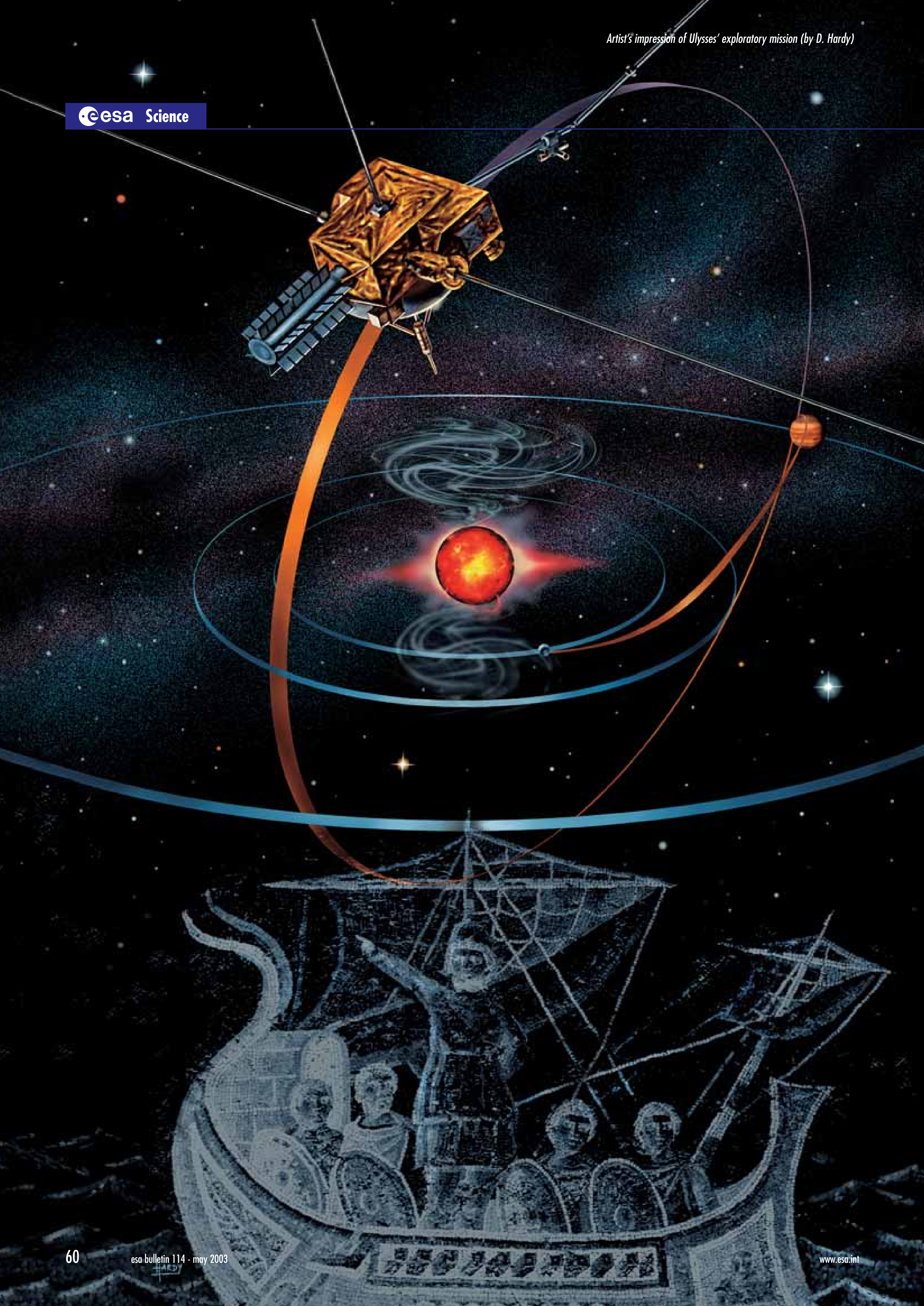

Artist's impression of Ulysses' exploratory mission (by D. Hardy)

News from the Sun's Poles Courtesy of Ulysses

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True to its classical namesake in Dante's Inferno, the ESA-NASA Ulysses mission has ventured into the 'unpeopled world beyond the Sun', in the pursuit of 'knowledge high'!

