SP-1312

Extract of Ulysses section

ESA's Report to the 37th COSPAR Meeting

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European Space Agency
Agence spatiale européenne

2.2 Ulysses

Introduction

Ulysses is an exploratory mission being carried out jointly by ESA and NASA. Its primary objective is to characterise the uncharted high-latitude regions of the heliosphere within 5 AU of the Sun, under a wide range of solar activity conditions. Ulysses has, for the first time, permitted *in situ* measurements to be made away from the plane of the ecliptic and over the poles of the Sun. Its unique trajectory (Fig. 2.2.1) has taken the spacecraft into the unexplored third dimension of the heliosphere.

The ESA contribution to the Ulysses programme consists of the provision and operation of the spacecraft and about half of the experiments. NASA provided the launch aboard Space Shuttle Discovery (together with the upper stage) and the spacecraft power generator, and is responsible for the remaining experiments. NASA also supports the mission using its Deep Space Network (DSN).

The broad range of phenomena being studied by Ulysses 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. A summary of the nine sets of instruments is presented in Table 2.2.1.

While the main focus of the mission is clearly the heliosphere and its variations in time and space, the investigations cover a wider range of scientific interests. Examples include studies related to Jupiter's magnetosphere (both *in situ* and via remote sensing), and radio-science investigations into the structure of the corona and a search for gravitational waves using the spacecraft and ground telecommunication systems. A major theme for Ulysses is the nature of the Local Interstellar Medium and its interface with the heliosphere; the mission continues to provide important contributions to our knowledge in this area, and to topics of a broad astrophysical nature.

In addition to the science teams selected at the start of the project, the group of scientists directly associated with the mission comprises nine European Guest Investigator (GI) teams and the European Interdisciplinary Investigators who were selected together with the hardware teams.

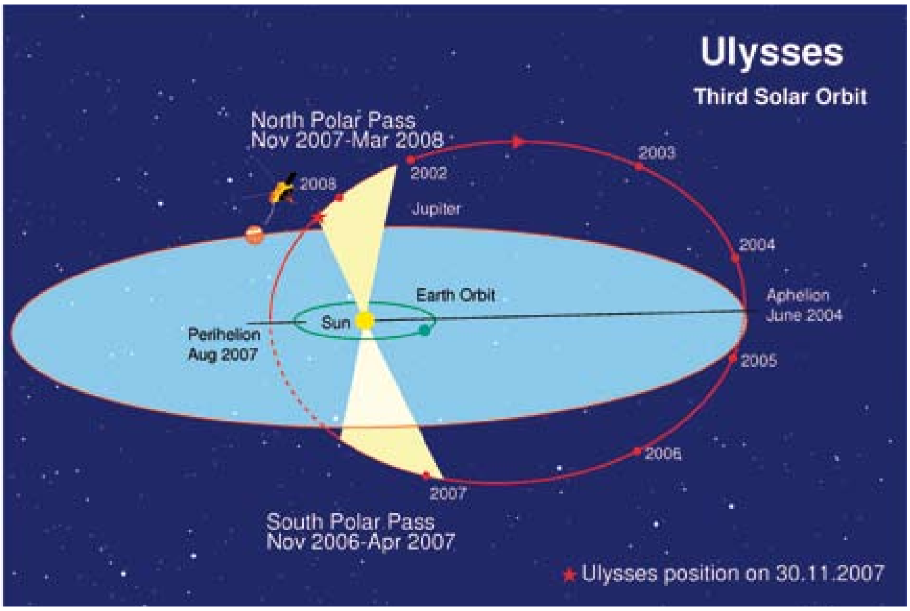


Figure 2.2.1. The Ulysses orbit viewed from 15 degrees above the ecliptic plane. Dots mark the start of each year.

For further information, see http://helio.esa.int/ulysses/

Table 2.2.1. The Ulysses scientific payload.

