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21. An unambiguous identification is not easy in this case because these are double coincidence counts that have a relatively high background and because the position of molecular ions on the *M/q* scale is not exactly the same as for atomic ions. By studying these events specifically, we may be able to confirm the existence of water group ions, which would most likely come from the icy satellites.
22. We thank P. Bedini, S. Lasley, F. Ottens, W. Rieck, C. Shafer, and R. Wimmer for supporting the SWICS experiment during the Ulysses-Jupiter Encounter, and the Ulysses teams of the European Space Agency–European Space Operations Center/European Space Technology Center and the National Aeronautics and Space Administration–Jet Propulsion Laboratory for their excellent work during this crucial period. Supported by the Swiss National Science Foundation, NASA contract JPL 955460, and the Bundesminister für Forschung und Technologie of Germany.

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Jupiter's Magnetosphere: Plasma Description from the Ulysses Flyby

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Plasma observations at Jupiter show that the outer regions of the Jovian magnetosphere are remarkably similar to those of Earth. Bow-shock precursor electrons and ions were detected in the upstream solar wind, as at Earth. Plasma changes across the bow shock and properties of the magnetosheath electrons were much like those at Earth, indicating that similar processes are operating. A boundary layer populated by a varying mixture of solar wind and magnetospheric plasmas was found inside the magnetopause, again as at Earth. In the middle magnetosphere, large electron density excursions were detected with a 10-hour periodicity as planetary rotation carried the tilted plasma sheet past Ulysses. Deep in the magnetosphere, Ulysses crossed a region, tentatively described as magnetically connected to the Jovian polar cap on one end and to the interplanetary magnetic field on the other. In the inner magnetosphere and Io torus, where corotation plays a dominant role, measurements could not be made because of extreme background rates from penetrating radiation belt particles.

During the Ulysses flyby of Jupiter, analogs of the familiar plasma regions and boundaries found in Earth's magnetospheric system were observed, including upstream electron and ion precursors of the bow shock, bow shock, magnetosheath, magnetopause and its boundary layer, outer and middle magnetosphere, and plasma sheet. With the exceptions of the larger scale of the Jovian system, its higher rotation rate, and the presence of the Io torus, the similarities between features in the magnetosphere of the Jovian system and of the terrestrial system are striking. Finding these similarities reinforces the idea that these features are common astrophysical phenomena that can be expected in other similar systems that may be inaccessible to space probes. These observations supplement and extend those of the earlier Pioneer (*1*) and Voyager (*2*) flyby missions because Ulysses flew during a different time era, along a different encounter trajectory (*3*), and carried instrumentation having different capabilities. Here, we report an overview of the observations made with the Ulysses solar wind plasma experiment.

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Because the velocity distributions of ions and electrons in the solar wind are very different, the experiment contains two spectrometers (*4*) to characterize them independently in three dimensions: one for the beam-like ions and one for the omnidirectional electrons. Detailed descriptions of the instruments are given elsewhere (*5*). Even though not ideally suited for magnetospheric observations, the instruments measured many of the plasma features of the Jovian magnetosphere during the entire 15-day flyby except for the day of closest approach. The electron results are displayed in a color-coded spectrogram of energy distributions in Fig. 1; Fig. 2, A and B, presents a plot of electron density and temperature parameters with various features of the encounter identified. The summary chart in Fig. 3 shows the flight path of Ulysses with magnetospheric features located along the trajectory. Spectrograms for both electrons and ions from two intervals on the outbound leg are shown with time expanded in Figs. 4 and 5. A summary log of the entry and exit times of the various plasma regions is presented in Table 1 with boundary identifications. More precise boundary locations will be determined later from a joint analysis of plasma and field (*6*) observations.

