indicative of their primarily silicon and iron composition. The outer planets have typical densities of about 1 g/cm^3, from which one concludes that they are composed primarily of the light elements. A major unknown has been the exact composition of the outer planets. Helium had been postulated on Jupiter, but the observations from Pioneer 10 were the first to verify its existence. A value for the abundance ratio of hydrogen to helium is now emerging from the data.

Another major unknown on Jupiter has been the total amount of energy radiated by the giant planet. Earth-based observations indicated that the infrared radiation emitted by the planet was much in excess of the energy it receives from the sun, implying an internal source of heat (*4*). However, these estimates were based only on measurements made on the day side of the planet, as the night side is inaccessible from the earth. The Pioneer 10 infrared radiometer has established that the excess radiation is 2 to 2.5 times the solar input and that there is no temperature change at the cloud top levels across the evening terminator of the planet. This value of the total heat released from Jupiter can now be used as a boundary value for future models of the atmosphere and the interior.

The magnetic field measurements at Jupiter will also enable us to investigate more exactly the core of the planet. Several models of the core have been proposed which include either frozen or liquid metallic hydrogen as well as a rocky core containing several tens of earth masses (*5*). Planetary dynamos are generally postulated to explain large magnetic fields such as Jupiter's and the earth's. The magnetic field observed by Pioneer 10 is essentially a dipole in nature but is considerably offset from the center of the planet. The vector moment is 4 gauss R_J^3. To be acceptable, models of the interior of Jupiter must now be able to explain the offset as well as the inclination.

The satellite Io represents a particularly interesting case in the Jupiter system. An ionosphere has been observed on Io. From the radio occultation experiment a peak electron density of about 6×10^4 cm^{-3} has been determined at an altitude of 60 to 140 km, with the ionosphere extending from near the surface to about 1000 km. The presence of an ionosphere at this altitude suggests the existence of a neutral atmosphere of about 10^{10} to 10^{12} molecules per cubic centimeter at the surface. In addition, data from the celestial mechanics experiments were used to establish a new value for the density of Io, namely 3.5 g/cm^3, close to the density of the moon and Mars. This experiment also determined that the densities of the other satellites are progressively lower in proportion to their distance from Jupiter, a situation which matches closely the distribution of planetary densities from Mercury to Jupiter.

Postencounter. All scientific instruments have survived the passage through Jupiter's radiation environment and continue to supply data on the solar wind plasma, dust particles, and cosmic rays in the unexplored region beyond Jupiter.

During its brief encounter with Jupiter, Pioneer 10 answered a number of basic questions, but at the same time exposed a variety of other puzzles—a perfectly normal situation in the process of scientific inquiry. These new questions and a more detailed description of the magnetosphere of Jupiter will be tackled by Pioneer 11 when it passes through another portion of the magnetosphere of Jupiter on 5 December 1974. Following that, a Mariner mission to Jupiter and Saturn scheduled for launch in 1977 will further extend and amplify our knowledge of Jupiter, its environment, and its satellites.

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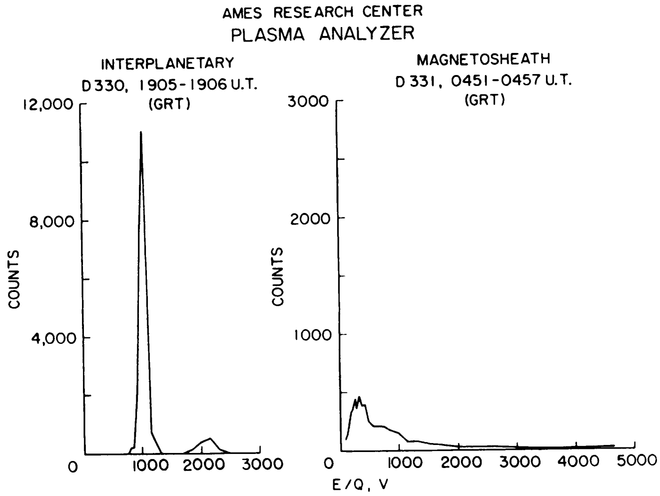
7 January 1974

Preliminary Pioneer 10 Encounter Results from the Ames Research Center Plasma Analyzer Experiment