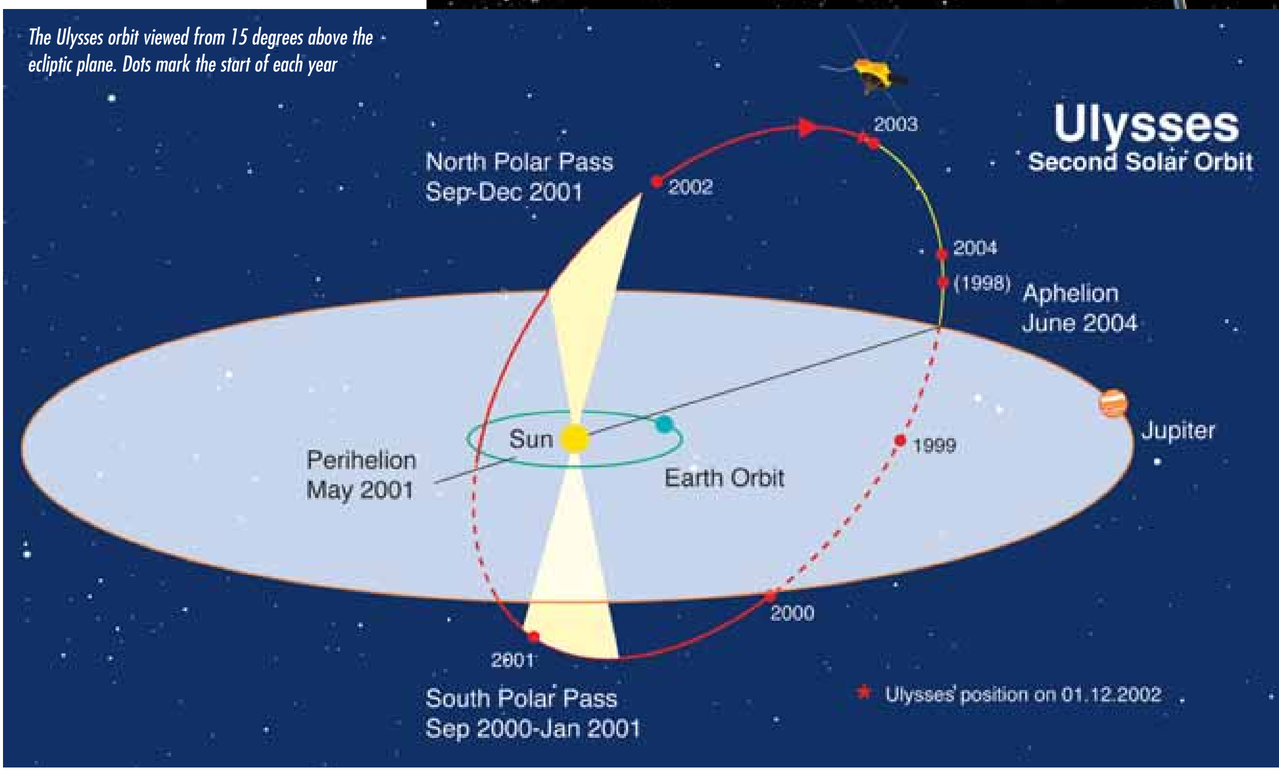
Introduction

Launched from Cape Canaveral more than 13 years ago, Ulysses is well on its way to completing two full circuits of the Sun in a unique orbit that takes it over the north and south poles of our star. In doing so, the European-built space probe and its payload of scientific instruments have added a fundamentally new perspective to our knowledge of the bubble in space in which the Sun and the Solar System exist, called 'the heliosphere'.

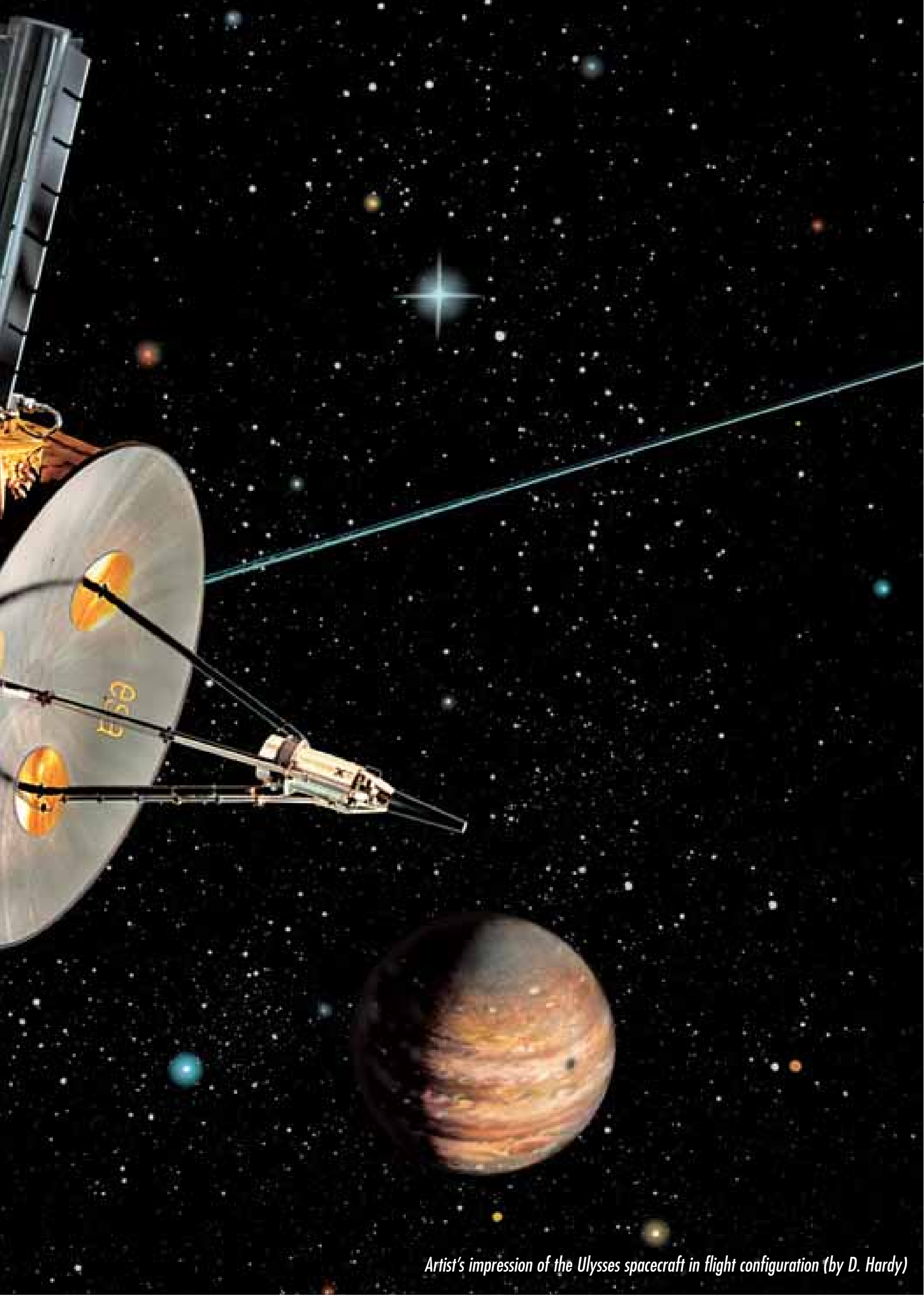
A small spacecraft by today's standards, Ulysses weighed just 367 kg at launch, including its scientific payload of 55 kg. The nine scientific instruments on board measure the solar wind, the heliospheric magnetic field, natural radio emission and plasma waves, energetic particles and cosmic rays, interplanetary and interstellar dust, neutral interstellar helium atoms, and cosmic gamma-ray bursts. The Ulysses science team responsible for the instruments is truly international, with investigators from many European countries, the United States, and Canada.

