point source) to improve the signal-to-noise ratio. Exposure times were calculated from IUE auroral spectra but depended on assumptions about the emission geometry in the large IUE aperture and so were initially quite inaccurate. A trade-off was necessary between longer exposure times to collect more photons and shorter ones to minimize the effect of Jupiter's rotation. A number of different exposure times were therefore tried, with the longer ones being more successful.
3. In images at longer wavelengths, selected to be in one of several strong absorption bands of methane (CH_4) such as 890 or 2200 nm wavelength, the polar caps of Jupiter are relatively brighter than the rest of the planet. The enhanced brightness is due to high-altitude particles that are relatively concentrated at the poles and that scatter sunlight before the CH_4 can absorb it. At other locations on Jupiter the CH_4 is an effective absorber. However, at the much shorter UV wavelengths of the HST images the particles are intrinsically strong absorbers and make the pole relatively darker than the rest of the planet. The darkening is zonal, not concentric with the subsolar point, which demonstrates independently of other considerations that it is due to latitudinally inhomogeneous composition and not to radiative transfer effects in a uniform atmosphere. The bottom of the images extends almost to the equator of Jupiter. It is not a coincidence that this effect occurs where it does on Jupiter. The source of the near IR–scattering/UV-reflecting particles is radiochemistry, induced by the influx of high-energy magnetospheric particles on Jupiter's atmosphere of H_2 and CH_4. When CH_4 is radiologically dissociated, the products polymerize to form the particles at the high latitudes where bombardment occurs.
4. System III is a longitudinal and rotational reference frame determined by the observed rotation rate (870.536° per day) of Jupiter's magnetosphere, which is identical to the rotation rate of the planetary interior. Two other atmospheric rotation rates are associated with Jupiter: System I (equatorial, 877.900° per day) and System II (high-latitude, 870.270° per day).
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10. The "brightest area, western or eastern part of the oval" refers to a single 5 by 5 box of the brightest pixels in those parts of the oval. The other areas refer to an average of ~20 such 5 by 5 boxes. For images 202 and 203, where the oval is tilted significantly earthward, the standard deviations are accordingly lower. For image 102, where the oval is not as favorably oriented, the standard deviations are irregular.
11. We thank J. E. P. Connerney for helpful private communications.

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Magnetic Field Observations During the Ulysses Flyby of Jupiter

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The Jovian flyby of the Ulysses spacecraft presented the opportunity to confirm and complement the findings of the four previous missions that investigated the structure and dynamics of the Jovian magnetosphere and magnetic field, as well as to explore for the first time the high-latitude dusk side of the magnetosphere and its boundary regions. In addition to confirming the general structure of the dayside magnetosphere, the Ulysses magnetic field measurements also showed that the importance of the current sheet dynamics extends well into the middle and outer magnetosphere. On the dusk side, the magnetic field is swept back significantly toward the magnetotail. The importance of current systems, both azimuthal and field-aligned, in determining the configuration of the field has been strongly highlighted by the Ulysses data. No significant changes have been found in the internal planetary field; however, the need to modify the external current densities with respect to previous observations on the inbound pass shows that Jovian magnetic and magnetospheric models are highly sensitive to both the intensity and the structure assumed for the current sheet and to any time dependence that may be assigned to these. The observations show that all boundaries and boundary layers in the magnetosphere have a very complex microstructure. Waves and wave-like structures were observed throughout the magnetosphere; these included the longest lasting mirror-mode wave trains observed in space.

The primary aim of the Ulysses mission is the exploration of interplanetary space out of the ecliptic plane, in particular over the poles of the sun. The requirement for rotating the orbital plane of the spacecraft to enable it to reach high solar latitudes has resulted in a unique Jovian flyby trajectory (*1*). Whereas the inbound portion of the orbit was close to the planet-sun line (similar to previous flybys), close to the planet the spacecraft reached higher latitudes than previous missions. The outbound orbit traversed the previously unvisited dusk sector, and the spacecraft exited the Jovian environment at high southern latitudes. We report on the observations made with the magnetometer (*2*) onboard Ulysses along this new flyby trajectory.