Abstract. *Preliminary results from the Ames Research Center plasma analyzer experiment for the Pioneer 10 Jupiter encounter indicate that Jupiter has a detached bow shock and magnetopause similar to the case at Earth but much larger in spatial extent. In contrast to Earth, Jupiter's outer magnetosphere appears to be highly inflated by thermal plasma and therefore highly responsive in size to changes in solar wind dynamic pressure.*

The Pioneer 10 Ames Research Center plasma analyzer experiment consists of a medium-resolution and a high-resolution quadrispherical electrostatic analyzer system. The medium-resolution analyzer has a 12-cm mean radius of curvature and a 1-cm plate separation. This analyzer utilizes five secondary-electron, suppressed-current collectors and attendant electrometer amplifiers. The high-resolution analyzer has a 9-cm mean radius of curvature and a 0.5-cm plate separation. The high-resolution analyzer employs 26 detectors (Bendix type CEM 4012 Channeltron) utilized in the pulse counting mode. The combined system covers the charged particle plasma regime for protons from 100 to 18,000 ev and for electrons from approximately 1 to 500 ev. The dynamic range of the experiment includes charged particle fluxes from approximately 1×10^2 to 3×10^9 cm^{-2} sec^{-1}. This experiment has not only operated flawlessly since launch on 3 March 1972 but has exceeded expectations with respect to sensitivity, resolution, dynamic range, and stability. The preliminary Jupiter results presented here are based on the real time data obtained during the Pioneer 10 Jupiter encounter. These data consisted of approximately one complete sample of the solar wind parameters taken at approximately 45-minute intervals so that the times [ground-received times (GRT)] and distances reported here are only approximate.

The first indication of the interaction of the solar wind with Jupiter occurred at approximately 2030 U.T., 26 November 1973, when the Pioneer 10 spacecraft was inbound at a planet center distance of 109 Jovian radii (R_J). At this time the solar wind bulk speed discontinuously decreased from 420 to approximately 250 km sec^{-1}, the temperature increased from 1×10^4 °K to over 10^6 °K, the density increased by a factor of 3 from approximately 0.03 to 0.1 proton per cubic centimeter, and the flow direction shifted from a direction roughly from the sun to a very large angle (by at least 40°) with respect to the Jupiter-sun line. This rather well-defined tran-



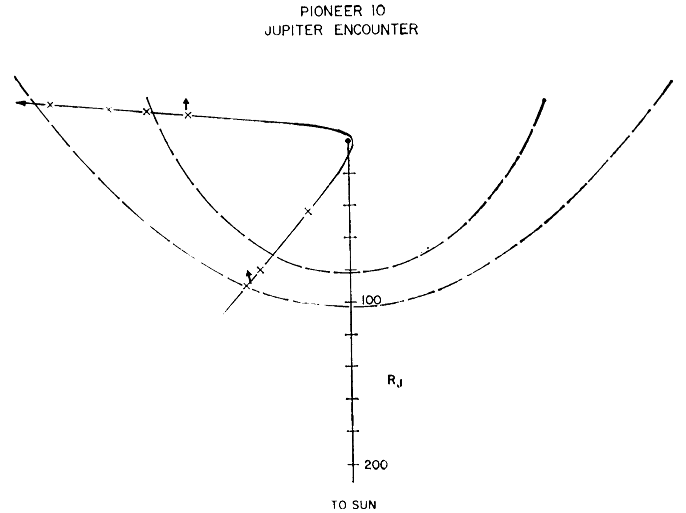


Fig. 1 (left). Comparison of the solar wind ion spectra taken upstream and downstream from Jupiter's bow shock for the inbound portion of the Pioneer 10 Jupiter flyby. Fig. 2 (right). Projection of the Pioneer 10 encounter trajectory onto Jupiter's orbital plane, with the shape and location of the bow shock and magnetopause scaled from the case at Earth. The crosses along the trajectory show the locations of various shock and magnetopause observations during the Pioneer 10 Jupiter flyby, where E/Q is energy per unit charge in volts.

sition is identified as a detached bow shock wave standing off from Jupiter's magnetosphere.

