SPACE PHYSICS ADVANCED OPTION ON THE SOLAR WIND AND HELIOSPHERE

STUDY MATERIAL AND WORKSHEET   Monday 28th October 2002

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I will be happy to discuss the material covered in this topic further with anyone who is interested or has specific questions – just send me an e-mail to make an appointment or take pot luck at finding me in.

KEY TOPICS

1. Introduction to the heliosphere

2. Magnetic field structure of the heliosphere

3. Large scale structure in the solar wind

4. Solar cycle variations in the heliosphere

1. Introduction to the heliosphere

1.1 Definition

The **heliosphere** is the volume of space, enclosed within the interstellar medium, formed by, and which encloses the solar wind, flowing out from the solar corona, and the Sun's magnetic field. The solar wind, consisting of ionised coronal plasma, flows supersonically and radially outward from the Sun due to the large pressure difference between the hot solar corona and the interstellar medium. The size of the heliosphere, believed to be 100 AU or more in radius, is determined by a balance between the pressure exerted by the solar wind flow and the pressure of the interstellar medium. We will make some rough estimates of this size in the worksheet section of this handout. It depends strongly on the properties of the interstellar medium which are rather poorly known. They are summarised in Table 1 and are mostly determined from spectroscopic measurements of interstellar gas.

   Table 1 Properties of the interstellar medium

Flow speed	25 ± 2 km/s
Flow direction	75.4° ecliptic longitude
	–7.5° ecliptic latitude
Neutral H density	0.10 ± 0.01 cm^{-3}
Proton density	< 0.3 cm^{-3}
Proton temperature	$(7 \pm 2) \times 10^3$ K
Electron density	assumed same as protons
Electron temperature	assumed same as protons
Magnetic field strength	$0.1 – 0.5$ nT
Magnetic field direction	unknown

1.2 Outer boundaries of the heliosphere

Figure 1.1 illustrates what we currently believe the outer boundaries of the heliosphere look like. Since no spacecraft has yet travelled far enough from the Sun to directly measure these outer regions this picture presently remains theoretical. The contact surface between the interstellar plasma and plasma of solar origin is known as the **heliopause**. Both the interstellar and solar wind plasmas are highly conducting, satisfying the frozen-in field picture, so that the two plasmas cannot intermix across the heliopause.

The heliosphere is believed to be moving at a speed of ~25 km/s through the interstellar medium. This can be said equivalently that there is an **interstellar wind** of 25 km/s impacting on the heliosphere. The speed of the interstellar wind has been estimated from direct measurements of interstellar neutral particles within the heliosphere. Neutral particles can flow through the heliosphere undeflected by its magnetic field and hence can be detected by spacecraft in the inner heliosphere. The plasma component of the interstellar wind is conjectured to be moving at the same speed. The heliosphere acts as an obstacle to the interstellar wind which is deflected to flow round the outside of the heliopause (analogous to the solar wind flowing round the magnetopause at the Earth). Depending on the density and other properties of the interstellar wind near the heliopause it is possible that this wind is supersonic. If this is the case then a **heliospheric bow shock** will form upstream of the heliopause to slow the plasma to subsonic speeds before it can be deflected. The region between the bow shock and heliopause is known as the **heliosheath** (analogous to the magnetosheath at the Earth).
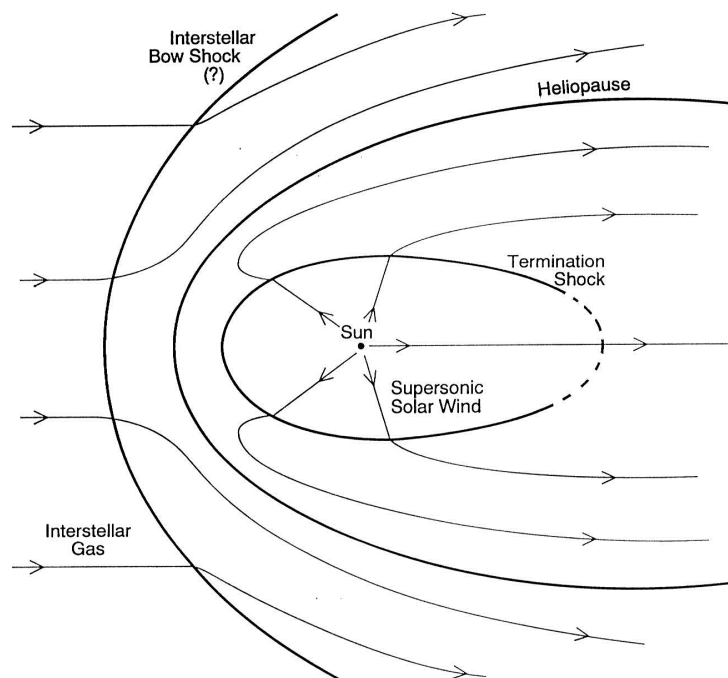

Figure 1.1 The structure and outer boundaries of the heliosphere.

The heliopause also acts as an obstacle to the radial outflow of the solar wind which must also be deflected to flow around the inside of the heliopause and eventually flow away in the direction of the interstellar flow to form a **heliotail**. We know that the solar wind is definitely supersonic. This was demonstrated in Parker's solar wind solution (see main lecture course) and has been measured as such by many spacecraft. Thus a standing shock wave must form in the solar wind at a certain

distance from the heliopause so that it is slowed to subsonic speeds and can be deflected. This shock wave is known as the solar wind **termination shock**.

