PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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The Heliosphere and the Ulysses Mission

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The heliosphere and the Ulysses mission

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The interplanetary medium consists primarily of the supersonic solar wind, carrying the frozen-in magnetic field extending from the solar corona. The properties of this medium are controlled by the state of the corona and by dynamic processes occurring in the medium itself. As a result, there are significant variations in those properties as a function of heliolatitude. *In situ* observations over the past three decades have been largely confined to the neighbourhood of the solar equatorial plane. While many of the important processes have been identified and studied extensively, observations are required as a function of heliolatitude to define large-scale structures and their dependence on processes in the solar corona. The Ulysses mission, launched in October 1990, is the first space probe dedicated to the exploration of the heliosphere out of the ecliptic plane. By January 1994, the spacecraft had reached a heliolatitude of 50° south. The first results of the mission are summarized here, including the evolution and disappearance of the interplanetary magnetic sector structure; the onset of the dominance of the high-speed solar wind stream originating in the expanding southern coronal hole; observations of the signatures of complex coronal mass ejections; the high-latitude structure of the heliospheric magnetic field, and the evolution of corotating interaction regions as a function of heliolatitude. In particular, the abrupt change in the rotation rate of the sector structure in mid-1992, followed by the equatorward extension of the southern polar coronal hole, represent new observations related to the evolution of large-scale coronal structures and solar magnetic fields and to processes controlling the solar activity cycle.

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1. Introduction: the heliosphere before Ulysses

The outer atmosphere of the Sun, the corona, is a hot and tenuous plasma. There is a large energy flow from the photosphere to the corona, driven presumably by the convective motions of the photosphere and mediated to the corona by complex magnetic and magnetohydrodynamic processes which are, in general, not well understood. These processes deposit a very large amount of heat in the corona, raising the temperature from the photosphere at some 6000 K to more than a million degrees in the corona, over a very short radial distance. The corona at this temperature is unstable and expands at supersonic speeds (at 400 km s^{-1} or more) into the heliosphere. This magnetohydrodynamic model of the solar corona was first proposed by Parker (1958), although the existence of the solar wind, a permanent outflow of plasma from the Sun, was expected on the basis of comet tail observations. The first interplanetary observations in the early 1960s

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confirmed the existence of a supersonic solar wind, of variable speed and density, but in relatively close correspondence with the values predicted on the basis of Parker's model.

Parker's model is a deliberately simplified, spherically symmetric model of the corona, in which the plasma flow from the corona is uniform. The magnetic field (observed at the solar surface to be about 1 gauss in strength, on average) is drawn out radially from the corona; the plasma in the solar wind being an almost perfect conductor, the magnetic flux remains frozen in the solar wind as it expands away from the Sun. Due to the Sun's rotation, and as the ends of the field lines remain attached to the photosphere, they are constrained to cones centred on the Sun and of half-angle equal to the colatitude of the origin of the field line in the photosphere. In the solar equatorial plane, the field lines are drawn out in the so-called Parker spiral, of classical Archimedean form.

While this simplified picture has the advantage of describing the basic physical structure of the heliosphere, it has always been clear that significant deviations from it could be expected because of spatial and temporal variations in the structure of the corona. In the first place, the appearance of the corona, as photographed in white light during total eclipses or using coronagraphs, is highly asymmetric. There are also temporal variations in the appearance of the corona on many time-scales, of which the eleven-year solar activity cycle is the most significant. The contrasting appearances of the corona at solar minimum and solar maximum are illustrated in the eclipse photographs shown in figure 1. The intensity of white light from the corona, generated by Thompson scattering of photospheric photons by electrons, is proportional to the plasma density. The energy density of the magnetic field in the closed regions of the corona is greater than that of the plasma, and is therefore able to contain it. Such photographs show that large volumes, at least in the lower corona, consist of magnetic field lines rooted at both ends in the photosphere, containing dense and hot plasma. Other regions, particularly near the solar poles during the minimum in solar activity, appear magnetically open, and have lower plasma density. These regions, the coronal 'holes' discovered in the soft X-ray pictures made of the Sun during the Skylab mission, have been identified as the source regions of the faster flows in the solar wind. There are significant variations in the structure of the corona during the solar cycle: during solar maximum, much of the corona appears to be magnetically contained, while, at solar minimum, the polar coronal holes, with an open magnetic field geometry, reach to relatively low latitudes. Occasionally, extensions of the polar coronal holes reach the solar equator over at least a limited range of heliolongitudes.