At 17:33 UT (universal time) on day 33 (2 February 1992), an abrupt appearance in the Fig. 1 spectrogram of a broad band of yellow extending to energies above 100 eV marks a single inbound crossing of the bow shock, where the solar wind electrons were heated and compressed. An ion spectrogram (not presented here) shows that the solar wind proton and helium ions were similarly heated, compressed, and deflected. A model consistent with past flyby results predicts a bow shock at ~80 Jupiter radii (R_J) for average solar wind conditions. Instead, this crossing, located in Fig. 3, occurred at 113 R_J as the magnetosphere expanded in response to a measured factor of 10 decrease of solar wind dynamic pressure during the day before the crossing. Quantitative electron density and temperature (T) jumps at the shock are ~0.06 to ~0.15 electron cm^{-3} and ~1.6×10^5 to ~1.3×10^6 K, respectively. The amount of heating at this crossing and other crossings during the flyby shows that ΔT scales as the change in flow velocity (ΔV) in the same manner as at Earth. This fact, combined with the fact that the downstream electron distributions had the flattened tops characteristic of distributions downstream from Earth's bow shock, suggests a heating mechanism at Jupiter like that at Earth. Figure 3 also locates several upstream episodes of interplanetary magnetic field (IMF) connection to the bow shock, observed at Jupiter for the first time in three-dimensional distributions of the solar wind electron velocity. Connection events have been observed many times at Earth (*7*) and also at comet Giacobini-Zinner (*8*). When connected, a flux of hot electrons from the shock streams sunward along the IMF, counterflowing against the usual electron heat flux from the hot solar corona.

From previous flybys it was expected that nearly a day would be required for Ulysses to cross the magnetosheath into the magnetosphere. Instead, this crossing, identified in the spectrogram in Fig. 1 by the descending yellow band and in the electron density–temperature plots in Fig. 2, A and B, by the elevated density and temperature profiles on day 33, took only ~4 hours. This unexpectedly short time shows that the magnetosphere continued to expand after the bow-shock crossing. A preliminary estimate of the expansion speed is ~100 km s^{-1}. This crossing, as well as others on the outbound leg, show that the magnetopause is not a sharp spatial boundary separating the lower energy electrons of the sheath and the higher energy, hot electrons of the magnetosphere. Instead, the two populations coexist in a boundary layer that extends inward from the magnetopause. A boundary layer internal to the magnetopause and containing solar wind plasma from the sheath was clearly present for all but one of the Jovian magnetopause crossings. In the first crossing on day 33, the boundary layer extended far beyond the magnetopause crossing, identified in field data (6) at 21:30 UT. By 23:10 UT, Ulysses had crossed the boundary layer into the magnetosphere proper, characterized by higher energy, hot magnetospheric electrons, as shown in the Fig. 1 spectrogram by the lighter blue color extending to the top of the panel at 862 eV.

