Ulysses at Jupiter: An Overview of the Encounter

E. J. Smith, K.-P. Wenzel, D. E. Page

In February 1992, the Ulysses spacecraft flew through the giant magnetosphere of Jupiter. The primary objective of the encounter was to use the gravity field of Jupiter to redirect the spacecraft to the sun's polar regions, which will now be traversed in 1994 and 1995. However, the Ulysses scientific investigations were well suited to observations of the Jovian magnetosphere, and the encounter has resulted in a major contribution to our understanding of this complex and dynamic plasma environment. Among the more exciting results are (i) possible entry into the polar cap, (ii) the identification of magnetospheric ions originating from Jupiter's ionosphere, Io, and the solar wind, (iii) observation of longitudinal asymmetries in density and discrete wave-emitting regions of the Io plasma torus, (iv) the presence of counter-streaming ions and electrons, field-aligned currents, and energetic electron and radio bursts in the dusk sector on high-latitude magnetic field lines, and (v) the identification of the direction of the magnetic field in the dusk sector, which is indicative of tailward convection. This overview serves as an introduction to the accompanying reports that present the preliminary scientific findings. Aspects of the encounter that are common to all of the investigations, such as spacecraft capabilities, the flight path past Jupiter, and unique aspects of the encounter, are presented herein.

The name of the Ulysses mission is intended to evoke an image of an adventurous traveler to previously unknown or unexplored regions. In this instance, the regions referred to are above and below the sun's poles at distances between 1.7 and 2.9 astronomical units (AU). While traveling through these regions, and enroute to them, Ulysses, a joint venture of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), will investigate the sun and solar wind, the heliosphere, interstellar matter, and signals from the galaxy (*1*, *2*).

Although it has long been a goal of space scientists to escape the narrow confines of the ecliptic plane in which Earth orbits the sun, practical considerations have prevented this until recently. Existing launch vehicles cannot supply sufficient energy to propel a spacecraft directly into a solar polar orbit from Earth. A spacecraft can achieve a polar orbit, however, by taking advantage of the gravity of another planet. Jupiter is the nearest celestial body capable of meeting these requirements, and the use of the gravity of Jupiter to carry out the primary mission of Ulysses has made possible its recent flight through the Jovian magnetosphere.

Ulysses was launched on 6 October 1990 by the space shuttle Discovery and three upper-stage solid rockets. A schematic of its resulting interplanetary trajectory appears in Fig. 1. Ulysses traveled to Jupiter along an elliptical orbit nearly coincident with the ecliptic plane. It arrived at Jupiter in February 1992, with its closest approach occurring at 12:02 universal time (UT) on 8 February. The targeting proved to be very accurate so that the desired highly inclined solar orbit was achieved. Ulysses will now descend toward the sun's south pole, continue along its elliptical path upward to the ecliptic plane, and then traverse the sun's north polar regions. The orbital inclination slightly exceeds 80°, and Ulysses will spend a total of 234 days above 70° heliographic latitude.

The opportunity to study Jupiter's magnetosphere (Fig. 2) was exploited to the greatest extent possible. Jupiter is a strongly magnetized, rapidly rotating planet. Its magnetosphere is the largest in the solar system, a fact reflected in the long interval of 12 days that it took for Ulysses to travel through it. The large Galilean satellites are embedded within the magnetosphere, and Io is known to be a prolific source of ions and neutral particles. Ions, predominantly of sulfur and oxygen, are distributed around the Io orbit to form a large torus. Electrons and ions from Io, Jupiter's ionosphere, and the solar wind are all present and are transported throughout the magnetosphere.

