The heliospheric current sheet

Edward J. Smith

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Abstract. The heliospheric current sheet (HCS) is the boundary between open oppositely directed magnetic field lines which commonly originate as the outward extension of the solar magnetic dipole. The dipole tilt, the rotation of the Sun, and the outward propagation of the solar wind cause peaks and valleys in the current sheet which spiral outward. The HCS extends throughout the heliosphere to the greatest distances reached by Pioneer and Voyager. It serves as a magnetic equator, and solar wind parameters including speed, temperature, density, and composition vary with distance from the HCS. Extrapolated back to the Sun, especially near solar minimum, the HCS corresponds to the low-latitude streamer belt. Both features are closely related to a neutral line obtained by extrapolating photospheric magnetic fields to a source surface at several solar radii. The current sheet and sector structure persist throughout the solar cycle including solar maximum. At 1 AU the width of the HCS is approximately 10,000 km while a surrounding plasma sheet is thicker by a factor of ~30. The field inside the HCS does not simply decrease to a null and then reappear with the opposite sense. Instead, the field rotates at nearly constant magnitude from one polarity to the other. In spite of theoretical expectations that fields on opposite sides of the HCS will merge or reconnect, there is little evidence that such is occurring. Many scientific questions remain unanswered. What are the global properties of the HCS near solar maximum, and how faithfully are they reproduced by source surface models? Are multiple HCS crossings caused by waves on the current sheet or by multiple current sheets? What is the effect of coronal mass ejections on the HCS and vice versa?

1. Introduction

This review addresses the following important questions: (1) What is the heliospheric current sheet, and what are its global properties? (2) How was it "discovered" and by whom? (3) Why is it important? (4) How is it related to the solar magnetic field, to the coronal streamer belt, and to the source surface neutral line? (5) How is it affected by coronal mass ejections and vice versa? (6) What is the internal structure of the current sheet? (7) What are major unanswered scientific questions?

2. The Heliospheric Current Sheet and Its Global Properties

The Heliospheric Current Sheet, or HCS, is the boundary encircling the Sun that separates oppositely directed magnetic fields that originate on the Sun and are "open" (only one end is attached to the Sun) (Figure 1). These fields are closely associated with the Sun's dipole magnetic field and have opposite magnetic polarities, e.g., outward (positive) in the north and inward (negative) in the south. The current sheet separates these oppositely directed fields as required by Maxwell's equations, with the vector difference between the fields on the two sides being a measure of the linear current density. If it were not for the underlying simplicity of the heliospheric magnetic field being dipole-like, there might have been several current sheets surrounding the Sun, and the HCS would be less distinctive. As it is, the HCS is unique and represents the magnetic equator of the global heliosphere.

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Many plasma physicists consider currents (and electric fields) to be of secondary importance compared to the plasma velocity $\mathbf{v}$ and the magnetic field $\mathbf{B}$ since, in a collisionless plasma, $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$ and the current density $\mathbf{J} = \mu\nabla \times \mathbf{B}$. Using this paradigm, problems are solved for $\mathbf{v}$ and $\mathbf{B}$, and the current is derived afterward if it is of interest. This approach is referred to as the "VB paradigm" [*Parker*, 1996].

In heliospheric physics the HCS is a distinctive feature of the solar wind, and its shape, dynamics, and relation to particles, including very energetic particles, are definitely of interest. As an example, there are two aspects of the HCS that are of immediate interest, the nature of the current streamlines in the sheet and the question of current closure. If solar rotation is ignored, the magnetic field is radial, and the current streamlines which must be transverse to the field are simply circles centered on the Sun. When solar rotation is included, the fields lie along Archimedes spirals, and the current streamlines also spiral outward from the Sun to form so-called reciprocal or hyperbolic spirals. The presence of a persistent radial current component is associated with the azimuthal field component and implies a net outward flow of millions of amperes. This outflow is compensated (the current is closed) by bulk radial currents flowing sunward above and below the current sheet which produce the spiraling of the field locally [*Smith et al.*, 1978].