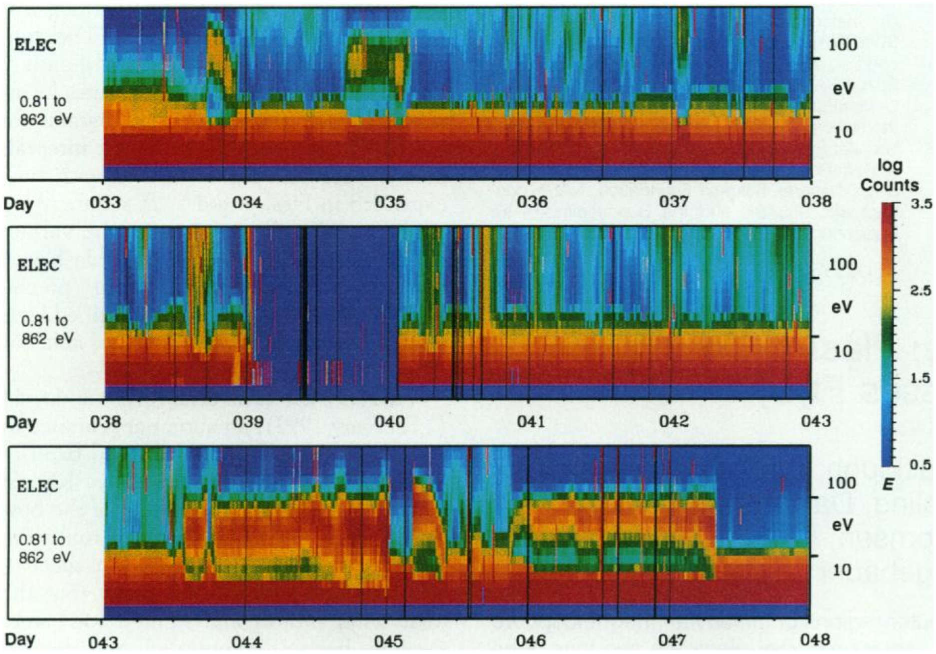

Fig. 1. Color-coded spectrogram of the entire 15-day Ulysses flyby. Electron energy spectra summed over all "look" directions are displayed in three panels starting at 00:00 UT on day 33 (2 February 1992) and ending at 24:00 UT on day 47 (16 February 1992). Twenty-level electron energy spectra in the form of counts per sample versus energy, extending from 1.59 to 862 eV, are displayed vertically, with counts color-coded as shown in the bar on the right. A uniform dark blue band of zero counts between 0.81 and 1.59 eV extends across the bottom of the panels because the lowest energy levels were not used. Above that band, a region of red, denoting highest counts, fading into yellow, extends throughout the sequence. Most of these counts are due to photoelectrons that have been ejected from the spacecraft by solar ultraviolet radiation. Those electrons with energies below the electrostatic potential of the spacecraft return, producing a background that must be removed from ambient spectra. Typical values of the highly variable spacecraft potential are +6 V in the solar wind, +4 V in the magnetosheath, and +20 V in the magnetosphere. The data are continuous except for day 39, when the instruments were switched off because of extreme background counting rates in the inner radiation belt.

After 19 hours in the outer magnetosphere, at 17:00 UT on day 34 a yellow-green band centered near 100 eV in the spectrogram of Fig. 1 reflects large changes of density and temperature as Ulysses passed back through the boundary layer and magnetopause into the magnetosheath. These observations suggest that an increase in solar wind dynamic pressure moved the magnetopause inward past Ulysses. Early on day 35, after 11 hours in this region, the pressure must have relaxed, because Ulysses returned to the magnetosphere proper, as indicated by the disappearance of lower energy electrons and the return of hot magnetospheric electrons.

Later, periodic appearances of hot, high-density regions developed as Ulysses moved into a latitude range in the middle magnetosphere in which planetary rotation carried the relatively thin and tilted plasma sheet past the spacecraft with a planetary rotation period of 10 hours. These plasma sheet encounters persisted for 6 to 7 days during both the inbound and the outbound portions of the middle magnetosphere passage. They are discernible in the spectro-