The in-ecliptic solar wind consists, for an interplanetary observer, of a succession of fast streams (speeds in excess of 550 $\mathrm{km\ s^{-1}}$) and slow streams (speeds below about 450 $\mathrm{km\ s^{-1}}$). At solar minimum, the sequence is maintained over several solar rotations. Fast solar wind streams compress the slower streams ahead, and the resulting structure consists of a series of corotating interaction regions, recognizable by their compressed magnetic fields, higher plasma densities and temperatures. At heliocentric distances beyond about 2 AU, these interaction regions also develop collisionless shock waves at their leading and trailing edges.

The solar corona at solar maximum activity appears to consist mostly of closed magnetic regions, even at high heliolatitudes. In interplanetary space, at low latitudes, there is a relative absence of fast solar wind streams, and there is

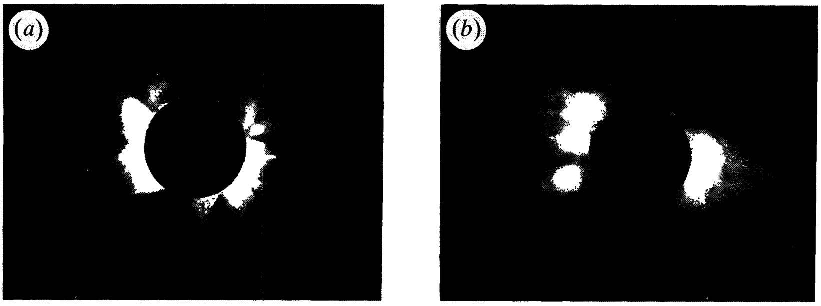

Figure 1. Eclipse photographs taken at solar maximum (left) and solar minimum (right) activity, illustrating the difference in the solar corona between the two activity levels and its heliolatitude dependence.

no discernible periodicity of interaction regions. Transient events in the corona, related to large-scale instabilities in the closed magnetic regions, result in the expulsion of coronal plasma, the so-called coronal mass ejections (CMEs). At solar maximum, the rate of occurrence of CMEs is such that much of the heliosphere, to several AU from the Sun, can be filled with coronal ejecta originating in CMEs (Hundhausen 1993). Solar flares, considered for a long time as the prime causes of transient interplanetary disturbances, are now thought to be only indirectly related to coronal events which give rise to CMEs (Gosling 1993).

The solar activity cycle is essentially a magnetic phenomenon. Historically, the solar cycle has been defined in terms of sunspot numbers; sunspots are known for their very strong magnetic fields (of order several thousand gauss). Other related measures of the activity can also be associated with the magnetic structure of the corona. At times other than near solar maximum activity, the northern and southern hemispheres of the Sun show oppositely directed dominant magnetic polarities. As solar maximum approaches, polarities in the two hemispheres become less well defined. Shortly after maximum activity, dominant polarities reappear, but opposite to those in the previous activity cycle. This can be expressed by the evolution of the dipole, quadrupole and octopole terms in the large-scale magnetic field of the Sun through the solar cycle (Hoeksema 1992). The nature of the processes leading to the reversal of the polar fields is an essential element in the solar activity cycle.

A major feature of the large-scale structure of the heliospheric magnetic field is the boundary, in interplanetary space, between field lines originating in the two hemispheres. On one side of this boundary, field lines are connected to the northern solar hemisphere; on the other side, field lines are connected to the oppositely directed southern hemisphere. The boundary is the heliospheric current sheet (HCS). If the boundary was simply in, or close to, the solar equatorial plane, an observer in the ecliptic plane would distinguish two magnetic sectors in each solar rotation. This is indeed the case during solar minimum. However, the boundary between the two polarities on the Sun (the heliomagnetic equator) is not normally along the solar equator, but can extend to both north and south of it as a function of heliolongitude, particularly when solar activity is high. In this case, there can be four or even six alternating polarity sectors in each solar rotation (when observed in the ecliptic), corresponding to the dominant northern and southern solar magnetic polarities. By implication, the HCS separating these sectors is warped, with significant north–south excursions in each solar rotation.