Expt. Code	*Investigation*	*Scientific Acronym*	*Principal Investigator*	*Collaborating Institutes*
HED	Magnetic field	VHM/FGM	A. Balogh, Imperial College London (UK)	JPL (USA)
BAM	Solar wind plasma	SWOOPS	D.J. McComas; Southwest Research Institute (USA)	Los Alamos National Lab (USA); Ames Research Centre (USA); JPL (USA); HAO Boulder (USA): Univ ofBoston (USA); MSFC (USA); MPS Lindau (D)
GLG	Solar wind ion composition	SWICS	J. Geiss, ISSI (CH); G. Gloeckler, Univ of Michigan (USA)	Univ of New Hampshire (USA); GSFC (USA); TU Braunschweig (D); MPS Lindau (D); Univ of Maryland (USA)
STO	Unified radio and plasma waves	URAP	R.J. MacDowall, GSFC (USA)	Obs de Paris Meudon (F); Univ of Minnesota (USA); CETP Velizy (F)
KEP	Energetic particles and interstellar neutral gas	EPAC/GAS	N. Krupp, MPS Lindau (D)	Imperial College (UK); Swedish Inst Space Physics Kiruna & Umeå (S); Aerospace Corp (USA); Univ of Bonn (D); MPE Garching (D); Polish Acad Sciences (P)
LAN	Low-energy ions and electrons	HI-SCALE	L.J. Lanzerotti, NJIT (USA)	APL Laurel (USA); UC Berkeley (USA); Univ of Kansas (USA); Obs de Paris Meudon (F): Univ of Thrace (Gr); Univ of Birmingham (UK)
SIM	Cosmic rays and solar particles	COSPIN	R.B. McKibben, Univ of New Hampshire (USA)	Imperial College (UK); ESA Research & Scientific Support Dept (NL); NRC Ottawa (Can); Univ of Kiel (D); CEN Saclay (F); Danish Space Research Inst (DK); NCR Milan (I); MPK Heidelberg (D); Univ of Maryland (USA); MPS Lindau (D)
HUS	Solar X-ray and cosmic gamma-ray bursts	GRB	K. Hurley, UC Berkeley (USA) M. Sommer (retired), Samerberg (D)	CESR Toulouse (F); SRON Utrecht (NL); Obs de Paris Meudon (F); GSFC (USA)
GRU	Cosmic dust	DUST	H. Krüger, MPS Lindau (D)	Univ of Canterbury (UK); ESA RSSD (NL); MPE Garching (D); JSC (USA); Univ of Florida (USA); MPK Heidelberg (D)

The spacecraft was launched by the Space Shuttle on 6 October 1990, using a combined IUS/PAM-S upper-stage to inject it into a direct Earth/Jupiter transfer orbit. A gravity-assist manoeuvre at Jupiter in February 1992 placed Ulysses in its final Sun-centred out-of-ecliptic orbit (Fig. 2.2.1), which has a perihelion distance of 1.3 AU and an aphelion of 5.4 AU. The orbital period is 6.2 years. Key mission milestones, including details of the polar passes (defined to be the parts

Table 2.2.2. Key dates in the Ulysses mission.

Event	*Date*
Launch	1990 10 06
Jupiter flyby	1992 02 08
start	1994 06 26
maximum latitude (80.2°, 2.3 AU)	1994 09 13
end	1994 11 05
1st Perihelion (1.34 AU)	1995 03 12
2nd Polar Pass (north)	
start	1995 06 19
maximum latitude (80.2°, 2.0 AU)	1995 07 31
end	1995 09 29
Start of Solar Maximum Mission	1995 10 01
Aphelion (5.40 AU)	1998 04 17
3rd Polar Pass (south)	
start	2000 09 06
maximum latitude (80.2°, 2.3 AU)	2000 11 27
end	2001 01 16
2nd Perihelion (1.34 AU)	2001 05 23
4th Polar Pass (north)	
start	2001 08 31
maximum latitude (80.2°, 2.0 AU)	2001 10 13
end	2001 12 12
Jupiter approach (0.8 AU)	2004 02 04
Aphelion	2004 06 30
5th Polar Pass (south)	
start	2006 11 17
maximum latitude	2007 02 07
end	2007 04 03
3rd Perihelion	2007 08 18
6th Polar Pass (north)	
start	2007 11 30
maximum latitude	2008 01 11
end	2008 03 15

of the trajectory when the spacecraft is above 70º heliographic latitude in either hemisphere), are presented in Table 2.2.2.

