

→ THE EPIC VOYAGE OF ULYSSES

Richard Marsden

Directorate of Science and Robotic Exploration,
ESTEC, Noordwijk, The Netherlands

Nigel Angold

Directorate of Operations and Infrastructure,
ESOC, Darmstadt, Germany

Ulysses has forever changed the way scientists view the Sun and its effect on the surrounding space. Here we look at the mission's major results and the legacy it leaves behind.

After almost 18 years of operation, the joint ESA/NASA mission Ulysses was officially due to come to an end in July 2008 because of the decline in power produced by its on-board generator. However, operations have continued since then on a day-to-day basis and will continue until the hydrazine fuel eventually freezes or runs out.

Once that happens, it will be impossible to point the high-gain antenna towards Earth and Ulysses' voyage of discovery will be over.

The spacecraft, which studies the Sun and its effect on the surrounding space, has survived for almost four times its expected lifespan. Hurling through space at an average speed of 56 000 km/h, Ulysses has now travelled a journey of over 8600 million km. The spacecraft and its suite of 10 instruments are highly sensitive, yet robust enough to have withstood the extreme conditions of deep space, as well as a close encounter with the giant planet Jupiter. This longevity

is testament to a creative team of ESA and NASA engineers who have risen to every challenge.

Looking back

Exploring our star's environment is vital if scientists are to build a complete picture of the Sun and its effect on the Solar System. Ulysses was designed to study this environment, which scientists call the 'heliosphere' – the sphere of influence of the Sun – in three dimensions. To do this, the space probe was placed in a unique orbit that carried it over the poles of the Sun.

The heliosphere is in fact a bubble in interstellar space that is created by the solar wind – a constant stream of particles emitted by the Sun. This 'wind' is very different from the wind on Earth, but its gusts and shocks, causing aurorae and magnetic storms, may affect our weather and can harm satellites, power supplies, and communications. The key goal of Ulysses was to provide the first-ever map of the heliosphere from the Sun's equator to the poles.

Ulysses was launched on its unprecedented journey of discovery in 1990 by a NASA Space Shuttle. The gravity of the planet Jupiter then deflected it into an orbit taking it 300 million km above the Sun's southern and northern poles, regions never studied before.

During its 18 years in space, Ulysses has rewarded scientists with the unprecedented depth and breadth of its results. These have not just been about the Sun and its influence

on nearby space, however: the mission has also provided surprising insights into the nature of our galaxy and even the fate of the Universe.