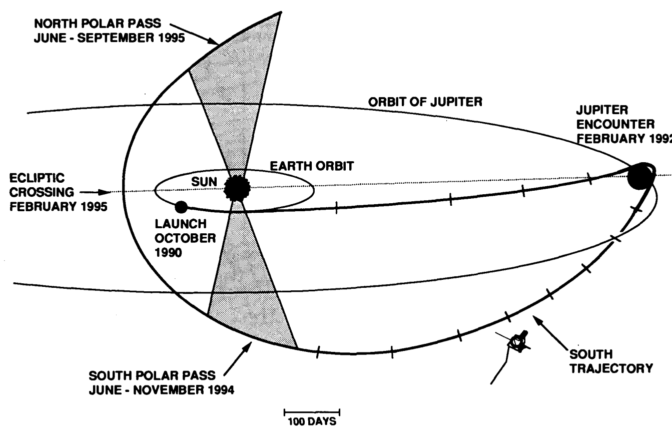

Fig. 1. Trajectory profile of the Ulysses mission. The in-ecliptic trajectory from Earth to Jupiter defines the initial mission phase. The Jupiter encounter effectively rotates the elliptical orbit with the aphelion near 5 AU so that the orbit is inclined 80° to the ecliptic plane. Key events with their dates are noted.

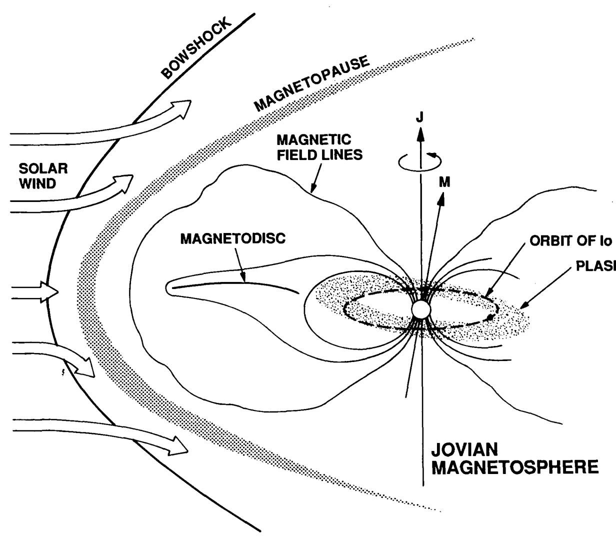

Fig. 2. Schematic of Jupiter's magnetosphere. The solar wind, approaching from the left, tends to be deflected around the magnetosphere by the bow shock. Entry of the shocked solar wind into the magnetosphere is opposed by the planetary magnetic field and its associated ionized gases. The outer boundary of the magnetosphere, called the magnetopause, is indicated. Major structural features within the magnetosphere are shown. J, rotation axis; M, magnetic axis.

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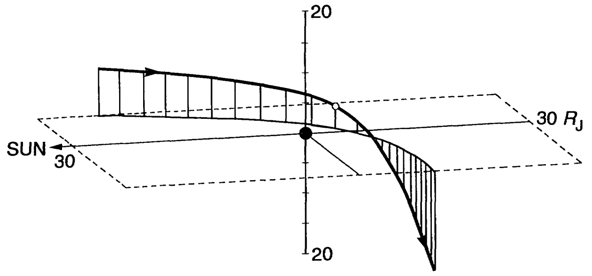

Fig. 3. The Ulysses trajectory past Jupiter (closed circle). The portion of the trajectory nearest closest approach (open circle) is shown in a three-dimensional view (heavy line). The trajectory is also shown as projected onto the plane (dashed lines) of the Jovian equator. The vertical lines denote intervals of 3 hours relative to closest approach. Distance is measured in Jupiter radii.