1.3 Heliospheric spacecraft

Many spacecraft have made measurements of the solar wind in the vicinity of the Earth since the early 1960s. The first long distance heliospheric explorers to travel beyond 1 AU were the two Pioneer spacecraft, launched in 1972 and 1973. Pioneer 11 has run out of power, but as of 2000 Pioneer 10 was continuing to be tracked at a distance of 76 AU with one cosmic ray instrument operating, headed down the heliotail direction. (During 2001 Pioneer 10 may also have ceased being tracked). Voyagers 1 and 2 were launched in 1977 on their grand tour of the outer planets. They now continue to operate with the aim of locating first the termination shock and then hopefully the heliopause. As of 2000 they were at 78 and 62 AU respectively with science instruments mainly still operating. Voyager 1 is gaining about 3.5 AU a year and is heading towards the nose of the heliosphere, thus the most likely to encounter the boundaries.

Travelling in the other direction, Helios 1 and 2, launched in 1974 and 1976, have explored the inner heliosphere between 0.3 and 1 AU from the Sun. More recently, Ulysses, launched in 1990, is in 6 year period polar orbit of the Sun, inclined at 80.2° to the equator with perihelion at 1.2 AU and aphelion at 5.4 AU. It is thus the first spacecraft to explore the 3D structure of the heliosphere over a large latitude range. A first solar minimum orbit of the Sun was completed in 1998, a second under solar maximum conditions is presently underway.

2. Magnetic field structure of the heliosphere

2.1 The Parker Spiral field

The heliospheric magnetic field originates as a result of the Sun's magnetic field being carried outward, frozen in to the solar wind. The simplest model describing the magnetic field in the heliosphere is that introduced by Parker in 1958 at the same time as his solar wind solution. This model has been introduced in detail in the main lecture course so will only be summarised here.

The Parker model of the heliospheric magnetic field is based on a number of simplifying assumptions. It ignores what happens to the magnetic field in the solar corona and begins at a distance from the Sun (at a 'source surface' at distance r_0) where we can assume that we have radially directed magnetic field lines frozen in to the outflowing solar wind. It also assumes that the speed of solar wind plasma packets does not change with distance. With the magnetic field remaining frozen in as the solar wind travels outwards, but with the footpoints of each field line remaining at a fixed point on the source surface, the heliospheric magnetic fields adopts a simple Archimedean spiral configuration as shown in Figure 2.1.

In equation form, working in spherical polar co-ordinates (r, θ, ϕ), firstly the radial component of the magnetic field can be shown from flux conservation to depend only on the distance r from the Sun:

$$B_r(r, \theta, \phi) = B_r(r_0, \theta, \phi_0)(r_0/r)^2$$

By considering the relative motion of a solar wind plasma parcel and its source point, the equation for the spiral field lines is obtained:
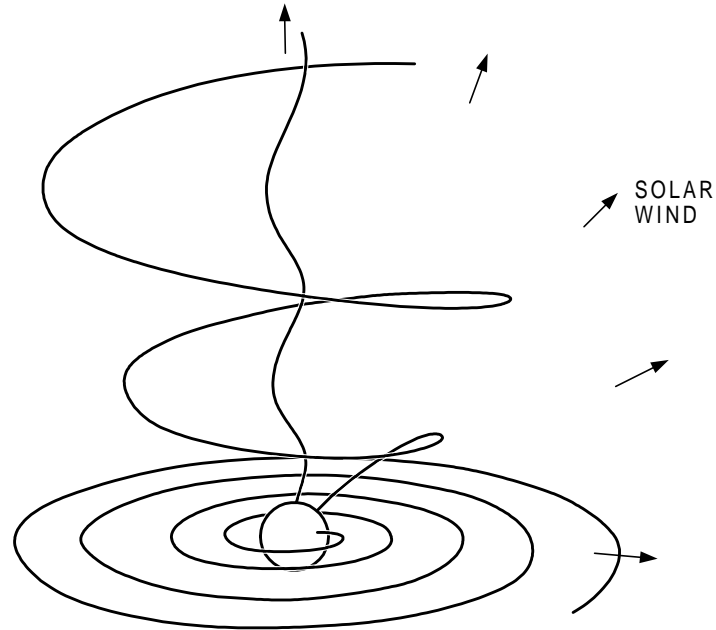
$$r - r_0 = -(\phi - \phi_0) V_r / \Omega \sin\theta$$

Figure 2.1 The Parker spiral configuration of the heliospheric magnetic field.

From this it can be shown that azimuthal (ϕ) component of the magnetic field falls off with distance as $1/r$, (as opposed to the $1/r^2$ for the radial component):

$$B_\phi(r, \theta, \phi) = -B_r(r_0, \theta, \phi_0)\ \Omega\sin\theta\ r_0^2 / V_r\ r$$

It is also implicit in Parker's model that the north-south (θ) component of the magnetic field should always be zero:

$$B_\theta(r, \theta, \phi) = 0$$

From these equations (see problems) we can deduce the angle that the spiral field lines should make to the radial at any position in the heliosphere. You should find that this angle depends on the distance from the Sun and latitude with respect to the rotational equator (remember that θ is co-latitude in spherical polars) and on the local solar wind speed. As seen in Figure 2.1, as we move away from the equator, the field lines gradually become less tightly wound with latitude until a field line originating exactly from the pole remains purely radial. Alternatively, at a co-latitude θ we can view the magnetic field lines as being wrapped around the surface of a cone of half angle θ.

Measurements of the magnetic field by the spacecraft that have explored the heliosphere in many directions have shown that the predictions of this simple model are confirmed on average to a good first approximation. However, over short time periods there are many deviations away from the predicted direction due to a variety of other phenomena, for example those discussed in section 3.

We will see that the solar wind speed is not necessarily uniform with position over the source surface near the Sun. Thus the simplistic picture in Figure 2.1 which assumes a single uniform solar wind speed throughout the heliosphere is already over idealised. However, along a single radial line extending out from the Sun, providing a solar wind packet does not encounter any obstacle to slow it down, observations show that it does indeed maintain a constant speed to a good approximation.

