Ulysses Above the Sun's South Pole: An Introduction

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Ulysses has explored the field and particle environment of the sun's polar region. The solar wind speed was fast and nearly constant above −50° latitude. Compositional differences were observed in slow (low-latitude) solar wind and in fast (high-latitude) solar wind. The radial magnetic field did not change with latitude, implying that polar cap magnetic fields are transported toward the equator. The intensity of galactic cosmic rays was nearly independent of latitude. Their access to the polar region is opposed by outward-traveling, large amplitude waves in the magnetic field.

The goal of the Ulysses mission was to escape the confines of the solar equator, where all previous measurements had been made, and to reach the vicinity of the sun's poles (*1*). The spacecraft, launched on 6 October 1990 from the space shuttle, used three upper stages to escape the Earth's gravity en route to Jupiter. The encounter with Jupiter on 11 February 1992 rotated the orbit 80° relative to the solar equator. The resulting flight path (Fig. 1) passed under the south pole of the sun, returned to the ecliptic (March 1995), and will pass over the north pole (June through September 1995). Ulysses reached a maximum latitude of −80.22° on day 256 (13 September) of 1994 (Fig. 2). The radial distance from the sun at that time was 2.29 astronomical units (AU).

Ulysses spins at five revolutions per minute about the center line of a high gain antenna pointed at Earth. The spacecraft contains nine body-mounted hardware experiments (*2*). Four sensors lie along an equatorial boom. Two long wires in the equator and a third deployed along the spin axis are radio- and plasma-wave antennas. These experiments (Table 1) are providing comprehensive measurements of essentially all of the fields and particles of scientific interest without gaps in energy or frequency coverage. Six interdisciplinary study teams (Table 2) are assisting in data interpretation.

The sun's outer atmosphere (*3*), which is normally visible only at times of eclipse, consists of two distinct regions: a narrow shell (the chromosphere) lying just above the solar surface (the photosphere) and a more extended highly structured upper atmosphere (the corona). At the high temperatures and low densities in these regions, the solar gas is a completely ionized plasma consisting solely of electrons and the electrically charged atoms (ions) from which they have been removed. A conversion of random thermal motion into directed motion, analogous to that occurring in a rocket engine, causes part of the corona to flow outward as the high-speed solar wind.

The sun, like most planets and other stars, is magnetized. Electrical currents inside the sun produce magnetic fields that extend upward through the surface and into the atmosphere. The magnetic fields impose a large-scale structure on the corona. Near the equator, the magnetic lines of force begin and end in the photosphere to form loops (closed field lines). These field lines are customarily stretched out and appear as visible coronal structures called streamers. At high latitudes, the field lines can have one end on the sun with the other end extending radially outward (open field lines). In these regions, the plasma continuously flows into space, and the lower density that results causes dark regions called coronal holes.

As the sun rotates, the solar wind in the ecliptic alternately comes from low and high magnetic latitudes, and its speed varies from low to high values. Before reaching the orbit of Earth, the high-speed wind overtakes the slower wind and compresses it to form regions of piled-up magnetized plasma (corotating interaction regions). This interaction can lead to the generation of collisionless shocks and the local acceleration of particles to high energies.

The solar wind expands and pushes the nearby interstellar plasma out of the solar system to an estimated distance of about 100 AU to form the heliosphere (*4*). Interstellar gas is only partially ionized and neutral atoms (mostly hydrogen and helium) can enter the heliosphere directly as can interstellar dust. Galactic cosmic rays, atomic nuclei accelerated to relativistic speeds in distant cataclysmic events, also enter the heliosphere but are strongly affected by the solar wind magnetic fields.

The recent polar pass by Ulysses showed that the solar wind (*5*) increased in speed from ~400 to ~750 km/s. Up to a latitude of ~−30° (approximately the tilt angle of the sun's magnetic dipole), large variations in speed were seen at the solar rotation period of ~26 days. Above ~−50° latitude, the solar wind became nearly constant in speed and was coming from a coronal hole covering the south polar cap.

The heavy ion compositions of the slow (low-latitude) and fast (high-latitude) solar wind were markedly different, with sharp compositional boundaries between the two types of flow (*6*). Magnesium, which ionizes relatively easily, was more abundant than oxygen in slow streams, but the Mg/O ratio changed abruptly between slow and fast streams. The abundances were not what would be expected for ions formed in the hot corona but are representative of values in the lower temperature chromosphere.

Measurements of the radial component of the magnetic field, which is most easily related to the global solar magnetic field, failed to show a latitudinal gradient (*7*). Because remote sensing solar measurements reveal a well-developed dipolelike magnetic field, magnetic flux from the poles is being moved toward the equator to yield a uniform field. Models used in the past, which have ignored the effect of magnetic stresses on solar wind acceleration, must be reexamined.

