

THE HELIOSPHERE

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1. Introduction

The heliosphere is the vast region of space surrounding the Sun and the solar system that is filled with the solar wind. Its inner boundary is the outer atmosphere of the sun, the solar corona. Its outer boundary is defined, in the first approximation, as a surface across which there is a balance of pressure between the solar wind and the Local Interstellar Medium (LISM). This outer boundary is to be found at probably about two and a half to three times the orbital distance of the furthest planet, Pluto. The main regions of the heliosphere, described in this chapter, are illustrated schematically in Figure 1, although there are many uncertainties concerning this simple picture. The objective of this chapter is to provide an overview of the heliosphere as understood, at the turn of the millennium, complete with our very comprehensive understanding of the solar wind and its large-scale dynamic structures that shape the heliosphere. Together with the development of solar wind studies, the study of the propagation of cosmic rays in the heliosphere has also been of great importance in shaping our understanding. These topics are reviewed at some length. The space missions that particularly contributed to the exploration of the heliosphere are also summarised.

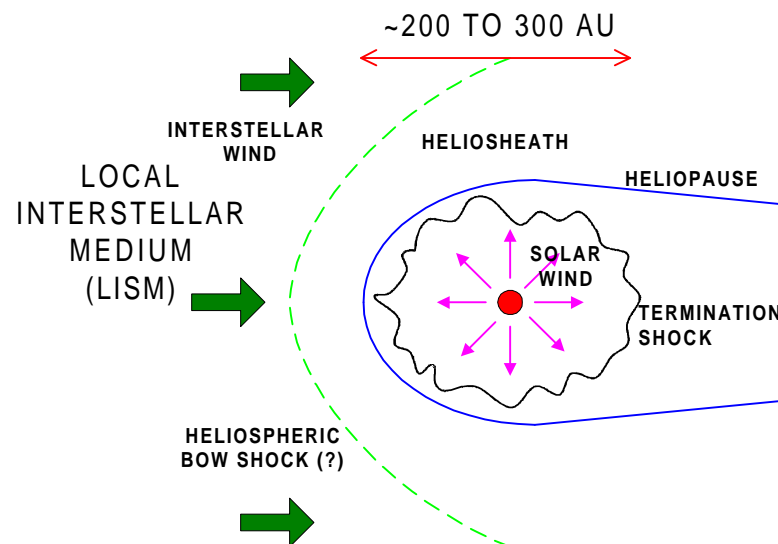


Figure 1: A schematic view of the heliosphere and its boundaries

The many topics related to the heliosphere have been the subject of several books, as well as numerous review articles. Of particular interest and relevance are the books edited by Schwenn and Marsch (1990,1991) on the results of the Helios mission in the inner heliosphere; three books related to the three-dimensional heliosphere and the Ulysses mission (edited by Marsden, 1986, 1995, and Balogh, Marsden and Smith, 2001, respectively); a volume on cosmic winds and the heliosphere (edited by Jokipii, Sonett and Giampapa, 1997);

three volumes published under the imprint of the International Space Science Institute, Bern, on the interstellar medium and the heliosphere, edited by von Steiger, Lallement and Lee (1996); on cosmic rays in the heliosphere, edited by Fisk, Jokipii, Simnett, von Steiger and Wenzel (1998); and on corotating interaction regions, edited by Balogh, Gosling, Jokipii, Kallenbach and Kunow (1999). A volume that gathered his many contributions to heliospheric physics was published by Burlaga (1995). The outer heliosphere has been the subject of a volume edited by Grzedzielski and Page (1990). In addition, there have been, over the past fifteen years, numerous review papers on aspects of the heliosphere; these, together with many original references are listed in this chapter.

2. The existence of the heliosphere and its main properties

The existence of the heliosphere, as a volume of space controlled by the Sun, was first proposed by Davis (1955), who based this concept on the modulation of cosmic rays in anti-phase with the solar activity cycle. Cosmic rays are very high energy particles which are accelerated (by vast shock waves generated by supernova explosions) in the galaxy, at considerable distances from the solar system. The intensity of cosmic rays observed at the Earth is nearly constant, but is a few percent higher at sunspot minimum than at sunspot maximum. This 11-year modulation cycle can only be explained by assuming that the sunspot cycle has an effect on the space surrounding the Sun which, in turn, affects the propagation of cosmic rays into the inner solar system, so that it is easier for cosmic rays to reach the Earth near solar minimum than around solar maximum. This explanation therefore implies that the medium surrounding the Sun undergoes changes between solar maximum and minimum. Given that these changes affect the propagation of high energy cosmic rays (which are electrically charged particles), the changes in the medium around the Sun need to involve magnetic fields and, in effect, changes in the magnetic field itself, in response to the solar activity cycle. Given also the large energies of cosmic ray particles that are affected, the volume involved in the modulation also has to be large on the scale of interplanetary distances.

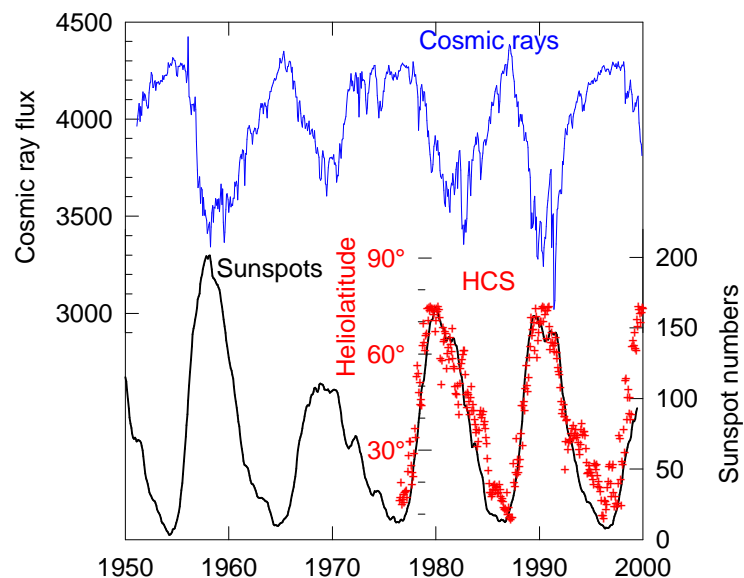


Figure 2: A composite plot showing the monthly number of sunspots (black trace), the daily average intensity of cosmic rays measured on the ground (blue trace) and the maximum heliolar latitude of the coronal magnetic neutral line, representing the coronal imprint of the Heliospheric Current Sheet (red symbols). There is clearly a very close correspondence between sunspots and the extension of the coronal magnetic neutral line; the anticorrelation between cosmic ray intensity and sunspot numbers is indicative of the modulation of galactic cosmic rays by solar activity in the heliosphere.

It is this relationship between cosmic ray fluxes and sunspots that is illustrated in Figure 2, in which fifty years of observations, covering close to five solar cycles, are shown. The historical background to the early cosmic ray modulation studies has been reviewed recently by Simpson (1998) and McDonald (2000). It is remarkable that the recognition of the relationship came so early, in the mid-1950s, even before it had been observed for a complete sunspot cycle. There is also a third quantity plotted in Figure 2; this quantity, labelled HCS in the figure, is the calculated maximum heliolatitude of the Heliospheric Current Sheet, in effect the physical extension of the Sun's magnetic equator into the heliosphere. The nature and importance of the HCS in structuring the heliosphere are described below. However, it is clear from the close match of this quantity to the sunspot numbers (once the two are superimposed, as in the figure) that the variation in the heliolatitude of the Sun's magnetic equator through the solar cycle is an important indicator of solar activity and, given the need for a physical description of the solar modulation of cosmic rays, the extension of the magnetic equator into the heliosphere is at least a part of the physical mechanism of the modulation process.

The necessary advance in understanding the magnetized medium surrounding the Sun assumed by Davis (1955) came about at the same time, from the recognition that the Sun continually emits a "corpuscular" radiation. The existence of such a radiation, to explain the geomagnetic effects that could be related to activity on the Sun, had been assumed much earlier by Chapman (see Chapman and Bartels, 1940, and references therein). The existence of the solar wind, as a constant outflow of plasma from the solar corona was first suggested by Biermann (see Biermann, 1957, and references therein) from the study of the ion tails of comets. The current understanding of the reason for the existence of the solar wind as a permanent outflow of supersonic plasma originated with Parker's theoretical model (Parker, 1958, 1963). Within four years of Parker's first theoretical predictions, the existence of the solar wind was confirmed by the early interplanetary space missions (for a summary of the early results, see e.g. Lüst, 1967). This confirmation (that included the charting of the interplanetary magnetic fields necessary for affecting the propagation of cosmic rays) finally placed on a firm foundation the concept of the heliosphere (e.g. Axford, 1972) and opened the way for its exploration in the space age, from the early 1960s.

The phenomenology of the heliosphere covers numerous space plasma phenomena on all scales, from the kinetic plasma scale where the dynamics of particle distributions dominate the physical processes, to the large magnetohydrodynamic (MHD) scales where the large scale dynamics of the solar wind and the magnetic field define the global properties of the heliosphere. Space plasma processes on many intermediate scales provide a constantly changing, dynamic environment in the different regions of the heliosphere. The relative accessibility of the heliosphere to direct observations by deep space probes has made it the largest astrophysical plasma regime that can be studied in detail. Heliospheric physics is now a discipline in its own right, with obvious and important links to solar physics, space plasma physics and, by extrapolation, with many topics in astrophysics in general.

The size of the heliosphere is not yet known precisely. The outer boundary is currently estimated to be somewhere between 80 and 120 AU from the sun. Both the size of the heliosphere and the nature of the outer boundary depend on the properties of the solar wind at large distances from the sun, on the properties of the LISM, and the physical processes involved in their interaction. Even though these properties are not known in sufficient detail to draw definitive conclusions on either the size of the heliosphere or the nature of the boundary, there are several estimates based on indirect observations which, surprisingly, agree quite well with each other. Such indirect evidence has also made it possible to introduce useful models that can be tested as further observations become available.

A great deal is known about the heliosphere from the sun out to the distance of the furthest direct, *in situ* observations, currently to 74 AU by the Voyager 2 spacecraft. The *in situ* observations, made since the early 1960s by deep space missions as well as by the continuous monitoring of the solar wind in the vicinity of the Earth, have provided a vast, even if in some respects selective data base for determining the structure and dynamics of the inner and middle heliosphere. At the same time, progress in understanding the physics of the solar corona, the inner boundary of the heliosphere, has led to a good understanding of the important relationships between solar and heliospheric phenomena. Space missions have also played the major role in increased understanding of the complex dynamics of solar and coronal phenomena relevant to heliospheric physics.

The role of space missions in exploring the heliosphere has led to phenomenological descriptions that emphasise the dependence of heliospheric phenomena on distance from the sun. Although any division of the heliosphere into different regions is somewhat arbitrary, the inner-, the middle- and outer heliospheric regions have been distinguished, based mostly on the dominant dynamic features observed.

The inner heliosphere is the region from the solar corona to about the orbit of the Earth. In this region the coronal sources of the different solar wind streams recognisably dominate the dynamics of the medium. The middle heliosphere, from about the Earth's orbit to Saturn's orbit at 10 AU, is the region where the dynamic evolution of solar wind structures forms large scale structures that begin to mask the solar origin of the different solar wind streams. In the outer heliosphere, the structures formed in the middle heliosphere continue to evolve, but dissipative processes on the one hand, and the intrusion of material from the LISM make the link between the observed structures and their solar origin recognisable only on the largest temporal and spatial scales.