2.2 The heliospheric current sheet

Figure 2.1 is also simplified since it does not indicate the direction of the heliospheric magnetic field lines. You have also seen in the main lecture course and in the first advanced option the answer to this question but we will explore it further here in the worksheet section.

Within the solar corona, forces associated with the magnetic field initially dominate the forces exerted by plasma motions. However, once distances are reached where the solar wind flow is established, any field line which has reached this far without returning to the solar surface will be carried out in the solar wind. Close to times of solar minimum activity the coronal magnetic field can be approximated to that of a simple magnetic dipole. Despite this, observations of the Sun's surface magnetic field at the photosphere using Z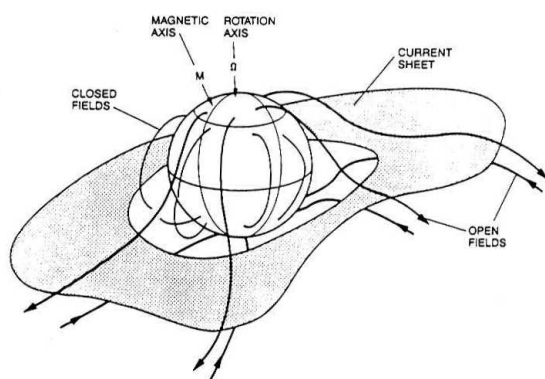eeman spectroscopy (impossible higher up due to thermal broadening) reveal a very complicated magnetic field pattern. This complicated pattern can be described by a spherical harmonic expansion (see first advanced option) and the distance dependence of these is such that the strength of the higher order harmonics falls off more rapidly with distance than that of the dipole, leaving the dipole as a good first order description of the coronal field at solar minimum.

Figure 2.2 The formation of the heliospheric current sheet.

Figure 2.2 shows how dipole field lines in the equatorial regions remain closed back down to the solar surface. However, field lines which originate at higher latitudes get picked up by the solar wind and carried out into the heliosphere. Near the equator there is a band where field lines with opposite directions originating from the northern and southern hemispheres meet. Following Maxwell's equations a sheet of current must form at this location as shown in Figure 2.2. This sheet of current is known as **the heliospheric current sheet**. This current sheet is carried out in the solar wind all the way to the outer reaches of the heliosphere. It forms a large scale boundary which effectively separates the two magnetic hemispheres of the heliosphere.

Even at solar minimum, the Sun's dipole axis is rarely exactly aligned with the rotation axis, typically being tilted at least at a small angle as also shown in Figu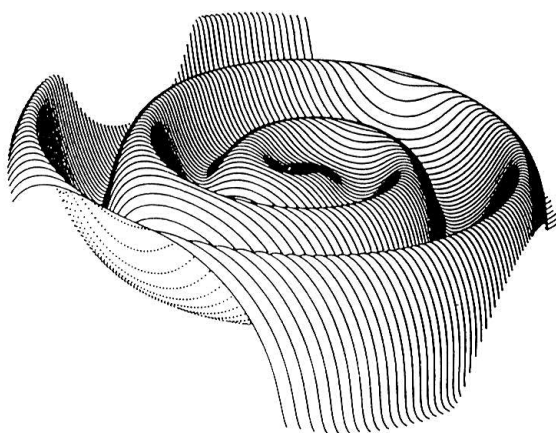re 2.2. As the dipole axis precesses about the rotation axis as the Sun rotates, the tilted heliospheric current sheet also rotates with the Sun. Thus a spacecraft located in the equatorial plane of the heliosphere, say near the Earth, should in principle observe outwardly directed field lines (one polarity) for half the time, and inwardly directed field lines (the other polarity) for the other half of the time. Figure 2.3 shows the shape of current sheet that results from a simple plane tilted current sheet at the Sun being carried out in the solar wind as the Sun rotates. This is sometimes referred to as the ballerina skirt model. In reality the heliospheric current sheet is not perfectly flat and is observed to often contain localised warps. This complicates the magnetic field polarity

Figure 2.3 The topology of the heliospheric current sheet.

pattern observed by spacecraft near the Earth. However, as the Ulysses mission has confirmed, when a spacecraft travels to latitudes higher than the tilt of the heliospheric current sheet only one polarity of magnetic field lines is observed as the spacecraft remains continuously in one magnetic hemisphere of the heliosphere.

3. Large scale structure in the solar wind

3.1 Three types of solar wind flow – fast, slow and transient

Since the first spacecraft observations near the Earth it has been known that the solar wind speed was divided into streams of slow wind (~400 km/s) and fast wind (>500 km/s). At that time it was thought that the slow wind was the basic type of wind as the speed was approximately that predicted by Parker's solar wind model. When Ulysses first flew over the Sun's poles prior to solar minimum in 1994 and 1995 it was confirmed that the true basic solar wind was in fact fast wind with a typical speed of 750 km/s and that this wind originated from the coronal hole regions (see previous advanced option) in the Sun's atmosphere. At that time the configuration of the coronal magnetic field was very similar to that shown in Figure 3.1(a) with the heliospheric current sheet tilted at an angle of 30° to the rotational equator. Once Ulysses had passed latitudes greater than 40° in 1994 it measured ~750 km/s wind speed continuously for over a year until it next returned to low latitudes. We think of the coronal holes as the source regions of the majority of the magnetic field lines which open into the heliosphere, thus it makes sense that it is easy for the solar wind to flow out along these field lines. Particularly during the declining and minimum phases of the solar cycle there are two large and relatively stable polar coronal holes in the Sun's atmosphere, one at each pole as shown in Figures 3.1(a) and (b).
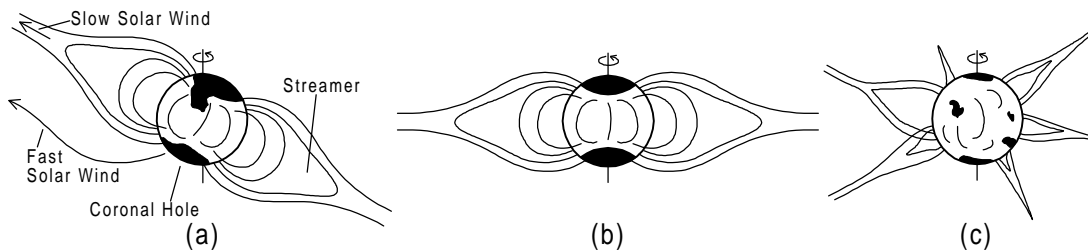

Figure 3.1 The magnetic structure of the solar corona at (a) intermediate stages of the solar cycle, (b) at solar minimum and (c) at solar maximum. (a) also shows the source regions of fast and slow solar wind.