Before Ulysses, it was anticipated that the flux of cosmic rays would be much greater in the polar regions than near the

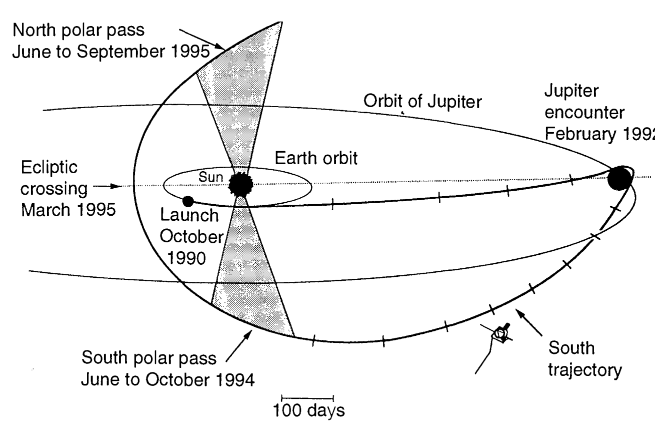

Fig. 1. The flight path of Ulysses from launch to the end of the prime mission. The scientific requirements imposed on the trajectory design were to spend as much time as possible above ±70° latitude and to achieve the highest possible latitude. The spacecraft will continue to follow the highly inclined ellipse for at least the next several hundred years.

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Table 1. The nine hardware and two radio experiments on board Ulysses. MPAe, MPE, and MPK are the Max Planck Institutes of Aeronomy; Physics and Astrophysics, and Nuclear Physics; UC is the University of California.

Investigation	Acronym	Principal investigator	Measurement
Magnetic field	VHM/FGM	A. Balogh, Imperial College, London (UK)	Spatial and temporal variations of the heliospheric magnetic field: 0.01 to 44,000 nT
Solar wind plasma	SWOOPS	J. L. Phillips, Los Alamos National Laboratory (USA)	Solar wind ions: 260 eV to 35 keV per ionic charge; solar wind electrons: 0.8 to 860 eV
Solar wind ion composition	SWICS	J. Geiss, University of Bern (Switzerland), and G. Gloeckler, University of Maryland (USA)	Elemental and ionic-charge composition, temperature, and mean speed of solar wind ions: 145 km/s (H^+) to 1350 km/s (Fe^{+8})
Radio and plasma waves	URAP	R. G. Stone, NASA Goddard Space Flight Center (USA)	Plasma waves, solar radio bursts, electron density, and electric field (plasma waves: 0 to 60 kHz; radio: 1 to 940 kHz; magnetic: 10 to 500 Hz)
Energetic particles and interstellar neutral gas	EPAC/GAS	E. Keppler, MPAe, Lindau (Germany)	Energetic ion composition: 80 keV to 15 MeV per nucleon; neutral helium atoms
Low-energy ions and electrons	HISCALE	L. J. Lanzerotti, AT&T Bell Labs, New Jersey (USA)	Energetic ions: 50 keV to 5 MeV; energetic electrons: 30 to 300 keV
Cosmic rays and solar particles	COSPIN	J. A. Simpson, University of Chicago (USA)	Cosmic rays and energetic particles ions: 0.3 to 600 MeV per nucleon; electrons: 4 to 2000 MeV
Solar x-rays and cosmic gamma-ray bursts	GRB	K. Hurley, UC Berkeley (USA) and M. Sommer, MPE, Garching (Germany)	Solar flare x-rays and cosmic gamma-ray bursts: 15 to 150 keV
Cosmic dust	DUST	E. Grun, MPK, Heidelberg (Germany)	Dust particles: 10^{-16} to 10^{-7} g
		Radio science	
Coronal sounding	SCE	M. K. Bird, University of Bonn (Germany)	Density, velocity, and turbulence spectra in solar corona and solar wind
Gravitational waves	GWE	B. Bertotti, University of Pavia (Italy)	Doppler shifts in spacecraft radio signal as a result of gravitational waves

ecliptic. In the polar caps, the radial magnetic field was expected to allow easier access of the cosmic rays to the heliosphere. However, the cosmic ray observations from Ulysses showed only a slight increase from the equator to the poles (8).

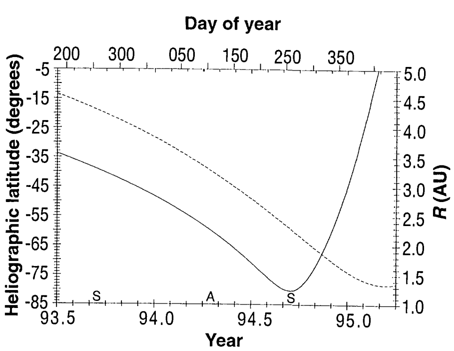

Fig. 2. Radial distance from the sun (dotted line) and heliographic latitude (solid line) of Ulysses while in the polar regions. The radial distance is given in astronomical units. The maximum heliographic latitude reached was beyond −80°. The polar cap is defined as the region above −70°. S, September; A, April.