There is, however, another, equally important way to divide the heliosphere. For as much as five or six years around solar minimum in each solar cycle, the polar regions of the heliosphere have significantly different properties from the equatorial region. Relatively uniform, high speed solar wind fills both polar regions, extending down to between twenty or thirty degrees within the equator. In the equatorial region, fast and slow solar wind streams intermingle and interact, making this region more structured and dynamic: it is this region which can be conveniently subdivided into the three regions, inner, middle and outer heliospheric regions described above. Due to the absence of direct observations in the polar regions at different heliocentric distances, its structure and evolution with heliocentric distance can only be extrapolated from the unique set of observations made at high heliolatitudes by the Ulysses spacecraft at distances of about 2 AU.

For several years in each 11-year solar activity cycle, around maximum activity, the heliosphere becomes considerably more complex than around solar minimum. This is due in part to the fragmentation of solar wind streams and in part to the considerable increase in the occurrence rate and intensity of solar transients, in particular Coronal Mass Ejections (CMEs). Instead of the relatively simple distribution of the solar wind sources in the corona at solar minimum when they are divided into large scale coronal holes emitting fast solar wind and the equatorial belt of slow solar wind, non-uniform but mostly slow solar wind is emitted from the whole corona at solar maximum. Short-lived, small-scale coronal holes still emit fast solar wind, but at lower speeds than wind from the large polar coronal holes near solar minimum. Superimposed on the slow solar wind from the corona, CMEs occur not only more frequently than at solar minimum, but are distributed more or less evenly at all latitudes. Until Ulysses explores the polar regions of the heliosphere during the current solar maximum activity period in 2000-2002, it is possible only to extrapolate the near-ecliptic conditions to those regions.

The terms used in this chapter, referring to the heliospheric medium and the heliospheric magnetic field, intend to underline the three-dimensional nature of the heliosphere and its phenomena. Historically, the terms “interplanetary medium”, “interplanetary magnetic field” have been extensively used to describe phenomena in the space between the orbits of the planets. This use of the terms was justified as most of the space missions that made observations in the solar wind remained in orbits restricted to close to the ecliptic plane, the Earth’s orbital plane. The main impetus for change came from the Ulysses mission, described below, with its objective to explore the three-dimensional properties of the heliosphere in its unique, polar orbit around the Sun. However, other missions, Pioneer 11 first, when in transit between Jupiter and Saturn, and, later on, the two Voyager spacecraft left the ecliptic plane, following their final planetary encounters, reaching now far beyond the furthest planets in the solar system. It has become therefore more appropriate to use the “heliospheric” terminology when describing phenomena in the three dimensional volume around the Sun.

3. The exploration of the heliosphere

Space probes have played a key role in the exploration of the heliosphere. Since the early 1960s, numerous missions have explored different regions in the vicinity of the Earth; in the distant, outer heliosphere; between the Sun and the Earth; and above the poles of the Sun. In the following, a few key missions that contributed in a significant way to our knowledge of the properties and structures of the heliospheric medium are described, highlighting their contributions to our knowledge of the heliosphere.

The Soviet space missions to the Moon (Lunik 1 and 2) carried plasma detectors that first observed the solar wind. However, the first extensive set of data confirming the existence of the solar wind and its main properties, such as its velocity, density, temperature, as well as its variability came from the Mariner 2 mission to Venus in 1962, launched on 27 August 1962 (Neugebauer and Snyder, 1962). Some of the properties of the embedded magnetic field were also observed on this mission (Coleman et al., 1962), in particular the general agreement of the orientation of the magnetic field with Parker’s predicted spiral geometry (Davis et al., 1964).

In the 1960s, early Earth orbiting spacecraft, with apogees reaching beyond the magnetosphere, provided further evidence concerning many of the basic properties of the solar wind and the magnetic field embedded in it. All the most important phenomena that shape and characterize the heliospheric medium were first noted by Earth-orbiting spacecraft. In particular, good agreement was found in general between the Archimedean spiral structure of the magnetic field lines proposed by Parker (1958, 1963) and the observed orientation of the magnetic field (Davis et al., 1964, Ness and Wilcox, 1964) on the Interplanetary Monitoring Platform (IMP-1) mission. On the same mission, the sector structure of the magnetic field, showing a recurring pattern of alternating polarities of the field as a function of solar longitude, was also identified (Wilcox and Ness, 1964). A later spacecraft in the same series, the remarkable IMP-8, launched in 1974, has continued to provide observations in the solar wind for nearly thirty years. These observations now constitute a historic data set that is used for studying long-term trends in solar wind and cosmic ray parameters.

The first space mission that provided a constant monitoring of the solar wind, the heliospheric magnetic field, as well as energetic charged particles and cosmic rays in the vicinity of the Earth, yet removed from the influence of terrestrial effects, was the International Sun-Earth Explorer (ISEE-3) mission. This was the first spacecraft to be launched to orbit one of the Sun-Earth system’s gravitational “neutral” points, named after Lagrange. The Lagrange point L1 is situated at about 1% of the distance (or about 1,500,000 km) between the Sun and the Earth, ahead of the Earth. An orbit around this point in space allows the spacecraft to monitor the solar wind, and even to provide a warning of 30 to 60 minutes if a solar storm (in effect a

Coronal Mass Ejection) is about to hit the Earth's magnetosphere. The ISEE-3 spacecraft, launched on 12 August 1978, remained in this orbit for four years, through the solar maximum in 1979-80, before becoming the prototype of space wanderers by being retargeted first to the Earth's distant magnetospheric tail and then, following some spectacular manoeuvres, to the first spacecraft encounter with a comet in 1985.

The L1 orbit, first used by ISEE-3, has been used very successfully, more recently (since the mid-1990s) by the Solar and Heliospheric Observatory (SOHO) and the Advanced Charge Composition (ACE) spacecraft. SOHO was launched to provide a comprehensive and often spectacular monitoring of the Sun and its corona, and ACE is following up, two solar cycles after ISEE-3, and with a more up-to-date instrumentation, the monitoring of the solar wind and its magnetic field.

The Pioneer series of missions, from the early 1960s, have explored the region of space between the planets Mars and Venus, as well as the distant heliosphere past Jupiter and Saturn. The first spacecraft to the outer planets were the Pioneer 10 and 11 missions. Pioneer 10 was launched on 2 March 1972; it reached Jupiter on 3 December 1973 to make the first close-up observations of the giant planet. After its encounter with Jupiter, the spacecraft followed a trajectory to the outer reaches of the heliosphere. Pioneer 11 was launched on 5 April 1973 and it reached Jupiter on 2 December 1974. At Jupiter, the spacecraft was targeted in such a way that the flyby would allow it to reach Saturn. This involved a trajectory that, for the first time, reached a heliolatitude of 16° above the ecliptic plane. The two missions were terminated in March 1997 and November 1995, respectively. At the time when the missions ended, Pioneer 10 was at a heliocentric distance of 67 AU, while Pioneer 11 was at 43 AU.

These two spacecraft were the first to make detailed observations of the heliospheric medium out to Saturn and beyond. The first phase of the Pioneer mission took place around the minimum activity period in solar cycle 21, in the mid-1970s. They were the first to observe the recurring sequence of Corotating Interaction Regions (CIRs) and their development with heliocentric distance (Smith and Wolfe, 1977); these large-scale structures that consist of successively compressed and rarified solar wind and magnetic field are the most important features of the inner and middle heliosphere around solar minimum.

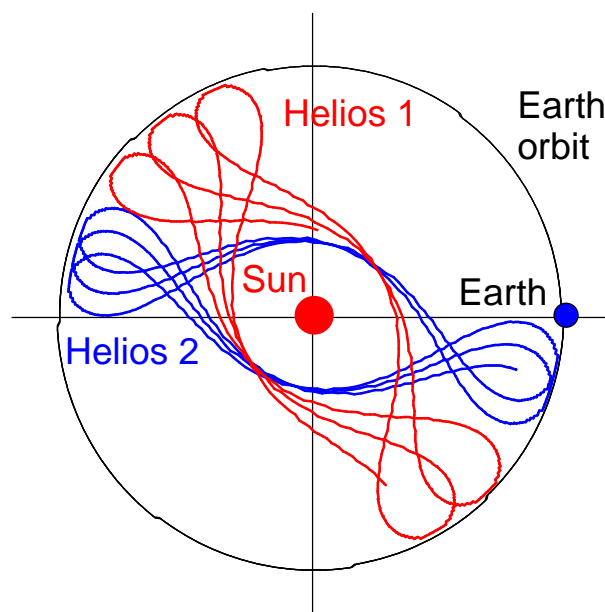


Figure 3: Orbits of the two Helios space probes in the inner heliosphere, in a coordinate system fixed with respect the Sun-Earth line.

The inner heliosphere, between the Sun and the Earth's orbit, was the target of the joint German/NASA Helios mission. The two Helios spacecraft were launched on 10 December 1974 and 15 January 1976, respectively, into high-eccentricity heliocentric orbits with a perihelion of 0.3 AU and an aphelion of 1 AU. A few consecutive orbits of the two Helios spacecraft are shown in Figure 3, in a coordinate system fixed with respect to the line joining the Sun and the Earth. These two spacecraft collected data on heliospheric processes in the region between the Sun and the Earth, in particular on the early evolution of heliospheric structures as a function of distance from the Sun (Schwenn and Marsch, 1990, 1991, Musmann et al., 1977).

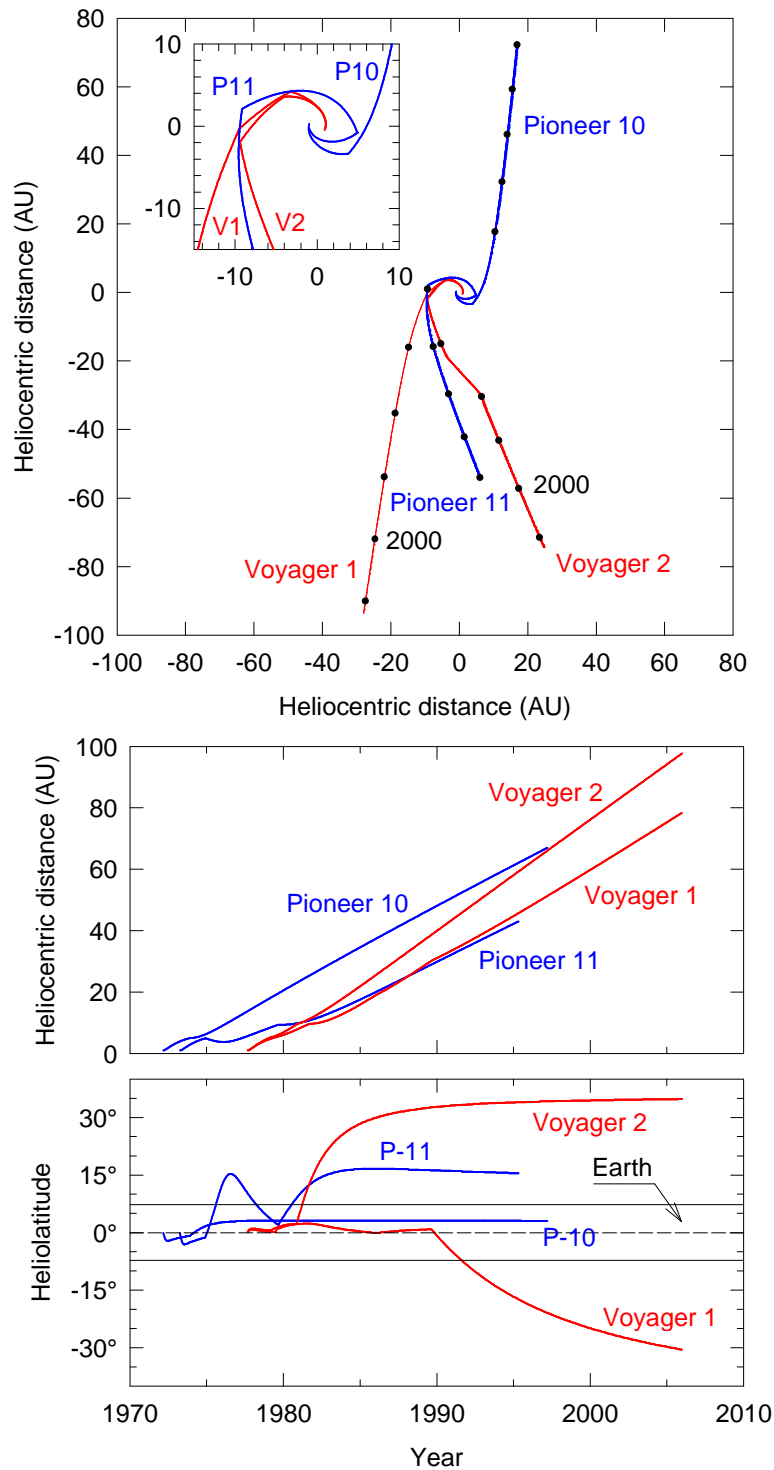


Figure 4: The race to the edge of the heliosphere. This figure shows, in the upper panel, the ecliptic projections of the orbits of the four spacecraft that have explored the outer regions of the heliosphere. The lower panels show the heliocentric distance and heliolatitude, respectively, of the four spacecraft. Note that the range of heliolatitudes covered by the Earth is also indicated in the lower panel. The two Voyager spacecraft are still functioning and are expected to survive long enough to observe the termination shock in the next few years.