2. The three-dimensional heliosphere

Interplanetary space probes have been, in the past, constrained to remain near the ecliptic plane, partly because most of them were also targeted for planetary fly-bys, but partly also because of the need for additional energy required to overcome the Earth's orbital velocity in the ecliptic. The Ulysses mission, previously the Out-of-Ecliptic, then the International Solar Polar mission, is the first space probe with the exploration of the heliolatitude dependence of heliospheric phenomena as its primary scientific objective. Prior to the Ulysses mission, the closeness of the solar equator to the ecliptic has constrained the range of observations in the solar wind and has therefore introduced a bias because of the concentration of closed magnetic structures in the solar corona at low latitudes during the greater part of the solar cycle.

Understanding the heliolatitude dependence of large- and small-scale structures in the solar wind is considered essential for understanding a range of physical processes concerning the Sun and the heliosphere. Among these processes are the acceleration of the solar wind, the evolution of coronal magnetic structures and the mechanisms behind the solar cycle itself. Other phenomena which are also affected by the three-dimensional nature of the heliosphere are the evolution and latitudinal extent of corotating interaction regions, the propagation of coronal mass ejections into the high-latitude heliosphere, the access and modulation of cosmic rays, and the propagation of energetic particles accelerated near the Sun or by propagating interplanetary shock waves.

The orbit of the Ulysses mission is shown in figure 2. Launched in October 1990, the spacecraft first travelled out to Jupiter, where, using the giant planet's gravitational field, the plane of its orbit was rotated to be nearly perpendicular to the solar equatorial plane. In September 1994, the spacecraft will reach a heliolatitude of 81° south, followed by a quick traversal to the northern polar regions in mid-1995. In early 1994, the spacecraft had reached over 55° south and is already observing the fast but relatively steady flow of the solar wind originating in the southern polar coronal hole, characteristic of conditions near solar minimum activity (Wenzel *et al.* 1992).

The early, in-ecliptic phase of the mission from 1 to 5.4 AU was characterized by the transition in solar activity from near maximum to the decline towards minimum conditions (Balogh *et al.* 1993*b*). From October 1990 to June 1991, several major solar transient events were observed, which dominated the interplanetary medium (Phillips *et al.* 1992). These were associated with the reorganization of large-scale coronal magnetic fields following the magnetic reversal which had taken place over several months in 1990. In the second half of 1991, a more stable coronal pattern allowed the development of corotating interaction regions, characteristic of the decline in solar activity and the development of long-duration coronal holes with equatorial extensions.

An overview of the magnetic field strength and solar wind velocity observed by Ulysses during its climb out of the ecliptic plane is shown in figure 3. (The solar wind data are shown by courtesy of the Ulysses plasma team, Los Alamos National Laboratory, from Bame *et al.* 1993, and Phillips *et al.* 1994; the magnetic field data are taken from observations made by the Ulysses magnetometer, Balogh *et al.* 1992.) During these two years, Ulysses travelled from the ecliptic plane to close to 50° in heliolatitude. The dominant features on these plots are the

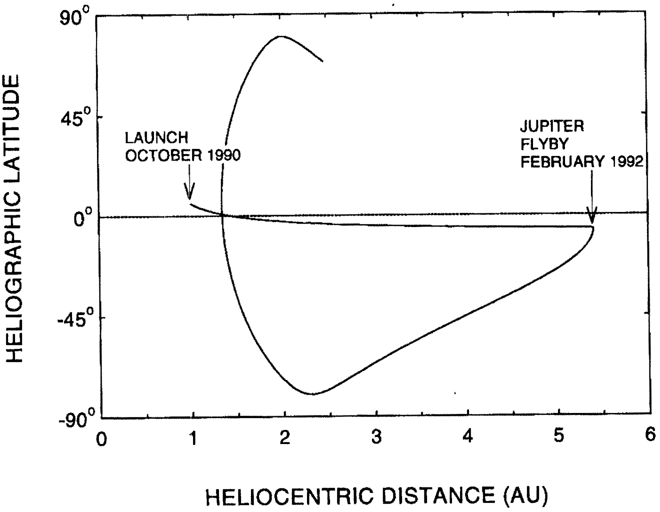

Figure 2. The orbit of Ulysses, shown in terms of its heliolatitude as a function of heliocentric distance.