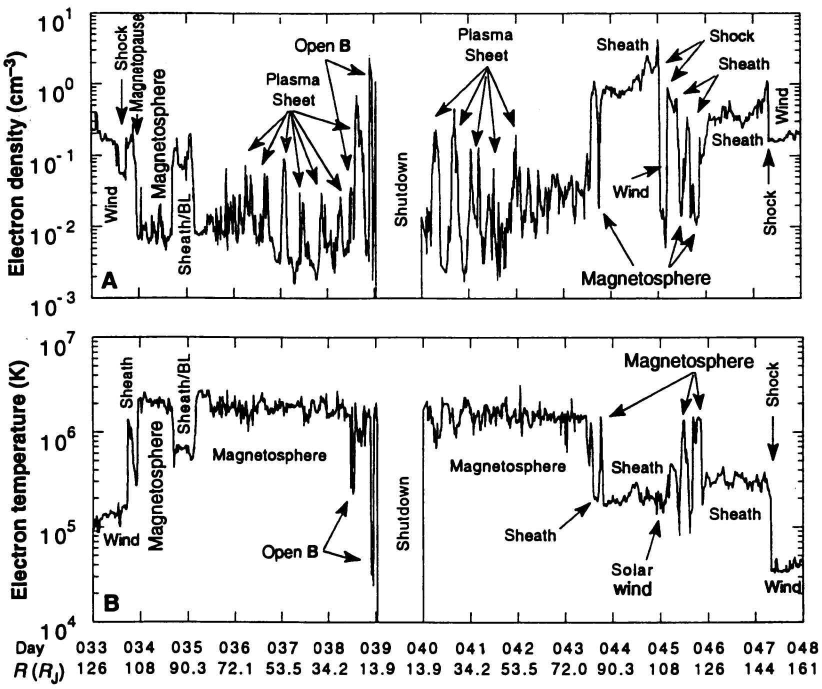

Fig. 2. Derived electron density (**A**) and temperature (**B**) measured during the Ulysses transit past Jupiter. Various features of the encounter are identified; open **B**, open magnetic field; BL, boundary layer. The parameters are based on numerical integration of three-dimensional electron distributions, measured every 17 min, together with two two-dimensional distributions. The energy range of analysis extends from the variable spacecraft potential, determined by inspection of each spectrum, to the top energy limit, 862 eV. A simple algorithm based on minimum count rates for each spectrum was used for background subtraction.

gram of Fig. 1 by the vertical bands of color but are most striking in the electron density record in Fig. 2A, which shows peak-to-valley variations of more than an order of magnitude for some of the plasma sheet encounters.

An interesting plasma event occurred during a 1.5-hour period starting at 21:30 UT on day 38 when Ulysses was at 15.6 R_J and a magnetic latitude of 34.5°. Although this short interval is not well resolved in the 15-day spectrogram, it can be identified by the short band of yellow crossing the red photoelectron band (see Fig. 1 and its legend) just before the day 39 marker. Higher resolution data display a number of features during this interval. (i) The persistent magnetospheric population of hot electrons, identified by the lighter blue color extending to the top of the spectrogram panels (862 eV), disappeared. (ii) A penetrating particle background in the ion spectrometer caused by high-energy, trapped magnetospheric particles fell to very low values. (iii) The persistent background of photoelectrons, returning to the spacecraft because of the positive spacecraft potential, disappeared or fell to very low levels, showing that the potential must have fallen to very low positive, or even negative, values. (iv) Distinct modulation in the angular distributions appeared.

Some of these features might be explained by the following scenario: Deep within the magnetosphere, Ulysses passed through a region in which magnetic field lines from the Jovian polar cap on one end were connected to the IMF on the other end. Such a magnetic configuration would have a number of important consequences: A trapped population of magnetospheric electrons could not be maintained, accounting for (i) above. Similarly, such a field could not contain the trapped population of energetic penetrating particles that caused the ion instrument background in other parts of the magnetosphere, explaining (ii) above. Referring to (iii), the field configuration must have changed the environment so as to clamp the spacecraft potential at low values. Possibly, low-energy plasma flowing up from the ionosphere along the open field lines inhibited the buildup of spacecraft charge. Low-energy electrons, with distributions unlike those of photoelectrons, were observed, but without an ion component. However, ionospheric ions would probably have energies below the threshold of the ion spectrometer (256 eV per charge) and thus could not be observed. In addition to this event, data show that a similar, less developed, open field event may have occurred earlier, between 12:30 and 13:30 UT on day 38, and other examples might have occurred during closest approach when the channel electron multipliers (CEMs) were turned off.