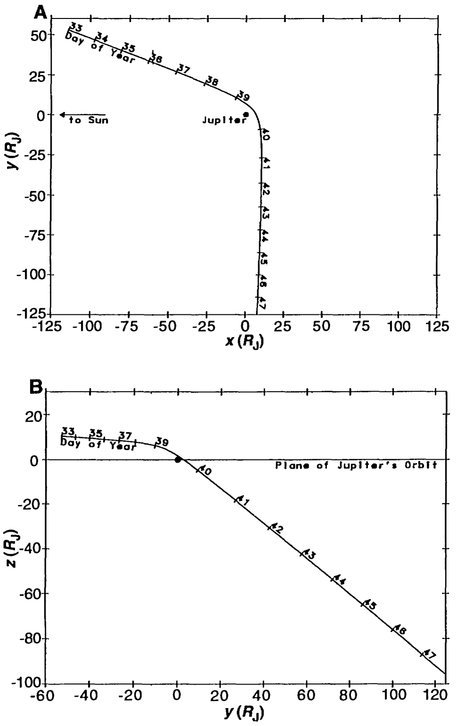

Fig. 4. Ulysses' trajectory near Jupiter. The trajectory is shown in plan and elevation. In (**A**), the flight path is projected onto Jupiter's orbital plane (essentially the equator). (**B**) The trajectory of Ulysses as seen from the solar direction. Numbers indicated show the day of the year.

A substantial fraction of these particles are accelerated to extremely high energies to form intense radiation belts. The presence of the ions in the rapidly rotating magnetic field causes the lines of force to stretch radially outward to large distances, producing the unique "magnetodisc." A complex buffer zone exists between the outer edge of the magnetodisc and the magnetopause or outer boundary of the magnetosphere, which separates the magnetized Jovian plasma from solar wind plasma. Upstream of the magnetosphere, in the free-streaming solar wind, a detached bow shock forms that slows the solar wind and allows it to be deflected around the magnetosphere.

The near-Jupiter trajectory of Ulysses is shown in Fig. 3. Ulysses approached Jupiter at a local time of 10.5 hours and at a Jovigraphic latitude of ≈5°N. Closest approach occurred at a radial distance of 6.31 R_J [1 Jupiter radius (R_J) = 71,398 km], at a local time of 1.5 hours, and at a latitude of 30°N. The outbound trajectory carried the spacecraft into the dusk sector at a local time of ≈18:00 hours. The Jovigraphic latitude outbound was the somewhat larger value of ≈37°S at large distances from Jupiter. (The spacecraft did not pass over Jupiter's pole as is sometimes assumed.) Referred to the planet, the instantaneous longitude of Ulysses was specified by the use of system III (1965) (*3*). The times implicit in this calculation, subsequent figures, Table 2, and the individual reports following are spacecraft event times (SCET). They are the universal time of events as they occurred at Ulysses after correction for the delay introduced by the propagation of the radio telemetry signals to Earth. An alternative view of the trajectory that is more useful for some purposes is presented in Fig. 4. A view of the trajectory as projected onto the Jovian equatorial plane is shown in Fig. 4A; the trajectory as seen from the sun-Jupiter direction appears in Fig. 4B.

Because the magnetic latitude of the spacecraft is an important parameter, the encounter trajectory is also shown in magnetic coordinates (Fig. 5). This traditional "wiggle" diagram shows Ulysses' instantaneous location relative to Jupiter's magnetic dipole represented as the equatorial distance (horizontal) and the axial distance perpendicular to the equatorial plane (vertical). The magnetosphere was greatly expanded because of a low external solar wind pressure leading to several crossings by Ulysses of the magnetic equator at large distances during the inbound leg. Along the outbound trajectory, the latitude of Ulysses was sufficiently high that no penetrations of the magnetic equator occurred except a single crossing just after closest approach.

The inbound trajectory of Ulysses was similar to those of the four spacecraft which earlier flew past Jupiter: Pioneer 10 and 11 (1972 and 1973, respectively) and Voyager 1 and 2 (1979) (*4–7*). A unique aspect of the Ulysses flight path was the penetration of the Io plasma torus (IPT) a few hours after closest approach in basically a north-to-south direction that contrasted with the nearly equatorial Voyager 1 traversal (Fig. 6). In addition to this direct penetration, the spacecraft radio signal passed through the IPT for a significant length of time, making it possible to probe the electron density distribution in the torus (*8*). Another unique aspect of the encounter was the outbound passage through the previously unexplored dusk sector of the magnetosphere.