Mission status

As can be seen from Table 2.2.2, the period covered by this report included the mission's third set of polar passes and the associated rapid transit from south to north through perihelion. Although clearly of high scientific interest, this part of the orbit is operationally challenging because of the appearance of a dynamic disturbance to the spacecraft once the axial boom moves out of the shadow of the spacecraft body. Asymmetric heating of the boom as Ulysses spins induces a nutation-like motion that, if unchecked, could severely degrade the downlink via the High Gain Antenna. Nutation typically lasts for ~12 months, and the current 'season' started as predicted in February 2007. Fortunately, procedures to control the disturbance that were developed during previous nutation episodes have once again been effective, and there has been little impact on the scientific measurements.

In addition to controlling nutation, management of the onboard thermal environment and the power provided by the radioisotope thermoelectric generator have been the main operational challenges for most of the period. The fact that the spacecraft was (relatively) close to the Sun during the pole-to-pole transit, however, has had a positive effect, since it was possible to switch off one of the main platform heaters for a number of months, thereby freeing up power for the payload. As a consequence, it has been possible to operate the full payload for much of 2007 without the need for power sharing.

In November 2007, the SPC agreed to extend the mission until March 2009. This fourth extension will enable the spacecraft to continue acquiring unique high-latitude data as part of the international network of spacecraft that includes SOHO and

Figure 2.2.2. Comet C/2006 P1 McNaught.

NASA's twin STEREO probes. On 15 January 2008, however, one day after reaching the maximum northern latitude, communication with the spacecraft via the onboard X-band transmitter was lost at the start of a routine test to prepare for the next phase of the mission. As a result, the Spacecraft Operations Team declared a spacecraft emergency in order to obtain additional ground station coverage from NASA's Deep Space Network. The team was then able to send the commands needed to switch to the S-band transmitter, and establish stable communications, albeit at a low bit rate. Subsequently, the bit rate was increased to 1024 bps using a 70m DSN station and the data recorded onboard the spacecraft during the anomaly could be played back. At the time of writing, the spacecraft is in a very stable configuration and there are no power or thermal concerns. Analysis of the anomaly is ongoing.

Scientific highlights

As noted above, from a science perspective the period covered by this report was dominated by the return to high latitudes that included the third south and north polar cap passages and the associated rapid transit from the southern to the northern hemisphere. In mid-2006, Ulysses once again became fully immersed in the fast solar wind from the coronal hole that covers the Sun's southern polar cap around solar minimum. In contrast to the first polar pass, however, the spacecraft had to climb to almost 50ºS, before leaving the slower, more variable wind behind. In mid-1993, the transition occurred nearer to 35ºS. The difference can be explained by the fact that the Sun's magnetic equator was still more highly inclined with respect to the rotational equator in 2006, even though the solar activity cycle was closer to its minimum compared with the previous occasion. (At solar minimum, the Sun's rotational and magnetic axes are most closely aligned.)

The Ulysses mission to date has observed the solar magnetic cycle for ~17 out of the ~22 years required for a full cycle. The picture that has emerged is one of remarkable simplicity: the magnetic field in the heliosphere appears to be organised into two regions of opposite polarity separated by a single current sheet, which appears to persist throughout the solar cycle. In past solar cycles, the average strength of the solar magnetic field that opens into the heliosphere has appeared to be relatively constant, particularly when comparing the field in successive solar minima, and it increases only by a factor of ~2 at solar maximum. The current sheet becomes tilted relative to the solar equator as the solar cycle progresses and ultimately rotates over, thereby accomplishing the reversal in polarity of the dipolar field of the Sun through a rotation in latitude rather than by polar field annihilation as in earlier models. Something new is happening, however. The magnetic field of the Sun today is not behaving as it did in previous solar cycles. At the time of writing this report, the polar field strength is only about half what it has been in previous cycles, despite the fact that we are now at solar minimum. Whether it will evolve further or remain at these lower levels remains to be seen, as do the implications for the next solar maximum. Similarly, the magnetic field in the heliosphere appears lower in this solar minimum compared with the previous one, despite the fact that in all previous solar minimum, during periods when good space observation has been available, the solar minimum field returned to the same, higher value.