As Ulysses approached the Io torus, background counting rates in both instruments due to penetrating particles from the inner radiation belt climbed above 10^6 count s^{-1}. To ensure the preservation of CEM gains for the primary mission over the solar poles, the CEMs were switched off during the day of closest approach. Thus, plasma was not observed in the more intense regions of the inner magnetosphere, where corotational features due to the high planetary rotation rate would be most observable, or in the Io torus, the most distinctive region of the Jovian magnetosphere. After the CEMs had been switched back on, Ulysses continued outbound through the middle magnetosphere, where particularly strong passages through the plasma sheet were observed on day 40 (see Fig. 2). During day 42, Ulysses passed into the outer magnetosphere, where plasma sheet excursions past the spacecraft disappeared or became indistinguishable from other activity. Then, in response to fluctuations of solar wind dynamic pressure or flow direction, or both, the magnetopause and bow shock passed Ulysses a number of times over a period of 4 days. The times of these crossings, determined from high time resolution electron data, are listed in Table 1.

Inbound during the encounter the ion experiment geometry did not permit measurement of magnetosheath ion flow, but outbound that flow was measured directly. Spectrograms of both ions and electrons for three magnetopause crossings on day 43 are shown in Fig. 4. These ion data confirm the identification of the magnetopause boundary layer discussed above. The coexistence of hot magnetospheric parti-

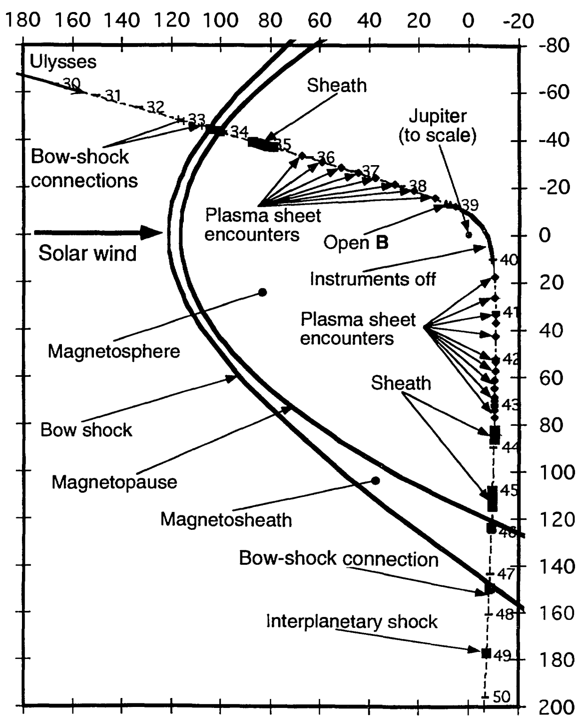

Fig. 3. Summary chart of the Ulysses flyby of Jupiter. The trajectory is shown in the plane of the encounter with various plasma features located and identified. Spacecraft position coordinates in planetary radii, R_J, are shown along the axes of the chart. Schematic conic sections, shown for illustrative purposes only, indicate the bow shock and magnetopause.

Table 1. Summary log of entry and exit times of the plasma regions encountered: solar wind (SW), magnetosheath (Msh), boundary layer (BL), and magnetosphere (Msp), with identification of the boundary crossed, bow shock (BS), or magnetopause (MP). The symbol MP? is used when the MP cannot be precisely identified and located with plasma data alone.

Day	Entry time (UT)	Exit time (UT)	Transition	Boundary
33	17:33	17:33	SW-Msh	BS
	21:35	23:00	Msh-BL-Msp	MP
34	16:55	17:20	Msp-BL-Msh	MP
	19:45	00:25	Msh-BL-Msh	MP?
35	01:00	01:25	Msh-BL-Msh	MP?
	02:50	04:00	Msh-BL-Msp	MP
43	13:37	13:57	Msp-BL-Msh	MP
	17:00	17:40	Msh-BL-Msp	MP
	18:20	19:10	Msp-BL-Msh	MP
45	00:37	00:37	Msh-SW	BS
	04:28	04:28	SW-Msh	BS
	09:45	10:30	Msh-BL-Msp	MP
	14:00	16:00	Msp-BL-Msp	MP?
	18:15	18:25	Msp-BL-Msp	MP?
	20:45	21:40	Msp-BL-Msh	MP
47	07:55	07:55	Msh-SW	BS

cles with magnetosheath particles on both sides of the magnetopause is clearly evident. Indeed, for these outbound crossings, hot particles are commonly present in the sheath outside the magnetopause, in contrast to the inbound crossing, where hot electrons were not observed until an hour after the magnetopause crossing. An interesting feature is seen in the crossing between 18:20 and 19:10 UT, where