The magnetic field strength measured during the inbound and outbound passes of the flyby is shown in Fig. 1, A and B, respectively. We have marked three separate regions on the inbound pass that categorize the general nature of the field data. The categorizations match those suggested previously (*3, 4*) and are made on the basis of the field morphology. The field is much more regular in the inner and middle regions, and the dominant feature is the periodic depressions in field strength [first observed by Pioneer 10 (*5*)], detected about every 10 hours, produced by encounters with, or approaches to, the magnetodisk. The distinction between the inner and middle regions is that the field is primarily radial in the middle regime [beyond about 30 Jovian radii (R_J)] and is dominated by the planetary dipole in the region defined as the inner magnetosphere. The outer region of the magnetosphere is characterized by a very disturbed field with large changes in field strength, some of which can be attributed to brief exits from the magnetosphere back into the magnetosheath. Other large deviations resemble the current sheet crossings recorded closer in. The real distinction between the regions is that the field in the outer region is not mainly radial, but rather is directed predominantly parallel to the planetary dipole.

The bow shock was encountered inbound at a radial distance from the planet of 113 R_J at 17:33 universal time (UT) on 2 February 1992. The shock was encountered only once inbound and was a quasi-parallel shock; the normal angle of 36° to the field was calculated with the use of magnetic coplanarity. The magnetopause current sheet was first encountered at a distance of 110 R_J at 21:30 UT on the same day. Other instruments on Ulysses identified magnetospheric signatures only about an hour later, implying the existence of a thick boundary layer.

All inbound Jovian spacecraft flyby trajectories, including that of Ulysses, entered the magnetosphere in the late morning equatorial sector. The magnetosphere observed by Ulysses was much expanded in comparison to the Voyager and Pioneer 11 inbound passes. Pioneer 10 first detected the magnetopause at 98 R_J.

The briefness of the magnetosheath sojourn indicates that the magnetosphere had expanded substantially between the shock and the first encounter with the magnetopause. Our data, which show a weak magnetic field immediately before the bow shock, after the termination of a corotating interaction region by a reverse shock 4 hours previously, are consistent with this

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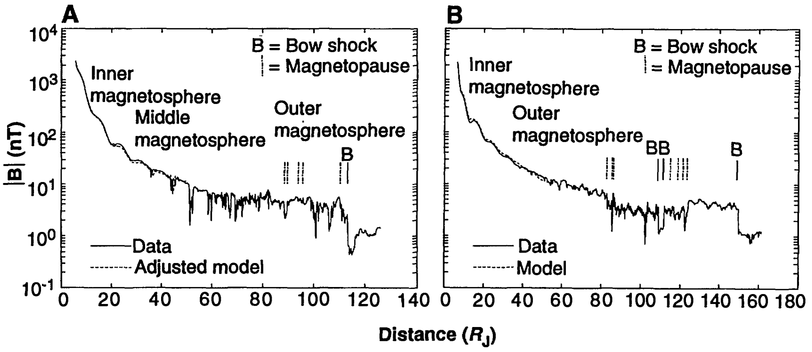

Fig. 1. Magnetic field magnitude measured during (**A**) the inbound pass and (**B**) the outbound pass of Ulysses versus radial distance from the planet. The dashed line superimposed on the data denotes the predicted model field.