Following its initial exploration of the solar polar regions in 1994-95, when the Sun was in its most quiescent state (known as 'solar minimum'), Ulysses returned for a second look in 2000-2001. This time, however, solar activity had reached the peak ('solar maximum') in its 11-year cycle, presenting scientists with a unique chance to compare conditions at these two extremes in stellar behaviour.

With a journey of well over 6.5 billion kilometres already under its belt, the intrepid European-built Ulysses spacecraft is still in excellent health, and continues to deliver first-class science.



The Ulysses orbit viewed from 15 degrees above the ecliptic plane. Dots mark the start of each year



Artist's impression of the Ulysses spacecraft in flight configuration (by D. Hardy)

History of the Mission

This joint ESA-NASA collaborative mission, the first ever to fly over the poles of the Sun, was launched by the Space Shuttle 'Discovery' on 6 October 1990, using a combined IUS/PAM-S upper-stage to inject the spacecraft into a direct Earth/Jupiter transfer orbit. Arriving at Jupiter in February 1992, Ulysses executed a gravity-assist manoeuvre that placed it in its final Sun-centered, out-of-ecliptic orbit. With a period of 6.2 years, the orbit is inclined at 80.2º to the solar equator, the perihelion (point of closest approach to the Sun) is at 1.3 AU (1 Astronomical Unit is the mean Sun-Earth distance, equal to 150 million km), and the aphelion at 5.4 AU (the most distant point in the orbit).

Ulysses' primary objective is to explore the heliosphere in four dimensions: three spatial dimensions plus time. Although Ulysses has made ground-breaking discoveries at many points along its unique trajectory, the 'polar passes' (the segments above 70º heliographic latitude in each hemisphere) have attracted special interest. The first such passes took place in 1994 (south) and 1995 (north), as the Sun's activity was approaching a minimum. Ulysses arrived over the Sun's south polar regions for the second time in November 2000. Solar activity reached its maximum in 2000, so that Ulysses experienced a very different environment from the one it had encountered during the first high-latitude passes.

With the completion of the second northern polar pass in December 2001, Ulysses provided the first, and for the forseeable future only, survey of the high-latitude heliosphere within 5 AU of the Sun over the full range of solar activity conditions. The spacecraft is currently heading away from the Sun once again, on its way towards aphelion at the end of June 2004.

The results from the first set of polar passes, in 1994-95, have been described in earlier Bulletins (e.g. ESA Bulletin 103, pp. 41-47), and in particular in the recent book 'The Heliosphere Near Solar Minimum: the Ulysses Perspective' (published by Springer-Praxis). We therefore focus here on just a few of the scientific highlights from the recent 'solar maximum mission'.