Although the plasma flow conditions in the Jovian magnetosheath were quite variable, the magnetosheath spectrum shown in Fig. 1 is considered to be typical. For comparison, Fig. 1 also shows the solar wind ion spectrum obtained in the interplanetary medium just upstream from the bow shock. Both of these spectra were obtained with the high-resolution analyzer. The interplanetary spectrum shows the hydrogen peak near 1000 ev and the He^{2+} peak near 2000 ev. The somewhat ragged appearance of the magnetosheath spectrum is probably due to sample aliasing caused by fluctuations in the Jovian magnetosheath flow characteristics. The low velocity, high temperature, and long nonthermal tail are, however, quite evident in this spectrum. As the spacecraft continued inbound, the observed magnetosheath characteristics were consistent with the flow expected around Jupiter's magnetosphere.

Shortly after 2015 U.T. on 27 November 1973 at a distance of 96 R_J the plasma flow abruptly ceased, an indication that the spacecraft had crossed the magnetopause and had entered Jupiter's magnetosphere. Like the bow shock, the magnetopause seemed to be a rather sharp and well-defined boundary. In the outer part of the Jovian magnetosphere, the electron component of a thermal plasma was detected by the medium-resolution analyzer. The electron energy was observed to be variable but in general peaked near 3 ev. Any ion component of the thermal plasma would have been below the energy range of this experiment. The presence of this thermal plasma indicates a general inflation of Jupiter's outer magnetosphere and is consistent with a high beta regime as contrasted to the case of Earth where, at least in the sunlit hemisphere, beta is generally low.

As the Pioneer 10 spacecraft continued inbound, the magnetosheath flow characteristics were again observed near 50 R_J and persisted for approximately 11 hours. This second observation of the magnetosheath indicates that external solar wind conditions must have changed such that the Jovian magnetosphere was compressed (or deflected) to a distance inside the position of Pioneer 10 at that time. The surprisingly spongy character of Jupiter's outer magnetosphere was even more dramatically illustrated during the outbound pass by Pioneer 10 where the magnetopause and shock were each observed on three separate occasions. The first outbound magnetopause traversal occurred at approximately 98 R_J and then again at 130 and 150 R_J. The bow shock was traversed by Pioneer 10 at approximately 124 R_J and 127 R_J, and the final crossing (as of this writing) occurred at a distance of 189 R_J.

These boundary traversals are illustrated in Fig. 2, which shows the Pioneer 10 Jupiter encounter trajectory projected on Jupiter's orbital plane. The dashed curves in Fig. 2 represent the relative shapes and locations of the bow shock and magnetopause scaled from the nominal case at Earth, with the shock location normalized to the observed location for the inbound leg of the Pioneer 10 trajectory. The other two crosses on the inbound portion of the trajectory indicate the observed locations of Jupiter's magnetopause. The first and third crosses proceeding away from Jupiter on the outbound trajectory represent the furthest in and the furthest out locations of the observed magnetopause. Likewise, the second and fourth crosses on the outbound pass show the innermost and outermost locations of the bow shock. The arrows on Fig. 2 represent projected plasma flow directions at specific times. Since Jupiter's magnetosphere seems to be surprisingly variable in size, the anomalously thin magnetosheath observed during the inbound pass may be due to relative motion outward of Jupiter's magnetosphere during the inbound pass by Pioneer 10.

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Notes

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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

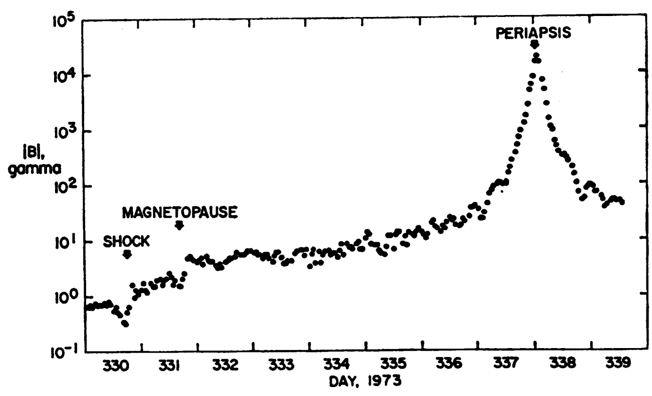

Fig. 1. Pioneer 10 encounter: Jovian field magnitude. One-hour averages of the field magnitude, $|B|$, are shown for 7 days from the bow shock crossing inbound to periapsis and for 2 days outbound.