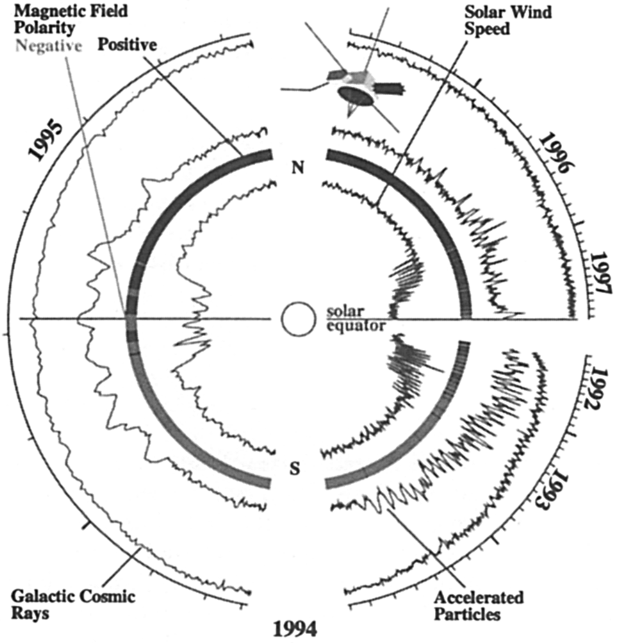
Session VI

The Solar Wind and Heliosphere



Polar plot of data acquired during the first solar orbit of *Ulysses*. From the centre outwards: solar wind speed; heliospheric magnetic field polarity (dark is positive, lig ht is negative); intensity of ~1 MeV protons (log scale); intensity of galactic cosmic ray protons (~1 GeV, log scale). All parameters are plotted as a function of spacecraft latitude. Also shown is the corresponding calendar date (adapted from Marsden, p. 525).

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Highlight Results from Ulysses

R. G. Marsden

Space Science Department of ESA, ESTEC, 2200 AG Noordwijk, The Netherlands

Abstract. Launched in October 1990, the ESA-NASA *Ulysses* mission has conducted the very first survey of the heliosphere within 5 AU of the Sun over the full range of heliolatitudes. The first polar passes took place in 1994 and 1995, enabling *Ulysses* to characterise the global structure of the heliosphere at solar minimum, when the corona adopts its simplest configuration. The most important findings to date include a confirmation of the uniform nature of the high-speed ($\sim$ 750 km s^{-1}) solar wind flow from the polar coronal holes, filling two-thirds of the volume of the inner heliosphere; the sharp boundary, existing from the chromosphere through the corona, between fast and slow solar wind streams; the latitude independence of the radial component of the heliospheric magnetic field; the lower-than-expected latitude gradient of galactic and anomalous cosmic rays; the continued existence of recurrent increases in the flux of low-energy ions and electrons up to the highest latitudes.

1. Introduction

The primary objective of the *Ulysses* mission has been to characterize, for the first time, the properties of the Sun's environment at all latitudes from the equator to the poles, and at distances ranging from 1 to 5 astronomical units. The scientific investigations address a wide range of heliospheric phenomena, including the solar wind, the heliospheric magnetic field, energetic particles and cosmic rays, natural radio emissions, interstellar gas and dust, and gamma-ray bursts (Wenzel et al. 1992).

A gravity-assist manoeuvre at Jupiter was used to place the spacecraft into its unique, out-of-ecliptic orbit. This orbit is such that *Ulysses* spends a total of 234 days above 70°solar latitude (typically 132 days at high southern latitudes, and 102 days in the north) and achieves a maximum heliographic latitude of 80.2°. Figure 1 shows a perspective view of the trajectory as seen from 15° above the ecliptic plane. The first high-latitude passes in 1994 and 1995 took place under near-quiet solar conditions. In September 2000, *Ulysses* began its second high-latitude survey, now near solar maximum. In the ten years since launch, *Ulysses* has provided an unprecedented perspective of the heliosphere. The observations obtained so far have resolved a broad range of questions in the space sciences, due in large part to the unique orbit of the spacecraft. They have also raised questions unanticipated from our previous knowledge of the heliosphere, and provided a firm base on which to continue our exploration of