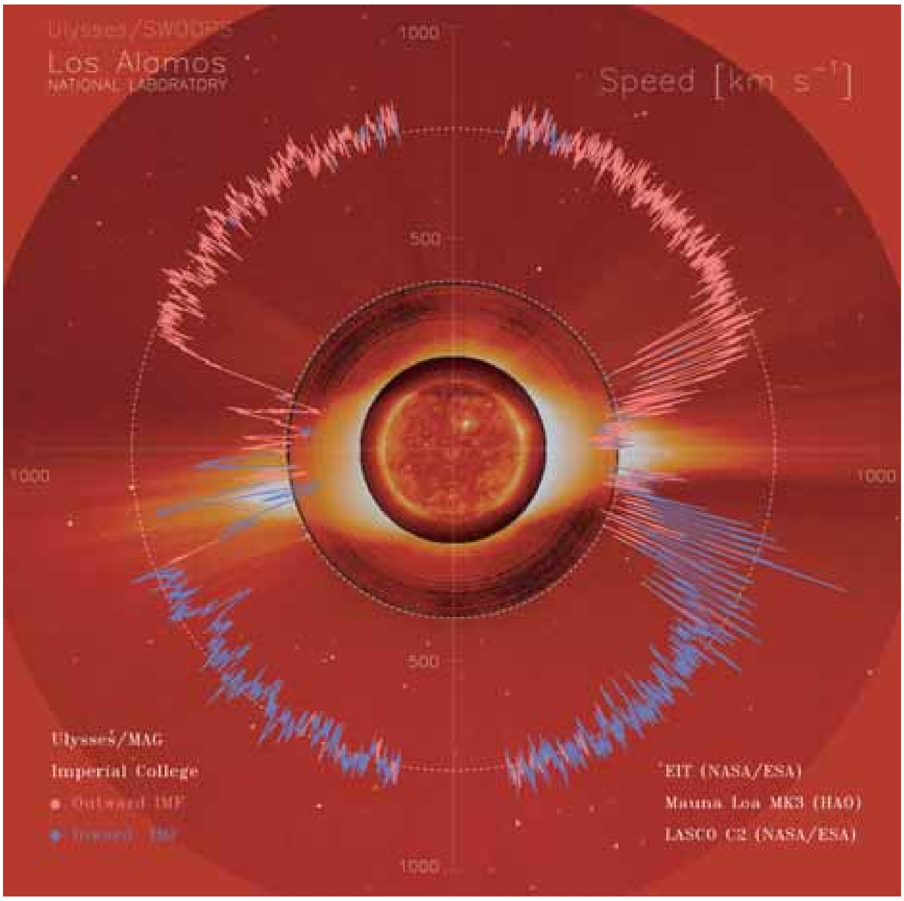
Scientific Highlights

Solar wind and magnetic field

Ulysses' exploration of the solar wind and its physical characteristics – speed, temperature and composition – during maximum solar activity has revealed an entirely different configuration from that observed near solar minimum. Then Ulysses found a heliosphere dominated by the fast wind from the southern and northern polar coronal holes* (not unlike the Earth's ozone holes), but during solar maximum those large polar coronal holes had disappeared and the heliosphere appeared much more symmetrical. The solar wind flows measured throughout the south polar pass, and much of Ulysses rapid transit from south to north, showed no systematic dependence on latitude. At all latitudes, the wind itself was generally slower and much more variable than at solar minimum.

** Coronal holes are extended regions in the Sun's atmosphere, or corona, that appear dark in X-ray images of the Sun (hence the name). This is because they are cooler, and less dense, than the surrounding corona. Coronal holes are largest and most stable at or near the solar poles, particularly near solar minimum, and are known to be the primary source of high-speed solar wind.*

