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ULYSSES MISSION: THE END OF AN ODYSSEY

Issautier, K.[1], Hoang, S.[1], Le Chat, G.[1], Meyer-Vernet, N.[1] and Moncuquet, M.[1]

Abstract. After almost 18 years in space, the Ulysses mission explored the entire heliophere out-of-the ecliptic plane over the solar activity cycle. The end of this unique mission is planned before the end of December 2008 due to the decline in power produced by its on-board generators. We enlighten some major impacts of the scientific results of the mission to the heliospheric community.

1 Introduction

The Ulysses mission is a cooperative programme between ESA and NASA, launched on 6 October 1990. The goal of the mission was to study in four dimensions (space and time) the heliosphere, the magnetic bubble created by the solar wind, which carries the solar magnetic field well beyond the outer reaches of the solar system. Ulysses was also designed to study the solar wind, a constant stream of charged particles expelled by the Sun at a speed up to 800 km/s. Ulysses provided the first-ever map of the heliosphere from equator to the poles thanks to its special out-of-ecliptic orbit over the Sun. Ulysses is in a six-year orbit around the Sun. Its long path through space carries it out of Jupiter's orbit and back again. Ulysses explored the uncharted high latitude regions of the heliosphere from 80^o south to 80^o north, within 5 AU of the Sun over a wide range of solar activities. About the orbit of Ulysses over the Sun, the most interesting periods are the fast latitudinal scans from 80^o S to 80^o N, lasting ten months, and occuring near solar minimum of activity in 1994-1995 and near solar maximum in 2001. Since February 2007 Ulysses undertook a third pole-to-pole fast transit near the minimum of cycle 23 when the solar magnetic dipole reversed with respect to the previous minimum (Smith et al., 2003). The spacecraft carried 10 instruments to diagnosing the heliosphere through the solar activity. French space laboratories, mainly supported by CNES, were fully associated to some of the main discoveries so far. Ulysses, which is studied the Sun and its effect on the surrounding space for almost four times its expected lifespan, will ceased to function because of the decline in power. We highlight below some major impacts on the heliospheric physics.

2 Legacy of Ulysses

Ulysses was the first mission to survey the environment in space above and below the poles of the Sun in the four dimensions of space and time. It showed that the sun's magnetic field is carried into the solar system in a more complicated manner than previously believed. Particles expelled by the sun from low latitudes can climb up to high latitudes and vice versa, even unexpectedly finding the way down to planets. Before Ulysses, the magnetic field was though to follows generally an archimedean spiral at all latitudes. Ulysses revealed it is more complex. It spreads in latitude much more than was though (Fisk et al. 1996). Ulysses fast latitude scans reveals that the radial field does not vary with latitude. The magnetic field is also more simple since it simply rotates to 180^o to achieve the polarity reversal. Indeed, 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 created by a bar magnet inside the Sun. When the solar activity is at minimum, this bar magnet is aligned with the rotation poles. Six years later, at maximum, the bar magnet has moved to lie at 90^o to the rotation poles. It then continues moving so that by the time of

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[1] Observatoire de Paris, LESIA, CNRS UMR 8109, Université Paris Diderot, UPMC, 92195 Meudon, France

the next minimum, it is aligned with the rotational pole again, but in the opposite orientation (Smith et al., 2003).

The fast solar wind is coming from polar coronal holes of the Sun, and is blowing at 800 km/s. This kind of wind was sporadically observed in the ecliptic plane before the Ulysses mission in contrast to the slow wind, of 400 km/s, predominantly present. Thanks to Ulysses unique trajectory, it was shown on the opposite that the fast wind is the common wind, present all over the solar cycle, "disappearing" at solar maximum when coronal holes are not anymore present on the solar surface. Ulysses thus demonstrated the bimodal nature of the wind: it discovered that a steady fast wind is present throughout most of the solar cycle. The average speed at high latitudes is 750 km/s at all phases. The slow wind emerges on another hand from the sun's equatorial zone.The transition from slow to fast wind is showed to be relatively abrupt (see review of Neugebauer, 2001)

Energetic particles were studies in great detail near equator in the past. Could particles accelerated at low latitudes near the sun or in interplanetary space reach high latitudes? At solar minimum, although acceleration sites are restricted to low latitudes, energetic electrons and ions can reach into the polar caps. At solar maximum, particles are present at all latitudes and are confined to the inner heliosphere in reservoirs from which they slowly escape. Energetic particles are present at all phases of the solar cycle, also at quiet times. Their fast transport to high latitude has revealed large scale restructuring of the coronal magnetic field, during solar events (Pick et al., 1995). Acceleration mechanism that operates is still under question.