Table 2 Characteristics of fast and slow solar wind

Property at 1 AU	Slow wind	Fast wind
Speed (v)	~400 km/s	~750 km/s
Number density (n)	~10 cm^{-3}	~3 cm^{-3}
Flux (nv)	~3×10^8 cm^{-2} s^{-1}	~2×10^8 cm^{-2} s^{-1}
Magnetic field (Br)	~3 nT	~3 nT
Proton temperature (Tp)	~4×10^4 K	~2×10^5 K
Electron temperature(Te)	~1.3×10^5 K (>Tp)	~1×10^5 K (<Tp)
Composition (He/H)	~1 – 30%	~5%

We now know that the slow wind is associated with the so called streamer regions in the solar atmosphere where the magnetic field lines close back down to the solar surface. It is not presently known for certain how the slow solar wind escapes from these regions. We can see that as the Sun rotates a spacecraft at the Earth will be seeing slow wind from streamers a lot of the time, but will lie above source regions of fast wind at times, leading to the type of mixture of stream speeds found in the early observations.

During the declining and minimum phases of the solar cycle when the Figure 3.1(a) type structure is dominant, we often approximate the flow pattern close to the Sun as a band of slow solar wind at low latitudes centred on the Sun's dipole equator and extending ~±10° either side, with fast wind at all higher latitudes.

This simple pattern of fast and slow wind is occasionally disrupted by the third type of solar wind flow, which we refer to as **transient** solar wind. These are streams of solar wind caused by the one-off eruptions of material from the Sun's atmosphere known as **coronal mass ejections**. They can happen at any time during the solar cycle but are more common during solar maximum. We will discuss transient solar wind flows in more detail in section 3.3.

3.2 Interaction of solar wind flows of different speed.

Returning to our discussion of figure 3.1(a) it is clear that as the Sun rotates there will be regions in the heliosphere, including at the equator, where slow wind will be originating from the Sun for part of the time and fast wind for the other part of the time. What happens when this fast wind catches up with slow wind emitted earlier? The underlying physics can be best understood by considering the interaction of the fast and slow wind along a particular radial line extending out from the Sun in one dimension. Suppose that slow wind initially flows from the solar corona along this line. At some time later, the rotation of the Sun supplies a coronal hole source of fast solar wind at the footpoint of our radial line. Because it is travelling faster the plasma in this fast wind will catch up with the slow wind ahead of it. Due to the fact that the fast and slow wind originate on different field lines (which are frozen-in to the respective plasma flows) the two plasmas cannot interpenetrate; in other words the faster plasma cannot overtake the slower plasma ahead of it. Thus, even though the flows are collisionless, a compression region builds up on the leading edge of the fast wind stream. Eventually solar rotation causes slow flow from a different coronal source region to become aligned with the footpoint of the radial line. Since the fast wind is running away from this second slow wind region, a rarefaction region develops on the trailing edge of the fast wind stream.

Figure 3.2 shows how the compression region develops with distance from the Sun. The only difference here is that a smooth bell shaped speed variation is assumed at the base of the radial line but the end result is essentially the same. The upper panel shows how the faster wind at the peak of the speed profile catches up with the slower plasma in front causing the speed profile to steepen. The lower panel shows the resulting pressure perturbation appearing due to the compression on the leading edge of the fast stream superimposed on the declining pressure profile with distance that is typical of the solar wind. The rarefaction region is not shown on this schematic.