A sketch of the spacecraft appears in Fig. 7. Ulysses rotates continuously about the center line of the high-gain antenna (HGA). The spacecraft equator contains the power generator, a boom that contains four experiment sensors, and a very long antenna. A third experiment antenna extends parallel to the spin axis opposite the HGA (*9, 10*).

The scientific capability of Ulysses is comprised of 11 investigations (Table 1) (*11*). The instruments were designed to return data from the solar polar regions that will be comparable to the best measurements available from the ecliptic. Noteworthy features are continuous coverage in

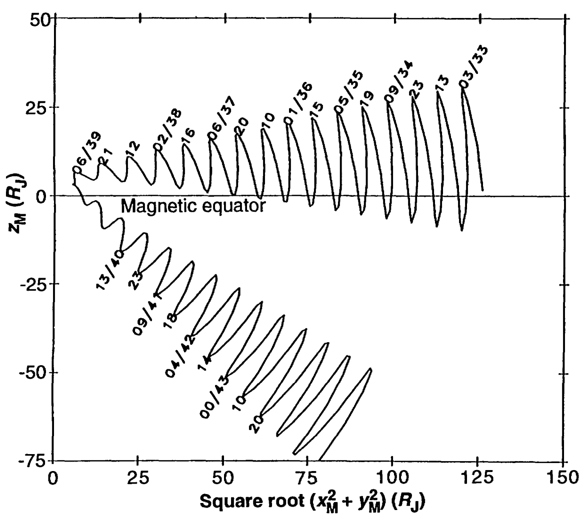

Fig. 5. The Ulysses trajectory in magnetic coordinates. The horizontal axis represents the component of spacecraft distance in the equatorial plane of the planet's magnetic dipole (subscript M, magnetosphere). The vertical axis is the distance from the magnetic equator in a direction parallel to the axis of the dipole. The trajectory appears to oscillate in this representation as a result of the rotation of the tilted dipole around Jupiter's spin axis. The times at which the spacecraft was at maximum latitude are shown as the nearest hour followed by the day of the year.

frequency from 0 to 1 MHz provided by the magnetometer and radio/plasma wave experiments and continuous coverage in charged-particle energies from a few electron volts (solar wind electrons) to hundreds of megaelectron volts (primary cosmic rays). The particle experiments have the capability to make composition, charge state, and anisotropy measurements.

Although designed to carry out the objectives of the primary mission, the experiments are well suited to studies of the Jovian magnetosphere and are superior in some respects to those of the earlier Pioneers and Voyagers. A major compromise between the primary scientific objectives of the mission and the secondary objectives of studying Jupiter was made in the choice of dynamic range. Some of the particle experiments and the x-ray experiment were unable to make measurements in the most intense parts of the radiation belts, and several were shut off near closest approach.

The joint European Space Agency/Jet Propulsion Laboratory mission operations team functioned 24 hours per day throughout the encounter. In general, the encounter plan developed several months in advance was followed. An unusually large number of commands were transmitted to Ulysses during the 17-day encounter as compared to those transmitted during normal operations. The operations team and the spacecraft performed flawlessly and, in spite of the hostile Jovian environment, no anomalies were experienced.

Table 2 provides an overall chronology of significant events presented in the accompanying reports. Times (SCET) are given as day of year, hour, and minute. The radial distance and the sun-Jupiter-spacecraft angle are also indicated. The latter is

Table 1. Ulysses' scientific investigations.