An essential feature of the HCS is the tilt of the Sun's magnetic dipole with respect to the rotation axis. Transformation of the plane current sheet in solar magnetic coordinates into a heliographic system reveals that as the solar wind convects outward, the HCS oscillates about the heliographic equator to form a series of peaks and troughs. In three dimensions the current sheet appears to be wavy and resembles the myth-

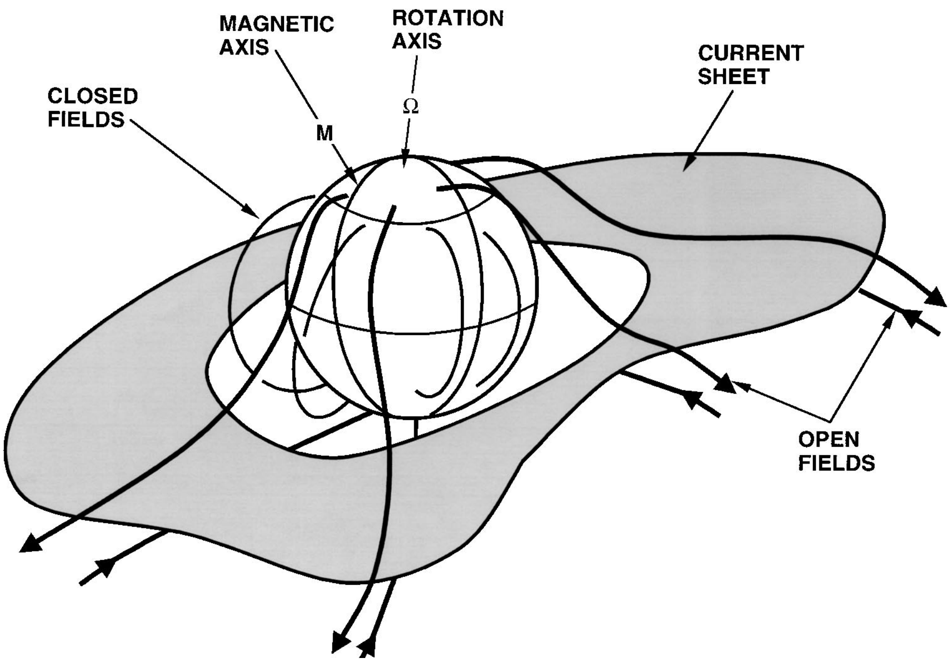

Figure 1. Schematic of the heliospheric current sheet. The shaded current sheet separates fields from the north and south solar magnetic poles which are open (only one end attached to the Sun). The normal to the current sheet represents the magnetic axis of the solar field and is shown tilted with respect to the Sun's rotation axis. Closed field lines (those which have both ends on the Sun) are shown at midlatitudes to low latitudes and lie inside the current sheet. The fields above and below the current sheet develop the spiral structure characteristic of the solar wind generally. From *Smith* [1993]. (Reprinted by permission of the University of Arizona Press. Copyright @ 1993 by the University of Arizona Press.)

ical "flying carpet" or a "ballerina skirt" (Figure 2). As far as we know, the HCS extends throughout most of the heliosphere, having been observed to be continuously present in the most distant magnetic field observations of Pioneer [*Smith*, 1989] and Voyager [*Burlaga and Ness*, 1993].

3. Discovery: How and by Whom

The discovery of the current sheet is intimately related to attempts to explain the sector structure of the heliospheric magnetic field (HMF). A surprising feature of the earliest magnetic field measurements in space was their organization into a few magnetic "sectors" in which the fields alternated between inward and outward [*Wilcox and Ness*, 1965]. The interface between the sectors, where the signs of the radial and azimuthal field components changed from positive to negative or negative to positive, was known as the "sector boundary" (SB). To the extent that the nature of this boundary was of interest, the early view was that the sectors took the form of "orange slices," with the sector boundaries being vertical or north-south surfaces parallel to the Sun's magnetic axis. Typically, two or four sectors were observed each solar rotation.