Because there is a pressure gradient at the leading edge of the compression, a forward propagating wave develops which acts to accelerate slower wind ahead of the compression. For a similar reason a backward propagating wave, known as a reverse wave, develops on the trailing edge of the compression acting to decelerate faster wind behind the compression. Both these pressure gradient forces are shown on Figure 3.2. Note that the speed of both waves is much slower than the solar wind speed so that although the reverse wave is propagating back towards the Sun in the frame moving with the solar wind, a fixed spacecraft would see the reverse wave convected outwards past it
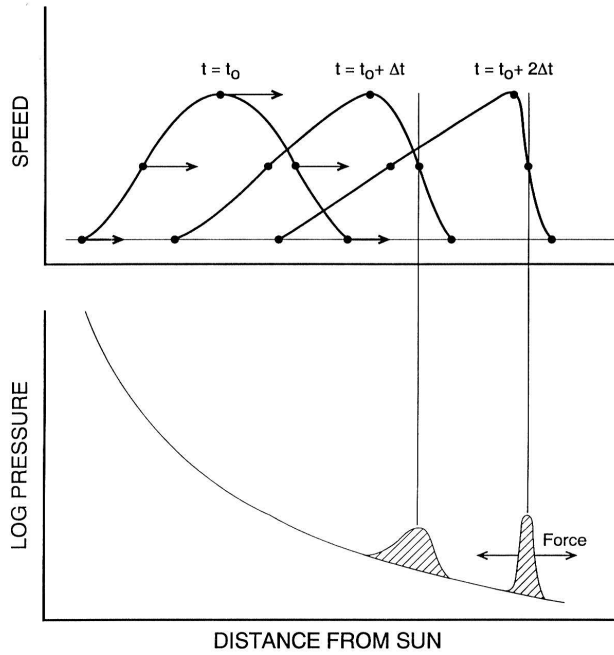
Figure 3.2 The steepening of a solar wind stream with distance from the Sun to form a compression region.
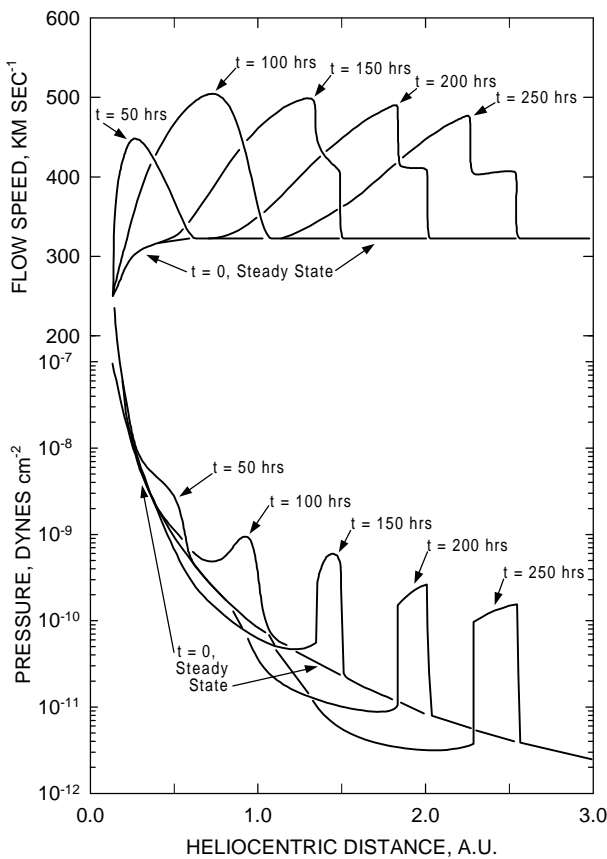

Figure 3.3 A plot of flow speed and pressure from a simple one dimensional simulation showing the formation and evolution of interaction regions with distance from the Sun.

carried along by the solar wind. The region of high pressure bounded by the forward and reverse waves is referred to as the **interaction region**.

The net effect of the interaction is to transfer momentum and energy from the fast wind to the slow wind and so damp out the steepening effect between the streams. This works fine as long as the speed at which the waves propagate is more than half of the speed difference between the two streams, but it turns out this is not always the case. The two waves actually propagate at a speed known as the 'fast mode speed', which is the characteristic speed, analogous to the sound speed in a normal gas, at which small amplitude pressure waves propagate in a plasma. If the speed difference between the fast and slow wind is more than twice the fast mode speed the stream front can steepen faster than the two waves can expand the compression region. Clearly we can't have unlimited compression and the result is that the two pressure waves eventually steepen into shock waves so that they can then propagate supersonically with respect to the fast mode speed. In the solar wind this typically happens between 2 and 3 AU from the Sun. The interaction region is now able to expand again and the forward and reverse propagating shock waves are able to damp out the speed difference with distance. Figure 3.3 shows how the speed and pressure profiles change with distance in a simple simulation. The shock waves can be identified as the discontinuous changes in speed and pressure in the rightmost profiles. The forward shock accelerates slower plasma ahead of it while the reverse shock decelerates the faster wind behind the interaction region causing the maximum speed of the stream to be reduced.
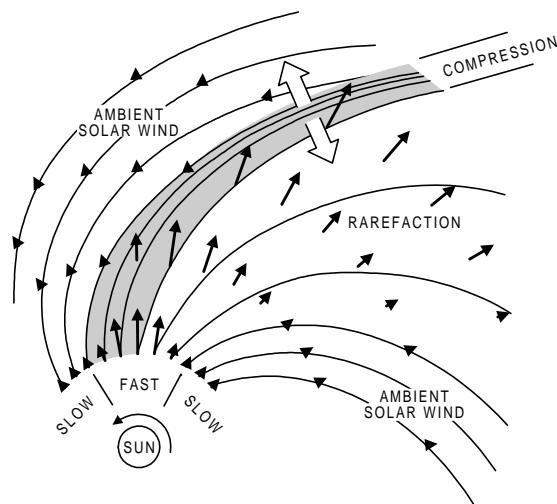
Figure 3.4 A schematic diagram of a corotating interaction region in two dimensions in the equatorial plane. The solid lines represent magnetic field lines while the length of the arrows are a measure of the flow speed.

The high pressure inside the interaction region is a combination of both the plasma pressure and magnetic field pressure. Density is typically high within the interaction region because of the compressed plasma and the magnetic field strength is typically high because of the magnetic field lines being pushed together.

In two dimensions, say for simplicity in the equatorial plane, the above process occurs at all longitudes. The state of evolution of the flows is however a function of longitude. Thus assuming that the pattern of fast and slow wind sources is time stationary at the Sun, the interaction region assumes a spiral configuration in the equatorial plane as shown in Figure 3.4. As the source regions rotate with the Sun, the whole spiral pattern rotates with them. Hence such large scale solar wind structures are known as **corotating interaction regions** or CIRs.