The Voyager 1 and 2 spacecraft, launched in September 1977 and August 1977, respectively, still provide the only opportunity in the next decade or two to reach the outer boundary of the heliosphere. Since their launch, the two spacecraft visited Jupiter and Saturn, and Voyager 2 also flew by the two outer gas giants, Uranus and Neptune. Both spacecraft are now on trajectories that approach the outer boundaries of the heliosphere: Voyager 1 at a speed of about 3.5 AU/year, Voyager 2 at about 3.1 AU/year. The best chance to reach and detect at least the termination shock of the heliosphere rests with these two spacecraft. The orbits of the two Voyager spacecraft are illustrated in Figure 4 (together with the trajectories of the Pioneer spacecraft to the end of their mission). The race is clearly on, and there are good arguments (see Section 7) that show that the termination shock may well be reached before the fuel needed to stabilise the spacecraft runs out. This new phase in the long journey away from the Sun has been called the Voyager Interstellar Mission; this implies the possibility that the Voyager spacecraft will be able to reach the heliopause, the boundary between the solar wind plasma and the interstellar medium. In the meantime, the Voyager spacecraft are returning valuable data, destined to remain unique for a long time, on conditions in the outer heliosphere.

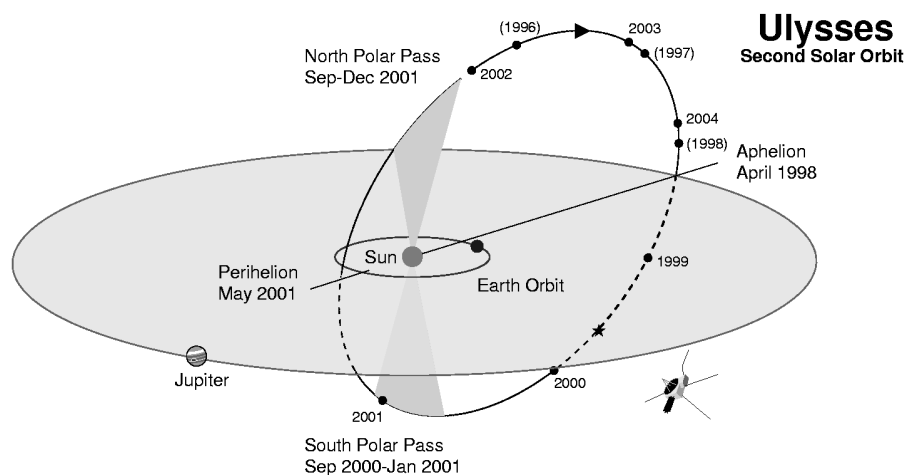


Figure 5: The second complete orbit of the Ulysses spacecraft around the Sun, illustrating the unique, high inclination reached by the mission to study the heliospheric medium over the polar regions of the Sun.

The first mission targeted specifically to explore the third dimension of the heliosphere is the Ulysses spacecraft, launched on 6 October 1990 and foreseen to operate at least until September 2004. As celestial mechanics makes it difficult to place a spacecraft in an orbit with a significant inclination to the ecliptic plane, Ulysses used a gravitational swing-by at Jupiter to reach an orbit with a heliographic inclination of 80° . This mission has provided a significant step forward in our understanding of the heliosphere by charting its structure as a function of heliolatitude. Much of what we now understand of the three-dimensional structure of the heliosphere comes from the observations made by Ulysses at high heliolatitudes, first under solar minimum conditions around 1994 to 1996, and more recently, since 1998, under conditions of solar maximum activity. Although the many earlier observations, by Earth-orbiting spacecraft, by the Helios, Pioneer and Voyager spacecraft identified many properties of the heliosphere, it was through the observations of Ulysses that

these earlier data could be fully integrated into a three-dimensional picture. The second solar orbit of Ulysses is shown in Figure 5.

4. The solar wind and the large-scale structure of the heliospheric magnetic field

The fundamental reason for the existence of the heliosphere is the solar wind. It is therefore appropriate to review some of its basic characteristics that are important in shaping the structure of the heliosphere. (For more detailed accounts, see the articles by Parker and Neugebauer and von Steiger in this volume.) By correctly identifying the appropriate solution to the hydrodynamic equations of a steadily expanding, uniform and isothermal corona, the existence of the solar wind flowing radially from the corona at an asymptotically constant, supersonic velocity is easily deduced. Some of the simplifying assumptions used in this first derivation were already recognized by Parker (1963) as the sources of likely discrepancies between observations and theory. After nearly forty years of measurements of the solar wind, its characteristics are much better known, and in fact are much better understood. Nevertheless, some basic questions concerning coronal heating mechanisms and the acceleration of the solar wind are still unanswered, although these questions, strictly without any answers forty years ago, are now much better understood.

Since the identification of coronal holes, it has been clearly established that these regions of open magnetic fields in the corona are the sources of fast ($> 600 \text{ km.s}^{-1}$) solar wind streams. The origin of the slow ($< 500 \text{ km.s}^{-1}$) solar wind is less well understood, although it is clearly associated with regions of the corona in which magnetic fields are predominantly in the form of closed loops and streamers. The dynamics of magnetic fields in the boundary regions between coronal holes and closed field regions play a significant role in the formation of the solar wind. The two kinds of solar wind, fast and slow, also have different characteristics in terms of temperature, density and elemental composition.

An accurate determination of the distribution of the solar wind as a function of time and location around the sun is not possible. There is no direct way to measure the solar wind speed and density close to the sun; it is possible, however, to infer the speed of the outflow at least occasionally. Two, mostly indirect means have been used. The first, the more direct of the two which relies on spectral imaging of coronal emission lines, has been implemented by instruments flown on the Solar and Heliospheric Observatory (SOHO) spacecraft as well as on the Spartan mission flown from the Space Shuttle. Doppler measurements have allowed estimates of the outflow velocities and associated densities to be determined, in particular in coronal holes where the fast solar wind originates. Other techniques, based on measurements of interplanetary scintillations (IPS), have been used to provide estimates of the solar wind speed close to the sun; these measurements are, in general, difficult to interpret as the speed profile has to be deduced from an integral of plasma in motion measured along the line of sight.

It is generally accepted that, whatever processes are responsible for the acceleration of the solar wind, the two kinds, fast and slow, originate in different coronal regions, with a sharp transition between source regions. The best evidence for this is provided by measurements of the composition of the solar wind. The main compositional differences are a drop in the abundance ratio of elements with low First Ionisation Potential (FIP) to those with a higher FIP, and a drop in the abundance ratio of the high to low ionization state of given elements, such as oxygen, in fast solar wind streams. These indicators imply a lower coronal temperature for the regions of origin of the fast solar wind, in agreement with their identification with coronal holes. It is important for the dynamics of solar wind streams that the compositional signatures show sharp boundaries between streams in the corona.

If it is assumed that, at some height in the corona, the solar wind accelerates away from the Sun uniformly, and if it is further assumed that the coronal magnetic fields are radially oriented at that height, the global equations that define the magnetic field in the solar wind can be easily deduced. The magnetic field lines are frozen into the plasma and convected in the solar wind. These equations that define idealized magnetic field lines in the heliosphere have been extensively used as the basic frame for organizing the actual observations. Parker's conceptual model is based on a uniform, radial solar wind velocity, and a uniform solar rotation.

The real solar wind differs in a number of significant respects from the ideal, uniform solar wind. Similarly, the coronal magnetic field which is convected in the solar wind, is also highly non-uniform and non-radial in the acceleration region, and therefore it is unsurprising that the Parker model of the heliospheric magnetic field is at best an approximation to what is actually observed in space. There are in fact many reasons for the differences between the ideal Parker geometry of the magnetic field and the observations. Some of these reasons are related to the propagation of non-uniform solar boundary conditions, such as differences in the rotation rates of the photosphere and coronal holes, and the motion of the footpoints of the magnetic field lines in the photosphere. Other departures from the ideal configuration are related to the dynamic evolution in the solar wind as it travels out into the heliosphere.

We can define, conceptually, source functions for both the solar wind, $\mathbf{V}_{SW}(r_0, \varphi, \vartheta)$, and the magnetic field $\mathbf{B}(r'_0, \varphi, \vartheta)$ on the surface of spheres (not rotating with the Sun) of heliocentric radius r_0 and r'_0 , respectively, with φ and ϑ being the heliographic longitude and latitude. For the solar wind, we can take, again conceptually, the radius r_0 to be close to the sun, but at a distance where most of the acceleration of the solar wind has already taken place. For the magnetic field, r'_0 is normally taken to be between 2 to 3 solar radii, based on potential magnetic field models of the corona (Wilcox et al., 1980, Hoeksema, 1991, 1995).

The general agreement of the magnetic field direction with the Parker model can be judged by the observations made by several space missions. The analysis was performed in each case using the actually measured solar wind speed, to calculate the difference of the magnetic field azimuth angle with respect to the expected Parker direction. Such analysis has been performed, e.g. by Thomas and Smith (1980), Smith et al., (1986) and Smith (1997), using Pioneer data out to 35 AU; Behannon et al. (1989), using Voyager data; Forsyth et al. (1996a, 1996b), using Ulysses data, in particular as a function of heliolatitude; and near the Earth (Lepping et al., 1996). The Ulysses results obtained during the fast latitude scan of the mission (when Ulysses moved from 80° south to 80° north in heliolatitude in 1994-95) are shown in Fig. 6.

The source functions of the solar wind and the heliospheric magnetic field are, in fact, strongly dependent on time on many scales. Along a radius vector from the sun (i.e. for a given ϑ and φ), the time dependence is introduced not only by the solar rotation, but also, on a range of both longer and shorter timescales, by the evolution of the source regions of the solar wind, and on short timescales by dynamic phenomena such as Coronal Mass Ejections (CMEs).