development and persistence of the large periodic variations in solar wind speed from mid-1992 to mid-1993 and the resulting compressed magnetic fields at the leading edges of the fast solar streams. The prominent fast solar wind stream was associated with the development and equatorward extension of the newly developing south polar coronal hole. At the start of the sequence, in July 1992, another coronal reorganization took place, and a large coronal mass ejection was detected by Ulysses at 5 AU. While the onset of the fast southern solar wind flow at Ulysses was due to a temporal evolution in the solar corona, the southbound trajectory of the spacecraft led to an increasingly deeper immersion in flows from the fast developing southern polar coronal hole. Up to May 1993, however, Ulysses sampled northern as well as southern solar magnetic polarities in each solar rotation, and observed relatively constant minimum and maximum solar wind velocities. The velocity peak at close to 1000 km s^{-1} in November 1992 was due to an exceptionally fast coronal mass ejection.

From May 1993, Ulysses passed south of the heliospheric current sheet which represents the interplanetary extension of the heliomagnetic equator, the notional line near the Sun separating the two dominant magnetic polarities on the Sun. For another four solar rotation periods, the (increased) minima in solar wind speed indicated that, at least for a restricted range of heliolongitudes, the spacecraft remained close to the heliospheric current sheet. But, from about September 1993, Ulysses remained in a constantly fast flow regime, thus observing, for the first time, solar wind flows and magnetic fields not only originating in a coronal hole, but also apparently largely unaffected by interaction processes between the Sun and Ulysses at some 3–4 AU. The properties of this fast flow, including the characteristics of the magnetic field, are considered to provide an important set of constraints on theories of solar wind acceleration.

The average polarity of the heliospheric magnetic field observed by Ulysses represents the polarity of the large-scale coronal open magnetic field lines; during the in-ecliptic phase, the sector pattern changed from a four-sector to a two-

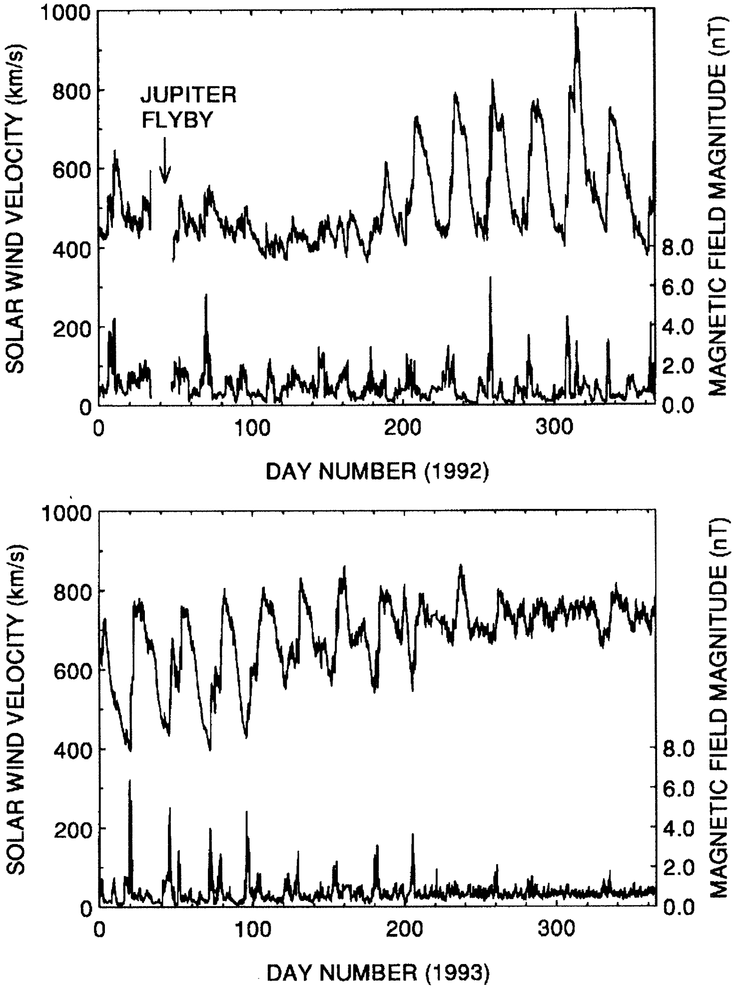

Figure 3. The solar wind speed and the magnitude of the heliospheric magnetic field observed by Ulysses in 1992–93 as the heliolatitude of the spacecraft changed from the ecliptic plane to close to 50° south.

sector pattern as solar activity declined and the corotating interaction regions became the dominant feature of the interplanetary medium. The sector pattern persisted to 30° southern latitudes (Smith *et al.* 1993) but underwent a significant change in July 1992, at the same time when the polar high-speed stream was first observed.