Orbit 1



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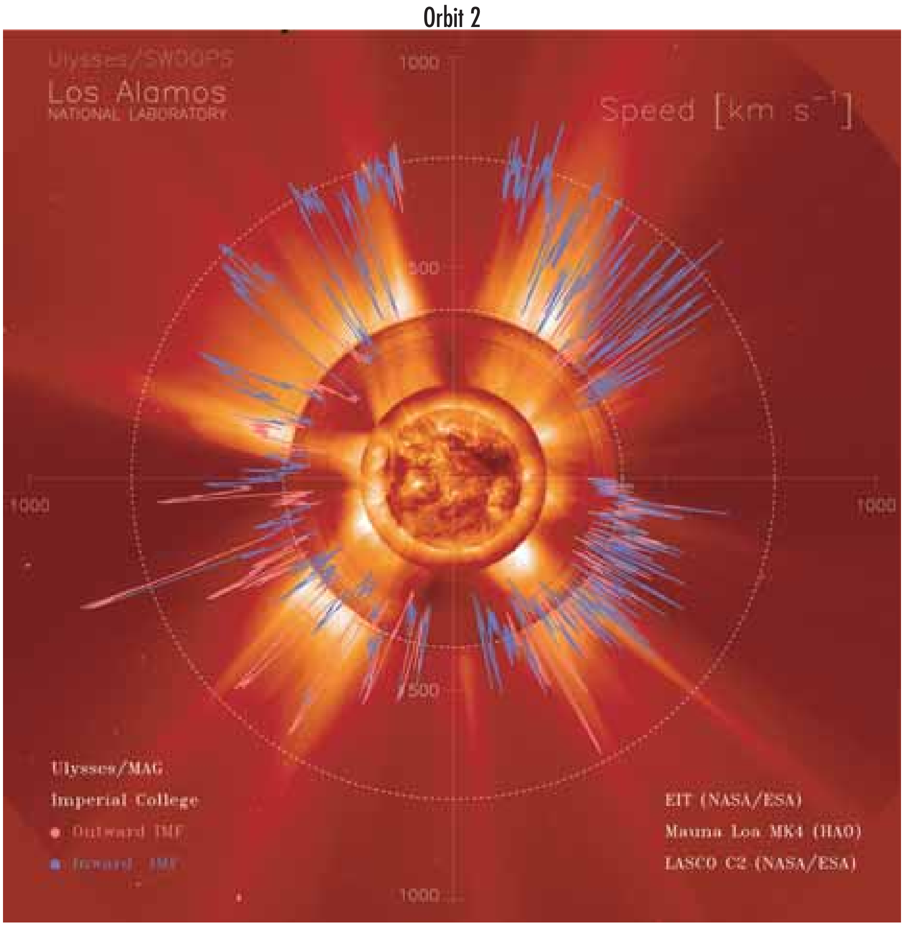
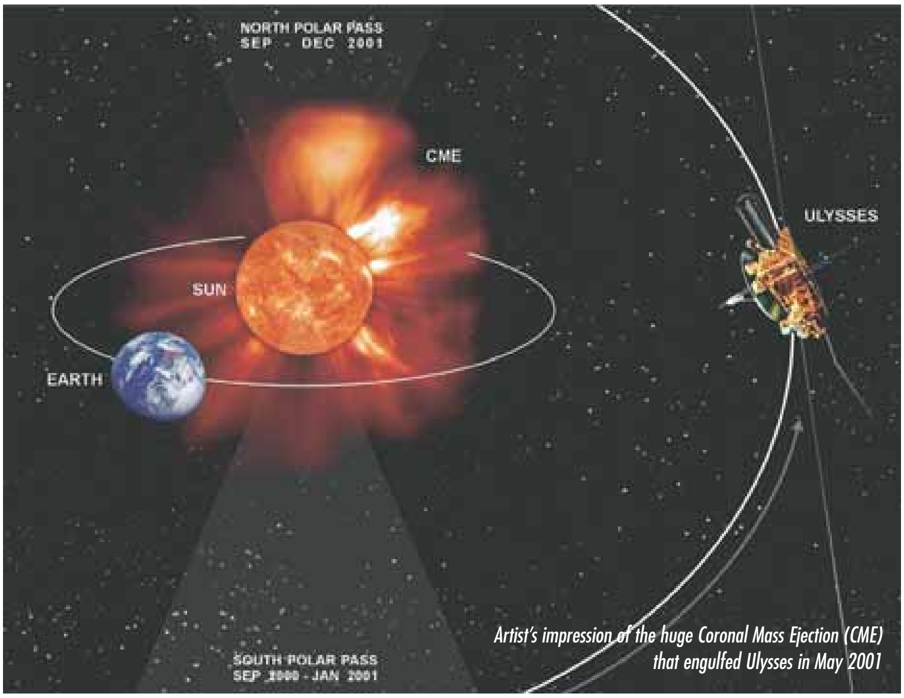


A comparison of solar-wind observations during the first (solar minimum) and second (solar maximum) orbits. The coloured traces show solar-wind speed as a function of Ulysses' latitude, against a background image of the Sun from SOHO/EIT/LASCO (Courtesy of D.J. McComas, SWRI / P. Riley, SAIC)

When Ulysses reached high northern latitudes in late 2001, however, it witnessed the formation and growth of a new polar coronal hole. This clearly marked the start of a return to more stable conditions. The solar wind became faster and more uniform, resembling the flows seen over the Sun's poles at solar minimum. By the end of 2001, regular excursions into variable, slower wind were once again the order of the day for Ulysses. The explanation for these differences can be found in the fact that the Sun had only just begun its transition to more stable conditions during the second northern polar pass, whereas solar-minimum-like conditions were already well-established in 1994/95.

A characteristic feature at times of enhanced solar activity is the frequent occurrence of so-called 'Coronal Mass Ejections, or CMEs'. These violent eruptions from the Sun are often associated with solar flares, and are one of the principal drivers of 'space weather' (on which there is an article elsewhere in this Bulletin). A typical CME can involve as much as 10 million million kg of ionized gas – equivalent to 25 million fully-loaded 747 jumbos! – travelling away from the Sun at speeds up to 1000 km/sec. When a fast-moving CME encounters the Earth's magnetosphere, the latter becomes compressed, resulting in magnetic storms that in turn are the source of many space-weather effects. A CME-driven shock wave that swept past over Ulysses in May 2001 was responsible for the most intense interplanetary magnetic field, and highest solar wind density, ever observed by the spacecraft.

The development of the global solar-wind characteristics discussed above was reflected in Ulysses' magnetic-field observations. One of the many questions that has been investigated is how the high solar activity level affected the structure and dynamics of the heliospheric magnetic field. Although the solar magnetic field, corona and solar wind were highly variable, the magnetic field at Ulysses



Artist's impression of the huge Coronal Mass Ejection (CME) that engulfed Ulysses in May 2001