A Ulysses result that has provided a new insight into particle acceleration processes is the identification of a population of energetic ions that have a unique character and are ubiquitously present in the solar wind. These ions, in the so-called 'suprathermal' energy range (having speeds above a few times that of the solar wind), are found to have an energy spectrum that obeys a single, well-defined, power law with exponent –1.5. The fact that these ion populations are always present and are not associated with shock waves (a common source of energy gain) has led to a number of theories regarding their origin. Most recently, members of the Ulysses Solar Wind Ion Composition Spectrometer (SWICS) experiment team have proposed that the observed properties can best be accounted for if the ions undergo random acceleration at compressions in the turbulent solar wind. They have shown that this process would generate the observed energy spectrum quite naturally, and that it should operate throughout the heliosphere. Interestingly enough, the same spectral shape has been found in ion data acquired recently by the Voyager 1 spacecraft that crossed the solar wind termination shock in December 2004 and is now traversing the outer boundary of the heliosphere in very different conditions from those at Ulysses. This is a clear demonstration of how universal this process is. Depending on the scale size of the turbulence involved, ions can be accelerated up to energies of at least several MeV per nucleon. Once again, observations from Ulysses have led to a re-evaluation of fundamental ideas concerning basic phenomena in the heliosphere, in this case the acceleration of charged particles and the relative importance of shocks in this process.

On 3 February 2007, the Ulysses spacecraft was almost radially aligned with Comet C/2006 P1 McNaught, the brightest comet observed from Earth in the last 40 years (Fig. 2.2.2). At the time, the Ulysses spacecraft was ~2.4 AU from the Sun at 79° south heliographic latitude and the comet was ~0.7 AU from the Sun. For a period of 4.5 days from 5 to 9 February, Ulysses was immersed in the tail region of this spectacular comet. The region of disturbance in the solar wind produced by the comet (Fig. 2.2.3) was nearly 10 million km wide at the distance of Ulysses. During the encounter, the speed of the solar wind dropped from ~750 km/s to a minimum of 360 km/s and the proton density dropped by more than two orders of magnitude. Simultaneously, very large fluxes of molecular and singly- and doubly-charged atomic ions of cometary origin were detected (Fig. 2.2.4). The slowing, depletion and heating of the solar wind was a result of charge exchange with neutral atoms and molecules from the comet, and with the pickup up by the solar wind of the newly-born cometary ions. Although no shocks were observed during the encounter, the magnetic field strength was slightly enhanced in broad regions at the leading and trailing edges of the comet's tail. The field was generally weaker inside the tail than