An important discovery soon after sectors were identified was a dependence of the sector structure on heliographic latitude (Figure 3). When the observations were used to produce a single measure of the dominant magnetic polarity per solar rotation and examined over several years, a sinusoidal variation was found, superposed on a long-term average of 0.5, that coincided with the annual excursions of the interplanetary spacecraft in latitude [*Rosenberg and Coleman*, 1969]. Shortly afterward, studies of high-latitude ionospheric currents observed in ground-based magnetic field data showed a close correlation between their polarity and the interplanetary sector structure [*Svalgaard*, 1975]. Since the ground-based observations were available for many years, the sector structure and dominant polarity could be studied over an extended interval of 4.5 sunspot cycles before observations in space began. This extended data set showed the same sinusoidal variation with latitude with the additional feature that the dominant polarity reversed along with the sign of the Sun's magnetic poles at or near sunspot maximum [*Wilcox and Scherrer*, 1972]. Clearly,

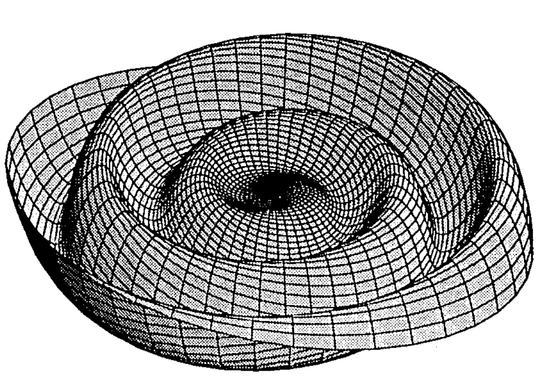

Figure 2. Three-dimensional representation of the HCS inside the heliosphere. The continuous HCS and its tilt relative to the solar rotation axis lead to a pair of peaks and valleys that spiral outward from the Sun. A spacecraft would cross the HCS twice per solar rotation and would observe two sectors. This view is from above the current sheet, which extends outward to ~15 AU during two solar rotations. The HCS does not stop at that distance but continues out into the heliosphere. From *Jokipii and Thomas* [1981].

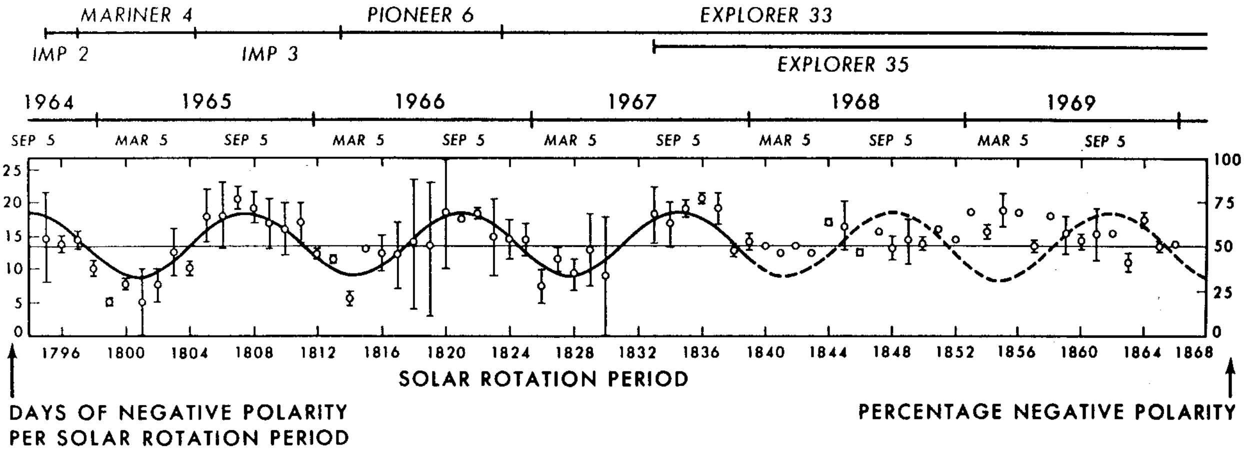

Figure 3. Magnetic field polarity and heliographic latitude. Observations of the magnetic sector structure at the various spacecraft shown in the upper bar were converted into the number of days during a solar rotation when the polarity was negative (left) or the fraction of a solar rotation that the polarity was negative (right). The data are plotted as a series of bars over an interval of over 3 years near solar minimum. The solid sinusoidal curve is the heliographic latitude of the Earth. The correlation reveals the dependence of the sector structure on the latitude of the spacecraft. From *Rosenberg and Coleman* [1969].

the sector structure exhibited a close correspondence between the fields in the ecliptic plane in which the Earth moved around the Sun and the Sun's polar magnetic fields.