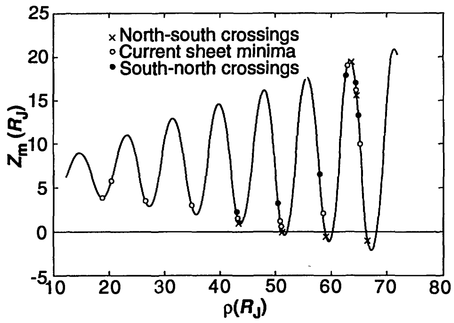

Fig. 2. Trajectory of Ulysses shown for 3 days before closest approach to Jupiter. The distance of the spacecraft from the magnetic equator is given by z_m, where the zero line denotes the magnetic equator; and ρ is the (cylindrical) radial distance of the spacecraft from Jupiter's rotational axis.

suggestion. The capability of the Jovian magnetosphere to dramatically change size in response to changing dynamic conditions is also evidenced by examples of subsequent brief multiple encounters with the magnetopause. Exits from the magnetosphere on 3 February 17:24 UT and 4 February 01:22 UT, respectively, are discernible as depressions in field strength but are also marked in the vector magnetic field data by the field turning northward (that is, opposite to the planetary field).

The unique feature of the Ulysses flyby orbit is its outbound pass along the dusk meridian, which enabled it to reach high southern latitudes. Only one previous spacecraft, Pioneer 11, moved significantly out of the equatorial regions on its outbound pass, approaching near the noon meridian of the planet. The magnitude of the field on the outbound pass is shown in Fig. 1B. On this pass there is no obvious delineation into three regions. Rather, we indicate simply an inner regime, where the field is dominated by the planetary dipole, and an outer regime, where the field points toward the planet. The outer regime is marked by a fluctuating field strength on time scales of about a few hours. Once outside the magnetosphere, there is evidence of some fluctuations associated with the planetary rotation, such as previously suggested (*6*). The variable size of the Jovian magnetosphere is even more strongly illustrated on the outbound pass. The first encounter with the magnetopause was on 12 February at 13:58 UT at a distance of about 83 R_J from the planet; the final encounter was at 124 R_J on 14 February at 20:49 UT.

Three bow-shock crossings were observed on the outbound pass. The first pair, corresponding to a short excursion into the interplanetary medium, was observed on 14 February at 00:37 UT and 04:27 UT, respectively, corresponding to Jovicentric distances of 109 and 112 R_J. The last bow-shock crossing was observed more than 2 days later, on 16 February at 07:53 UT, at a Jovicentric distance of 149 R_J. On both occasions when Ulysses exited into the interplanetary medium the bow shock was near perpendicular, and normal angles of 80° and 82°, respectively, were calculated with the use of magnetic coplanarity.

Although the Jovian internal planetary field is very large in comparison to any other planetary field measured, the magnetic field through much of the Jovian magnetosphere is actually dominated by the current systems external to the planet. The most notable feature of the inner and middle magnetosphere is the magnetodisk first seen by the Pioneer spacecraft (*5, 7*), an intense ring of current flowing around the planet in roughly the magnetic equatorial plane. Plasma and field measurements from Voyager 1 and 2 confirmed that the bulk motion of the plasma is azimuthal and that Io is the main source of the plasma (*4, 8*). The magnetodisk currents result from the requirement that the centripetal acceleration associated with the planetary rotation must be balanced by an electromagnetic **J** × **B** force. The magnetodisk current distends the field in the radial direction, thereby increasing the radial component and decreasing the southward component. Because the planetary dipole is not aligned with the rotation axis as the planet rotates, a spacecraft at equatorial latitudes crosses the current sheet twice per rotation. In the simplest model, in which the sheet is regarded as confined to a thin region in the vicinity of the equatorial plane (*9*), the encounters will occur near the spacecraft's encounters with the magnetic equator. The predominant force creating the current is likely to be centrifugal in origin; thus, more sophisticated modeling can change the expected latitude of the disk slightly (*10*). As the spacecraft's latitude increases, the locations of the encounters move together in both time and longitude, until (considering that the disk actually has a finite thickness) one expects single encounters near the longitude where the (centered) dipole is tilted away from the spacecraft.