3.3 Transient solar wind flows

Coronal mass ejections (or CMEs) are large scale one off eruptions of material from the solar atmosphere which then continue to propagate out into the heliosphere to become the transient solar wind streams observed by in-situ spacecraft. The typical mass in ejected in a CME is estimated to be $\sim 10^{15}$ g. They are well known from observations with coronagraph instruments which block out the Sun's light and allow observations of the scattered light from the solar corona. An example coronagraph observation of a CME is shown in Figure 3.5. Their speeds can be estimated from a sequence of such images and

Figure 3.5 An example of a CME observed by the LASCO coronagraph on the SOHO spacecraft on 5th October 1996.

are typically found to be in the range from 100 – 1500 km/s. Clearly a fast CME travelling at 1500 km/s is going to be travelling much faster than any solar wind ahead of it and will cause interaction in a similar manner to that described in the previous section.
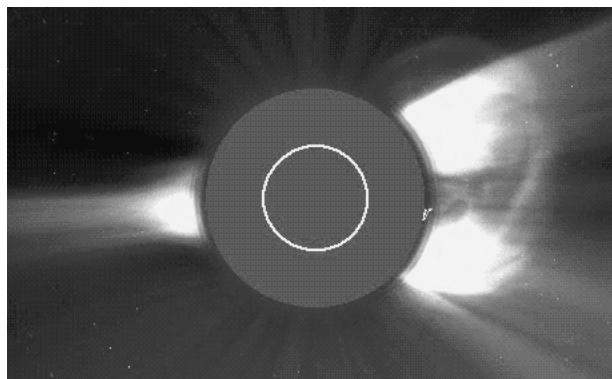
Measurements of transient solar wind flows at the Earth have shown speeds up to ~1100 km/s and indeed have compression regions on their leading edge and are often found to be driving shock waves. In fact since CIR shocks usually don't form until beyond 2 AU, the majority of shock waves which pass the Earth are due to fast coronal mass ejections.

The exact launch mechanisms for CMEs is not well understood, however their origin is observed to be from the regions of closed magnetic fields associated with coronal streamers (see Figure 3.1(a)). Unlike the normal heliospheric magnetic field, the eruption of a CME is thought to carry previously closed magnetic field lines out into the heliosphere. Thus these events should contain magnetic field
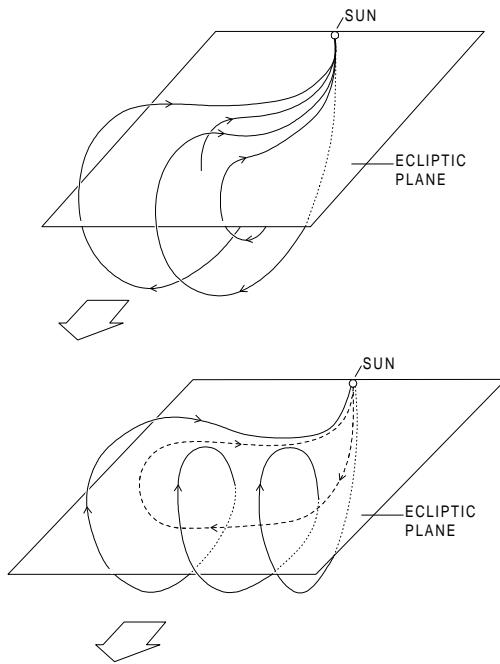
Figure 3.6 Sketch showing two possible configurations of magnetic field lines closed back to the Sun within a CME. The top panel shows simple loops while the lower panel shows a flux rope like structure.

lines which connect back to the Sun at both ends as shown in the simplest way in the top panel of Figure 3.6. A substantial percentage of CMEs have been associated with the eruption of prominence or filament structures (see first advanced topic) from the low corona. These structures are believed to be supported by coiled spiral magnetic field lines often referred to as a flux rope. When the prominence erupts the field lines which were supporting it get carried out too and will be convected out though the heliosphere as part of the transient flow as shown schematically in the lower panel of Figure 3.6. It is not uncommon for the magnetic fields measured in transient streams to undergo slow rotations often lasting more than a day that would be consistent with such coil-like structures. These events often have strong magnetic fields and low temperatures consistent with their origin in the low corona and their resulting low plasma beta leads to the magnetic field structures being maintained as they propagate through the heliosphere.

4. Solar cycle variations in the heliosphere

For this section we return to Figure 3.1 illustrating the magnetic field structure of the solar corona at the different phases of the solar cycle. It should be clear from section 3.1 that the tilt of the heliospheric current sheet and the pattern of fast and slow solar wind sources is strongly tied to the tilt of the Sun's magnetic dipole axis to that of the rotation axis. It turns out that this dipole tilt angle is a function of the solar cycle. Exactly at solar minimum, in principle the tilt angle is zero giving a heliospheric current sheet exactly in the equator as in Figure 3.1(b). As solar activity increases the dipole tilt increases through an intermediate stage similar to Figure 3.1(a) until at solar maximum some would argue that the tilt angle is 90°. In fact a better description at solar maximum may be that the dipole is very weak leaving higher order components of the magnetic field to dominate, for example a quadrupole. The magnetic structure of the corona as inferred from coronagraph observations of streamers is shown in Figure 3.1(c). There is not much evidence of a simple dipole here! As solar activity continues through maximum, the dipole axis does not change its sense of rotation. Rather it emerges into the next solar minimum with the opposite polarity to the previous one. Thus we say that the solar magnetic field reverses at solar maximum and the true solar cycle is 22 years long rather than 11 years. As a result the magnetic field polarities in the northern and southern hemispheres of the heliosphere also change sign from one solar minimum to the next. Whereas at solar minimum the heliospheric current sheet is confined to near the rotational equator, at solar maximum it can just as easily be found over the polar regions as the very recent results from the Ulysses mission are showing.

What about the solar wind flow pattern at solar maximum? Associated with the corona evolving into the configuration shown in Figure 3.1(c) the large stable polar coronal holes disappear to be replaced by smaller ones at all latitudes. Thus fast streams of solar wind still occur but slow wind appears to dominate all latitudes since there are streamers present everywhere. The much higher frequency of coronal mass ejections produce many transient wind streams as well. This much less time stable

coronal structure means that large scale corotating interaction regions are unable to form although shorter lived interaction between fast and slow wind streams still takes place.