Over an interval of several years these observations suggested to a number of investigators that the magnetic sectors were separated by a current sheet enclosing the Sun which was the physical counterpart of the discrete sector "boundary." The first person to make this connection was H. Alfven, who was concerned about the closure of the currents associated with the "orange slices" and preferred a more or less equatorial current sheet which he likened to a "ballerina skirt" [*Alfven*, 1977].

Another early advocate of this interpretation was M. Schulz, who (on the basis of a comment by L. Davis [*Davis*, 1972]) developed a model of the warped current sheet [*Schulz*, 1973]. Independently, working on cosmic ray phenomena, E. Levy proposed a similar equatorial current sheet and drew a model with the oppositely directed spiral field lines above and below the sheet [*Levy*, 1976]. A. Hundhausen also produced a model of the current sheet and showed its relation to the underlying solar magnetic field [*Hundhausen*, 1977]. By the mid-1970s this interpretation had attracted a number of powerful advocates.

L. Svalgaard and his colleagues developed a model based on an analogy to the seam of a baseball, which they took to be equivalent to the centerline of a magnetic arcade at the solar surface [*Svalgaard et al.*, 1975]. Furthermore, using the long interval afforded by the ground-based measurements, it was demonstrated that the amplitude of the sinusoidal variation with latitude changed in a characteristic fashion during the sunspot cycle [*Svalgaard and Wilcox*, 1976]. The amplitude, corresponding to the inclination of the SB, was high near sunspot maximum and low near sunspot minimum.

In 1976, definitive evidence of the inclined current sheet/sector boundary was provided by Pioneer 11 magnetic field observations [*Smith et al.*, 1978]. Following the earlier encounter with Jupiter in 1974, the Pioneer spacecraft was redirected to a subsequent encounter with Saturn in 1979. In order to reach Saturn the spacecraft followed a flight path that took it out of the ecliptic to what was then an unprecedented heliographic latitude of 16°. For several solar rotations near maximum latitude the magnetic field was found to have only one sign (positive) or, equivalently, to consist of only a single sector (Figure 4). No doubt, the timing was fortunate since solar activity was near a minimum and the inclination of the HCS was low.

The convincing evidence provided by Pioneer 11 settled the nature of the sector structure and sector boundary. Clearly, one sector was seen by spacecraft (or Earth) when they were located above the current sheet, and the opposite sector was observed when they were below it. The appearance of four or more sectors was readily explained by adding local "warps" to the current sheet caused by a more complex solar coronal magnetic field or by appealing to large-scale solar wind dynamics (fast-slow stream interactions).

4. Importance and Implications

Abandoning the "orange slice" model had an important consequence for studies of cosmic ray propagation. As long as the sectors were axially aligned with the Sun's rotation axis, their effect on cosmic rays was expected to "average out," and they were thought to be of little or no significance. However, an inclined current sheet would have a significant effect on the global heliospheric field and on the drift motions of the cosmic rays. These implications were pointed out by R. Jokipii and his colleagues, who proceeded to include drift effects in the basic transport equation used to describe the behavior of energetic particles [*Jokipii et al.*, 1977]. In particular, the HCS was shown to cause fast drifts along it and to act as a major "source" or "sink" of cosmic rays in the heliosphere (depending on the polarity of the fields above and below it, which change sign from one sunspot cycle to the next). The influence of the HCS was evident in the model as a correlation between cosmic ray intensity and the changing inclination of the current sheet. This aspect of the model was shown to be consistent with observations [*Smith*, 1990].

Since the HCS serves as a magnetic equator, many solar wind properties are organized with respect to it (Figure 5). Studies of various plasma parameters, including solar wind speed, density, temperature, and composition (ratio of alpha particle to proton densities), show a close correlation with the