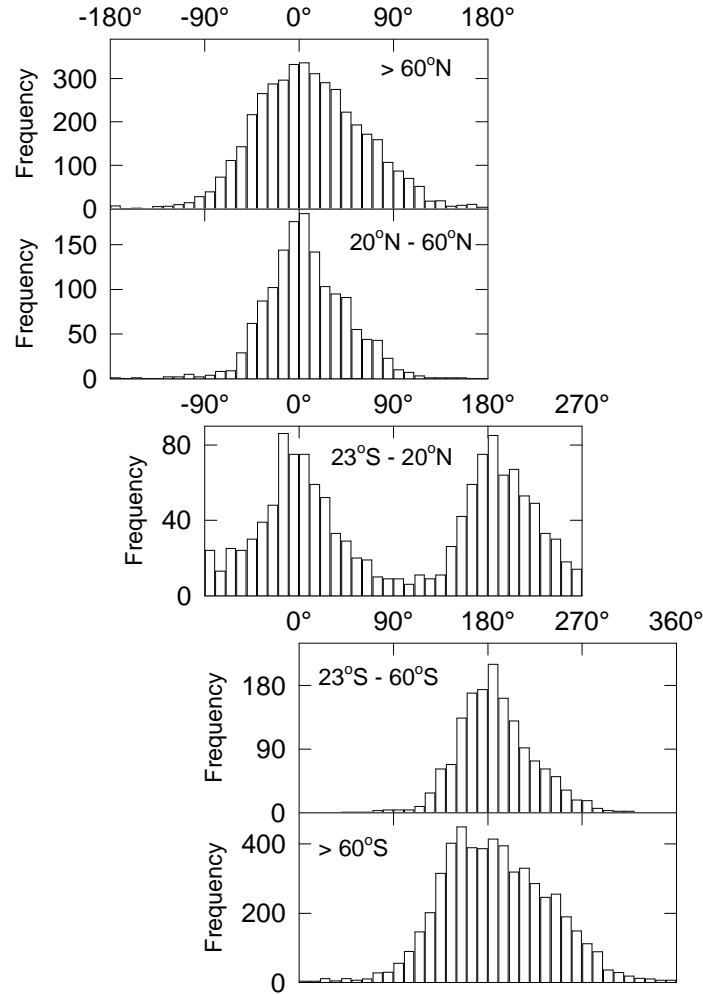


Figure 6: The distribution of the azimuthal direction of the heliospheric magnetic field as a function of heliolatitude, measured by the Ulysses spacecraft during its first fast latitude scan. These plots demonstrate that the sector structure of the magnetic field is restricted to the equatorial regions during solar minimum; away from the equatorial regions, the magnetic field is unpolar, with opposite polarities in the northern and southern hemispheres. The plots also show that the distributions are peaked around the expected direction, according to Parker's simple model.

In the solar wind, both the source magnetic field and the solar wind speed can undergo temporal changes. Neglecting temporal variations in the magnetic field, the time dependences in $\mathbf{V}_{SW}(r_0, \varphi, \vartheta)$ introduce a range of dynamic effects in the heliosphere. The evolving interactions of the non-uniform flows along a streamline of the solar wind introduce a corresponding structuring in the heliospheric magnetic field. In these interactions, the magnetic field plays only a peripheral role on the large scale (because of the dominance of the flow energy of the solar wind), but it is an essential ingredient of the small-scale processes that provide the physical basis for the MHD treatment of interacting solar wind streams.

Two timescales of major importance for both the solar wind and the HMF are the solar rotation period and the solar cycle. Around solar minimum, the corona is in a relatively stable state, with coronal holes, the regions of origin of the fast solar wind, covering both polar regions. The coronal streamer belt, a region of mostly closed magnetic field lines, is restricted to within about 15° to 30° of the solar equatorial plane. Slow solar wind streams are associated with the streamer belt. The relative stability of the coronal configuration, which persists over several solar rotations, introduces a periodicity in the function $\mathbf{V}_{SW}(r_0, \varphi, \vartheta)$ through its dependence on φ . For an interplanetary observer within about 15°

to 25° of the solar equatorial plane, V_{SW} at the source surface switches from high speeds (above 700 km s^{-1}) to low speeds (below 500 km s^{-1}), corresponding to solar longitudes with coronal holes and the streamer belt, respectively. This periodicity generates a quasi-steady pattern of fast solar wind streams interacting with the preceding slow solar wind streams which result in the formation of the Corotating Interaction Regions (CIRs), as discussed below.

The source functions, simplified but appropriate to solar minimum conditions and in agreement, to the first approximation, with the Ulysses observations (Phillips et al., 1995a, Balogh et al., 1995), are illustrated in Fig. 7. In particular, the existence of a sharp boundary between fast and slow solar wind streams has been shown through the analysis of freezing-in temperatures and abundance ratios of the solar wind ions (Geiss et al., 1995). For interplanetary observers within the ecliptic, the source functions in the lower panels of Fig. 7 generate the alternating fast and slow solar wind streams and magnetic polarities with the period of the solar rotation.

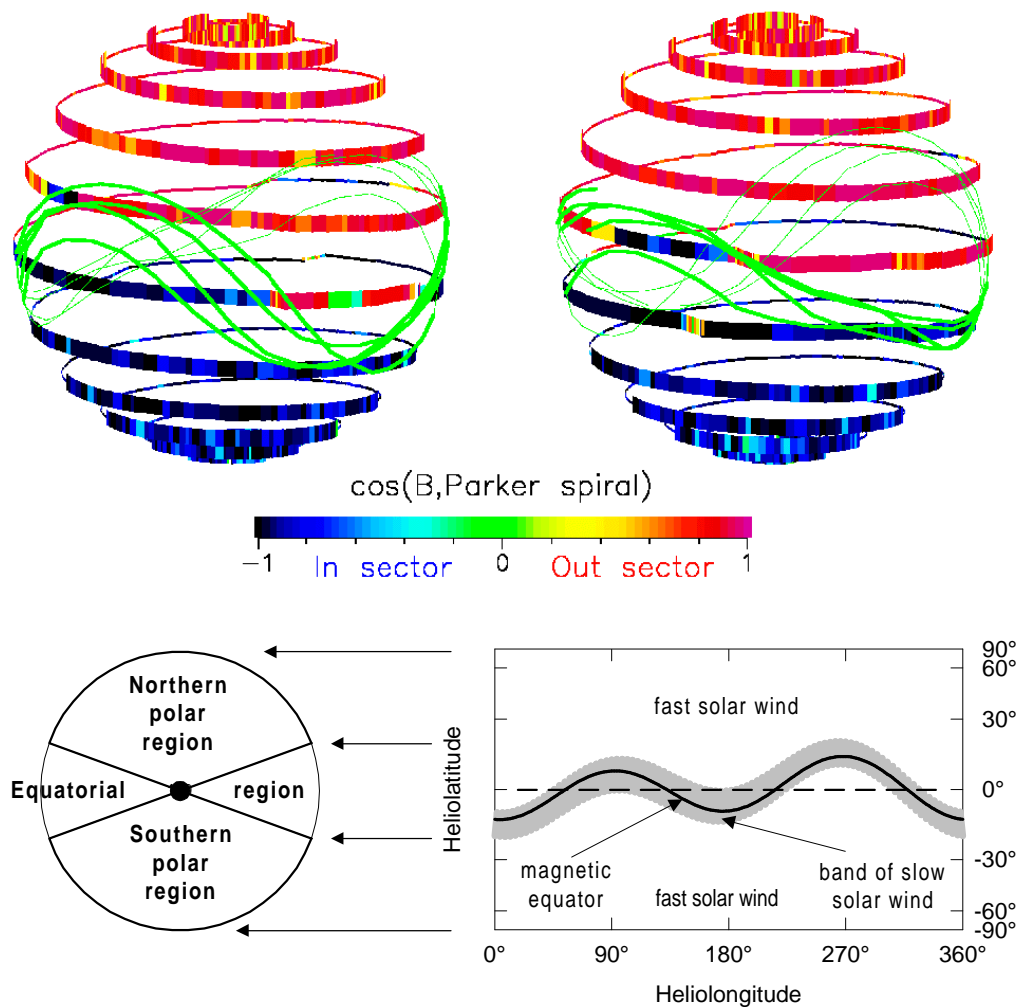


Figure 7: A schematic illustration of the source functions of the solar wind and its embedded magnetic field near solar minimum. In the upper panel, the magnetic polarities of the Sun's two hemispheres are illustrated, as observed by the Ulysses spacecraft in 1994-95. The green lines separating the two hemispheres represent the Sun's magnetic equator, as determined by coronal magnetic field modelling (Wilcox et al., 1980). The lower panel shows schematically the magnetic equator, the coronal streamer belt surrounding it and the coronal source regions of the fast solar wind. Although coronal holes only fill a small area in the corona, due to the non-radial expansion of the fast solar wind, most of the heliosphere is filled with fast solar wind at solar minimum.

The regions of origin of the solar wind undergo a significant change between solar minimum and solar maximum. At solar maximum, there are no dominant large-scale coronal holes and therefore the details of the source function are far more difficult to discern than at solar minimum; in terms of the function \mathbf{V}_{SW} there are no clear periodicities at the solar rotation period. Although stream-stream interactions may still occur, persistent, corotating patterns no longer form at solar maximum. The somewhat surprising result, nevertheless, is that at least on average, extensive observations have shown that the magnetic field configuration in the heliosphere remains close to the simple Parker model. Despite its obvious simplicity and the many modifications that need to be made to make it conform to the actual observations, it has remained a useful frame of reference for organizing the observations.

Other than the large-scale dynamic processes that modify significantly the structure of the heliospheric medium (which are discussed below), there are two ways in which even a relatively steady solar wind and magnetic field can modify the structure of the Parker geometry. The first of these is due to the evolution of transverse components of the magnetic field as a function of heliocentric distance. Transverse components are due to non-radial contributions at the source surface that may arise from the random motion of the footpoints of the magnetic field. These are propagated out into the solar wind, at least partly in the form of long wavelength, large amplitude Alfvén waves. As the basic magnetic field equations show, these components depend on the inverse of the heliocentric distance, while the radial component of the magnetic field decays as the square of the distance from the Sun. Near the solar equatorial plane, the magnetic field is twisted into an increasingly tight Archimedean spiral (so that the magnetic field becomes close to perpendicular to the radial direction), and the effect of the slowly decaying random components in the transverse direction to the solar wind flow make a relatively small contribution to the structure of the field. However, sufficiently far from the Sun, at high heliolatitudes, where the Parker geometry implies relatively radial fields, the transverse component can, in principle, become the dominant one, as pointed out by Jokipii and Kóta (1989).

The second process that brings about a potentially significant modification of the Parker geometry of the magnetic field was identified by Fisk (1996a). This effect arises from the modification of the magnetic field line geometry by the difference in rotation rates between the solar photosphere and the overlying coronal holes. The footpoints of the magnetic field lines are anchored in the photosphere that rotates considerably slower at high heliolatitudes than near the equator. The fast solar wind that transports the magnetic field from the corona expands non-radially from the polar coronal holes. These coronal holes rotate faster than the underlying high latitude photosphere, in fact at approximately the equatorial rotation rate of the photosphere. At the same time, the coronal holes rotate around an axis (notionally, the magnetic dipole axis) of the Sun that is somewhat offset from the rotation axis near solar minimum. These processes are schematically illustrated in Fig. 8. This figure is drawn in the frame of reference that corotates at the equatorial rotation rate. The axis M is the axis of symmetry of the expansion of the fast solar wind from the Sun's polar coronal hole. This axis is fixed in this frame of reference and is offset from the rotation axis Ω of the Sun. The magnetic field line that is anchored in the photosphere at the heliographic pole undergoes non-radial expansion and moves to point p on a concentric outer surface. The footpoints of other field lines rotate around Ω at the slower rate appropriate to the high latitude photosphere but are entrained through the faster rotating coronal hole. The circles on the outer surface in Fig. 8 represent the footpoints of the magnetic field lines that are carried out into the solar wind, representing, at that latitude, the function $\mathbf{B}(r_0', \varphi, \vartheta)$.