A recent model of the planetary field, developed on the basis of data from the Voyager and Pioneer epochs, is known as the O_6 model (*9*); it includes both internal and external sources of the field. The internal planetary field is derived from a spherical harmonic expansion analysis and is given by a tilted dipole with additional quadrupole and octupole terms. The external field sources are represented by a current flowing in the equatorial plane in rings with a rigid rectangular cross section in the meridian extending over a specified range of radius r and (small) thickness. The external current sheet is thus parameterized by its inner and outer edge and by its thickness together with the density of the current, which is taken to decay inversely with radial distance from the planet. This model has been used for the first evaluation of the Ulysses observations in a form that allows its critical parameters to be adjusted for best fit to the data. The coordinate system (r, θ, ϕ) we use in this paper for representing the Jovian field is a right-handed spherical polar set whose z-axis is northward and aligned with the (centered) planetary dipole.

In Fig. 1A a dashed line superimposed on the plot denotes the model field predicted on the inbound pass. To achieve the fair fit to the data illustrated, we used a magnetodisk current density per unit radius that was 45% less than the one used for the Pioneer and Voyager epochs (*11*).

Although the model provides a good description of the radial variation of the field, it is evident that the rigid current sheet that it contains does not accurately predict the positions of the encounters with the current sheet. In Fig. 2 we show the spacecraft trajectory projected into a magnetic meridian and mark the encounters with the sheet as determined by the onset of decreases in the radial component and the minima in the field. As observed, sheet warping or motion can cause multiple min-

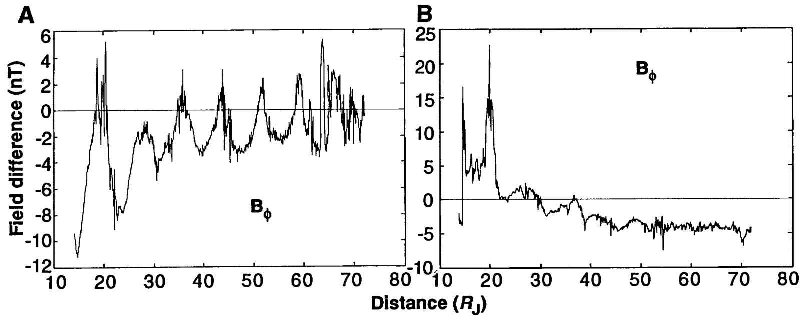

Fig. 3. Difference between the observed and model field for the azimuthal ($B\phi$) component versus radial distance for the inbound pass (**A**) and the outbound pass (**B**).

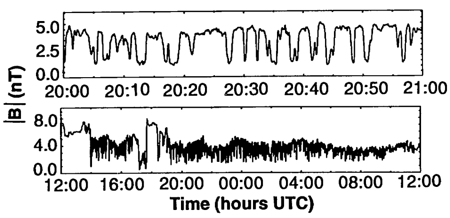

Fig. 4. Mirror-mode waves observed in the dusk-side magnetosheath. The lower panel shows the long duration of the observations; in the upper panel, the microstructure of the waves is illustrated on an expanded time scale.

ima to be detected on a single sheet encounter, and this becomes more common farther from the planet. More sophisticated models of the current sheet that take into account the effects of the symmetry of the sheet with respect to the rotation axis, the finite propagation times, and the warping of the sheet as a result of stresses imposed at large distances by the solar wind have been proposed (*12*).

Ten current sheet crossings that took place over a radial distance range from 68 to 47 R_J have been analyzed. It is assumed that the structure is planar; minimum variance analysis has been used to determine the normal to the sheet and the normal magnetic field component. A sense of polarization can also be attributed to each sheet by measurements of the sense of rotation of the field in the plane of the sheet with respect to the normal field component. The observed sense of polarization is consistently right-handed [the electron sense, as predicted (*13*)]. One can estimate the sharpness of the kink in the field represented by the current sheet by calculating $\sin^{-1}(B_n/B)$, where B is the field outside the sheet. The average inclination of the exterior field to the current sheet in the ten crossings was 6°.

As noted previously, the field in the outer magnetosphere on the inbound pass is primarily in the θ direction, but it does exhibit at times the presence of substantial current sheets. The characteristic of this region is the highly disturbed field. The most extreme examples are several encounters with null fields in which the "dropouts" lasted several minutes, observed on 4 and 5 February at Jovicentric distances of 82, 78, and 72 R_J.