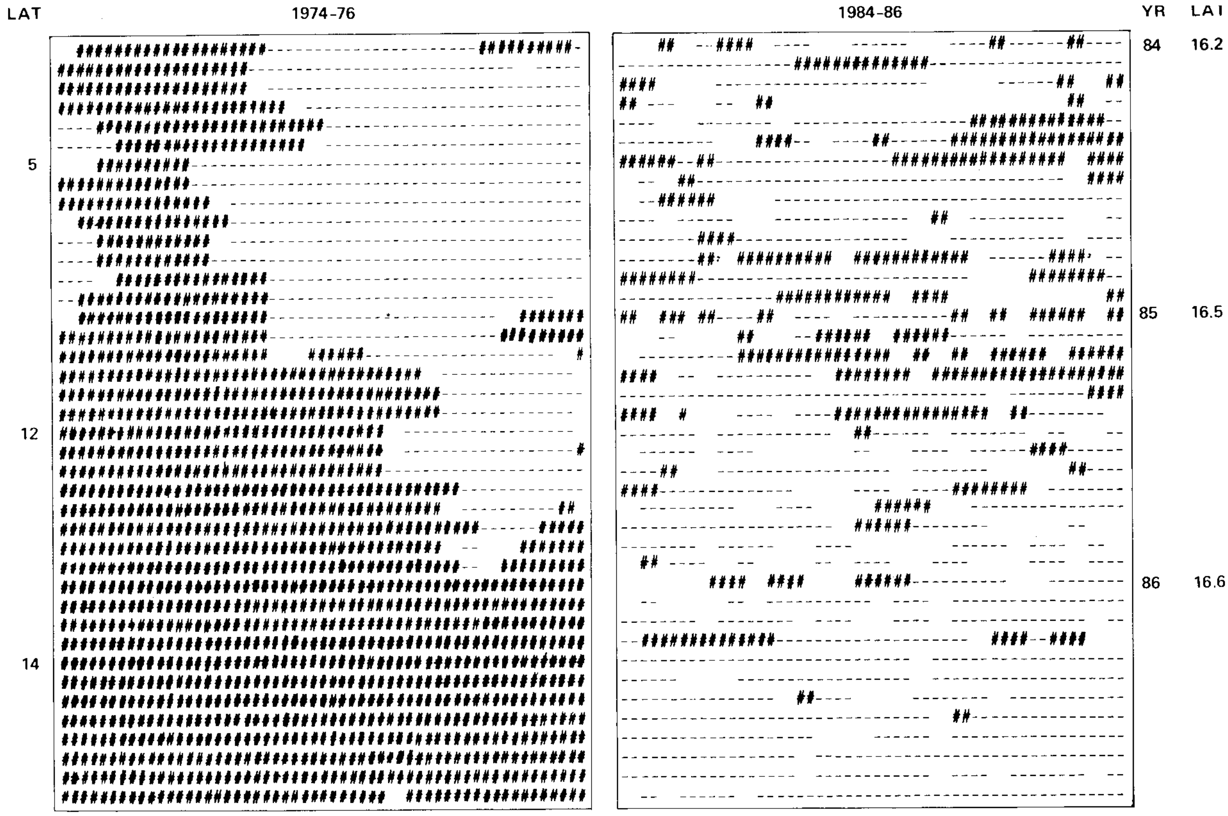

Figure 4. Pioneer 11 observations above the HCS. Two panels are shown, covering two intervals near solar minimum (in 1976 and 1986). The polarities observed by Pioneer 11 (at the latitudes shown in the left and right columns) are plotted for successive solar rotation periods. Two pound signs signify positive polarity on a given day while a pair of negative signs indicate a negative polarity. Blank spaces indicate missing data or days when the sector structure could not be determined. In 1976 the spacecraft was located above the HCS and sampled a single polarity corresponding to outward directed fields from the Sun's north pole. In 1986, when Pioneer was again above the HCS, the field was inward while the north magnetic pole of the Sun was also inward (negative). From *Smith* [1989].

current sheet [*Borrini et al.*, 1981; *Gosling et al.*, 1981; *Zhao and Hundhausen*, 1981]. Indeed, the latitude gradients of these and other parameters are best organized by heliomagnetic coordinates or distance from the HCS.

Knowledge as to whether solar wind streams originate above or below the HCS, i.e., their polarity, is useful in many circumstances. An example is the investigation of corotating interaction regions (CIRs), in which a sequence of streams are to be sorted out or merged interaction regions are to be identified along with their constituent streams. Studies of solar wind structures at widely separated locations in the heliosphere also frequently benefit from knowing the magnetic polarities of the structures. A particularly important use of such information is in identifying solar wind structures with the corresponding features on the Sun, e.g., coronal holes [*Hundhausen*, 1977].