The compound effect of the difference in the rotation of the coronal holes and the footpoints of the magnetic field is that field lines originating at high latitudes are emerging in the solar wind at lower latitudes. This effect thus modifies the Parker configuration that implies that the

heliolatitude of the magnetic field lines is constant (in other words, that magnetic field lines are draped on the surface of cones axially aligned with the solar rotation axis). Simulations (Fisk, 1996a) have shown that magnetic field lines originally at 70° heliolatitude in the inner heliosphere can provide a direct magnetic connection to much lower heliolatitudes at distances of 15 to 20 AU from the Sun.

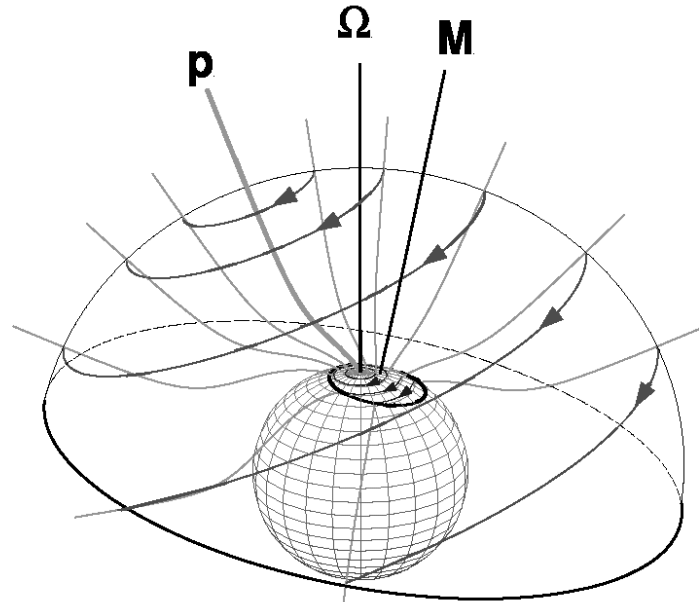


Figure 8: The model of the origin of the heliospheric magnetic field proposed by Fisk (1996a). This model takes into account the differential rotation of the photospheric footpoints of the magnetic field lines and their rigid rotation in the coronal holes; as a result, there is a transport of the magnetic field lines to latitudes considerably lower than their origin in the corona.

This effect has been introduced to explain the propagation of energetic charged particles accelerated by shock waves associated with Corotating Interaction Regions from mid- to high heliolatitudes. This structuring of the magnetic field lines away from high latitudes is firmly based on the observation of the non-radial expansion of the solar wind and the faster rotation rate of the polar coronal holes. The extent to which it occurs and can be discerned in the observations of the magnetic field direction depends on the detailed geometry of the coronal holes and the stability of the source regions of the fast solar wind. It is likely that this effect is significant at times of low solar activity. Even in the absence of a steady state modification of the overall structure of the heliospheric magnetic field, this effect probably introduces a significant level of magnetic flux transport away from the polar regions and contributes to the transport of energetic particles in heliolatitude an effect that is difficult to explain otherwise.

5. Large scale dynamic phenomena in the heliosphere

The solar wind emitted from the corona is not uniform either spatially or temporally. The sources of the solar wind and the associated coronal magnetic structures vary considerably, in particular over the solar activity cycle, but also on the timescale of the solar rotation period. Along any given radial direction from the Sun, in a non-rotating frame, the solar wind streams can have different speeds, densities and other characteristics. The interaction between such solar wind streams of different velocities, densities, temperatures and composition along a streamline generates a wide range of dynamic structures in the heliosphere.

Corotating Interactions Regions are a subset of large-scale structures in the heliosphere which arise from the dynamic interaction between fast and slow solar wind streams. The conditions

for the formation of CIRs are that both fast and slow solar wind streams be simultaneously present at a given (low-to-mid-) heliolatitude, and that the coronal sources remain approximately stable for several solar rotations. Slow streams are normally confined to the vicinity of the HCS. This holds demonstrably in the declining phase of the solar cycle and at solar minimum. Fast streams originate in the polar coronal holes and their equatorward extensions in the declining and minimum phases of the solar cycle; the coronal evolution of the source regions is slow on the timescale of the solar rotation.

On the other hand, it is not yet clear what are the characteristics of fast solar wind streams at solar maximum when all coronal holes are small and, because of the implicitly large spreading factor of magnetic field lines in the corona, cannot generate high speed streams (Wang and Sheeley, 1994). The observations made by Ulysses in the rising phase of the current solar cycle show that the solar wind becomes very disturbed and variable, generally slow ($\sim 350 \text{ km s}^{-1}$) with occasional, non-recurring periods of higher speeds (up to 550 to 600 km s^{-1}).

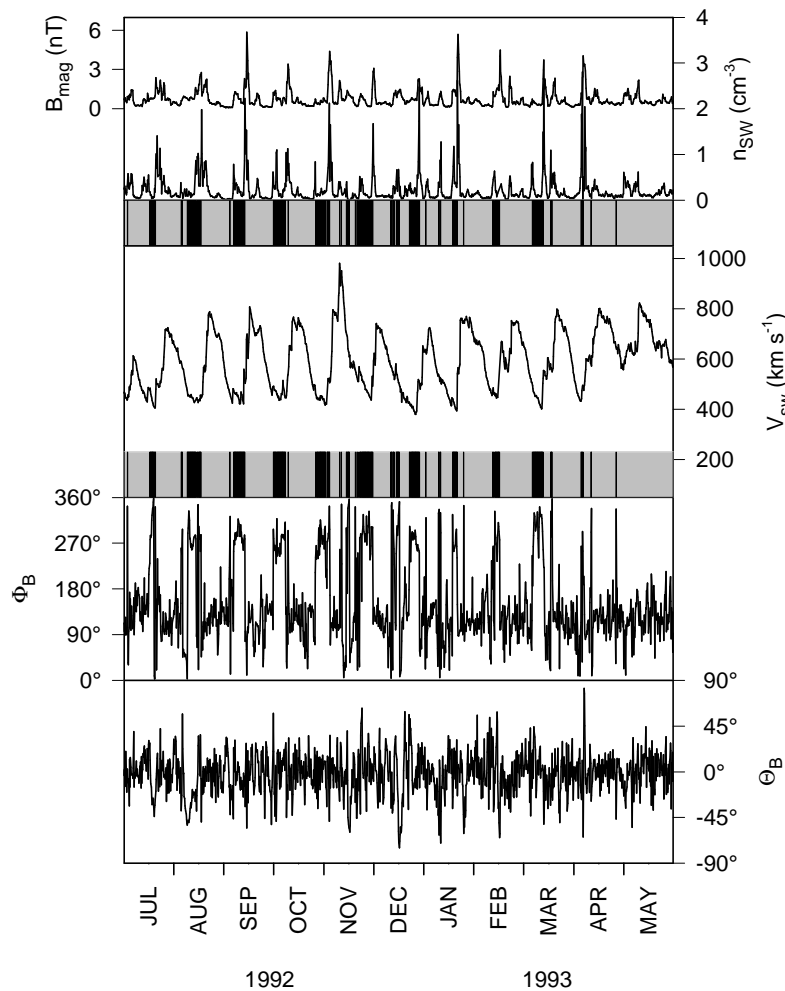


Figure 9: The series of Corotating Interaction Regions observed by the Ulysses solar wind and magnetic field instruments, as the spacecraft moved from near the solar equatorial plane towards the south pole of the Sun. The large excursions in solar wind velocity in each solar rotation cause the compression of the slower solar wind stream ahead of the fast stream, resulting in a periodic increase in solar wind density and in the strength of the magnetic field. The magnetic sectors corresponding to the series of CIRs is also shown, as is the meridional angle of the magnetic field (in the lowermost panel) which shows the field deflections associated with the CIRs.

The interaction between high and low speed streams operates from close to the sun. The resulting structures and their evolution have been extensively observed by the two Helios spacecraft between 0.3 and 1 AU (for a review, see Schwenn, 1990). There is also a wealth of data, covering more than three decades of observations, at 1 AU. CIRs evolve as a function of heliocentric distance; their evolution and eventual merging has been observed by the Pioneer and Voyager probes into the outer heliosphere (Smith, 1989, Burlaga et al. 1984). In particular, the characteristic forward-reverse shock pair delineating the CIRs tends to develop only beyond 1 AU.

The three-dimensional characteristics of CIRs at mid-latitudes were observed by Ulysses in 1992-93 (Bame et al., 1993). These observations were found to match well (Gosling et al. 1993) the three-dimensional model proposed by Pizzo (1991). This series of CIRs is illustrated in Fig. 9. A more detailed description, together with a discussion of the shock waves associated with them has been given by Gonzalez-Esparza et al. (1996). The Ulysses observations clearly established the three dimensional nature of CIRs, their tilted propagation and the asymmetry in the propagation of the associated shock waves (Riley et al. 1996).

CIRs therefore can be regarded as three-dimensional shell-like structures extending to about 30° to 40° away from the ecliptic plane during the declining phase of the solar cycle, but probably only to 15° to 30° at solar minimum. However, the actual latitudinal extent is likely to be longitude-dependent, due to the longitude dependence of solar wind streams from the northern and southern hemispheres and to the (related) longitude dependence of the HCS.

CMEs introduce a significant perturbation in the structure of the inner heliosphere in the form of Interplanetary Plasma Clouds (IPCs). CMEs carry a large amount of mass and momentum capable of distorting the ambient solar wind and magnetic field, and can drive large-scale shock waves which cause the characteristic Forbush decreases in the cosmic ray flux in the inner heliosphere. Their plasma and magnetic structures are in general complex and differ significantly from the ambient HMF. While the signatures of many CMEs are readily identifiable in solar wind and magnetic field data, many critical questions remain concerning the contribution of CMEs to the structure and dynamics of the heliospheric medium. The observational data base is far from complete for both CMEs near the sun and the IPCs. There is no comprehensive survey of CMEs available which could be in any way comparable to those which exist for instance for flares or sunspots. The existing and foreseeable heliospheric data set, even including the magnetosphere as an "IPC detector", is even less comprehensive, based as it is on a very incomplete temporal and spatial sampling.

While case studies exist that link reliably some individual CMEs with their heliospheric IPC counterparts (see e.g. Weiss et al. 1996), in general the link between solar and heliospheric observations is difficult to establish. The lack of comprehensive heliospheric coverage, even if more comprehensive solar data become available, will remain a limitation.

Information on the temporal, heliographic and size distribution of CMEs as a function of the solar cycle, even if somewhat patchy, is available over the past twenty years (e.g. Hundhausen, 1993). However, there is no single set of necessary and sufficient parametric signatures in heliospheric data to recognise the presence of CME ejecta or structures unambiguously. Solar wind data normally furnish the primary information, recognising CMEs most commonly by the presence of bidirectional streaming of electrons, interpreted as tracers of magnetic structures that may be closed in the heliosphere or connected at both ends of the field lines to the corona. Given the identification of the CME signatures in the solar wind data, in a fraction of the cases (up to 50% or so) it is possible to identify an associated magnetic signature, based on smooth (low variance) and smoothly rotating magnetic field structures overlapping the solar wind signatures.