Ulysses detected and studied dust flowing into our solar system from deep space and showed that it was 30 times more abundant than astronomers suspected. Ulysses also detected heavy atomic nuclei racing into the solar system. Known as cosmic rays, these are thought to have been accelerated by the explosion of high-mass stars. Ulysses estimated that the average 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. Galactic cosmic rays observed near the equator before Ulysses were known to be affected by changes in solar activity. At both minimum and maximum, the distribution of cosmic rays is essentially spherically symmetric: the flux is the same at the equator and in the polar regions. Do they have easy access to polar regions of the heliosphere where the magnetic field is radial and weak? They don't because their access is opposed by large-amplitude waves on the magnetic field in the fast wind from the poles (Heber & Potgieter, 2008) .

During Ulysses pole-to-pole exploration around the Sun, the Unified Radio And Plasma (URAP) instrument acquired in routine the electron density and temperature versus the heliolatitude using the QTN method. It is based on in situ measurement of the electric field using wire antennas connected to a sensitive receiver. The QTN method has been successfully applied to various environments encountered by Ulysses. For specific plasma conditions, the radio technique is the only way to measure the density. The QTN method on Ulysses gave in routine the electron density and temperature of the solar wind, and produced unique measurements of the Io plasma torus aboard Ulysses, which led to a new understanding of the Io torus structure and stability. Because of its reliability and accuracy, this technique is also used to calibrate and crosscheck other plasmas sensors (Issautier et al., 2001; Maksimovic et al., 1995; Zouganelis, 2008). The accurate electron diagnostics give the unique opportunity to understand the 3D structure of the solar wind over a full solar cycle. Especially, for the first time the radial profiles of the electron density and temperature in the steady state fast solar wind were obtained with accuracy during both solar minimum (in 1994-95 and in 2007) and maximum (2001) (Issautier et al., 1998; Maksimovic et al., 2000; Issautier et al., 2004; Issautier et al., 2008). A north/south asymmetry was found and studied over the full solar cycle (Issautier et al., 2003), thus extending our understanding of the origin of the fast solar wind and its properties (Meyer-Vernet & Issautier, 1998; Zouganelis et al., 2004; Maksimovic et al., 2005)

As a beautiful by-product from the URAP experiment, a result regarding the plasma populating the inner magnetosphere of Jupiter, known as the Io plasma torus (IPT), was obtained by the Ulysses radio spectra acquired in 1992. In contrast to the Voyager 1 or Galileo spacecraft, Ulysses passed through the IPT on a north-to-south trajectory (of course because of Ulysses' primal aim of going out of the Ecliptic) and nearly tangentially to a magnetic shell ($L \cong 8\ R_J$), which allowed us, for the first time, the determination of the electron density and temperature along the magnetic field (Meyer-Vernet et al., 1993; Moncuquet et al, 1995). The principal and most unexpected result was that the electron temperature increased substantially with magnetic latitude (doubling over 7° of latitude) and was anticorrelated with the electron density, obeying a polytropic law $T \propto n^{\gamma-1}$, with an index γ of 0.48 (Meyer-Vernet et al., 1995). The need for a new plasma torus model, especially its latitudinal structure, was driven by this result (Moncuquet et al., 2002; and references therein).

In radioastronomy, combined observations derived from the HISCALE, URAP instruments, VIIM and FCM magnetometers and Nançay radio heliograph, discovered the existence of magnetic channels, anchored in active regions of the sun corona, which can survive over very large distances in the interplanetary medium, beyond 4 AU. Triggered by these beams, Langmuir waves were observed in these channels, being sources of solar Type III bursts (Buttighoffer et al., 1995). In addition, radio observations combined with the Artemis radio spectrograph provided for the first time measurements of their directivity. Ulysses also allowed tracking type II bursts over long distances, a day before the shock hits the spacecraft, and unambiguously identifies the source region of electrons, upstream of the shock. Finally, the URAP receivers monitored the Saturn kilometric radiations, which are used to derive the rotation period of the planet. Observations have shown a striking difference in this rotation, up to 1% from Voyager (Galopeau & Lecacheux, 2000). This problem is now extensively studied from Cassini observations around Saturn.