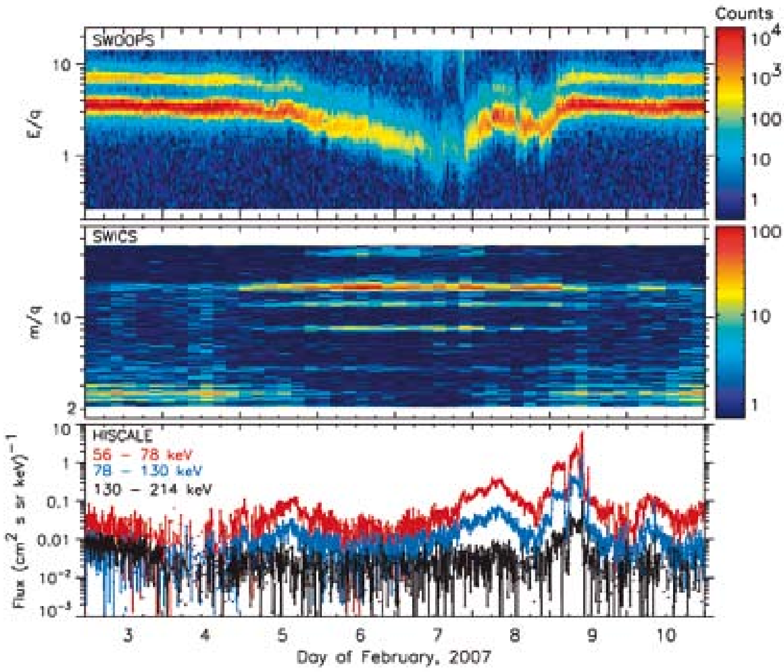


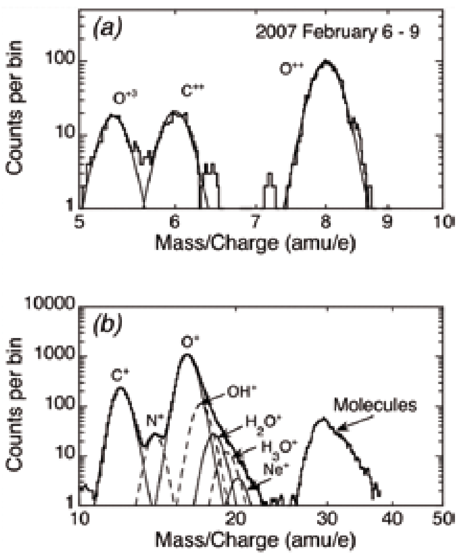
Figure 2.2.3. Top: Energy/charge spectrogramme of ions observed by the Ulysses/SWOOPS instrument during the tail crossing of comet McNaught. Middle: Mass/charge spectrogramme of ions observed by the Ulysses/SWICS instrument. Bottom: Fluxes of energetic particles in the three lowest energy channels of the Ulysses/HISCALE instrument.

in the unobstructed solar wind and pointed nearly radially inward during much of the encounter, opposite to its normal outward direction in the southern polar hemisphere at this phase of the present solar cycle. There were, however, shorter periods when the field pointed nearly radially outward, indicating the filamentary structure of the comet tail. This is the third confirmed crossing of a comet tail during the mission (the others were comet Hyakutake in 1996 and comet McNaught-Hartley in 2000).

The study of cosmic ray modulation has continued to produce surprises, most recently that the measurements of the cosmic ray latitude gradient during Ulysses' rapid pole-to-pole transit in this solar minimum seem to show no significant gradient. Modulation models that include particle drift motions predicted a positive latitude gradient for the previous minimum in 1994–95, which was indeed observed, and a negative gradient for this solar minimum, which, as of the most recent data in hand, was not. A possible explanation is that this solar minimum is anomalous, with the current sheet tilt remaining high and the solar dipole field being much weaker than in the last two minima, thus producing a less well organised and weaker global field in the heliosphere. This suggests that there may be more surprises as the level of solar activity picks up again from this weak solar minimum.

The discovery of interstellar dust flowing through the heliosphere is one of the major discoveries of the Ulysses mission. Measured from launch until 2004, the approach direction of the interstellar dust grains was coincident with the flow direction of the neutral interstellar helium. In 2005, however, the direction shifted by at least 30° away from the ecliptic plane. At the same time, the width of the distribution increased. Since the grains carry an electric charge, their flow can be affected by the heliospheric magnetic field. The change in flow characteristics occurred as the new polarity of the heliospheric magnetic field became clearly established, suggesting that the change in direction may be associated with reversal

Figure 2.2.4. Mass/charge spectra measured by Ulysses/SWICS summed over the interval February 6-9 2007.



of the heliospheric dipole magnetic field. Further measurements in 2006, which had limited statistics, neither confirmed nor refuted the change in direction.

During Ulysses' perihelion and polar passes, interstellar grains cannot be distinguished from particles of solar system origin. Beginning in Spring 2008, however, the interstellar dust will be distinguishable again from interplanetary grains and it will be possible to check if the shift in impact direction still persists, and to determine through models if it is associated with heliospheric interactions or is an intrinsic change. If the shift turns out to be intrinsic, this has profound consequences for the dust dynamics, gas-dust mixing and homogeneity of the Local Interstellar Cloud. If, on the other hand, the shift is dominated by the heliospheric interaction, it provides a clear test for models of grain charging and the electromagnetic interaction of the grains with the heliospheric magnetic field.

Ulysses data archive

Data from the Ulysses investigations and flight project are being archived and made accessible to the public through two channels: the ESA Ulysses Data Archive at ESTEC, and NASA's National Space Science Data Centre (NSSDC). There is no formal proprietary period for Ulysses data, which are placed in the public archives immediately following verification by the PI teams. The ESA archive provides a number of online facilities to browse and download selected measurements made by the scientific instruments. The user is able to view summary plots of the main parameters measured, and (if of interest) download ASCII data files and accompanying documentation for further analysis. A new, web-based plotting interface was introduced in 2007 that allows the user flexibility in defining start and end times and provides the capability to combine parameters from different experiments on the same plot. The ESA archive is accessible via the Ulysses homepage.