Exploring the Sun's Poles

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The Ulysses spacecraft has produced not only a wealth of data but also a series of unexpected results during its crossings of the Sun's poles.

The primary objective of the Ulysses mission – launched in October 1990 – has been to measure the particles and fields that populate the heliosphere in the previously unexplored region of space extending from the Sun's equator to the poles. The broad range of phenomena that have been studied includes the solar wind, the heliospheric magnetic field, solar radio bursts and plasma waves, solar and interplanetary energetic particles, galactic cosmic rays, interstellar neutral gas, cosmic dust, and gamma-ray bursts.

Ulysses has been returning high-quality scientific data from the nine onboard instruments continuously since launch. This unique set of measurements has resulted in a wealth of scientific papers, including eight sets of coordinated publications already in print. The most recent results will be reported in a special issue of *Astronomy and Astrophysics*. The following sections summarise a selection of the most significant results from among the many recent findings. Other "firsts" include the first-ever direct measurement of atoms of interstellar helium and interstellar dust grains, the observation of recurrent interplanetary dust streams originating in Jupiter's magnetosphere, and many new findings concerning the wide variety of natural radio signals of heliospheric and Jovian origin.

Two Solar Wind Regimes Confirmed

The phenomena being studied by the Ulysses mission are strongly influenced by the 11-year solar activity cycle. The polar passes of the prime mission occurred during the descending phase of the current solar cycle (no. 22), close to solar minimum. At this time, the Sun is in its most simple state: large coronal holes extend from the polar regions in both hemispheres; the Sun's surface magnetic field is largely dipolar, being positive (outward) in the north and negative (inward) in the south; there is a relative paucity of energetic flare and other transient events.

Prior to the high-latitude *in-situ* observations made by Ulysses, it was expected that the particles and fields over the poles would reflect these conditions. In particular, it was generally expected that the solar wind speed would increase with increasing latitude, that some imprint of the dipole-like surface field would be found in the heliospheric magnetic field, and that the cosmic ray flux would be higher over the poles as a result of drift motions causing a net flow from the poles to the equator along near-radial magnetic field lines.

As Ulysses climbed in latitude towards the south pole, the solar wind speed did indeed increase from ≈ 400 to ≈ 750 km/s. Up to a latitude of ≈ 30°S, the tilt of the heliospheric current sheet with respect to the Sun's rotation axis gave rise large excursions in velocity as a high-speed stream passed over the spacecraft once per ≈ 26-day rotation. Poleward of ≈ 35°S, the solar wind speed was typically 750 km/s and showed no periodic variations. These observations confirm the expectation that, near solar minimum, there are two distinct solar wind regimes: slow and medium-speed wind flowing from the coronal streamer belt that encircles the equator, and fast wind from the polar coronal holes. Ulysses observations have also shown that the boundary between these regimes extends in height from the chromosphere, where compositional signatures have their origin, up through the corona where the solar wind is heated.

During its rapid pole-to-pole transit in 1994/95, Ulysses found the streamer belt – the source of slow and medium speed wind – to be somewhat narrower than two years earlier: in contrast to the situation in 1993, as the probe headed south, the region of slow (and medium) speed wind now extended from 22 °S to 21 °N (see figure). Since crossing the northern boundary at 21 °N, Ulysses has only seen fast solar wind.

The radial component of the heliospheric magnetic field measured by Ulysses in both hemispheres showed no variation with latitude, in contrast to what would be expected if the Sun's dipolar surface field (for which the radial component is greatest over the poles) was simply carried radially outward by the solar wind. This result implies that magnetic stresses in the solar wind near the Sun's surface act to redistribute the magnetic flux. This in turn suggests a greater role for large-scale divergence of the flow than was previously assumed.