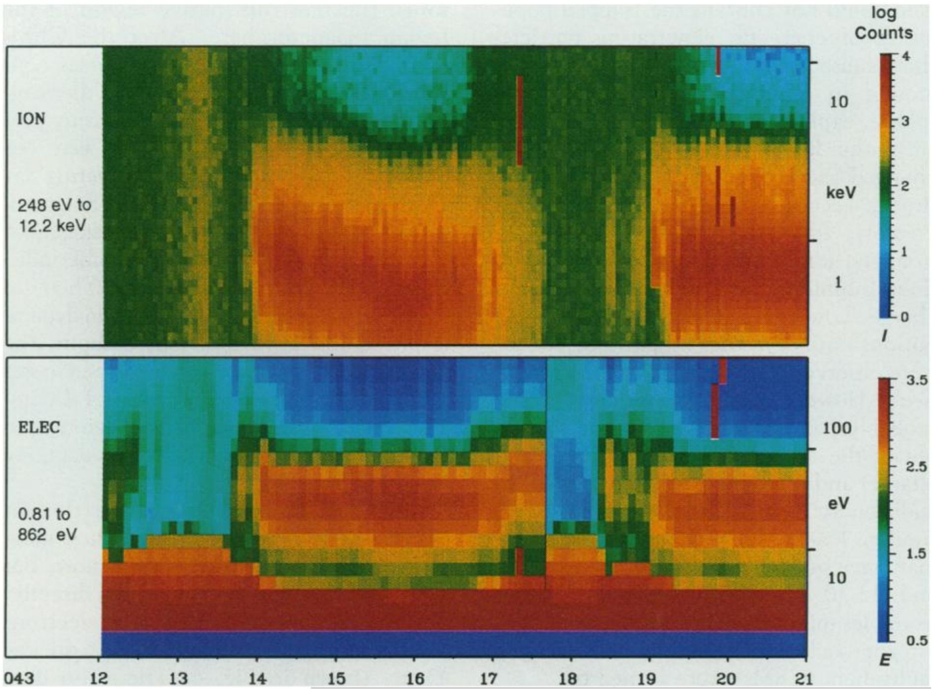

Fig. 4. Ion and electron energy spectrograms from day 43 showing three magnetopause crossings. Coexistence of energetic magnetospheric particles with magnetosheath particles across the boundaries is clearly evident from the overlapping of green at higher energies with yellow in the ion data, and light blue at higher energies with yellow in the electron data.