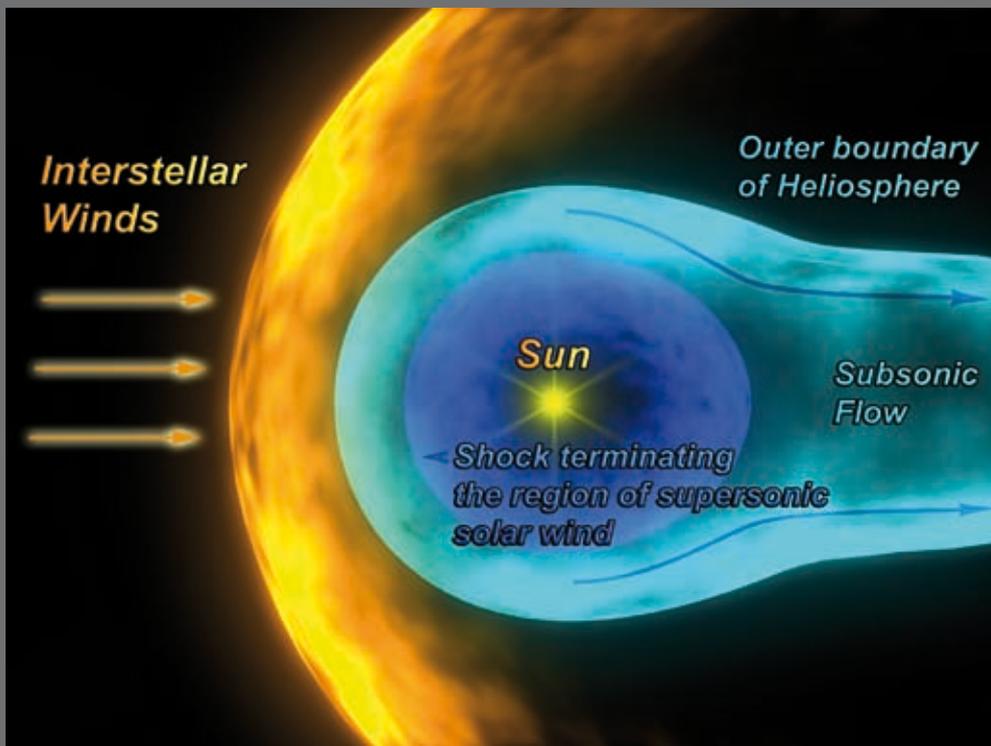
The discoveries

Solar winds

Prior to Ulysses, scientists had only been able to measure the solar wind near the ecliptic plane (the plane in which the planets and most spacecraft orbit the Sun). The picture that emerged was of a wind that had a speed of typically 400 km/s, with occasional higher speed gusts. Ulysses soon showed that for much of the sunspot cycle, there is a wind from the cooler regions close to the Sun's poles that fans out to fill two thirds of the heliosphere, blowing at a uniform speed of 750 km/s, much faster than the 'slow' wind that emerges from the Sun's equatorial zone. Rather than being 'typical', the slow wind is a minor player whose origin still remains unclear.

Magnetic field reversal

When the mission was extended beyond the original goal of one orbit of the Sun, scientists were then able to watch how the solar wind changed with time. The Sun does not emit solar wind steadily, but the emission varies through a cycle of magnetic activity lasting approximately 11 years. The cycle culminates in the reversal of the direction of the Sun's magnetic field. Ulysses saw that on a large scale, the complexity of the magnetic field near the solar surface simplifies into a field equivalent to that created by a bar magnet (a dipole) inside the Sun. When solar activity is at a



The outer boundaries of the heliosphere, the huge bubble in space created by the solar wind, are formed by the interaction with the interstellar wind, a continuous stream of gas of electrically-charged particles of interstellar origin. Ulysses found that the interstellar wind is fast enough to cause a shockwave outside the heliosphere

→ History of Ulysses

The idea of sending a probe to explore the regions of space far away from the Solar System's ecliptic plane is by no means new. The first mention of an out-of-ecliptic mission was made in 1959, only two years after the launch of Sputnik. At that time, however, many of the necessary tools were not yet available. For example, it was not known if it would be possible to navigate a spacecraft over such large distances in deep space. In particular, the technique of using a planetary body to provide a gravity assist had yet to be demonstrated.

Missions in the early 1970s, particularly Pioneers 10 and 11, provided some essential knowledge – that gravity assists were possible and that high-radiation areas, such as the immediate neighbourhood of Jupiter, could be survived by spacecraft.

Europe and NASA studied the possibility of an 'out-of-ecliptic' (OOE) mission in the early 1970s. The mission would consist of two spacecraft flying in formation out to Jupiter and then one of them heading for the northern region of the Sun and the other for the southern region. Two spacecraft at opposite poles from