Magnetic clouds form an important and relatively easily recognisable subset of magnetic signatures of IPCs (for a review, see Burlaga, 1991). These belong to a more general class in which large-scale magnetic flux ropes (Gosling, 1990) with a more complex geometry, resulting from 3D reconnection (Gosling et al., 1995), may be present. Considerable complexity, indicating the presence of both open and closed magnetic structures in CMEs, has been identified through the study of magnetic polarity reversals and associated bidirectional electron streams (Kahler et al., 1996).

There is a large uncertainty concerning the heliospheric extent of CMEs. At the sun, their average latitude and longitude scales appear to be about 40° , but with a significantly long tail of the distribution to larger values (Hundhausen 1993). A key question for the structure of the HMF particularly near solar maximum (when CMEs may dominate the dynamics even in the inner heliosphere, see below) is the distribution of CME sizes and locations. Most CMEs appear to originate from the streamer belt (which therefore gives a good indication for their expected location). It has been suggested (Crooker et al., 1993) that the HCS acts as a conduit for CMEs of all sizes; in that case, both the detailed structure of the HCS and its large scale properties may well be significantly modified by the frequency and size distribution of CMEs. However, CMEs may well be emitted from regions less clearly identified with the large scale streamers. Ulysses in particular detected CMEs at relatively high latitudes, well polewards of the HCS (Gosling et al. 1994). These were also remarkable for being associated with forward-reverse shock pairs, apparently driven by the internal pressure of the CMEs.

Given the non-uniform nature of the heliospheric medium, disturbed both by the interaction of non-uniform solar wind flows and by transient phenomena, the interacting regions of plasma are continually transported away from the Sun, shaping in a complex way the heliosphere. This is recognisable both in the non-uniform properties of the solar wind and of the heliospheric magnetic field, as observed by the spacecraft in the different locations in the heliosphere. A particularly important question for the large-scale structure of the heliosphere is the dynamic evolution of the large-scale non-uniformities as a function of heliocentric distance.

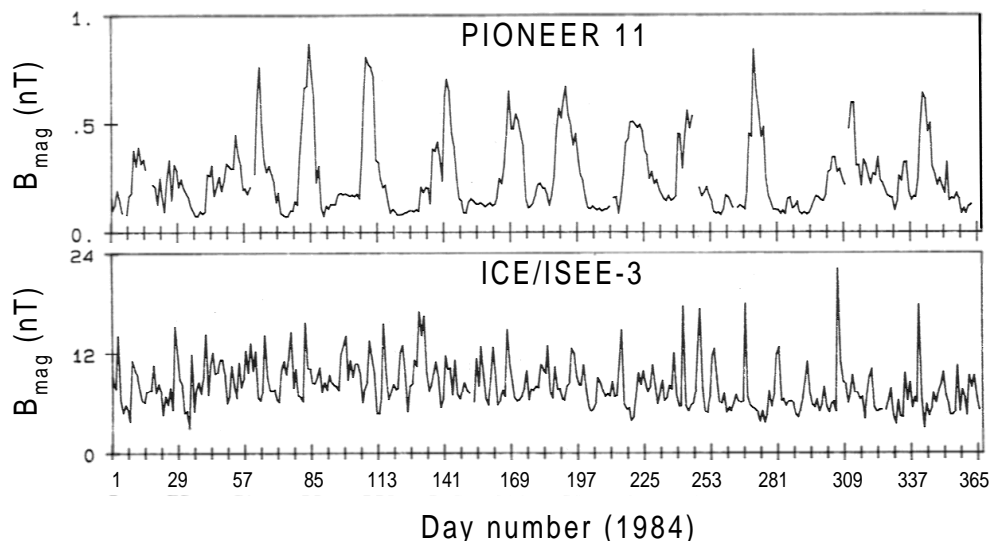


Fig. 10. Comparison of the magnetic field magnitude observed in 1984, during the declining phase of the solar cycle, by ICE (ISEE-3) at 1 AU and Pioneer 11 at 16 AU, showing the coalescence of CIRs into Merged Interaction Regions.

The CIRs observed in the inner heliosphere evolve as they are convected out to 10 AU and beyond (Burlaga et al., 1984, 1996, Burlaga and Ness, 1994, 1998, 2000, Ness and Burlaga, 1996, Smith, 1989). The evolution is accompanied by merging of the interaction regions as

successive CIRs widen with heliocentric distance, and the leading forward shock waves interact with the trailing reverse shock waves of preceding CIR. This leads to a coalescing of the compressed regions of magnetic field with heliocentric distance, as is shown in Figure 10, in which the magnetic field strength measured simultaneously at 1 AU and at 16 AU are shown for a whole year, as the solar cycle was approaching its minimum activity phase. At the distance of the Earth, an evolving four-sector magnetic field structure was observed at the time, together with two CIRs in each solar rotation period. This structure is caused by fast solar wind streams generated in near-equatorial coronal holes, located both north and south of the Sun's magnetic equator. These lead to the complex pattern of compressed magnetic fields through the formation of the CIRs at 1AU, where the finer details of the non-uniform solar wind streams are still discernible. However, as the interaction regions are convected away, the compressed regions in each solar rotation period merge and lead to the simpler, larger scale structure observed by Pioneer 11 at 16 AU, where only one compression region was seen in each solar rotation period.

In general, these Merged Interaction Regions, born of CIRs, dominate the regions around the solar equatorial plane out to beyond 15 or 20 AU around solar minimum as illustrated schematically in Figure 11. The periodicity at the solar rotation period in solar wind parameters, as well as in the magnetic field strength, remains a recognisable feature of the equatorial region around solar minimum at least to 50 AU, as observed by Voyager 2 up to 1995 (Lazarus et al., 1998).

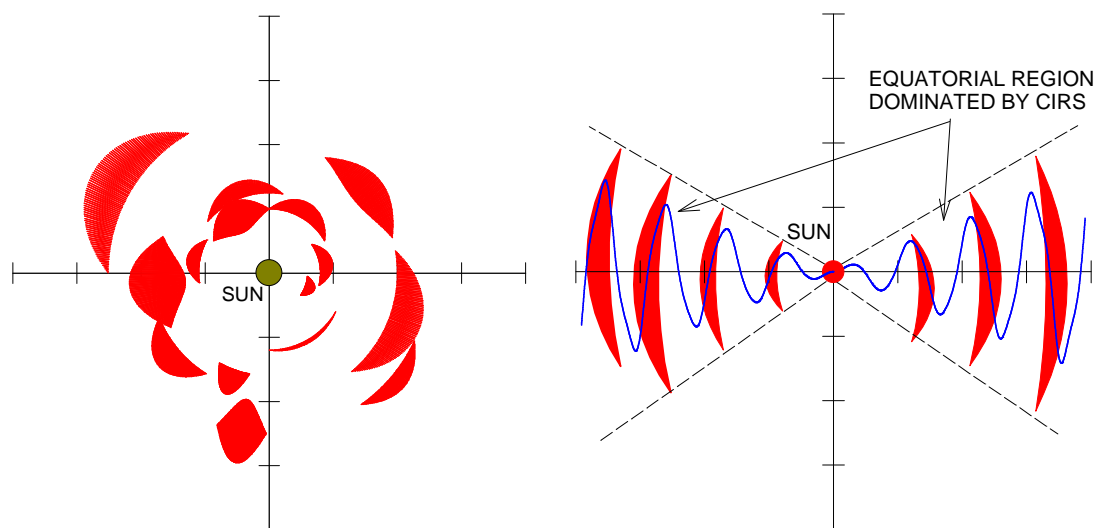


Figure 11. The two states of the inner and middle heliosphere, near solar maximum and solar minimum. The left panel show schematically the situation near solar maximum when the Sun is surrounded by several CMEs of different sizes, emitted at all latitudes; the right panel shows the situation in the late declining and minimum phases of the solar cycle when CIRs and the wavy heliospheric current sheet dominate the low heliolatitude region.

The structures that dominate the heliosphere around solar maximum are the heliospheric counterparts of the Coronal Mass Ejections. As already mentioned, the frequency, average size and heliolatitude range of CMEs all increase around solar maximum. At the same time, coronal holes, the sources of the high speed solar wind, only exist as relatively small, transient features. Although the interaction between the generally slow solar wind and the rare, fast solar wind from the transient coronal holes remains a recognisable feature of the heliospheric medium, the resulting pattern is not stable on the scale of the solar rotation. The situation generally prevailing near solar maximum is also illustrated schematically in Figure 11.

6. Cosmic ray modulation as a probe of the heliosphere

The phenomenon of cosmic ray modulation, as outlined in Section 2, was at the origin of the naming of the heliosphere as a volume of space controlled by solar phenomena. Its study remains central to understanding the large-scale processes that shape the heliosphere, although the physical processes that control the access of cosmic rays into the inner heliosphere are now understood to be considerably more complex than originally assumed. The following comments relate the propagation and access of cosmic rays to the properties of the heliospheric medium. In the first instance, the basic transport processes are outlined; these processes are always active, but the properties of the medium change with the phase of the solar cycle. Around solar maximum, however, other, more extensive large-scale structural changes occur, as a result of an increased frequency and spatial extent of Coronal Mass Ejections. These structures have a considerable effect on the propagation of cosmic rays and are thought to be a major factor in the decrease in cosmic ray intensity in the inner heliosphere at solar maximum activity.

The intensity of cosmic rays in the heliosphere at a given location, in the relatively steady state of propagation conditions in the years around solar minimum, is the result of four different effects, as identified by Parker (1965). The first is diffusion in the irregular magnetic field, both parallel and perpendicular to the average magnetic field. An important question is the relative importance of parallel and perpendicular diffusion terms. Although early models of cosmic ray propagation assumed that diffusion along the magnetic field was the dominant motion of the particles, the measurement of the latitude gradient of cosmic ray intensity by Ulysses has highlighted the likelihood that diffusion perpendicular to the magnetic field lines is more important than expected (McKibben, 1998, Potgieter, 1998). The investigation of the diffusion coefficients applicable to cosmic rays in the heliosphere is a difficult task, but it is central to the understanding of the nature of the statistical and turbulent properties of the heliospheric magnetic field (e.g. Giacalone, 1998).

The second effect is the drift of particles in the large-scale average magnetic field. As was noted by Jokipii et al. (1977) and Jokipii and Thomas (1981), electrically charged energetic particles undergo a significant drift motion in the large-scale heliospheric magnetic field that follows the Parker geometry described earlier. The drift of particles depends on the sign of their charge: electrons and positive ions drift in opposite directions. If A denotes the projection of the Sun's magnetic dipole axis, the sign of A reverses when the solar magnetic fields reverse near solar maximum. Consecutive solar cycles have therefore alternating signs of A . The direction of particle drift velocities depends on the sign of the product qA , where q is the charge (positive for ions, negative for electrons) of the particles. When qA is positive (as was the case during the last solar activity minimum in 1995-96), ions are expected to enter the inner heliosphere over the solar poles, whereas electrons enter along the sun's equatorial plane. This preferred entry for oppositely charged particles reverses in consecutive solar cycles. When particles enter in the equatorial region, the wavy Heliospheric Current Sheet, together with the Corotating Interaction Regions present up to mid-latitudes, makes their access more difficult than over the solar poles. Evidence for drifts being an important large-scale effect on cosmic rays comes from the measurement of the recovery from the lower intensities at solar maximum. If particles enter preferentially over the solar poles, then the cosmic ray intensities increase earlier in the inner heliosphere (e.g. near the Earth) than in the outer heliosphere (e.g. at Voyager). In the next solar cycle, the process is reversed: particles enter preferentially in the equatorial region, so that the recovery after solar maximum is observed first in the outer heliosphere, before it is observed near the Earth. This process is illustrated in Figure 12.