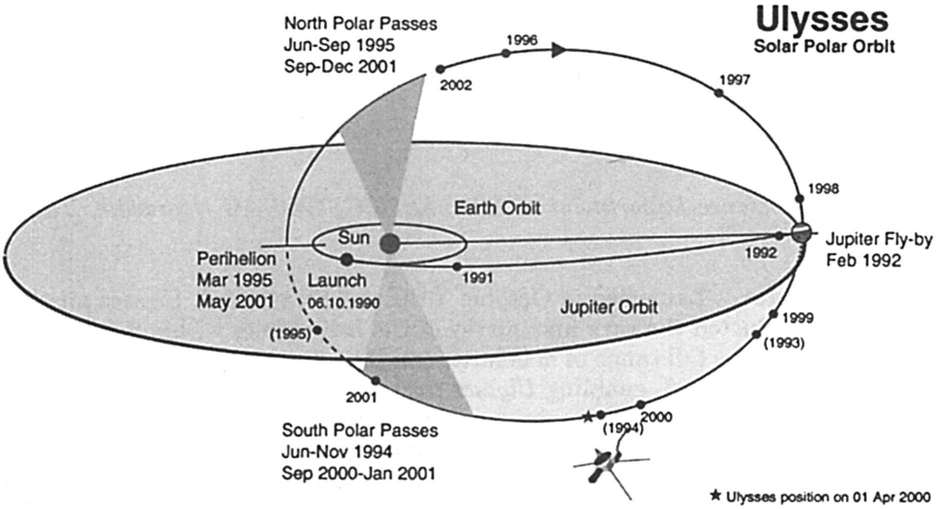

Figure 1. The *Ulysses* out-of-ecliptic orbit viewed from 15° above the ecliptic plane. Dots mark the start of each year.

the heliosphere. The main purpose of this article is to highlight the major findings of *Ulysses*' "solar minimum mission".

2. Scientific highlights

The scientific accomplishments of *Ulysses* to date have been reported in more than 950 publications covering a wide range of solar, heliospheric and astrophysical phenomena (e.g., Marsden 1995; Marsden et al. 1996; Marsden & Smith 1997, and references therein). These accomplishments include the following:

- The characterisation of two distinct solar wind states, a fast high-latitude wind that only occasionally extends down to low latitudes, and a slow low-latitude wind centred about the heliospheric current sheet. These are separated by a sharp boundary extending from the corona down to the chromosphere (e.g., Geiss et al. 1995a).

- The discovery that the magnitude of the radial component of the heliospheric magnetic field does not increase towards the poles (Smith & Balogh 1995). The constancy of the radial field implies that the dipole-like configuration of the Sun's surface field is not maintained, and that as a result, the polar solar wind undergoes significant non-radial expansion.

- The discovery that corotating solar wind stream structures with forward and reverse shock waves, well-studied at low latitudes (e.g., Gosling et al. 1993; Gosling and Pizzo 1999) and expected to be confined to those regions, produce effects extending to the highest latitudes explored by *Ulysses.* These effects include the recurrent modulation of galactic cosmic rays (Simpson 1998) and injection of accelerated lower-energy particles into the polar regions (Sanderson et al. 1994; Simnett et al. 1994), suggesting a revised global structure for the heliospheric magnetic field (Fisk 1996), or enhanced cross-field diffusion (Kota & Jokipii 1995).

- The discovery that the influx of cosmic rays at high latitudes is smaller than predicted for this phase of the solar activity cycle (Simpson et al. 1995).
- The determination of the flux and flow direction of interstellar dust grains passing through the solar system (Gruen et al. 1993).
- The measurement of the flow parameters of interstellar helium, leading to an improved description of the motion of the solar system through the local interstellar cloud (Witte et al. 1996).
- The derivation of the density of interstellar atomic hydrogen and helium, leading to improved knowledge of the interaction of the local interstellar cloud with the heliosphere (Gloeckler 1996).
- The first-ever measurement of the interstellar ^{3}He/^{4}He ratio (Gloeckler & Geiss 1996), the value of which suggests that the amount of dark matter produced in the Big Bang was greater than previously thought.
- The measurement of individual isotopes of cosmic ray nuclei, showing a source composition that is generally consistent with solar system matter (Connell & Simpson 1997).
- The determination of the positions of gamma-ray bursts with unprecedented accuracy (Hurley et al. 1995), including a contribution to the first plausible identification of an optical counterpart.
- The discovery of a new class of forward-reverse shock pairs associated with coronal mass ejections (CMEs) at high latitudes (Gosling et al. 1994). Over-expansion of the CME caused by internal pressure is the source of these shocks.