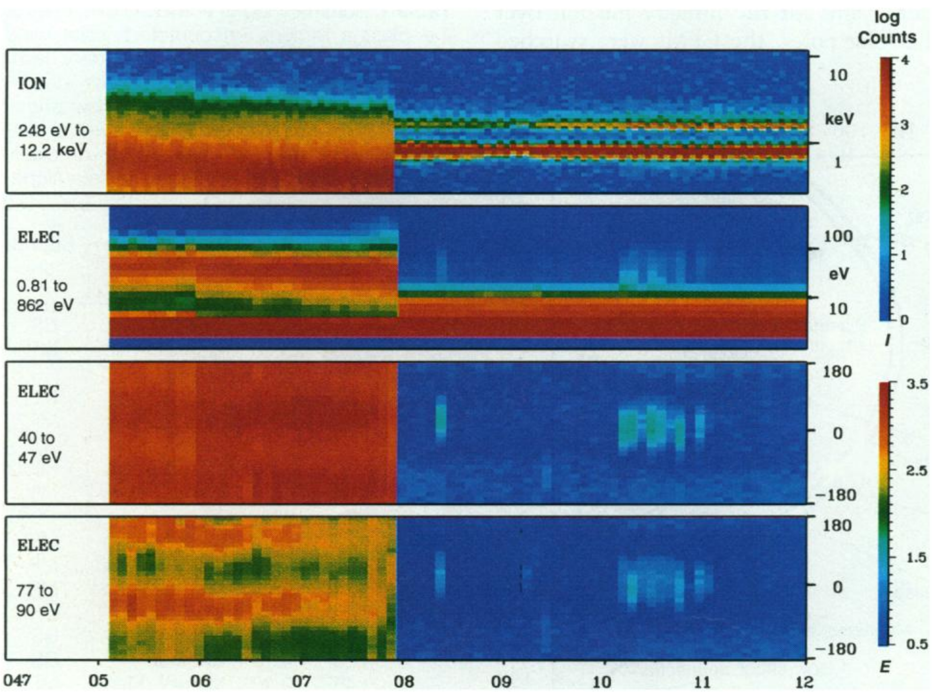

Fig. 5. Ion energy per charge and electron energy and angular distribution spectrograms showing the final exit of Ulysses through the bow shock on day 47. The angular distributions are for electrons in the two energy intervals given in the figure. After the bow-shock crossing, the apparent modulation of the well-resolved solar wind protons and helium ions is an artifact caused by use of interleaved energy level sets having wider spacing than ordinarily used for the solar wind.

sheath plasma ions entering the boundary layer apparently were accelerated to a speed higher than they had in the magnetosheath. This was probably a result of local reconnection between the IMF and the Jovian magnetic field, as has been observed extensively at Earth (9). Overall, the observation of an Earth-like magnetopause and boundary layer suggests that the solar wind interaction with the outer magnetosphere at Jupiter is similar to the terrestrial interaction and suggests the probable importance of reconnection for Jovian magnetospheric processes.

On day 45, Ulysses entered the solar wind and then returned to the magnetosheath. After the first bow shock crossing at 00:37 UT (see Fig. 1), the ion observations (not given here) showed the presence of upstream ions with properties similar to those of the "diffuse" suprathermal ions commonly observed at Earth in the upstream solar wind when a spacecraft is connected to the bow shock by the IMF (*10*). As at Earth, the presence of these upstream ions was correlated with compressive magnetic fluctuations.

Ulysses made its final bow-shock crossing at 07:55 UT on day 47. Figure 5 illustrates results from both the preshock magnetosheath and the postshock solar wind in which important Earth-like features are exhibited. In the solar wind, hot electrons due to magnetic connection are seen flowing upstream with varying intensity along the IMF, manifested by the lighter blue swath centered near 0° in the angular distribution spectrograms. Near 180°, the usual solar wind heat flux from the solar corona produces another less intense band. This bidirectionality is a common feature of bow-shock connection in the solar wind (*7*). In the angular distribution spectrograms of magnetosheath electrons in Fig. 5, it is evident that the electrons with energies from 40 to 47 eV have an anisotropy that is perpendicular to that of the electrons with energies from 77 to 99 eV. Comparison of the anisotropy at higher energies with the magnetic field orientation, provisionally given by the ~0° orientation of the postshock heat flux along the IMF and confirmed to be near 0° in the magnetic field data, reveals that the anisotropy at lower energies is aligned along the field, whereas at higher energies it is aligned perpendicular to the field. Earlier work has shown the same feature in the terrestrial magnetosheath (*11*). It has been suggested that leakage of higher energy electrons upstream along the field is responsible for the switchover in the orientation of anisotropy as a function of energy.

The plasma observations from the flyby are rich in detail, showing that the outer regions of the Jovian magnetosphere are remarkably similar to those of Earth. We anticipate that, as the plasma observations are analyzed in greater detail and as joint studies with combined data sets from the various investigations are completed, new discoveries will be made and our understanding of Jupiter's magnetosphere will improve significantly.