The model field predicted by the O_6 model is shown superposed on the plot of the field magnitude on the outbound pass in Fig. 1B. Although the fit is reasonable, the current per unit radius used to obtain the fit is (surprisingly) exactly the same as that from the Pioneer and Voyager epochs, that is, twice the value suggested by the assessment made on the inbound pass. The difference in the amount of current apparently seen on the inbound and outbound passes is surprising, and it seems worthwhile to inquire into the cause. The magnetopause was encountered inbound very far from the planet, and thus a mechanism might operate whereby current was spread over a larger volume, thereby reducing the local density. However, despite the large number of dynamical signatures in the field, particularly in the outer regions, there seems to be no sign of any long-lasting increase in the current per unit radius occurring at any time on the inbound pass that could explain the increased densities on the outbound pass. Thus, although observations on the inbound pass are compatible with an inflated magnetosphere, there is no direct evidence (at this stage) of whether the outbound pass represents a more "normal" (or Voyager-like) state of the magnetosphere.

A first conclusion following from the above observations concerns the model fitting of the data around the closest approach to the planet. In principle, the Ulysses data would be used to refine previous estimates of the internal field of Jupiter or even to put constraints on potential changes in the internal field since the Voyager epoch. However, the passage of Ulysses almost precisely through the expected inner edge of the current sheet as it passed through closest approach and our current expectation that the current sheet itself is either not axisymmetric with respect to the planet or that it changed substantially while Ulysses was near closest approach leave a very ambiguous situation that will require careful analysis.

The rotation of Jupiter provides the main source of energy for the magnetosphere and is responsible for enforcing (partial) corotation on the plasma. An obvious mechanism for tapping this energy source is via the field-aligned current system that transmits torque from Jupiter's ionosphere to the magnetospheric plasma (*14*). The magnetic momentum flux in the ϕ direction along the background field direction is given by the expression $(\mathbf{B}\Delta B_\phi/\mu_O)$, so that $\Delta B\phi$ is a direct measure of the transfer of stress along the field in the sense of planetary rotation. Planetary angular momentum should be transported toward the equator on flux tubes that are rotating about the planet, so that $\Delta B\phi$ should be negative (or positive) above (or below) the equator when significant amounts of momentum are being transmitted from the planet to the equatorial region. The signature of the field-aligned currents is seen as sharp gradients in $\Delta B\phi$, which represent localized current sheets. The field is swept back from the corotation direction where angular momentum is being transferred from the planet to the equatorial plane, whereas a swept-forward signature implies that the transfer is in the opposite sense and that momentum is being transferred to the planet's ionosphere from a source in space.

We examine observations from both the inbound and outbound passes and calculate $\Delta B\phi$ by subtracting the model field, which does not take account of momentum transfer. Figure 3, A and B, shows inbound and outbound passes, respectively. On the inbound pass, both sweeping-back and sweeping-forward signatures are seen, although the sweeping-back signature ($\Delta B\phi < 0$) is predominant. The regular structure matches that of the current sheet encounters. Observations of the steep gradients in $\Delta B\phi$ as the spacecraft passes through the sheet confirm the existence of sheets of field-aligned current.

Outbound, where the spacecraft has traveled to higher latitudes and is below the equatorial plane, the dominant features are the large fluctuations in $\Delta B\phi$ seen between 15 and 22 R_J radial distance (these would magnetically map to equatorial distances of 20 to 30 R_J in a dipole field). Although the field is swept back throughout this region, the field-aligned currents associated with the sweep back are not distributed in radial distance; instead, they seem to occur in paired sheets encountered near 15 R_J and then again in a more complex signature near 20 to 22 R_J. These signatures yield a current strength of about 10^{-2} A m^{-1} (at 20 R_J). On the assumption that the resultant current flow between the ionosphere and the equatorial plane extends over a significant fraction of the longitude of the putative auroral zone, this would represent a current that could range from 10 to 100 MA.