In the following sections, we will describe a number of these findings in more detail.

2.1. Global heliospheric structure

One of the main goals of the *Ulysses* mission was to determine the global structure of the heliosphere, in particular with regard to the distribution of solar wind plasma, and its frozen-in magnetic field. The latitude survey carried out by *Ulysses*, the first ever, has resulted in the following picture of the heliosphere at solar minimum. The three-dimensional structure is characterised by a basic north-south symmetry, and is dominated by the presence of the fast solar wind from polar and high-latitude regions that expands to occupy a large fraction of the heliospheric volume; the slow wind is confined to low latitudes. Observations made by *Ulysses* during its rapid pole-to-pole transit near perihelion have revealed that the transition from slow to fast wind is surprisingly abrupt. This is graphically illustrated in Figure 2, which shows a polar plot of the solar wind

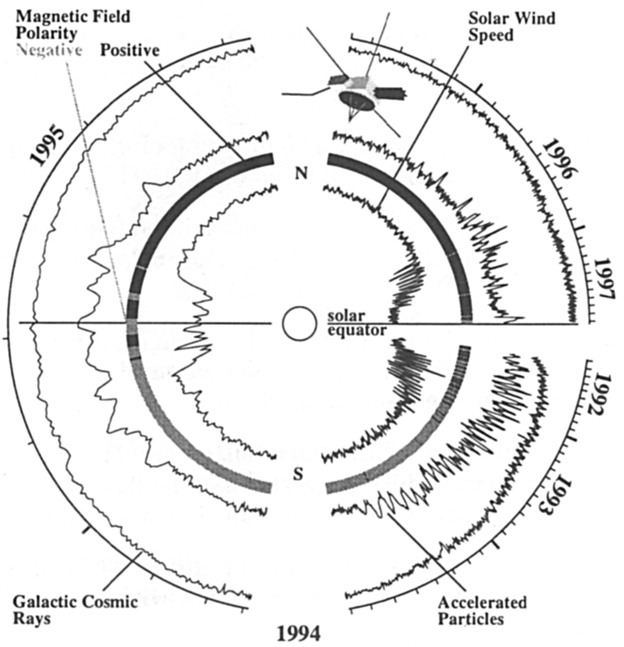

Figure 2. Polar plot of data acquired during the first solar orbit of *Ulysses*. From the centre outwards: solar wind speed; heliospheric magnetic field polarity (dark is positive, light is negative); intensity of ~1 MeV protons (log scale); intensity of galactic cosmic ray protons (~1 GeV, log scale). All parameters are plotted as a function of spacecraft latitude. Also shown is the corresponding calendar date.

speed and other parameters measured by *Ulysses* as a function of heliolatitude.

Note that nearly all other space missions have been confined to the narrow region of the heliosphere at low latitudes dominated by slow wind, and that *Ulysses* has provided the first direct, detailed view of the "true" solar wind flowing from the polar coronal holes. This fast-flowing solar wind has been found by *Ulysses* to be relatively constant near solar minimum, with a speed of approximately 750 km s^{-1}. On the other hand, while clearly much less variable than the low-latitude slow wind, closer inspection has shown that even the fast wind is far from quiescent. New observations from the SOHO spacecraft present a picture of the solar atmosphere that, even at solar minimum, is highly dynamic, and this is clearly reflected in the *Ulysses* solar wind data.