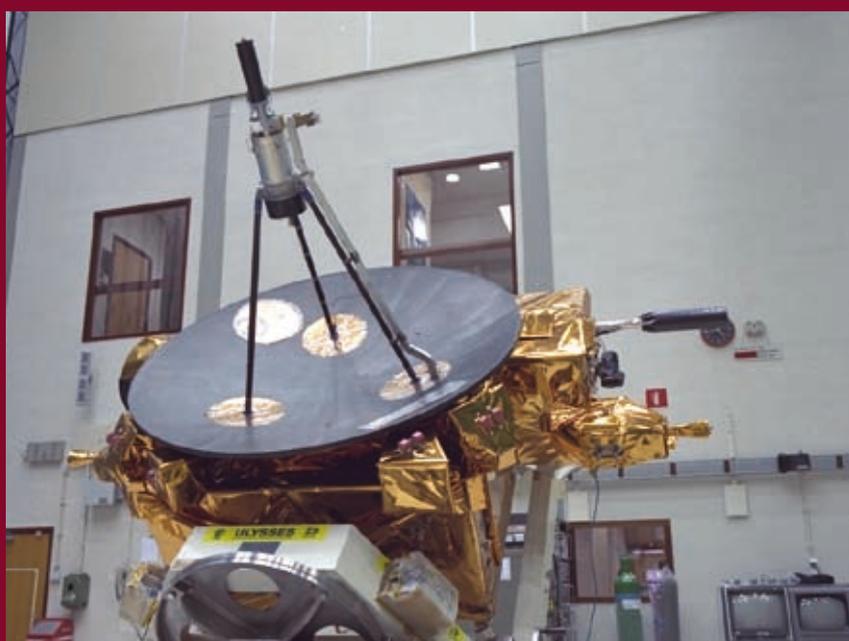
each other would be able to almost completely map the Sun. The mission was approved in 1977, the payload approved in 1978 and a provisional launch date set for February 1983.

By 1980, NASA was concentrating on the Space Shuttle. Financial cutbacks were made in other areas of its space programme including delaying the launch of OOE, or International Solar Polar Mission (ISPM) as it was then called, until 1985. A year later, NASA cancelled its ISPM spacecraft and delayed the launch by a further 13



Artist's impression of the Ulysses spacecraft after separation from the NASA Space Shuttle

months. ESA decided, however, to go ahead with a single-spacecraft version of the mission, using the European-built spacecraft with half the instruments on board provided by the United States.



Ulysses in the 'clean room' of ESA's ESTEC test facilities in 1985

Now renamed *Ulysses*, it was due to be launched on board a Space Shuttle in May 1986. In January 1986, the *Ulysses* spacecraft was shipped out to Kennedy Space Center to finally prepare for launch. On 28 January 1986, the Challenger disaster occurred and put an immediate stop to all Shuttle launches and therefore the *Ulysses* mission. The spacecraft had to be dismantled and shipped back to Europe.

When Shuttle launches were restarted in 1988, *Ulysses* was given a new launch opportunity for 1990 and was launched successfully on 6 October 1990.

Ulysses is a joint ESA/NASA mission. ESA managed the mission operations and provided the spacecraft, built by Dornier Systems, Germany (now Astrium). NASA provided the Space Shuttle *Discovery* for launch and the

inertial upper stage and payload-assist module to put *Ulysses* in its correct orbit. NASA also provided the radioisotope thermoelectric generator that powered the spacecraft and payload.

ESA's ESTEC and ESOC managed the mission with NASA's Jet Propulsion Laboratory (JPL), with tracking by NASA's Deep Space Network. A joint ESA/NASA team at JPL oversaw spacecraft operations and data management. Teams from universities and research institutes in Europe and the United States provided the ten science instruments.



Launch of *Ulysses* on the NASA Space Shuttle *Discovery* on mission STS-41 in 1990



minimum, this dipole is aligned with the rotation poles. Six years later, at maximum, the dipole has moved to lie at 90° to the rotation poles. It then continues moving so that by the time of the next minimum, it is aligned with the rotational pole again, but in the opposite orientation. These results could only have been obtained from the unique perspective offered by *Ulysses*.

Dust, gas and energetic particles

Previously, the heliosphere was thought to be impenetrable to small dust particles from deep space, but *Ulysses* showed that this was not true. The spacecraft carried a superb instrument for diagnosing these invading particles. It found 30 times more dust from deep space in the vicinity of the Solar System than astronomers had previously expected.

Ulysses detected heavy atomic nuclei racing into the Solar System. Known as 'cosmic rays', these are thought to be accelerated by the explosions of high-mass stars. *Ulysses* estimated that the average age of a cosmic ray entering the Solar System is 10–20 million years and they have spent their lives streaming through the galaxy's outer regions before finding their way into the Solar System.