Large amplitude, long-period magnetic waves were continuously present in the flow from the polar coronal hole (7). The waves cause the field direction to vary continuously. The wave forms are irregular, covering a broad band of wavelengths, and constitute a form of turbulence. Correlations between the magnetic field and solar wind velocity show that they are Alfvén waves propagating outward from the sun. The longest wavelengths are comparable to the radii of gyration of the cosmic rays and are thought to be impeding their entry into the polar region. The origin of the waves and their effect on the solar wind are also recognized as important issues.

These and other results reported in the accompanying reports are causing a revision in many of our preconceived ideas regarding the solar wind and the heliosphere. The observations have been obtained near sunspot minimum, when the sun is in a particularly simple state. It will also be important to compare the present observations with those obtained next summer when Ulysses passes over the sun's north polar regions.

In the intervening interval, Ulysses will pass through perihelion at 1.34 AU and, as the spacecraft approaches the sun, will gain speed. The latitude gradients in all of the important physical parameters will once again be surveyed, this time over a much shorter time interval, which will help discriminate against time variations that might masquerade as spatial variations.

After the spacecraft reaches +70° on 29 September 1995, it will once again head out toward the orbit of Jupiter at 5.3 AU. The orbital period of Ulysses is 6.3 years, so that on the next revolution around the sun, the spacecraft will pass over the south and north polar regions during the coming solar maximum in 2000 and 2001.

Table 2. Interdisciplinary studies and their team leaders.

Study	Researcher
Solar wind outflow	A. Barnes, Ames Research Center (USA)
Comets	J. C. Brandt, University of Colorado (USA)
Energetic particle transport	J. R. Jokipii, University of Arizona (USA)
Mass loss and ion composition	G. Noci, University of Florence (Italy)
Solar wind discontinuities	M. Schulz, Lockheed Palo Alto Research Laboratory (USA)
Shocks and waves	C. P. Sonett, University of Arizona (USA)

REFERENCES AND NOTES

1. The international Ulysses mission is a joint undertaking of the American and European space agencies. The spacecraft was designed, built, tested, and is being operated under the direction of the European Space Agency (ESA). The National Aeronautics and Space Administration (NASA) was responsible for the launch and is acquiring the data with the antennas of the Deep Space Net. Scientists in both Europe and the United States supplied the experiments and are interpreting the results (Tables 1 and 2). The scientific objectives are described in E. J. Smith, D. E. Page, K.-P. Wenzel, *Eos* **72**, 241 (1991); K.-P. Wenzel, R. G. Marsden, D. E. Page, E. J. Smith, *Astron. Astrophys. Suppl. Ser.* **92**, 207 (1992).
2. The scientific experiments are described in detail in a series of articles in *Astron. Astrophys. Suppl. Ser.* **92**, 207–440 (1992).
3. H. Zirin, *Astrophysics of the Sun* (Cambridge Univ. Press, New York, 1988); P. V. Foukal, *Solar Astrophysics* (Wiley, New York, 1990).
4. S. Grzedzielski and D. E. Page, Eds., *Physics of the Outer Heliosphere: Proceedings of the 1st COSPAR Colloquium Held in Warsaw, Poland, 19–22 September 1989*, vol. 1 of the *COSPAR Colloquia Series* (Pergamon, New York, 1990).

5. J. L. Phillips *et al.*, *Science* **268**, 1030 (1995).
6. J. Geiss *et al.*, *ibid.*, p. 1033.
7. A. Balogh *et al.*, *ibid.*, p. 1007.
8. J. A. Simpson *et al.*, *ibid.*, p. 1019.
9. This work was supported by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with NASA. E.J.S. is the Ulysses Project Scientist for NASA; D.E.P. is the ESA Science Coordinator in residence at JPL; R.G.M. is the ESA Project Scientist.

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The Heliospheric Magnetic Field Over the South Polar Region of the Sun

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Magnetic field measurements from the Ulysses space mission over the south polar regions of the sun showed that the structure and properties of the three-dimensional heliosphere were determined by the fast solar wind flow and magnetic fields from the large coronal holes in the polar regions of the sun. This conclusion applies at the current, minimum phase of the 11-year solar activity cycle. Unexpectedly, the radial component of the magnetic field was independent of latitude. The high-latitude magnetic field deviated significantly from the expected Parker geometry, probably because of large amplitude transverse fluctuations. Low-frequency fluctuations had a high level of variance. The rate of occurrence of discontinuities also increased significantly at high latitudes.