Investigation	Principal investigator	Measurement	Instrumentation
Magnetic field	A. Balogh, Imperial College of Science and Technology, London	Spatial and temporal variations of the heliospheric and Jovian magnetic field in the range 0.01 to 44,000 nT	Triaxial vector helium and flux gate magnetometers
Solar-wind plasma	S. J. Bame, Los Alamos National Laboratory	Solar-wind ions between 260 eV/Q and 35 keV/Q Solar-wind electrons between 1 and 900 eV	Two electrostatic analyzers with channel electron multipliers
Solar-wind ion composition	J. Geiss, Universität Bern, and G. Gloeckler, University of Maryland	Elemental and ionic charge composition, temperature, and mean velocity of solar-wind ions for speeds from 175 km/s(H^+) to 1280 km/s(Fe^{8+})	Electrostatic analyzer with time-of-flight and energy measurement
Low-energy ions and electrons	L. J. Lanzerotti, AT&T Bell Laboratories	Energetic ions from 50 keV to 5 MeV Electrons from 40 to 300 keV	Two sensor heads with five solid-state detector telescopes
Energetic-particle composition and interstellar gas	E. Keppler, Max-Planck-Institut, Lindau	Composition of energetic ions from 80 keV to 15 MeV/per nucleon Interstellar neutral helium	Four solid-state detector telescopes LiF-coated conversion plates with channel electron multipliers
Cosmic rays and solar particles	J. A. Simpson, University of Chicago	Cosmic rays and energetic solar particles in the range 0.5 to 600 MeV/nucleon Electrons in the range 2.5 to 6000 MeV	Five solid-state detector telescopes, one double Cerenkov and semiconductor telescope for electrons
Unified radio and plasma waves	R. G. Stone, Goddard Space Flight Center	Plasma waves Solar radio bursts Electron density Magnetic field: 0.1 to 500 Hz Electric field: plasma waves: 0 to 60 kHz Radio receiver: 1 to 940 kHz	72-m radial dipole antenna 8-m axial monopole antenna Two-axis search coil
Solar x-rays and cosmic gamma-ray bursts	K. Hurley, University of California at Berkeley, and M. Sommer, Max-Planck-Institute, Garching	Solar-flare x-rays and cosmic gamma-ray bursts in the energy range 5 to 150 keV	Two Si solid-state detectors Two CsI scintillation crystals
Cosmic dust	E. Grün, Max-Planck-Institut, Heidelberg	Direct measurement of particulate matter in mass range 10^{-16} to 10^{-6} g	Multi-coincidence impact detector with channeltron
Coronal sounding	M. K. Bird, Universität Bonn	Density, velocity, and turbulence spectra in the solar corona and solar wind	Spacecraft transponder
Gravitational waves	B. Bertotti, Universitá di Pavia	Doppler shifts in radio signal received at Earth due to passage of wave	Spacecraft transponder

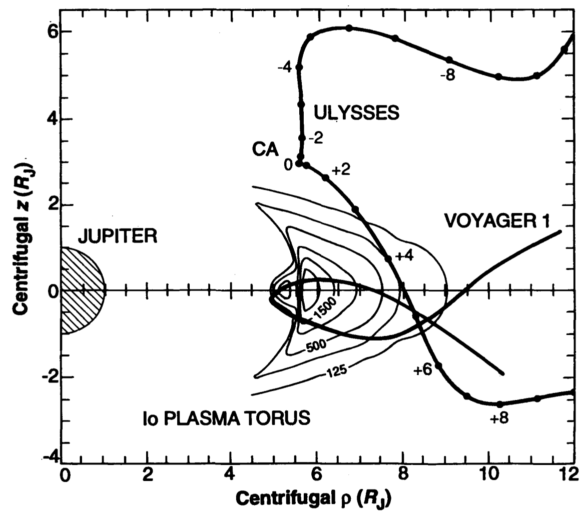

Fig. 6. Passage of Ulysses through the IPT as compared to the passage of Voyager 1. The trajectories of Ulysses and Voyager 1 (heavy lines) are shown near Jupiter in cylindrical coordinates, ρ, parallel to the centrifugal equator, and *z*, perpendicular to the centrifugal equator. Numbers along the Ulysses trajectory denote hours before (negative) and after (positive) closest approach (CA). The light lines are contours of equal plasma density (per cubic centimeter) inferred from Voyager 1 observations (*8*).