Optional Further Reading

Introduction to Space Physics by M.G. Kivelson and C.T. Russell, Cambridge University Press, 1995, Chapter 4.

Physics of Solar System Plasmas by T.E. Cravens, Cambridge University Press, 1997, Chapter 6.

WORKSHEET

1. The size of the heliosphere.

The distance of the heliopause from the Sun is determined by the point where a pressure balance occurs between the solar wind and the interstellar medium.

(a) The dynamic pressure exerted by the solar wind flow incident on a surface is given by ρv^2. Convince yourselves that this quantity has the dimensions of a pressure.

(b) Using the data from Table 2 for the slow wind estimate the plasma, magnetic and dynamic pressures at 1 AU. Ignore the contribution due to helium. (You will need to look up at least the proton and electron masses and Boltzmann's constant.) The dominance of the dynamic pressure that you should find is preserved all the way out through the heliosphere, in fact a consequence of the solar wind remaining supersonic. So we can safely ignore the magnetic and plasma pressures in the solar wind when estimating the size of the heliosphere. Assuming that the solar wind speed remains constant and the density falls off as an inverse square law with distance allows you to use the 1 AU data to estimate the dynamic pressure at any distance from the Sun.

(c) Using the data from Table 1 estimate the values of the same three pressures in the interstellar medium and their uncertainties. Can you ignore any of the three here?

(d) Use the above information in a pressure balance calculation to determine the distance to the heliopause and its uncertainty.

2. On the Parker spiral model of the heliospheric magnetic field.

(a) From the equations given above derive the equation for calculating the 'spiral angle', that is the angle that heliospheric magnetic field lines make to the radial direction. Assuming a solar rotation period of 26 days, calculate the spiral angle in the equatorial plane of the heliosphere at 1 AU and 5 AU for solar wind speeds of 400 km/s and 800 km/s.

(b) The Parker field line equations imply the presence of volume currents everywhere in the heliosphere. Assuming that $B_r(r_0, \theta, \phi_0) = B_{r0}$ for all θ and ϕ (i.e. the magnetic field strength is

uniform at r_0) show that the volume current density vector is radial everywhere and has a magnitude given by

$$j_r = -2 \, B_{r0} \, \Omega \, r_0^2 \cos \theta \, / \, \mu_0 \, v_r \, r^2$$

[Hint: you may need to go and look up the form of the curl operator in spherical polar co-ordinates.]

(c) Imagine the heliospheric magnetic field to be configured as in Figure 2.1 but with outward field lines in the northern hemisphere and inward field lines in the southern hemisphere separated by a heliospheric current sheet which lies exactly in the equator. Away from the heliospheric current sheet, is the volume current described in (b) directed inward or outward (i) in the northern hemisphere and (ii) in the southern hemisphere?

(d) Assuming the same magnetic field configuration as in (c), it can be shown that the current in the heliospheric current sheet may be described by a surface current density k where

$$k_r = 2 \, B_{r0} \, \Omega \, r_0^2 \, / \, \mu_0 \, v_r \, r \qquad \text{and} \qquad k_\phi = 2 \, B_{r0} \, r_0^2 \, / \, \mu_0 \, r^2$$

[You can attempt to show this if you want to – it may be easy but I haven't had time to check!]

What pattern do the current streamlines in the heliospheric current sheet describe? What is the direction of the current flow (inward or outward)?

(e) By integrating the current densities as described in (b), (c) and (d) over θ and ϕ as appropriate, show that the net current flow out of the sun is zero.

3. A chance to interpret some real space physics data…

Figure 1 shows a corotating interaction region observed by the Ulysses spacecraft at 5 AU from the Sun in 1992 while Figure 2 shows a transient solar wind stream caused by a coronal mass ejection, also observed by Ulysses this time at about 2 AU in 1991. In both cases the spacecraft was near enough to the equator that you don't have to worry about latitude effects.

In Figure 1 from the top the panels show the solar wind speed, the tangential and normal components of the solar wind velocity (we haven't discussed these so don't worry about them), the proton density (n_p), the proton temperature (T_p), the magnetic field strength ($|B|$), the azimuthal and meridional angles of the magnetic field, and finally the total pressure obtained by summing the magnetic field and plasma pressures. For the purposes of this discussion we can define the azimuth angle of the magnetic field ϕ_B as the angle obtained by projecting the vector onto the equatorial plane and measuring the angle that the projection makes to the radial direction taking positive in a right handed sense. θ_B is the angle between the magnetic field vector and the equatorial plane. The same parameters appear in a different order in Figure 2, with the addition of the helium to hydrogen ratio (He/H) which we have not discussed in this handout.

(a) Figure 1 shows four vertical dashed lines marking four boundaries in the CIR. These are labelled FS for forward shock, HCS for heliospheric current sheet, SI for stream interface – this is the contact surface between the two separate plasmas which started off as slow and fast near the Sun, and RW for reverse wave. Using the information contained in this handout write down the principle features in the figure which you think led to the identification of these boundaries.

(b) The heliospheric current sheet in our simples model discussed in section 3.1 should lie in the centre of the band of slow solar wind. Can you explain why it appears here in the middle of an interaction region?

(c) Are there any further features in Figure 1 that you think you can explain based on the information in this handout?