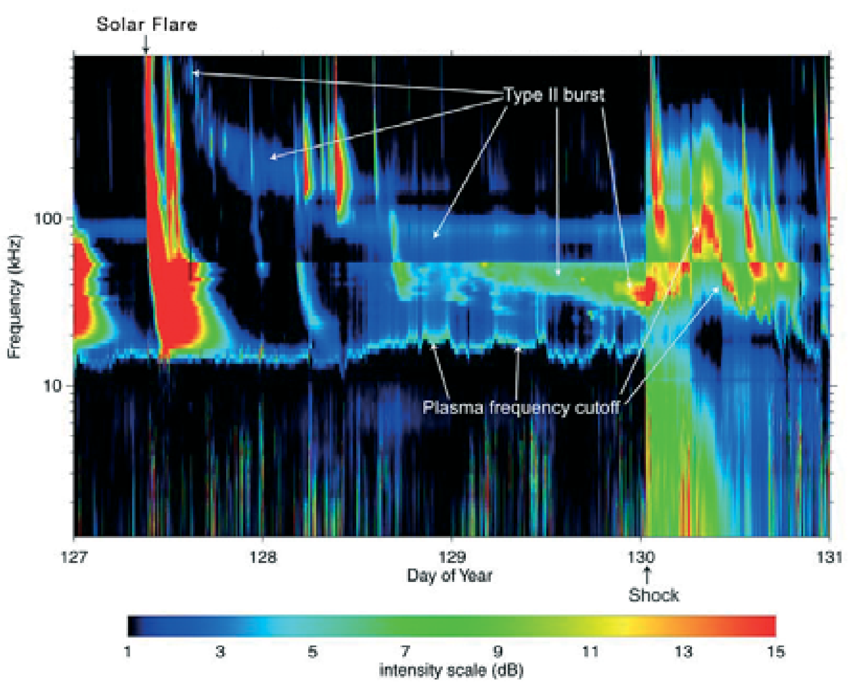
(~1.5 – 2.5 AU from the Sun) maintained a surprisingly simple structure, rather like a bar magnet. In contrast to the situation at solar minimum, however, the equivalent magnetic poles were located at low latitudes rather than in the polar caps. This is consistent with the presence of coronal holes near the Sun's equator, and their absence at the poles. The spreading out of the field lines from these equatorial sources to high latitudes, in turn, caused the solar wind to be deflected poleward.

Another phenomenon of great interest was the reversal of the Sun's magnetic polarity that occurred during the 2000 and 2001 polar passes. It was found that the reversal process is a complex one that takes several months, while the corona evolves to reflect the changes occurring at the Sun's visible surface, or 'photosphere'. This meant that although ground-based observations showed that the reversal of the surface magnetic field in the southern polar cap had already taken place when Ulysses was at high southern latitudes, the heliospheric field measured at the spacecraft still had the 'old' (negative) polarity. A year later, when Ulysses reached high northern latitudes, both the surface and heliospheric magnetic fields had the same 'new' (negative), polarity. Presumably, the newly formed fields in the south polar cap had not yet been carried out into space by the solar wind, suggesting that the open fields measured by Ulysses in fact originated at lower latitudes. In contrast, the polar cap fields in the north had evolved sufficiently by the time Ulysses was at high northern latitudes for them to be carried out by the fast solar wind.

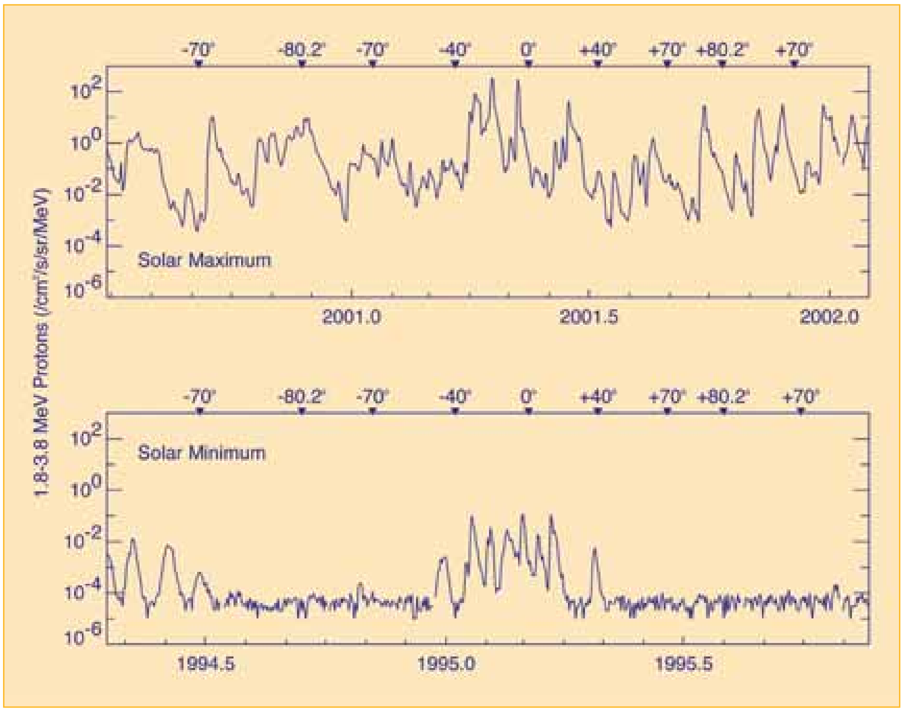
Energetic particles

One of the key discoveries made during the high-latitude passes of Ulysses at solar minimum was the unexpected ease with which energetic charged particles, mainly protons, were able to gain access to the polar regions of the heliosphere. This was surprising because the source of these particles was known to be confined to much lower latitudes. This discovery prompted theorists to re-assess existing models of the heliospheric magnetic field, and even led to new suggestions regarding the source of the solar wind itself. An obvious question, then, when Ulysses returned to high latitudes at solar maximum, was: Do energetic particles have the same easy access when the heliosphere is much more chaotic? Ulysses provided an unequivocal answer: Yes. In fact, the intensity profiles of energetic particles recorded at all latitudes were very similar to measurements made near the Earth, close to the solar equator.