In addition to the absence of a latitudinal gradient in the radial field component, the Ulysses observations have revealed the existence of unexpectedly large directional fluctuations in the magnetic field over the poles. Fluctuations of this kind, which certain models had predicted to occur as a result of random motions of the foot-points of the field lines in the photosphere, clearly will affect the motion of galactic cosmic rays entering the heliosphere. This is borne out by the findings of the cosmic-ray experiments aboard Ulysses. These measurements show a latitudinal gradient for most species that is smaller than expected, implying that the enhanced latitudinal transport of cosmic rays resulting from the large directional fluctuations in the magnetic field plays an important role in pro-

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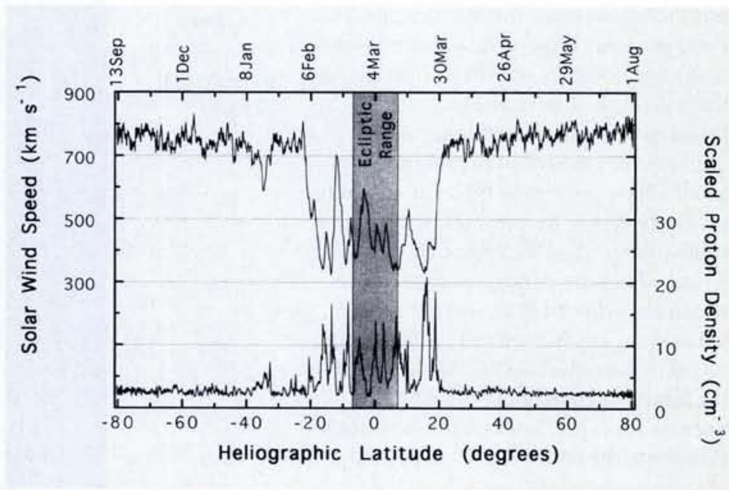


The solar wind speed (top trace) and density scaled to 1 AU (bottom trace) measured by the SWOOPS solar wind plasma experiment, plotted as a function of solar latitude for Ulysses' pole to pole transit. The latitude range of Earth's orbit is shaded. (Courtesy of J.L. Phillips, Principal Investigator).

ducing the observed degree of spherical symmetry in the distribution of galactic cosmic rays in the inner heliosphere.

Interstellar Pick-up Ions

Another area of research using Ulysses high-latitude data that has proved to be very fruitful is the study of interstellar pick-up ions. These particles flow into the heliosphere as neutral atoms of interstellar gas, and are subsequently singly ionized and "picked up" by the electromagnetic fields in the outflowing solar wind. With the exception of helium, pick-up ions are difficult to measure with instruments on near-Earth spacecraft, because the parent atoms become ionized before they are able to reach the inner realms of the heliosphere. Ulysses' unique orbit, extending as it does to more than 5 Astronomical Units (AU) from the Sun, provides a much more suitable vantage point. Hydrogen, carbon, nitrogen, oxygen, and neon pick-up ions of interstellar origin have been detected for the first time by Ulysses. These measurements have resulted in estimates of the relative atomic abundances of the parent interstellar gas. Furthermore, by using simultaneous measurements of both singly and (much rarer) doubly ionized helium of interstellar origin, it has been possible to determine the absolute abundance of neutral helium in the local interstellar medium. The value obtained, 0.015 atoms/cc, is in excellent agreement with the direct measurements of neutral helium made for the first time by new instrumentation flown on Ulysses.

Fluxes Related to Solar Oscillations

An intriguing new result based on Ulysses data has emerged from sophisticated time-series analysis of charged particle flux measurements. It is evidence that time variations in the particle fluxes can be ascribed to solar seismic oscillations. The characteristics of acoustic standing waves at the Sun, which is known to vibrate rather like a drumskin, have been reliably established using optical techniques. These oscillations, referred to as pressure or p-modes, have periods of typically 5 minutes (or equivalently, frequencies in the range 1000-5000 μHz). Much more elusive are the so-called gravity or g-mode oscillations which are believed to arise from density variations deep in the Sun's interior. The unequivocal detection of g-modes is one of the foremost goals of helioseismology, because these oscillations contain information about the Sun's core. Unexpectedly, the observed time variations in particle fluxes measured aboard Ulysses appear to be due to many discrete periodic components rather than exhibiting a more-or-less continuous distribution. In particular, in the frequency range 1 - 140 μHz, the observed components are a good match to those predicted for solar g-modes. Moreover, at higher frequencies (1000-5000 μHz), spectral lines found in the particle flux data appear to correspond to the optically-detected p-modes.