The *Ulysses* magnetic field measurements indicate that the radial field component, and consequently, the magnetic flux, are independent of latitude (Smith

& Balogh 1995). This has lead to the unanticipated conclusion that the magnetic field pressure controls the solar wind flow near the Sun, driving a non-radial expansion by more than a factor of 5 from the polar coronal holes. Another characteristic property of the fast high-latitude wind that has been revealed by *Ulysses* is the continual presence of large amplitude transverse waves in the magnetic field (Balogh et al. 1995). The wave amplitudes typically equal or exceed the magnitude of the background field and, as such, are an example of strong turbulence. The waves are observed over a wide range of periods, the longer period variations probably originating in the random-walk of field lines at the sun (Jokipii & Kota 1989), which in turn is a signature of the non-quiescent solar surface. Although the spiral magnetic field structure predicted by the earliest models of the solar wind (Parker 1958) is preserved to the highest latitudes, a significant departure from this so-called Parker field configuration has been discovered. A likely explanation for this is that the observed deviations are the result of the large amplitude waves referred to above.

The north-south symmetry discussed earlier is associated with the heliospheric current sheet (HCS) that separates oppositely directed magnetic fields in the two hemispheres and defines the Sun's magnetic equator. The corresponding magnetic axis passes through the Sun's polar caps, and it is the tilt of this axis relative to the Sun's rotation axis which causes alternating slow (low-latitude) and fast (high-latitude) solar wind streams to sweep over an observer in the ecliptic. Because of the radial outflow of the solar wind, the fast streams eventually run into the slower wind ahead, forming so-called corotating interaction regions (CIRs) (Smith & Wolfe 1976). These are regions of compressed solar wind plasma, which, as the name suggests, corotate with the Sun. At distances beyond 1 AU, CIRs are often bounded by forward and reverse shock waves (e.g., Gosling & Pizzo 1999). The investigation of CIRs themselves, and their influence on the energetic particles and cosmic rays that populate the heliosphere, forms a major theme in the scientific output of *Ulysses*.

2.2. Energetic particles and cosmic rays

Prior to *Ulysses*, it was known that the shocks associated with CIRs are able to accelerate low-energy charged particles. Characteristic increases in particle intensity are frequently observed when a CIR sweeps past a spacecraft once per solar rotation. At much higher energies, the same CIR can act as a temporary shield against incoming cosmic rays, causing the observed intensity to decrease rather abruptly, then slowly recover. Surprisingly, *Ulysses* discovered that the recurrent effects in energetic particle and cosmic ray intensity extend to much higher latitudes than the CIRs themselves (Kunow et al. 1999). Under the influence of the magnetic configuration of the Sun, the angle between the Sun's rotational and magnetic axes changes with the solar cycle. Near solar minimum, the magnetic and rotational axes are nearly aligned, so that the CIRs are restricted to relatively low heliographic latitudes (typically less than 30 degrees). As shown in Figure 2, the series of recurrent increases and decreases starting at low latitudes clearly extends to regions far beyond the latitude range of the CIRs or their associated shocks.

The *Ulysses* observations could be explained if the particles are able to move across the mean magnetic field to higher latitudes much more easily than previously thought. An alternative explanation is that the differential rotation of photospheric foot points of heliospheric magnetic field lines interacts with the non-radial near-Sun expansion of the solar wind to produce field lines that deviate drastically from the traditional constant-latitude spirals. The result is to bring field lines from high latitudes near the Sun to low latitudes at 15 AU or more from the Sun, thereby connecting *Ulysses* to the acceleration region of the energetic particles. This remarkably different magnetic topology is not detectable near the ecliptic plane; it could only be discovered by observations at high heliolatitudes (Fisk 1996; Zurbuchen et al. 1999). If confirmed by further work, this theory based exclusively on *Ulysses* data will revolutionize our understanding of the heliospheric magnetic field and cosmic ray transport.

A major goal of *Ulysses* was to investigate the physics of propagation of energetic particles in the heliosphere. In particular, the question was posed as to whether or not cosmic rays would have easier access to the inner heliosphere along relatively straight magnetic field lines expected over the poles of the Sun. *Ulysses* showed that the cosmic ray intensity increased by less than a factor of two from the equator to the poles, implying nearly equal difficulty of access (Simpson et al. 1995). A possible explanation is found in the *Ulysses* discovery that large amplitude waves in the magnetic field, which obstruct cosmic ray propagation, are a characteristic feature of the high latitude fast solar wind.