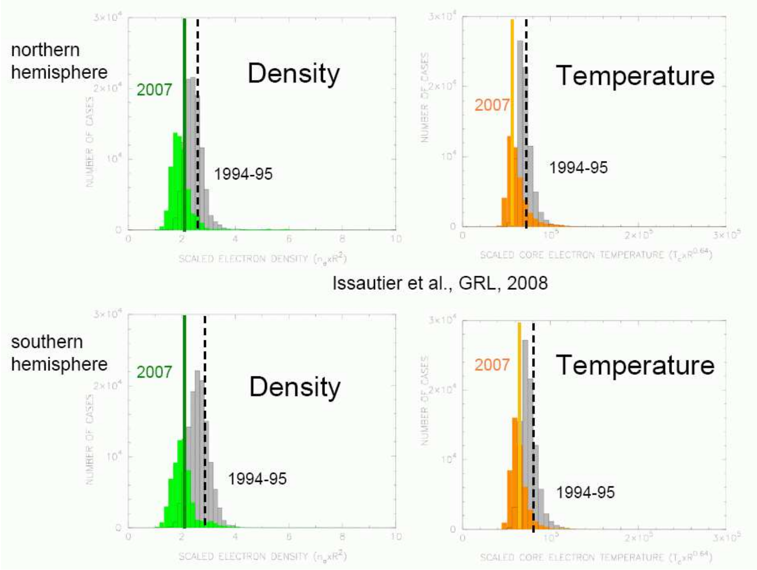

Fig. 1. Histograms of the electron density and temperature measured in 2007 and 1994-95 during Ulysses fast polar pass at high latitudes for northern and southern hemispheres. Adapted from Issautier et al., 2008.

3 Latest solar wind results from Ulysses' third orbit

In 2007, Ulysses undertook its third polar pass over the Sun. The fast solar wind coming from polar coronal regions on the Sun surface is now not so dense, not so hot compared to measurements previously obtained near solar minimum in 1994-95 during Ulysses first orbit, a solar cycle ago.

Electron properties of this fast wind have been investigated using the onboard URAP radio experiment. We observe a significant drop of 20 % of the electron density as well as a drop of 13% of the electron temperature of the solar wind (Issautier et al., 2008). During that period, the solar wind is still blowing fast at 750 km/s. Fig. 1 illustrates these results. It shows histograms of the electron density and temperature respectively of the fast solar wind. We compared theses numbers for both solar hemispheres (north and south) during Ulysses fast polar scans near minimum of activity in 1994-95 and 2007. Vertical lines represent averaged values showing the drop on each hemisphere.

These results are based on wave measurements using electric antennas and a sensitive receiver. It gives an accurate plasmas diagnostics of a few percent. It is important to point out that the weaker solar wind observed in 2007 is also confirmed by other plasmas properties as discussed by McComas et al. (2008) and Smith et al. (2008) from other instruments on Ulysses, thus avoiding any instrumental effects due to the aging of Ulysses and its 18 years in space.

The fast solar wind is significantly less dense and cooler suggesting the present solar cycle minimum is unusual. Indeed, sunspots number is dramatically low during this minimum. However, the structure of the magnetic configuration of the Sun's corona does not show a classical minimum structure: During the third Ulysses polar pass at high latitudes, polar coronal holes are not as well developed as in 1994-95. One more thing to note is that as seen for example on STEREO coronal images, a mid-latitude coronal hole is present at the surface of the Sun, which is unusual during this stage of the cycle. These results call in question our knowledge on the solar cycle and enlighten that the variations observed in the solar wind properties might be related to the 22-year solar cycle or longer periods, due to fluctuations of the solar dynamo.

4 The end of Ulysses

Ulysses uses a small Radioisotope Thermoelectric Generator (RTG). The amount of power available gradually decreases with time. Since 2002, due to lack of power, not all of the instruments and systems could remain switched on. Thus, they were alternatingly switched off. But one has to be careful not to switch anything off for too long to avoid creating cold spots within the spacecraft body, otherwise its thruster fuel will freeze when it reaches the critical level of temperature of 2^o C . Once this appends, as it inevitably will, there is no way to control the spacecraft.

Last year, the power drop became too serious. Ulysses no longer has enough power to run all of its communications, heating and scientific equipment simultaneously. It was thus decided to test a new power-saving strategy: the main transmitter was switching off for a while. Unfortunately, it was impossible to switch it on again and it has left in addition a cold spot critically near a fuel line. This has a consequence of reducing the data transmission rate, and using a less powerful transmitter on board and large ground antennas (70 m) on Earth. Now Ulysses is slowly cooling as it is going away from the Sun. Once the temperature falls below 2^o C, its hydrazine fuel will freeze, and it will be impossible to manoeuvre because it will be impossible to point the high gain antenna towards Earth. Ulysses will however continue unrelentingly its journey around the Sun.

Be that as it may, the rich treasure of unprecedented observations will keep the mission alive long after the actual spacecraft has died.

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