Farther out one encounters minor swept-back and swept-forward signatures; however, beyond a radial distance of 38 R_J, the field lines adopt a systematic configuration, indicating that the magnetic field is swept toward the magnetotail. We suggest that this field configuration is due to an outflow resulting from equatorially confined material expanding into the magnetotail as it rotates from the dayside.

The Jovian magnetosphere and its neighboring regions are rich in low-frequency wave phenomena. Fluctuations in the interior of the magnetosphere extend to the time resolution of the instrument. Both transverse (Alfvén) and compressional magnetohydrodynamic waves have been detected. Waves were first detected upstream of the bow shock (foreshock) and then in the magnetosheath and the magnetosphere. Here we present only one set of observations from the outbound pass. In Fig. 4 we show the overview of the field magnitude for an entire day (12 February, 12:00 UT to 13 February, 12:00 UT), together with 1-s high-resolution data for a swathe of 1 hour. The structures are characterized by large variations in the ambient magnetic field magnitude (a factor of ~3 in this example), with little or no change in field direction. The structures are neither sinusoidal nor periodic; the time scale of fluctuation is about 1 to 2 min. These structures are believed to be nonoscillatory mirror-mode waves (*15*) and have previously been detected in Earth's and in Saturn's magnetosheath (*16*), as well as in interplanetary space (*17*). These are the longest lasting such wave trains observed in space.

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The Hot Plasma Environment at Jupiter: Ulysses Results

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Measurements of the hot plasma environment during the Ulysses flyby of Jupiter have revealed several new discoveries related to this large rotating astrophysical system. The Jovian magnetosphere was found by Ulysses to be very extended, with the day-side magnetopause located at ~105 Jupiter radii. The heavy ion (sulfur, oxygen, and sodium) population in the day-side magnetosphere increased sharply at ~86 Jupiter radii. This is somewhat more extended than the "inner" magnetosphere boundary region identified by the Voyager hot plasma measurements. In the day-side magnetosphere, the ion fluxes have the anisotropy direction expected for corotation with the planet, with the magnitude of the anisotropy increasing when the spacecraft becomes more immersed in the hot plasma sheet. The relative abundances of sulfur, oxygen, and sodium to helium decreased somewhat with decreasing radial distance from the planet on the day-side, which suggests that the abundances of the Jupiter-derived species are dependent on latitude. In the dusk-side, high-latitude region, intense fluxes of counter-streaming ions and electrons were discovered from the edge of the plasma sheet to the dusk-side magnetopause. These beams of electrons and ions were found to be very tightly aligned with the magnetic field and to be superimposed on a time- and space-variable isotropic hot plasma background. The currents carried by the measured hot plasma particles are typically ~1.6 × 10^{-4} microamperes per square meter or ~8 × 10^5 amperes per squared Jupiter radius throughout the high-latitude magnetosphere volume. It is likely that the intense particle beams discovered at high Jovian latitudes produce auroras in the polar caps of the planet.

This report discusses the initial results obtained from measurements made by the HI-SCALE (heliosphere instrument for spectra, composition, and anisotropy at low energies) experiment as the Ulysses spacecraft traversed the Jovian magnetosphere. The primary objectives of the HI-SCALE investigation (*1*) at Jupiter are to make measurements of the hot plasma (≳40 keV and ≳50 keV for electrons and ions, respectively) population, including spatial distributions and flows, and to characterize the composition of the hot plasma and energetic particle populations (*2*). Of particular interest are the plasma conditions and plasma physics of the high-latitude magnetosphere of this rapidly rotating astrophysical object that could be measured for the first time during the outbound Ulysses pass.

The HI-SCALE instrument (*3*) operated flawlessly throughout the encounter. During the one day around closest approach (day 39, 8 February 1992), the protective covers that are included on three of the particle telescopes were closed, and the entire instrument was turned off. The covers prevented the three non–foil-covered detectors from being implanted with the low-energy heavy ions in the magnetosphere, possibly producing damage or increased thresholds, or both.