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4. Both instruments utilize spherical section electrostatic analyzers that direct analyzed particles into arrays of channel electron multipliers for detection. Electrons are measured from 1.59 to 862 eV and ions from 256 eV per charge to 35 keV per charge. The electron spectrometer is oriented to cover a range of polar angle of ±73° with respect to the equator of the spinning spacecraft, a range suitable for both magnetospheric and solar wind electrons. The ion spectrometer is designed to detect the narrow, antisunward beam of solar wind ions over limited ranges of azimuth and polar angle; this is generally less suitable for magnetospheric ions, which have broad distributions, often have unfavorable flow directions, and usually have low flux intensities. Sets of counts are obtained every 5.7 min for electrons and 4 min for ions as a function of azimuth (spin angle), polar angle (channel electron multiplier number), and energy (analyzer voltage level). Pertinent plasma parameters such as number density and temperature are derived from these sets.
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Energetic Charged-Particle Phenomena in the Jovian Magnetosphere: First Results from the Ulysses COSPIN Collaboration

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The Ulysses spacecraft made the first exploration of the region of Jupiter's magnetosphere at high Jovigraphic latitudes (~37° south) on the dusk side and reached higher magnetic latitudes (~49° north) on the day side than any previous mission to Jupiter. The cosmic and solar particle investigations (COSPIN) instrumentation achieved a remarkably well integrated set of observations of energetic charged particles in the energy ranges of ~1 to 170 megaelectron volts for electrons and 0.3 to 20 megaelectron volts for protons and heavier nuclei. The new findings include (i) an apparent polar cap region in the northern hemisphere in which energetic charged particles following Jovian magnetic field lines may have direct access to the interplanetary medium, (ii) high-energy electron bursts (rise times ≤1 minute and energies extending to >~17 megaelectron volts) on the dusk side that are apparently associated with field-aligned currents and radio burst emissions, (iii) persistence of the global 10-hour relativistic electron "clock" phenomenon throughout Jupiter's magnetosphere, (iv) on the basis of charged-particle measurements, apparent dragging of magnetic field lines at large radii in the dusk sector toward the tail, and (v) consistent outflow of megaelectron volt electrons and large-scale departures from corotation for nucleons.

Measurements of the population of high-energy electrons, protons, and heavier nuclei in Jupiter's magnetic field are essential for understanding the energetic and dynamic processes that govern the Jovian magnetosphere. For example, high-energy electrons [energy (E) > ~1 MeV], whose speed is near that of light, are trapped in the Jovian magnetic field and constrained to travel along the field lines. Their flow along the field lines and their intensity levels provide information about both their origins and the large-scale structure of the magnetic field far from the point of observation. Their speed of propagation along the field also makes them sensitive probes of rapid changes in the magnetic field configuration along the field lines on which they are trapped. Considered together with observations from radio, magnetic field, and plasma investigations, measurements of the trapped electrons and nucleons provide the evidence needed to begin to understand the complex flow of energy between particles and electromagnetic fields and radiation that characterizes the Jovian magnetosphere.

Previous missions that penetrated the magnetosphere of Jupiter (Pioneer 10 and 11 in 1973 and 1974, respectively, and the Voyager 1 and 2 missions in 1979) probed the sunward side and the dawn side (Fig. 1) of the magnetosphere. The Ulysses spacecraft investigated for the first time the region at high latitudes on the dusk side and also reached higher latitudes on the day side than any previous flyby. Ulysses has confirmed many results and conclusions from the earlier missions (*1*, *2*) and, through the broader range of sensitivity of its instrumentation and the exploration of new regions of the magnetosphere, has yielded many surprises and new understandings of the energetics and dynamics of the magnetosphere and its high-energy particles. In this paper, we summarize the most significant results concerning the high-energy particles to come from our early analysis of data from the cosmic ray and solar particle investigations (COSPIN) experiment.

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