2.3. Interstellar gas and pickup ions

Ulysses has observed for the first time a variety of atoms entering the heliosphere from interstellar space. With a new technique to directly detect low energy (>30 eV) atomic helium, the local angular distribution of He was measured and, from these observations the velocity vector and kinetic temperature of the interstellar neutral helium at the boundary of the heliosphere have been determined with unprecedented precision (Witte et al. 1993). The velocity vector describes the motion of the solar system through the surrounding Local Interstellar Cloud (LIC). Furthermore, from the neutral and pickup helium (see below) observed locally with *Ulysses* it was possible to infer for the first time the neutral helium density in the LIC (0.0155 particles cm^{-3}).

Ulysses discovered a vast heliospheric population of ions (so-called *pickup* ions) produced from interstellar atoms and dust grains by photoionization and charge exchange with the solar wind. Measurements of these pickup ions (H^+, He^{++}, $^3\mathrm{He}^+$, $^4\mathrm{He}^+$, C^+, N^+, O^+ and Ne^+) by *Ulysses* have lead to important new results. For example, the abundance of atomic N, O and Ne in the local interstellar cloud was established for the first time (Geiss et al. 1994). The discovery of C^+ (Geiss et al. 1995b) revealed new sources of neutral particles in the heliosphere: "re-cycled" solar wind ions that have been absorbed by interplanetary dust grains and then re-emitted in the inner solar system.

2.4. Cosmic dust

The dust detector on the *Ulysses* spacecraft is the first to directly detect dust at high ecliptic latitudes. The experiment has discovered a flux of interstellar grains passing through the solar system (Gruen et al. 1993; Gruen et al. 1994). The detections occur at the rate of about one detection every 3 or 4 days. Streams, or bursts, of dust were also discovered to be emanating from the Jovian system.

An analysis of all *Ulysses* data has identified a total of 11 such streams, and showed that the dust grains are electrically charged and their trajectories are bent by the solar wind magnetic field.

2.5. Astrophysics

The study of the Sun and its environment by *Ulysses* has an obvious importance to stellar astrophysics, providing the only possible detailed analysis of the interaction of a typical star with its surroundings. *Ulysses* has also made important contributions to astrophysical studies that reach far beyond the heliosphere. For example, the gamma ray burst (GRB) experiment provides a distant point in space to obtain arc-minute positions for cosmic gamma-ray bursts. Important contributions from the *Ulysses* experiment include the detection of a giant periodic flare from a soft gamma-ray repeater (Hurley et al. 1999).

Ulysses has also carried out cosmic ray studies with significance for astrophysics, providing isotopic abundance determinations of unequaled precision for many of the more abundant elements in the cosmic radiation. The measurements of the isotopes of iron and nickel have already eliminated some models for heavy element nucleosynthesis and for the origin of cosmic rays (Connell & Simpson 1997). Isotopes of less abundant elements such as Cl and Ar, which have important implications for nucleosynthesis and propagation theory, have also been measured (Connell 2000).

The *Ulysses* measurements of the ratio of helium isotopes (^{3}He/^{4}He) in the local interstellar gas (Gloeckler & Geiss 1996), the first of their kind, have made it possible to compare present-day light element abundances in the Local Interstellar Cloud with their values at the time of the formation of the Solar System. The abundances were found to have remained essentially unchanged, placing new constraints on models of Galactic chemical evolution. These data have also lead to important refinements in another fundamental cosmological parameter, providing information on conditions that obtained in the Big Bang.

3. The future

The main goal of the *Ulysses* mission is to explore the heliosphere in the three spatial dimensions. Without doubt, this goal has been successfully achieved for the heliosphere close to solar minimum. In reality, however, there is also a fourth dimension to be considered: time. The heliosphere is a dynamic structure that changes quite dramatically over the period of a solar cycle (approximately 11 years). In order to understand fully the way the heliosphere evolves with time, measurements are also needed at solar maximum. With this in mind, *Ulysses* is now visiting the Sun's southern polar regions for a second time. The pass over the south pole will occur in November 2000, with the northern polar pass one year later. The main goals for this phase of the mission will be to map the large-scale source regions of the slow and fast solar wind at solar maximum, and to observe the switch in polarity of the Sun's magnetic field. This change has an effect on the global structure of the heliosphere, and *Ulysses* will be ideally placed to investigate this.

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