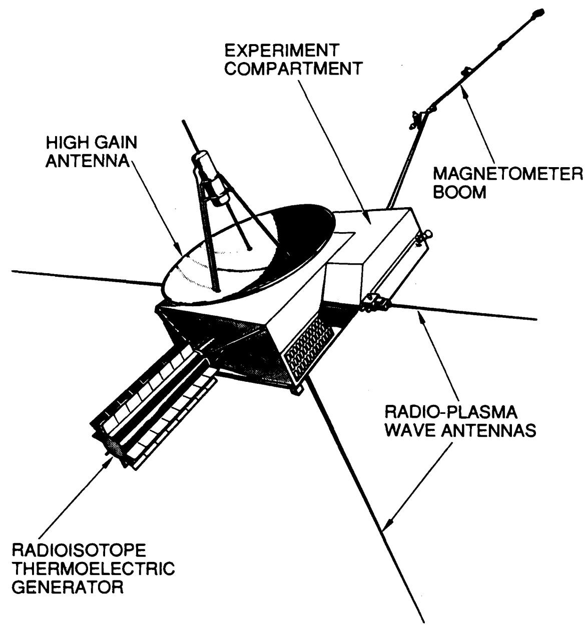

Fig. 7. The Ulysses spacecraft. The major elements of the spinning spacecraft are shown. Only a portion of the long wire antennas deployed in the equatorial plane (also containing the experiment boom and the radioisotope thermoelectric generator) can be seen in this view.

Table 2. Sequence of events in Ulysses' flyby of Jupiter, covering days 33 to 47, 2 February to 16 February 1992.

Event	Time (day, hour, min)	Distance from Jupiter (R_J)	Sun-Jupiter-spacecraft angle (degrees)
Bow-shock crossing	033/17:33	113	26.2
Magnetopause crossings	033/21:30 to 035/04:00	110 to 87	26.3 to 27.8
Crossings of magnetodisc/plasmadisc	036/06:30 to 037/22:00	67 to 36	30.0 to 37.7
High-latitude observations of energetic particle dropout, possible cusp or polar cap	038/22:30 039/06:30	15 8.7	58.7 89.6
Closest approach	039/12:02	6.31	143.1
Observations of Io plasma torus	039/14:00 to 039/19:30	6.7 to 10.1	164.0 to 146.7
Observation of field-aligned currents and streaming electrons and ions	041/01:00 to 043/13:00	35 to 82	106.5 to 96.2
Magnetopause crossings	043/13:57 to 045/21:40	83 to 124	96.2 to 93.4
Bow-shock crossings	045/00:37 to 047/07:52	109 to 149	94.2 to 92.4

the angle of a cone whose axis is the sun-Jupiter direction; thus, it is restricted to 180°. Allowance may need to be made for the spacecraft being on one side of the axis or the other in order to interpret the geometry properly. The meaning and significance of these events are discussed further in the scientific reports that follow.

An important accompaniment to the encounter was a set of supporting observations carried out by ground-based observers, particularly those involved in the Jupiter Watch program, as well as by observers making use of Earth-orbiting spacecraft including the Hubble Space Telescope (HST) and the International Ultraviolet Explorer (IUE). This remote sensing of emissions from Jupiter's auroral regions and the IPT has helped establish the context in which the encounter took place.

Ulysses is only the fifth spacecraft to fly through Jupiter's magnetosphere. Upon its arrival, the solar wind ram pressure was low, and the magnetosphere extended beyond 100 R_J at the point of entry. The physical state of the magnetosphere was more reminiscent of the Pioneer 10 and 11 arrivals than of the Voyager arrivals, which found a more compressed magnetosphere.