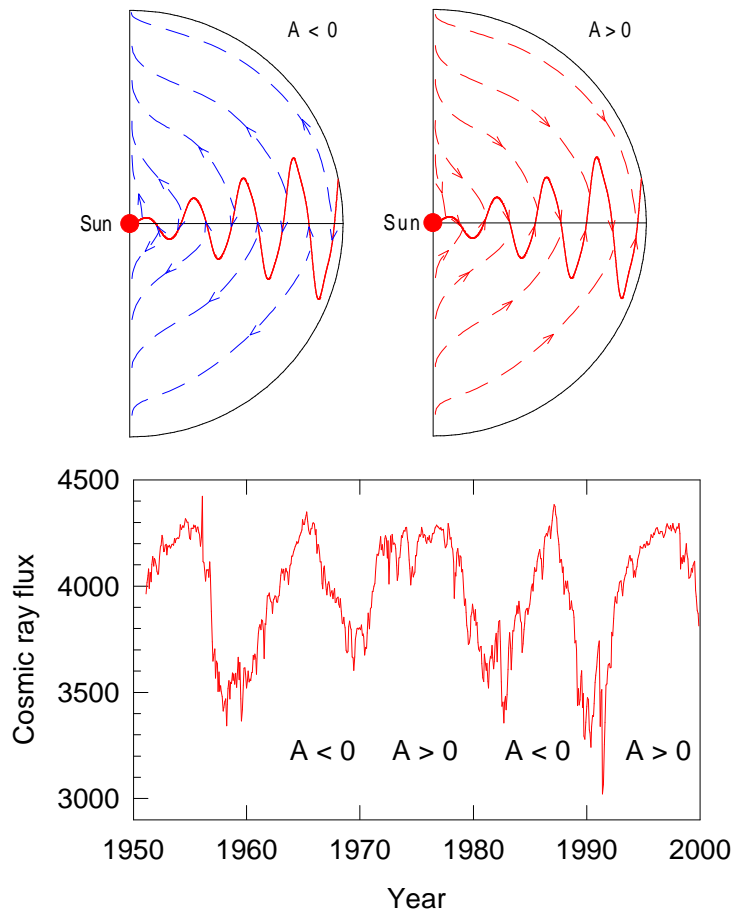


Figure 12: The preferential drift pattern of cosmic rays in the heliosphere during alternate solar cycles. The upper two panels show the drift paths for positively charged particles, the lower panel shows the different cosmic ray intensity patterns corresponding to the alternating magnetic polarities of the polar regions of the Sun.

Convection away from the Sun and adiabatic deceleration in the expanding solar wind are the third and fourth effects of the heliospheric medium on cosmic rays. As the cosmic ray particles gyrate around the magnetic field, the field lines are convected outwards in the solar wind, away from the Sun, carrying with them the particles. At the same time, the expansion of the solar wind leads to an adiabatic deceleration of the particles; this can also be interpreted as a rarefaction of the scattering centres as the solar wind expands.

The basic elements of the modulation process by the heliospheric medium and its structural changes as a function of the solar cycle are quite well understood (e.g. Potgieter, 1998). However, one of the objectives of the Ulysses mission was to verify that the intensity of cosmic rays was, as expected on the basis of modulation theory, significantly higher over the polar regions of the Sun than near the ecliptic plane, at least at solar minimum. This expectation was effectively proved wrong: the heliolatitude gradient of cosmic ray intensity was found to be very much smaller than predicted by theoretical models (e.g. McKibben, 1998). The cause of this effect, implying a more isotropic propagation of cosmic rays than expected in the heliospheric medium, is not yet well understood. The most important property of the medium that may influence the propagation of cosmic rays at high heliolatitudes is the much higher than expected level of fluctuations in the direction of the magnetic field in the uniformly high speed solar wind (Smith et al., 1995, Horbury et al., 1996, Forsyth et al., 1996b). These fluctuations can contribute significantly to the diffusive propagation of cosmic rays perpendicular to the average magnetic field direction; the effect of

an increased perpendicular diffusion is a reduction in the heliolatitude gradient in cosmic ray intensity, in agreement with the observations of Ulysses.

In addition to the effects of the magnetic fluctuations on the cross-field diffusion of cosmic ray particles, the transport of magnetic field lines from high to medium heliolatitudes proposed by Fisk (1996a), described in Section 3, may also contribute to an evening out of cosmic ray fluxes away from the solar equatorial plane. At larger distances over the solar poles, the growth of large transverse fluctuations in the magnetic field may also be present, as proposed by Jokipii and Kota (1989), making the access of cosmic rays more difficult in the high latitude heliosphere.

Given that the presence of CIRs and the wavy Heliospheric Current Sheet in the equatorial region of the heliosphere influence strongly the access of cosmic rays in that region, and that the propagation of cosmic rays is nearly isotropic at high heliolatitudes, a simplified overall picture of the heliosphere, as seen by cosmic rays around solar minimum is as shown in the left panel of Figure 13.

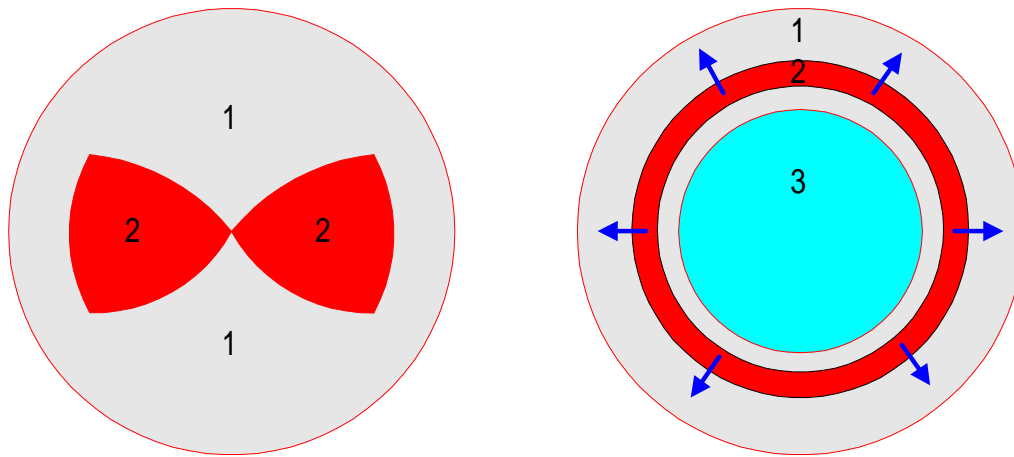


Figure 13. A schematic summary of the properties of the heliospheric medium that control cosmic ray modulation. The sketch on the left illustrates the status around solar minimum, when cosmic ray access into region 1 is through almost isotropic diffusion, whereas in region 2 access is restricted and controlled by CIRs. The sketch on the right shows the status around solar maximum, when the propagation conditions in the outer heliosphere (region 1) remain probably similar to those near solar minimum, region 2 represents the GMIRs, the major obstacles to cosmic access into the inner heliosphere, and region 3 which is highly disturbed by the presence of frequent CMEs of all sizes.

As already mentioned, the principal cause of the decrease in cosmic ray intensity in the inner heliosphere is the increase in frequency and spatial distribution of Coronal Mass Ejections. CMEs introduce major structural disturbances into the solar wind; when these disturbances are spread in all directions around the Sun, the access of cosmic rays is significantly impeded from the outer into the inner heliosphere. There is, in addition, a further effect: in each solar cycle, there are a few very large CMEs, associated usually with significant flaring activity on the Sun. The solar disturbances that give rise to such large CMEs often produce in fact a series of outbursts, closely following each other. CMEs are usually associated with a decrease in cosmic ray intensity (Forbush decreases) lasting several days, as the magnetic configuration of the CME limits their access into the volume occupied by the CME. It is natural to suggest that as the frequency of CMEs increases, the relatively small cosmic ray decreases are added together to lead to the more general decrease in cosmic ray intensity observed as solar activity increases towards maximum (for a review of this suggestion, see, e.g., Cane, 2000).

An alternative view, based on the cosmic ray and magnetic field observations made by the Voyager spacecraft, is that the decrease in cosmic ray intensity occurs in steps, coincidentally with the passage of strong magnetic fields through the heliosphere, resulting from the merging of large CMEs in the middle heliosphere (McDonald et al., 1981, see also, for a review, e.g. McDonald, 1998). These so-called Global Merged Interaction Regions (GMIRs) form moving shells surrounding the Sun, formed of turbulent magnetic fields, with larger than average magnitude, and provide an outward propagating obstacle to the galactic cosmic rays (Burlaga et al., 1985). In the right panel of Figure 13, a schematic view of the heliosphere is shown, valid around solar maximum activity. In this schematic representation, the effects of both frequent, smaller CMEs are shown in the inner heliosphere, together with the outward propagating GMIRs in the outer heliosphere.

Anomalous cosmic rays (ACRs) represent a special component of the high energy particles observed in the heliosphere. This component of the high energy particle population (with energies from about 15 MeV to a few hundred MeV) consists of (mostly) singly ionised He, N, O and Ne ions, as well as protons (e.g. Cummings and Stone, 1996, 1998). Their characteristic energy spectrum and elemental composition led to their identification as a population originating in the heliosphere, by acceleration at the termination shock (Pesses et al., 1981) from a seed population of interstellar atoms ionised in the heliosphere (Fisk et al., 1974, see also, for a recent review, Jokipii and Giacalone, 1998). The study of the radial gradient of ACRs as the Voyager spacecraft has travelled out towards the outer boundary of the heliosphere has provided two important suggestions concerning the termination shock. The first is the likely distance of the termination shock: two different methods of extrapolating the Voyager observations has led to estimates between about 70 and 95 AU, at different epochs in the solar cycle (Cummings and Stone 1998). The second, based on the measured spectrum of the ACRs and its variation with heliocentric distance, implies a lower than expected Mach number for the solar wind in the outer heliosphere, and therefore a relatively weak termination shock (Fisk, 1996b).

7. The boundaries of the heliosphere

In simple terms, it can be stated that the outer boundary of the heliosphere is defined as the surface across which there is a pressure balance between the supersonic solar wind and the Local Interstellar Medium. However, as the presence of the LISM cannot be sensed as the solar wind flows outwards at supersonic speeds, the solar wind suddenly has to slow down as its dynamic pressure becomes equal to the static pressure of the LISM. At this point, mass balance also has to be preserved. This can only happen through a shock wave, as the supersonic flow meets a static “obstacle”. The shock wave is facing inward, and must surround the heliosphere globally, as the LISM envelops the solar system and the region filled with the solar wind. The shock wave at which the solar wind thus slows down is the termination shock of the heliosphere, probably its most important boundary. In the frame of the solar wind, the termination shock is a reverse shock, somewhat similar to the reverse shocks encountered at the trailing edges of CIRs.

The properties of the LISM that are relevant for estimating the extent of the heliosphere have been extensively reviewed in articles in von Steiger et al. (1996); of particular relevance to establish the properties of the LISM and their impact on the termination shock are the contributions by Fisk (1996b), Frisch (1996), Geiss and Witte (1996) and Lallement (1996).

The details of the termination shock, such as its distance from the Sun, its large-scale geometry, its thickness and its dynamics are very largely speculative at this stage (see, e.g. Axford, 1972, 1996, Lee, 1996, Suess and Nerney, 1997). The dominant pressure term inside the termination shock is the dynamic pressure of the supersonic solar wind; other terms contributing to the total pressure in the solar wind, such as the pressure of the magnetic field

and the thermal pressure of the plasma are much smaller. Estimating the external pressure is a considerably more difficult task, as the parameters of the LISM are only known indirectly, with large uncertainties. Although the basic equation used to estimate the distance to the termination shock is relatively simple:

$$\frac{1}{R_{TS}^2} (\rho_{SW} V_{SW}^2)_{1AU} = P_{LISM}$$

The term on the right hand side of this equation is made up of a number of contributions which are difficult to estimate. In this equation, R_{TS} is the distance of the termination shock, measured in AU, ρ_{SW} and V_{SW} are the density and velocity of the solar wind, respectively, and P_{LISM} is the total pressure in the LISM. The values used for the solar wind density and pressure in this equation are taken from their observations at 1 AU, at the orbit of the Earth. This formula assumes that the solar wind dynamic pressure scales as the inverse square of heliospheric distance. The general validity of this approach, using Voyager observations in the outer heliosphere, was examined by Belcher et al., (1993).