The evolution of the magnetic polarities observed by Ulysses from launch to the end of 1993 is illustrated in figure 4. On this figure, the average orientation of the magnetic field (towards or away from the Sun) observed at Ulysses is projected back to the Sun, using the solar wind velocity observed by Ulysses and assuming that the velocity is constant along a streamline. Dark and light areas represent magnetic field orientations towards and away from the Sun, and correspond to the dominant polarities in the southern and northern solar hemispheres, respectively. A very good match has been found between the polarities thus deduced and those

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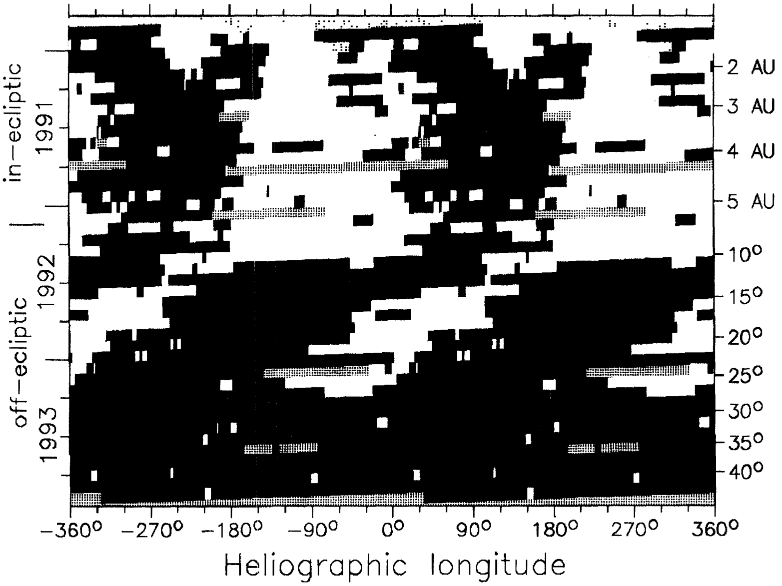

Figure 4. The evolution of the magnetic field polarities observed by Ulysses between launch and the end of 1993, projected back to the Sun. For greater clarity, two solar rotations are shown side by side.

modelled using photospheric magnetic field measurements (Balogh *et al.* 1993*a*). The figure shows the sector pattern in the ecliptic plane for the early part of the mission as already described above. The horizontal axis in the figure represents the synodic solar rotation period (two periods are shown side by side, for clarity); the sector pattern is seen to corotate with the Sun up to mid-1992. The apparent westward drift of the sector pattern from that time represents an almost 28-day apparent rotation period in the large-scale coronal magnetic structures. This drift is likely to be caused by the relative evolution of axisymmetric and non-axisymmetric terms in the solar magnetic field and represents an important constraint on theories of the solar cycle.

From May 1993, the orientation of the magnetic field measured by Ulysses corresponds to that in the large southern polar coronal hole (as represented by the dark area in figure 4). As already stated, this penetration into a region of the heliosphere dominated by fast solar wind flows provides opportunities for the study of the interplanetary signatures of solar wind acceleration mechanisms closer to the Sun and relatively undisturbed by interplanetary interactions. Current research work on the Ulysses magnetic field data indicates that there is a significant hardening of the power spectral index at high latitudes: in the ecliptic plane, spectral indices are closer to the values (between -1.5 and $-5/3$) deduced from turbulence theory, whereas at the highest latitudes reached by Ulysses the spectral index is closer to -1.2. The high-latitude fluctuations are, as expected, at least in part Alfvénic (uncompressive transverse fluctuations in the magnetic field), but compressive waves and discontinuities are nevertheless also present in the observations. These characteristics, to be studied in greater detail, provide the best evidence that long-scale wave dissipation is the dominant acceleration mechanism in the solar wind.