Measurements made by *Ulysses* showed that energetic particles originating in solar storms close to the Sun's equator are much more mobile than previously thought, and are even able to reach the polar regions. Since these particles are constrained to move along the magnetic field lines in the solar wind (much like beads on a wire), this in turn means that the structure of the magnetic field itself is more complex than previously thought.

Interstellar helium isotopes are especially interesting to cosmologists because theory predicts that their abundance was more or less fixed within a few minutes of the Big Bang. *Ulysses* collected rare samples of these isotopes, supplying evidence to support the idea that the Universe will expand forever because insufficient matter was created in the Big Bang to halt its outward march.

The engineering challenge

The *Ulysses* mission's life expectancy was five years. Thanks to a dedicated ESA/NASA engineering team, this turned into over 18 years, nearly 4 times longer than expected.

The mission officially began in 1977 and, after a number of delays, was launched from the Space Shuttle's payload bay on 6 October 1990. The first challenge for the team came soon after launch.

Shortly after a 7.5-metre axial boom was deployed, the spacecraft started wobbling. This was potentially disastrous. The spinning spacecraft was designed to point toward Earth with an accuracy of 0.5° , but was wobbling by several degrees, threatening to severely degrade all observations.

The team analysed the problem and discovered that the Sun's heat was causing the boom to flex as the spacecraft spun about its axis. This in turn induced the wobble. Once they had diagnosed the problem, they devised a way to use the spacecraft thrusters to correct for this anomalous motion, until the wobble eventually disappeared as the boom moved into the shadow of the spacecraft body. It was realized that the disturbance would return for a period of

about a year once per orbit, as Ulysses came closer to the Sun and the boom became illuminated again. Each time, the team was successful in keeping the wobble to a minimum. In fact, the team got to know the wobble so well that they predicted its reappearance in February 2007 almost to the day.

After the first passes over the solar poles in 1994–95, the mission was extended and the team faced the task of keeping Ulysses alive. It was challenging because the power available to the spacecraft was constantly ebbing away. Ulysses uses a small Radioisotope Thermoelectric Generator and due to the half-life of the radioactive heat source, the amount of power available gradually decreases with time. Over its lifetime, Ulysses has lost almost a third of its available power so the operations team came up with ingenious ways of conserving energy.

Eventually, however, not all of the instruments and systems could remain switched on simultaneously. So, since 2002, the team has been running the spacecraft with one or more of the instruments turned off at any one time. Other systems have been turned off intermittently, too.

Switching instruments off robs the spacecraft of heat, so the team had to be extremely careful to make sure the power dissipation was distributed evenly throughout the spacecraft to avoid creating cold spots. Nursing Ulysses in this manner, they managed to coax it through a third solar orbit.

But, as the spacecraft began its fourth journey into deep space last year, the power drop became too serious and the team had no alternative but to switch off the main transmitter at times when there was no contact with the ground stations. Unfortunately, the transmitter power supply failed and it could not be turned back on again. This loss meant that data could only be sent back to Earth via a

lower-power secondary transmitter, with a corresponding reduction in data rate.

More critically, both the dwindling power and transmitter failure have created a cold spot in a fuel line and hydrazine is close to freezing. Efforts to delay this freezing have included flowing fuel through the cold portion of pipework and this has resulted in much faster use of hydrazine than during the rest of the mission.

So, in the next few months, the fuel will either freeze or run out and it will no longer be possible to point the spacecraft towards Earth. Finally the voyage of Ulysses will be over but, true to its mythical namesake, Ulysses will have provided valuable scientific data up to the end, even under these adverse conditions.

The legacy

Ulysses has been a major scientific endeavour with many pay-offs. Up to 200 scientists across Europe and America have worked on the instrument teams and many more continue to access the mission's archived data, which is made available via the Internet. Around 1500 papers have been published so far using Ulysses data.

This rich treasure of unprecedented observations will keep the mission alive long after the actual spacecraft has died. ■



An artist's impression of Ulysses' journey. The gravity of Jupiter (yellow orbit) deflects Ulysses into an orbit over the Sun's northern and southern poles (red)