The most important contributions to the external pressure are the thermal and magnetic pressure of the LISM; and its dynamic pressure, as the Sun and the solar system move through the medium surrounding it at a speed about 20 to 25 km s⁻¹. In addition, the pressure of the neutral component of the LISM may well be important, and even the pressure exercised by the galactic cosmic rays has been considered as a term that cannot be neglected. An important question, but one that is difficult to answer, is whether the flow speed of the LISM is supersonic. The sketch used to introduce the heliosphere in the Introduction (Figure 1) was drawn assuming a supersonic flow past the heliosphere. In this case, the boundary between the shocked (subsonic) solar wind plasma outside the termination shock and the LISM, the heliopause is a surface similar to the magnetopause around the Earth's magnetosphere. There is also, in this case, a heliosheath, in which the subsonic LISM, slowed down at a heliospheric bow shock flows past the heliosphere. The geometry shown in Figure 1 is, in very simplified terms, the picture that is generally assumed when describing the heliosphere.

An alternative view of the heliosphere is shown in Figure 14. The main difference in this view is the absence of a bow shock; the flow speed of the LISM is assumed to be subsonic. While this figure represents a possible particular case, it indicates the basic features that may be expected if a bow shock is not formed in front of the heliosphere, upstream, by a supersonic LISM. The heliopause remains a necessary feature in this model, as the surface separating the plasmas of interstellar and solar origins. In this case, the heliosheath is the region outside the termination shock, but inside the heliopause. The idealised streamlines of the subsonic solar wind plasma show that it is in fact turned towards the direction of the interstellar flow to form the heliotail (Sues and Nerney, 1990).

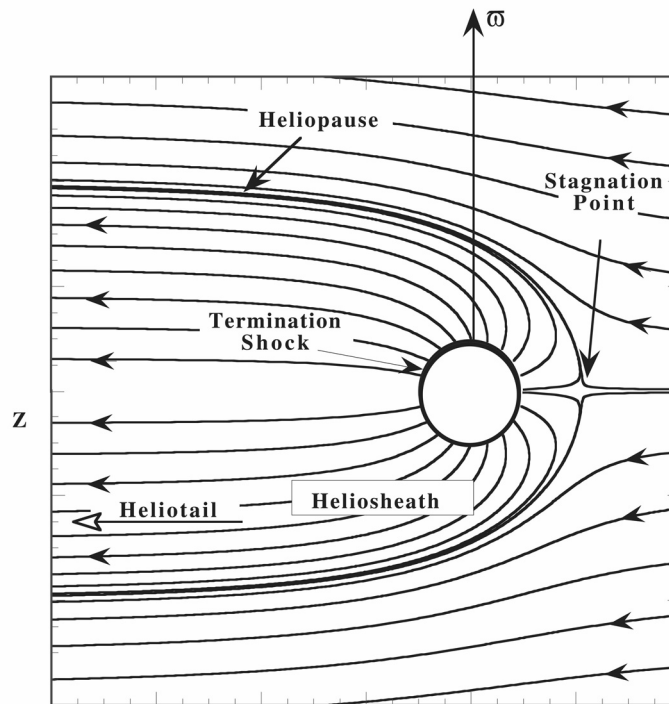


Figure 14: A model of the heliosphere assuming that the LISM is not supersonic. This picture represents an alternative view of the heliosphere to the schema shown in Figure 1. (By courtesy of S.T. Suess, NASA/Marshall Space Flight Center, Huntsville, AL, USA.)

It is important to revisit the idealised picture drawn of the termination shock above. Although the basic elements of the interaction are correctly represented by the pressure balance equation described above, a first, necessary correction is the three dimensional nature of the shock, as it envelops the heliosphere. The observations in the heliosphere show that the solar wind is present in all directions around the Sun; however, it is very non-uniform, both in density and speed, so that there is, at any time, a very large range of variability in the dynamic pressure of the solar wind as a function of heliographic latitude and, in fact, longitude. The processing of the solar wind in the outer heliosphere modifies, through the dynamic interaction of the different solar wind streams, the non-uniform distribution of the dynamic pressure observed in the inner heliosphere. This means that it is somewhat unclear to what extent the simplest assumption, that of spherical symmetry of the termination shock is in error. It is nevertheless highly likely that there is at least a strong latitudinal dependence in the termination shock distance; this asymmetry may well be dependent on the phase of the solar cycle. The first complete latitude survey of the dynamic pressure of the solar wind by Ulysses showed (Phillips et al., 1995a) that the solar wind dynamic pressure was in fact higher at high heliolatitudes than in the equatorial regions, at least around solar minimum when the high speed solar wind streams from the polar coronal holes dominated the heliosphere away from the equatorial plane. This observation led to the suggestion that the termination shock was at a greater distance from the Sun over the polar regions, when compared to its distance in the equatorial plane.

Another factor in the estimates of what happens near the boundary of the heliosphere is the role played in the dynamics by the neutral gas originating in the LISM, but streaming unimpeded into the heliosphere at the relative speed between the heliosphere and the LISM. Neutral particles are eventually ionised by either UV radiation from the Sun or by the charge exchange mechanism with the solar wind plasma (e.g. Isenberg, 1999 and references therein). It is these particles, once picked up by the solar wind that are then convected outwards towards the termination shock and so constitute the seed population to the so-called anomalous component of the cosmic rays. The analysis and extrapolation of the ACR

observations by Voyager have placed potentially important constraints on both the strength of the termination shock and on its heliocentric distance as already described in Section 6.

The pressure of pickup ions in the outer heliosphere may in fact contribute to a slowdown of the solar wind (Richardson et al., 1995, Burlaga et al., 1996). A study based on the comparison of solar wind speeds at Ulysses in the inner heliosphere and Voyager 2 in the outer heliosphere (Wang et al., 2000) has yielded an estimate of a slowdown of up to 10% out to about 60 AU. Such a change in the solar wind speed clearly needs to be taken into account when examining the pressure balance that is the basis of estimating the distance of the termination shock.

In addition, the potentially large variability of the termination shock distance, in response to varying conditions in the solar wind in phase with the solar activity cycle, remains a topic of great interest as the Voyager spacecraft approaches this first boundary of the heliosphere. The dynamic pressure of the solar wind may vary by as much as a factor 2; this figure leads to a variation in the termination shock distance of about 20 AU (Wang and Belcher, 1999). Other efforts at modelling (see, e.g., Zank and Pauls, 1996), taking into account the effects of the interstellar neutral atoms penetrating into the heliosphere and their conversion into a population of pickup ions, as well as the variability in solar wind dynamic pressure clearly show that the both the location and structure of the termination shock are subject, at present to uncertainties (see also review by Lee, 1996). The only resolution will come from the direct observation of the termination shock itself. Even given the uncertainties, the Voyager spacecraft is expected to provide this vital evidence of the outer boundary of the heliosphere within the next decade.

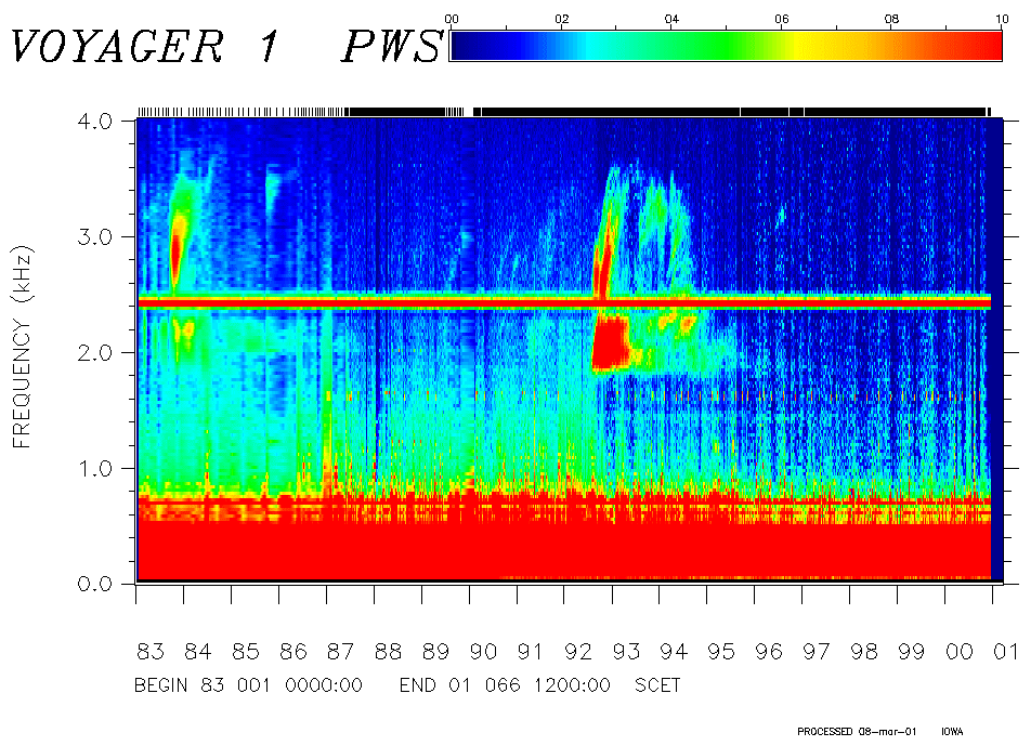


Figure 15. Observations of radio waves by the Voyager 1 plasma wave instrument from 1983 to 2000. The events in 1983 and 1992-93 have been interpreted as radio waves generated at the heliopause, in response to strong shock waves that travelled out from the Sun at times of exceptionally high solar activity. (By courtesy of D.A. Gurnett and W.S.S. Kurth, University of Iowa.)

Another estimate of the location of the boundary of the heliosphere comes from the remarkable observations made by the plasma wave instrument on the two Voyager spacecraft

(Kurth et al., 1984, Gurnett and Kurth, 1996), illustrated in Figure 15. First in 1983, then again in 1992-93, significantly enhanced wave activity was detected by the plasma wave instruments between 2 and 3 kHz. These long-lasting events have been interpreted (see review by Gurnett and Kurth, 1996) as radio waves generated far in the outer heliosphere, in the vicinity of the heliopause, in response to shock waves propagating from the Sun. The waves are likely to be emitted as a result of a shock-driven Langmuir-wave mode conversion mechanism at (or twice) the plasma frequency.

In both cases, there was very intense solar transient activity, about 400 days prior to the onset of the radio wave events. Several very large CMEs were observed in 1982 and in the first half of 1991 which, judging by their effects on cosmic ray propagation in the heliosphere, created major, shock-led disturbances in the heliosphere as a whole. It is these two systems of shock waves, reaching the heliopause, that are thought to have been at the origin of the events detected by both Voyager spacecraft. Given the delay between the solar events that gave rise to the disturbances, and given a range of assumptions concerning the propagation of the shock waves through the heliosphere, it is possible to estimate the distance to the heliopause to be between about 110 and 160 AU. Although the range of the estimate is very wide, the remarkable fact remains that the observations represent a remotely sensed, but nevertheless relatively direct detection of the heliospheric boundary.

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