Scientists knew that the source of energetic particles at solar maximum and



Radio and plasma wave measurements of the May 2001 Coronal Mass Ejection (CME) (Courtesy of R.J. MacDowall, GSFC)



Energetic-particle flux at solar maximum and solar minimum. In the lower panel, energetic particles are generally absent above ± 40°. The periodic flux increases on the left-hand side are part of a long sequence that began at the Sun's equator and extended to the south polar cap. No such increases are seen in the northern hemisphere. By contrast, at solar maximum (upper panel), elevated fluxes are present at all latitudes

solar is not the same. As noted earlier, fast CME-driven shock waves give rise to the numerous large increases in particle flux that are characteristic of solar maximum. In addition to revealing the presence of large fluxes of energetic particles over the poles, the Ulysses measurements indicate that the number of these particles in many events is comparable to that measured simultaneously in the ecliptic near 1 AU. This has led to the idea of the inner heliosphere near solar maximum acting as a 'reservoir' for solar energetic particles.

The precise mechanism by which the particles fill this reservoir is still being debated. It is certainly different from that in operation at solar minimum. Whatever the mechanism, however, Ulysses has shown that energetic charged particles can gain access to all regions of the heliosphere during all phases of the solar cycle far more easily than expected. This in turn has consequences for our ability to predict the 'space weather' that astronauts venturing far away from Earth are likely to encounter.

Cosmic rays

Galactic cosmic-ray particles moving through the heliosphere are affected by a combination of processes that include scattering by small-scale twists and turns in the heliospheric magnetic field, and drift motions caused by the large-scale pattern of field lines. The direction in which the cosmic rays drift depends on the electric charge carried by the particles, and on the Sun's magnetic polarity.

At the time of the Ulysses solar-minimum high-latitude passes, the Sun's field was such that the predicted flow direction of positively charged cosmic-ray particles entering the heliosphere was inward over the poles. By the same token, these particles were predicted to leave the heliosphere along the helio-magnetic equator. Under these conditions, Ulysses was expected to observe more cosmic-ray nuclei over the poles. Such an increase was indeed found, but was smaller than expected, suggesting that charged particles of all energies are less restricted in their motion by the heliospheric magnetic fields than previously thought.

With the Sun returning to a more stable state following the solar-maximum activity, the associated reversal of the dominant magnetic field polarity provides a unique opportunity to test our understanding further. Now we expect positively charged particles to flow into the heliosphere along the helio-magnetic equator, and be transported outward via the poles. There should be fewer cosmic-ray nuclei at high latitudes than near the equator. The expectation is that these patterns will soon become established, enabling Ulysses to add another chapter in the investigation of global particle transport in the three-dimensional heliosphere.

Local Interstellar Medium

Ulysses science does not focus exclusively on the Sun. Observations made by the instruments on board have also added significantly to our knowledge of the Interstellar Medium (ISM) surrounding the heliosphere. The Sun has recently entered a rather small, but relatively dense, warm cloud – the Local Interstellar Cloud or LIC – with profound consequences for Earth that are not yet fully understood. The physical characteristics of the LIC have a strong influence on the heliosphere, determining its size and shape, and Ulysses is unique in having the right orbit and instruments to measure the properties of this LIC gas. The Ulysses GAS instrument, for example, provided the first and most comprehensive direct measurement of interstellar helium. As a result, we now know precisely the relative velocity between the Sun and the LIC (26.4±0.5 km/sec), the temperature of the LIC gas (6480±400 K), and the density of interstellar neutral helium (0.015±0.002 cm^{-3}). On an even grander scale, measurements of the chemical and isotopic composition of the LIC permit us to make inferences about the history of the Universe.

Other Results

The above highlights represent only a small fraction of the new scientific insights being provided by the unique data sets acquired by Ulysses' instruments. Other

areas of research to which the mission is making valuable contributions include the search for the origin of gamma-ray bursts, the nature of the interstellar dust grains that enter the heliosphere, and the source of the solar wind itself.

In all of these areas, the combination of a unique orbit that takes the spacecraft to high latitudes and also allows it to 'dwell' for extended periods at distances of several AU from the Sun, and the technical excellence of the scientific instruments on board, makes Ulysses a remarkable research tool. Add to this the unprecedented data coverage provided (a better than 95% average throughout the mission), and it is clear that the mission to date can be qualified as an outstanding success. This success has been augmented in recent years by the role that Ulysses plays in both the interplanetary network of gamma-ray detectors, and especially within the fleet of solar and solar-terrestrial missions that includes SOHO, ACE, Wind, and Voyager-1 and 2. Many multi-spacecraft studies rely on Ulysses' unique capabilities.