Although the high-latitude solar wind is relatively featureless (when compared to the large dynamic fluctuations at low latitudes), some unexpected observations have been made of both short- and long-term phenomena which remain to be fully explained. At the shortest end of the scale, apparent nulls in the magnetic field have been seen, corresponding to diamagnetic 'holes' in the solar wind. These nulls are of short duration, 30–60 s; plasma physics processes generating and maintaining such structures in the solar wind remain to be fully explained (Winterhalter *et al.* 1994).

At larger scales, the observation of coronal mass ejections in February 1994 at some 55° heliolatitude was unexpected. CMEs are phenomena essentially connected with the breaking away of expanding closed coronal magnetic structures and are, in the main, associated with the coronal streamer belt which at the current phase of the solar cycle is restricted to low and medium latitudes. The magnetic field observations made by Ulysses of the CME between 7 and 14 February 1994 are shown in figure 5. The characteristic magnetic flux rope geometry associated with CMEs is clearly seen in the smooth rotation of the magnetic field vector on 10 February (day 41). The region surrounding the flux rope was bounded by a forward and possibly a reverse shock wave; a CME of similar characteristics was observed in June 1993 and attributed to a class of CMEs whose existence had been postulated but had not previously been observed (Gosling *et al.* 1994). In these rare examples, the plasma pressure internal to the expanding magnetic flux rope is much higher than that of the surrounding solar wind and therefore results in an over-expansion leading to the formation of shock waves at the leading and trailing edges of the CME. The high-latitude CME in February 1994 has not yet been associated with any specific coronal feature, but its detection deep in the coronal hole solar wind flow (in which coronal magnetic field lines have an open geometry) implies the existence of an unusual coronal configuration or a non-radial propagation path from the Sun.

3. Conclusions and expectations

The three-dimensional nature of the heliosphere has already been placed on a firm observational basis by the Ulysses mission. While some of the large-scale features of the high-latitude observations, such as the dominance of the high-speed solar wind flow originating in the polar coronal hole, follow expectations and thus confirm the general validity of heliospheric models, many details of the observations, such as the power spectral exponent of magnetic fluctuations, magnetic 'holes', and high-latitude coronal mass ejections are new and will lead to a better understanding of the origin of the solar wind and of coronal processes associated with the solar cycle.

The measurement of wave flux in the solar wind which originates in coronal holes and which is relatively undisturbed by larger-scale interaction processes is directly related to the acceleration of the solar wind. This measurement can only be made by Ulysses at high latitudes. Recently proposed empirical models of coronal heating and solar wind acceleration have established a relationship between the divergence of magnetic field lines in the corona and solar wind speeds in the heliosphere (Wang *et al.* 1990; Wang 1993). The combined measurements of solar wind speeds and the large-scale magnetic field geometry, together with mea-

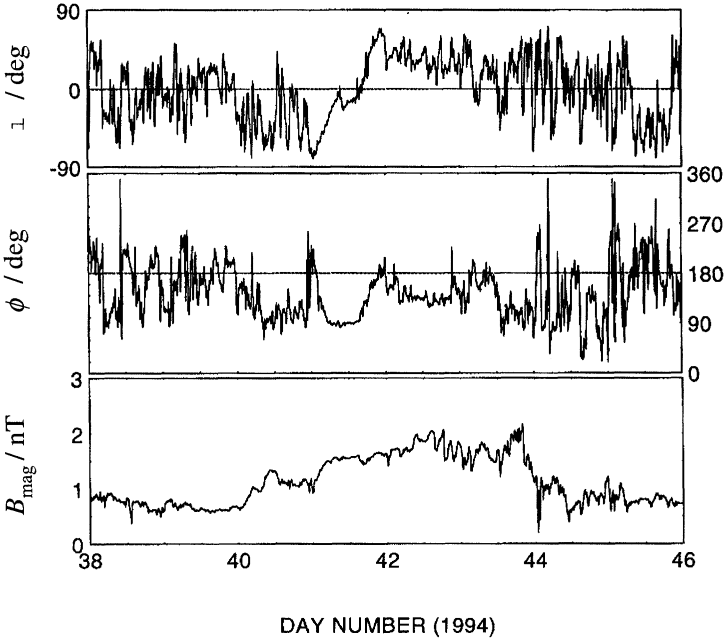

Figure 5. The magnetic signature of a coronal mass ejection observed by Ulysses in February 1994, when the spacecraft was immersed in the solar wind flow from the southern polar coronal hole. The smooth rotation of the magnetic field vector on day 41 (10 February 1994) is the signature of the magnetic flux rope characteristic of coronal mass ejections.

surements of the wave characteristics across the polar coronal hole, will provide the required evidence for testing such models and will also provide quantitative boundary conditions for them in the heliosphere.