(d) In Figure 2 the region between the dashed lines marked BDE represents the material within the transient stream that was ejected as part of the CME. BDE stands for bidirectional electrons which are slightly higher energy electrons which stream in both directions along the magnetic field due to both ends of the field lines connecting back to the Sun. These were observed in the region between the dashed lines. Based on the information in this handout describe as many features as you can in this figure.
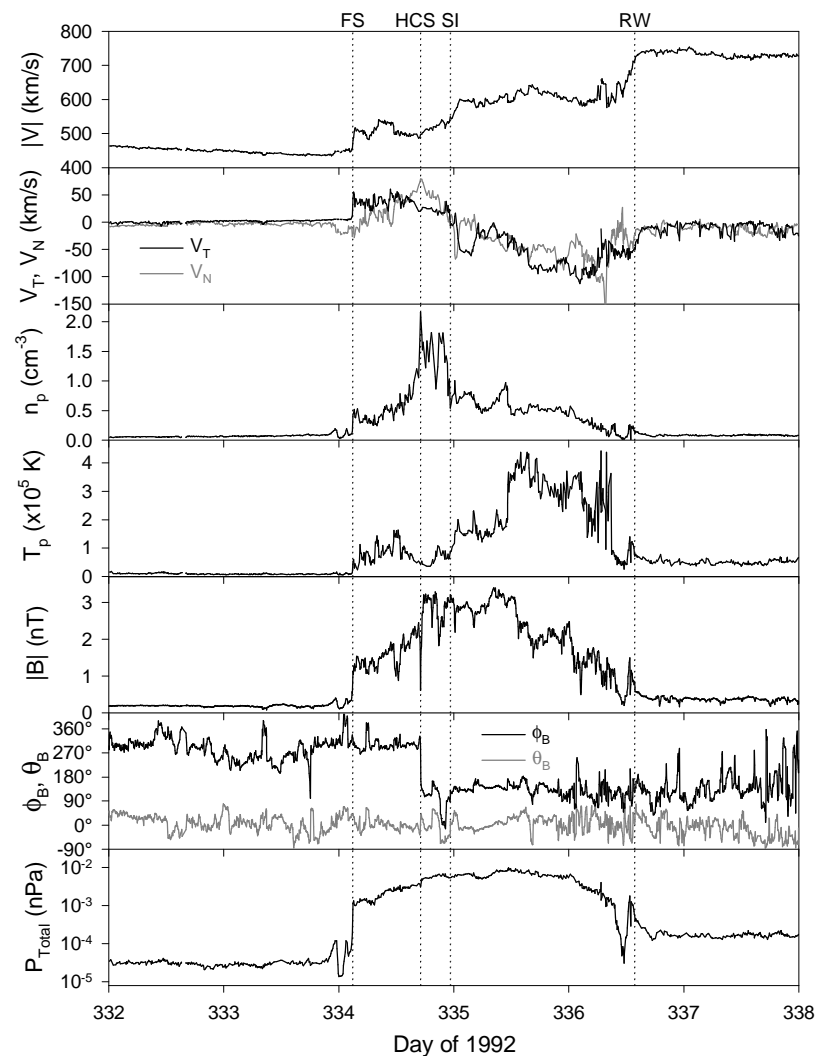

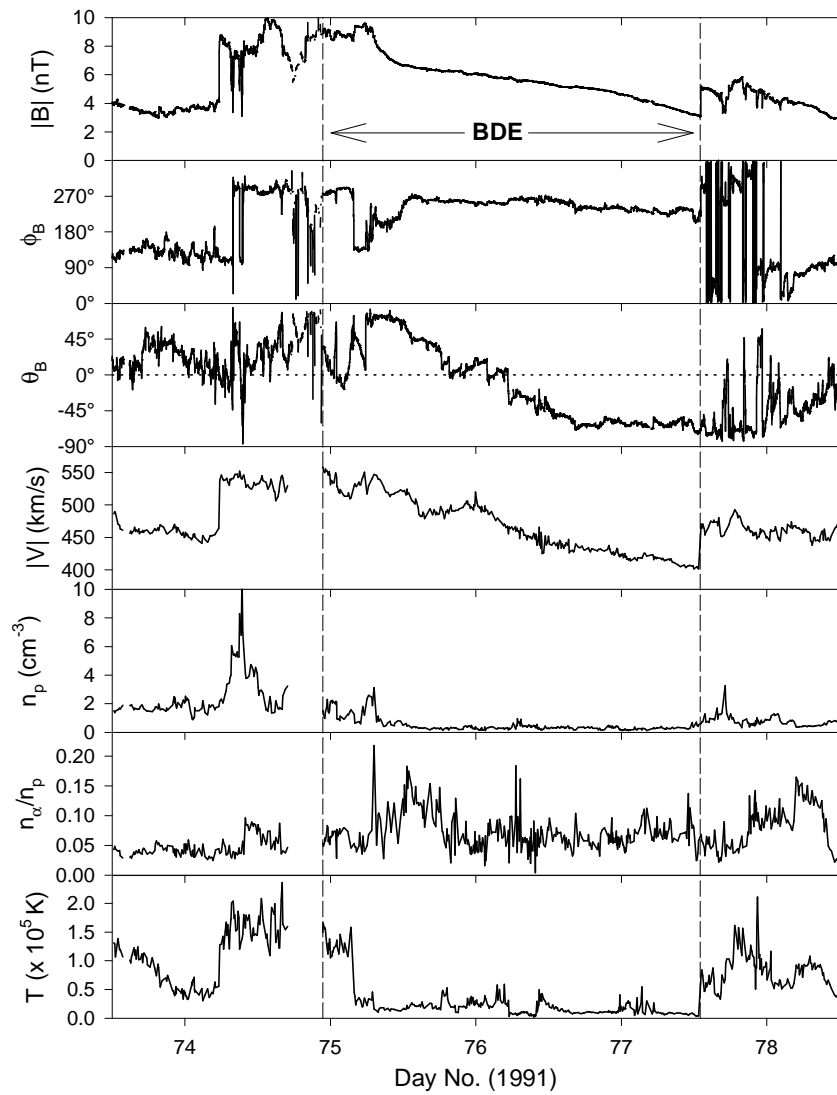**Figure 1** An example of a corotating interaction observed by Ulysses at 5 AU in 1992.

Figure 2 An example transient solar wind stream observed by Ulysses at about 2 AU in 1991.

Solutions to the worksheet problems will be available in the last week of term.