The characterization of the intrinsically three-dimensional nature of the heliosphere is the prime objective of the Ulysses space mission (*1*). The asymmetric and time-dependent solar corona, combined with the rotation of the sun, makes high-latitude phenomena different from those seen near the ecliptic plane. We discuss observations made by the magnetometer on board the Ulysses spacecraft (*2*) on the structure and characteristic features of the magnetic fields over the southern polar region of the sun. Magnetic fields in the heliosphere have their origin in the outer atmosphere of the sun, the solar corona. The corona consists of highly ionized solar material at temperatures in excess of 1.5×10^6 K, threaded by magnetic field lines rooted in the photosphere. A fraction of the mechanical energy emerging from the solar convection zone is transformed, by as yet not fully understood processes, into heat in the corona. The corona is fundamentally unstable: Part of the coronal plasma is accelerated to supersonic speeds and escapes into space to form the solar wind. The origin of the solar wind is not well understood, but is related to the large-scale structure of the magnetic field and to the heating and dynamics of the corona. In space, the solar wind plasma is an almost perfect electrical conductor, and therefore it drags out the magnetic field lines embedded in it. The large-scale structure of the corona undergoes major changes through the 11-year solar activity cycle. During solar minimum, large areas in the polar regions of the corona, the polar coronal holes, have an open magnetic field line structure. Coronal holes that extend toward the equator in the declining phase of the solar cycle have been identified as the sources of fast solar wind streams, with speeds up to 800 km/s.

The strength of the heliospheric magnetic field observed by the Ulysses magnetometer from the jovian encounter near the ecliptic to the highest southern latitude in the orbit at 80.2° showed the transition from low-latitude to high-latitude conditions (Fig. 1). During the low-latitude to mid-latitude part of the orbit, slow solar wind associated with coronal regions close to the heliospheric current sheet (the extension of the heliomagnetic equator into interplanetary space) was periodically compressed, with a period approximately that of the solar rotation rate, by high-speed flows from the developing southern polar coronal hole (*3*). This led to the train of periodic magnetic field enhancements in the corotating interaction regions (CIRs). The CIRs were bounded by forward and reverse shock waves. During this interval, the average direction of the heliospheric magnetic field alternated between the two magnetic polarities associated with the northern and southern solar hemispheres. This alternating field divides the solar rotation periods into the well-known two-sector structure representative of this phase of the solar cycle. However, throughout this interval, the sector structure showed an apparent eastward drift, corresponding to a recurrence rate of the coronal structures responsible for the CIRs slower than the solar rotation period at the equator. The likely cause of this effect has been identified as the eastward drift of the nonaxisymmetric terms of the solar magnetic field (*4*), a diagnostic of the evolution of solar magnetism from solar maximum to minimum activity. The last crossing of the heliospheric current sheet was observed at a heliolatitude of 30° south (*5*). Signatures of CIRs nevertheless continued to 45° south. Forward shock waves associated with CIRs were last observed at 35°, while, contrary to expectations, reverse shocks became relatively more frequent and persisted to about 45° south (*6*). The explanation proposed for this observation is based on a three-dimensional model of the development of CIRs at mid- to high latitudes (*7*). The formation of shock waves, their topology and their propagation at the high-latitude edges of CIRs remains to be fully explained.

Well after the disappearance, at mid-latitudes, of shock waves caused by CIRs, Ulysses observed a series of shock waves at high latitudes (Table 1). Five of the seven shock waves were apparently associated

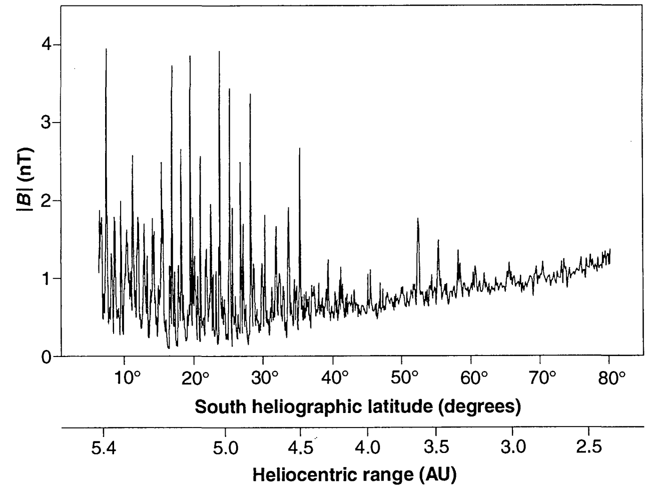

Fig. 1. Hourly averages of the magnetic field magnitude measured along the Ulysses orbit, as a function of heliolatitude and heliocentric distance.

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