Heliospheric structure, as a function of heliolatitude, will be observed over the full range of heliolatitudes by Ulysses during its passage from the south pole to the north pole of the Sun in late 1994 and early 1995. This survey of all heliolatitudes is expected to be sufficiently fast to eliminate significant time dependences, given the minimum activity levels on the Sun. The northern polar passage will provide a second observational test of high-latitude heliospheric models.

A second set of solar polar passages in 2001–2 has been proposed, to provide what is expected to be a very different state of the high-latitude heliosphere. As already shown in figure 1, the corona at solar maximum is significantly different, with closed magnetic structures at all latitudes. Observations during that period will not only provide a different set of boundary conditions in the solar wind, but will allow the direct observation of the reorganization of the large-scale heliospheric magnetic structure during the polarity reversal at solar maximum.

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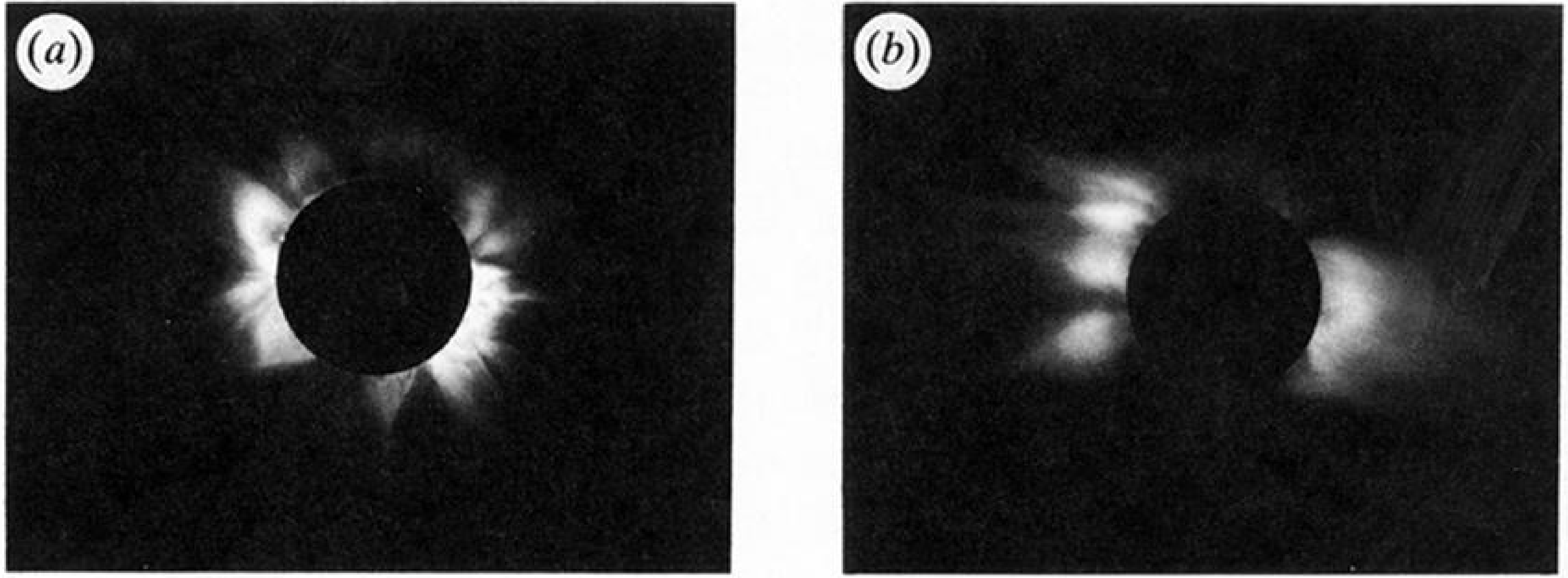

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