The Ulysses experiments are highly complementary, an important advantage considering some of the unusual regions through which the spacecraft passed. In the inner magnetosphere inside 15 R_J and at high latitudes, for example, the energetic particle population suddenly dropped to interplanetary levels, the low-energy plasma electrons simultaneously developed the characteristics of the external solar wind or magnetosheath, and bursts of electromagnetic waves identified as auroral hiss were observed. The magnetic field measurements, on the other hand, showed only the presence of the strong planetary field. These observations are interpreted as indicating the entry of the spacecraft into a region of "open" field lines extending outward from Jupiter into interplanetary space, probably the polar cap, a characteristic feature of Earth's magnetosphere.

Hot plasma ions that, with the magnetic field, dominate the magnetospheric structure and dynamics were identified, and three major sources were shown to be contributors. The IPT produces copious numbers of sulfur and oxygen ions. The solar wind, perhaps as a result of the open field lines, contributes hydrogen (H^+) and helium (He^{2+}). Ions of ionospheric origin, such as H_3^+, were also present. The high-energy–trapped radiation was shown to be a mixture of ions from the IPT and the solar wind. The IPT turned out to be more patchy than anticipated, with significant differences in density at different longitudes. A characteristic electromagnetic emission, called narrow-band kilometric radiation, was shown to originate from five separate bright radio sources distributed along, and rotating with, the torus.

In the previously unexplored dusk sector at high latitudes, intense beams of hot ions and electrons were observed to be streaming both inward and outward along magnetic field lines. Characteristic small-scale deviations of the planetary field indicated the simultaneous presence of field-aligned currents. Very short bursts of high-energy electrons accompanied by bursts of radio waves were also seen. A reasonable interpretation is that these phenomena are manifestations of the Jovian aurora.

Also in the dusk sector, the magnetic field was found to be bent out of the meridian planes associated with the corotating planetary field as a consequence of being swept downstream into the tail of Jupiter's magnetosphere. The times of occurrence of the peaks in the flux of trapped energetic particles support this interpretation. This major structural feature shows a surprisingly strong influence of the solar wind on Jupiter's magnetosphere and was not anticipated by the most widely accepted magnetospheric models before the encounter.

The overall result of Ulysses' encounter with Jupiter has been a major contribution to our understanding of Jupiter's unusual and complex magnetosphere. The comprehensive set of Ulysses measurements will continue to grow in scientific worth as more research workers become involved, as the data are examined in greater detail, and as comparisons are made with the earlier Pioneer and Voyager observations and the forthcoming Galileo orbiter. This adventure has been a productive side trip on the journey of Ulysses to the sun's polar regions.