Obvious questions are: how are the solar oscillations transmitted into the heliosphere, and how are they able to modulate the fluxes of energetic charged particles? The key to the problem may be the supergranulation motion caused by large-scale convection at the Sun's surface. The particles are linked to the Sun through the heliospheric magnetic field, which in turn is tied to the supergranules. If the observed motion of the supergranules is not random, but is due to the superposition of many g-modes, these oscillations could be transmitted to the particles via transverse waves on the field lines.

The Ulysses Mission

The Ulysses programme is carried out jointly by the European Space Agency (ESA) and the US National Aeronautical and Space Administration (NASA), the European contribution consisting of the provision and operation of the spacecraft, and about one-half of the experiments. NASA provided the launch, the spacecraft power generator, and is responsible for the remaining experiments. In addition, NASA also supports the mission using its Deep Space Network to track the spacecraft.

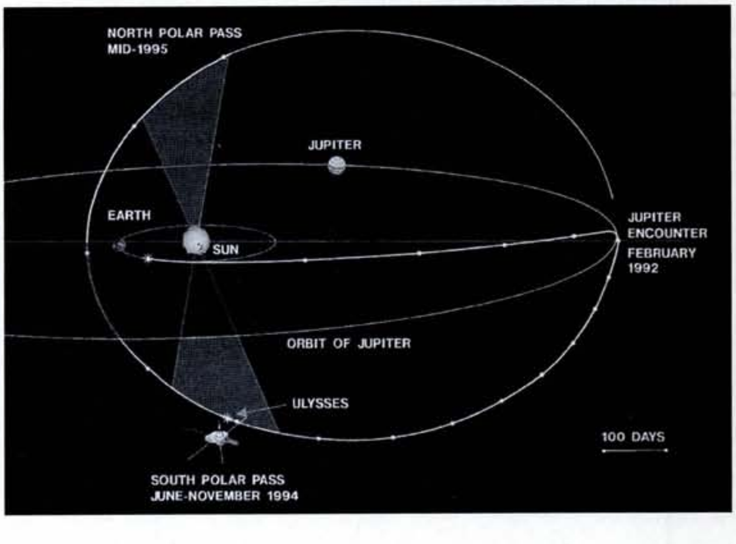
Following its launch by the space shuttle, Ulysses was injected into a direct Earth/Jupiter transfer orbit. A gravity-assist manoeuvre at Jupiter in February 1992 placed the spacecraft in its final Sun-centred out-of-ecliptic orbit, which has a perihelion distance of 1.3 Astronomical Unit (1 AU = 1.5×10^8 km) and an aphelion of 5.4 AU. The orbital period is 6.2 years.

With the mission now in its sixth year, all spacecraft systems and the scientific payload's nine sets of instruments have continued to function well, and the data coverage has been excellent, averaging better than 95% to date.

During the prime mission, Ulysses' unique orbit enabled the spacecraft to make two polar passes, which are defined to be the part of the trajectory above 70° heliographic latitude in either hemisphere. The first polar pass (over the south solar pole) commenced on 26 June 1994 and ended on 5 November, the second pass (north) occurring one year later (19 June 29 September), making a total of 234 days (corresponding to approximately 9 solar rotations) above 70° latitude. The maximum heliographic latitude reached by Ulysses was the same in both hemispheres, namely 80.2°. The spacecraft is currently at mid-northern latitudes, heading out towards the orbit of Jupiter.

Based on the unqualified scientific success of the mission to date, and the excellent health of the spacecraft and its payload, both ESA and NASA have undertaken to continue operating the spacecraft for a second orbit of the Sun. Constituting what is essentially a new mission, the second solar orbit will bring Ulysses back over the solar poles in 2000 and 2001. In contrast to the high-latitude phase of the prime mission, which took place under quiet solar conditions, the second set of polar passes will occur close to solar maximum.

Information concerning Ulysses can be obtained via WWW at the Ulysses/ESA Home Page URL: http://estsck.estec.esa.nl/uds/ulysses/welcome.html. Data from the Ulysses investigations and flight project are being archived and made accessible to the public through two channels: ESA's *Ulysses Data Archive* located at ESTEC, and the National Space Science Data Center (NSSDC). Contact: ESA's Ulysses Data System Coordinator, C. Tranquille (ctranqui@estsck.estec.esa.nl).



The Ulysses orbit viewed from 15 degrees above the ecliptic plane.