showed that Pioneer was nearest the magnetic equator. This correlation established that the spacecraft was in the outer radiation belts. The field strength rose rapidly to a maximum reading of 18,500 γ, or slightly less than 0.2 gauss, at closest approach.

The passage outbound through the magnetosphere was at a Sun-Jupiter-Pioneer angle of ~100° at ~0530 hours local time. The field was much more regular than during the inbound traversal with clear evidence of 10-hour

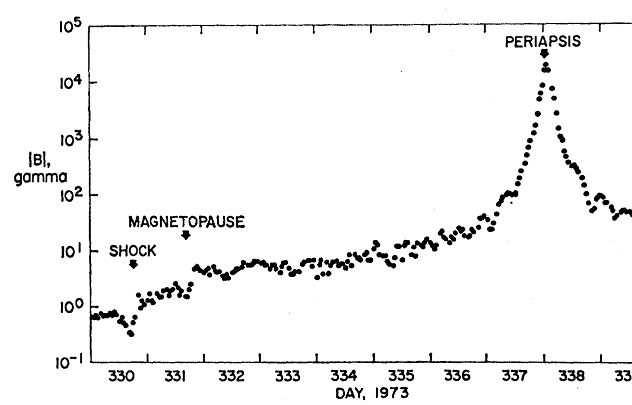

Fig. 1. Pioneer 10 encounter: Jovian field magnitude. One-hour averages of the field magnitude, $|B|$, are shown for 7 days from the bow shock crossing inbound to periapsis and for 2 days outbound.

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