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3. "Jupiter System III" (1965), adopted by the International Astronomical Union in 1976, is based on a sidereal rotation period of 9 hours, 55 min, and 29.71 s. According to the usual astronomical convention, longitude is measured clockwise from the prime meridian (the longitude corresponding to the Jupiter-Earth direction in 1965.00). For a further discussion, see A. J. Dessler, in (*7*), pp. 498–504. Trajectory information was supplied by the Ulysses project at the Jet Propulsion Laboratory.
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5. T. Gehrels, Ed., *Jupiter* (Univ. of Arizona Press, Tucson, 1976).
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9. The Ulysses spacecraft (Fig. 7) spins about the center line of the HGA at a rate of 5 rpm. The radio system transmits at X band or S band or both, and the spin axis must be re-aligned every few days to orient the HGA toward Earth as the spacecraft moves along its trajectory. Power is supplied by a radioisotope thermoelectric generator mounted outboard of the spacecraft body in the equatorial plane. Other appendages support scientific investigations: (i) a radial boom containing two magnetometer sensors, an x-ray/gamma-ray sensor and a set of search coils, (ii) a pair of wires deployed in the spacecraft equator forming a long (72 m) radio wave/plasma wave antenna, and (iii) an 8-m antenna deployed in the direction opposite the HGA and parallel to the spin axis that also detects radio-plasma waves (*9, 10*). An on-board tape recorder is normally used to maintain continuous coverage with a single 8-hour acquisition interval at a 34-m-deep space net (DSN) antenna. During the Jupiter flyby, however, the DSN provided continuous coverage in real time (two 34-m passes and one 70-m pass per day) from 31 January to 16 February (closest approach ± 100 R_J). It was thereby unnecessary to use the spacecraft recorder and possible to maintain a high data rate of 1024 bits per second. The spacecraft was designed and built by Dornier GmbH, Friedrichshafen, Germany, under a contract with the European Space Research and Technology Centre (ESTEC), Noordwijk, Netherlands.
10. Spacecraft coordinates form the reference system used in many of the accompanying reports. The center line of the HGA is taken as the polar or *z*-axis. Sun sensors determine the time at which the *x*-axis crosses the plane defined by *z* and the direction to the sun, *s*. Actually, the third axis, *y*, is the cross product between *z* and *s* ($z \times s$), and *x* is orthogonal to *y* and *z* to form a right-handed system. At the encounter, the sun, as seen from the spacecraft, was to the right of *z* ("sun right"), making *y* point southward.
11. Extensive descriptions of the instruments, along with preliminary interplanetary observations, are available in "Ulysses Instruments: Special Issue," *Astron. Astrophys. Suppl. Ser.* **92** (January 1992).

12. Portions of this report represent work done by the Jet Propulsion Laboratory of the California Institute of Technology for the National Aeronautics and Space Administration. J. Wolf assisted in the preparation of the trajectory figures.

12 June 1992; accepted 13 August 1992

Volcanic Activity on Io at the Time of the Ulysses Encounter

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The population of heavy ions in Io's torus is ultimately derived from Io volcanism. Ground-based infrared observations of Io between October 1991 and March 1992, contemporaneous with the 8 February 1992 Ulysses observations of the Io torus, show that volcanic thermal emission was at the low end of the normal range at all Io longitudes during this period. In particular, the dominant hot spot Loki was quiescent. Resolved images show that there were at least four hot spots on Io's Jupiter-facing hemisphere, including Loki and a long-lived spot on the leading hemisphere (Kanehekili), of comparable 3.5-micrometer brightness but higher temperature.

The ultimate source of the heavy ions of the Io plasma torus and the rest of the Jovian magnetosphere is Io's volcanism (*1*), although the path taken by oxygen, sulfur, or other atoms between volcanic eruption and escape from Io is not well established. One clue as to the mechanisms involved is provided by the time variations that are seen in both the volcanic activity and the magnetospheric ion populations (*2–5*). We present ground-based observations of Io's 2.2- to 4.8-μm volcanic thermal emission made during the period October 1991 to March 1992, surrounding the Ulysses encounter with Jupiter. The observations record exposed surface materials at temperatures of 300 to 700 K. Although this range may not include all types of volcanic activity, the thermal emission provides our only current technique for monitoring Io volcanism from Earth.

The most sensitive ground-based measurements of Io's volcanism are obtained during eclipses of Io by Jupiter's shadow, when reflected sunlight is eliminated (*4*). At wavelengths less than 8 μm, passive thermal radiation is negligible, and essentially all the radiation is volcanic thermal emission. However, only the Jupiter-facing hemisphere of Io can be observed in a Jupiter eclipse. We used a 1- to 5-μm infrared camera with a 62 by 58 pixel InSb array ("ProtoCAM") at the 3.2-m aperture NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. Approximately ten eclipses of Io are observed each year. Atmospheric conditions frequently allow direct resolution of individual volcanic hot spots on Io's 1-arc-sec-diameter disk. Photometry of occultations of Io by Jupiter's disk provides additional constraints on the fluxes

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