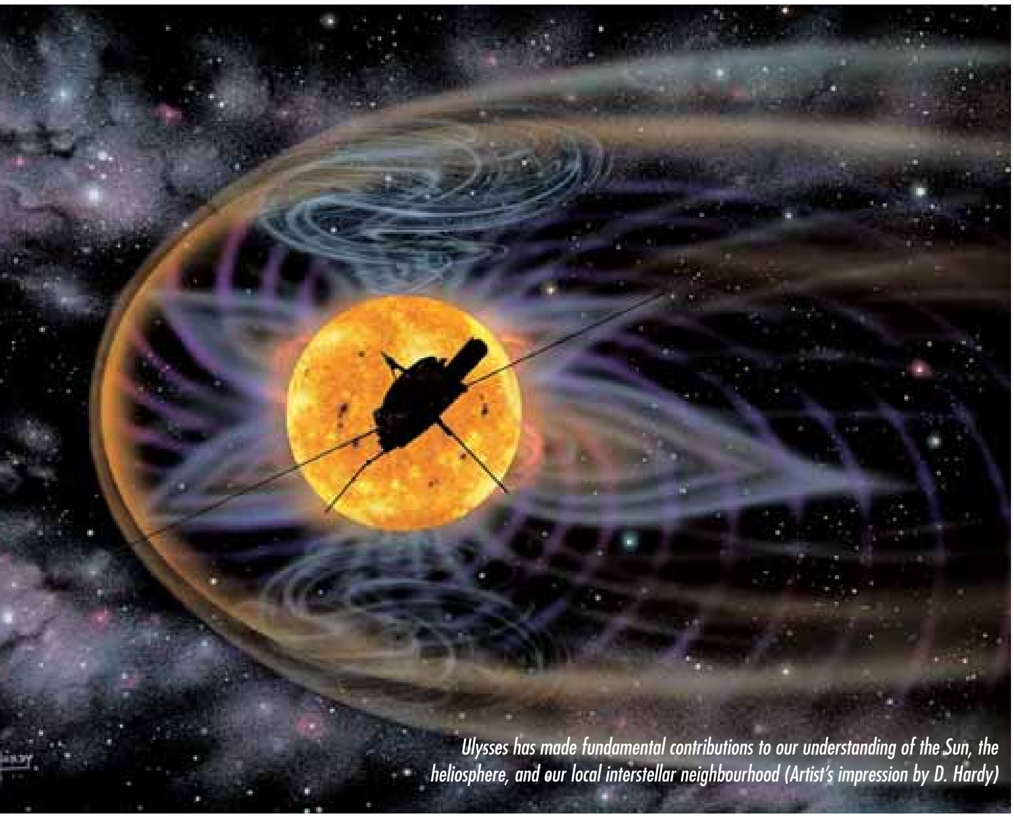
The Future

The Ulysses mission was originally foreseen to end in October, 1995. Owing to the outstanding scientific success, and equally, to the robustness of the spacecraft and its scientific payload, ESA and NASA have already approved two mission extensions. The first, until December 2001, enabled comprehensive observations to be made over the Sun's poles at both solar minimum and solar maximum. The second, with funding for spacecraft operations until September 2004 and archiving activities within ESA until December 2006, is providing the opportunity to observe the initial effects on the global heliosphere of the Sun's magnetic-field reversal.

So what does the future hold for Ulysses? Many questions still remain to be answered concerning the heliosphere and its many constituents. Plans for follow-up missions to Ulysses exist, in particular ESA's Solar Orbiter. With a likely launch in 2011-2012, Solar Orbiter will extend the range of out-of-ecliptic measurements to include imaging and spectroscopy of the Sun's polar regions, but from lower latitudes than Ulysses. On the NASA side, a mission called Telemachus (son of Ulysses) is being studied, which will also carry remote-sensing instruments and will use the same Jupiter flyby technique as Ulysses to reach the highest latitudes, but with perihelion much closer to the Sun (0.2 AU). If approved, Telemachus will be launched in the 2010-2015 time frame. In the meantime, Ulysses remains the only spacecraft able to sample the Sun's environment away from the ecliptic plane.

Global coverage of the inner heliosphere between the Sun and the Earth is a key element of the recently launched International Living With a Star (ILWS) initiative, the principal goal of which is to stimulate, strengthen and coordinate space research in order to understand the processes governing the Sun-Earth system as an integrated entity. Among the space missions expected to make major contributions to ILWS is NASA's STEREO, planned for launch in December 2005. By putting two space probes at different locations in the ecliptic plane, in heliocentric 1 AU orbits that will lead and trail the Earth, the STEREO mission, together with Ulysses at high latitudes, could form part of a valuable ILWS network to further extend our three-dimensional studies of the heliosphere. Such a network would also include SOHO, and possibly NASA's ACE spacecraft.

Even without this network, there are many important contributions to our knowledge of the heliosphere that only Ulysses, with its extended record of continuous observations, and unique orbit, can make. From a technical point of view, extending the mission beyond 2004 with a core payload able to acquire a meaningful set of scientific measurements is a possibility. To this end, the NASA project has submitted a proposal for review by the Sun-Earth Connections Senior Review panel in mid-2003. If successful, this could open the way to a continuation of the epic journey on which Ulysses set out in October 1990, with the possibility of a third set of polar passes in 2007/2008.



Ulysses has made fundamental contributions to our understanding of the Sun, the heliosphere, and our local interstellar neighbourhood (Artist's impression by D. Hardy)