The HCS also represents an example of a basic plasma structure in the heliosphere. From this point of view it is an important example among many other current sheets observed in space such as solar wind discontinuities or current sheets embedded in cometary or magnetospheric tails. Localized current sheets also occur on the Sun and are considered an essential feature of isolated coronal streamers. The physics of such structures, including their dynamical behavior and possible magnetic reconnection, is of obvious scientific interest.

5. Relation to the Solar Magnetic Field, the Streamer Belt, and the Source Surface Neutral Line

The fields adjacent to the HCS are closely identified with the Sun's polar cap magnetic fields and with open solar magnetic fields generally. The inclination of the HCS is closely correlated with sunspot number and varies from low to high inclination between solar minimum and solar maximum. This relation can be easily explained in terms of the behavior of the solar magnetic dipole, which is nearly aligned with the Sun's rotation axis near minimum and almost equatorial at maximum. These changes parallel the near absence and subsequent growth of the number of sunspots and their associated toroidal magnetic fields, which determine the strength of the equatorial magnetic dipole moment [*Wang et al.*, 2000b]. Near solar maximum the polar fields are weak and in the process of reversing while the fields in active regions, which determine the resultant equatorial dipole, are numerous and strong.

When the position of the HCS is extrapolated inward to the Sun, it is found to correspond to the low-latitude streamer belt or "coronal disk" [*Gosling et al.*, 1981; *Howard and Koomen*, 1974; *Smith et al.*, 1978; *Mihalov et al.*, 1990]. Such a correspondence is easier to establish during solar minimum when a single sequence of streamers dominates the coronal structure. However, as solar maximum approaches, the dipole-like coronal structure gives way to a dominance by higher-order magnetic multipoles, many of which underlie additional streamers. It is then not possible to make such a simple identification with solar structure. Support for the association of the HCS with streamers is still provided by the correlation with solar wind properties, which are considered to be representative of the kinds of plasmas in the dense streamers.

The HCS is, in fact, found inside a wider region of high-density plasma where the magnetic field strength is reduced. At the much thinner current sheet the field direction changes abruptly, often without a further significant decrease in magnitude. The combination of increased plasma density and decreased field magnitude leads to a characteristic increase in the plasma β, the ratio of plasma thermal pressure to magnetic pressure (Figure 6). Since the change can be reasonably abrupt at the two edges, this parameter is a useful identifier of the heliospheric plasma sheet (HPS) surrounding the HCS [*Winterhalter et al.*, 1994]. This terminology heightens the analogy with other plasma sheets although many authors prefer to use the term "streamer belt" for the plasma surrounding the HCS.

In a recent study, *Wang et al.* [2000a] compared observations of the streamer belt made by the Solar and Heliospheric Observatory (SOHO) Large-Angle and Spectrometric Coronograph (LASCO) with a model in which the visible radiation is caused by Thomson scattering from electrons in a very narrow layer centered on the source surface neutral line (see below). They conclude that the streamer belt is simply the tilted and warped HPS seen in projection. A model of the origin of the plasma sheet is discussed by *Wang et al.* [1998].

Many research workers also identify the HCS as simply an extension of the streamer belt. However, such an association depends on details which are not yet understood. Where do the open field lines in and near the current sheet originate? Do they originate above and below the streamer belt, or within streamers? The relation of the streamer belt to the HCS is an important issue deserving of further study.

The HCS is also closely associated with slow solar wind. One of the most successful three-dimensional models of the solar wind is the "tilted dipole" model, which, at its solar origin, has the current sheet at the center of a low-latitude band of slow wind with fast solar wind at higher latitudes in the north and south hemispheres [*Pizzo*, 1991]. This simple model has successfully reproduced several important aspects of corotating interaction regions, especially three-dimensional effects associated with the tilted interfaces that develop where fast wind overtakes slow wind. As the solar wind is speeded up ahead of the interface and slowed down behind it, the HCS is deformed and no longer lies at the center of the band of slow wind. In addition, the model predicts the development of folds in the HCS at midlatitudes that take on the appearance of a breaking wave [*Pizzo*, 1994].

An early effort to explain the sector structure involved Earth-based observation of the Sun "as a star," i.e., measurements of the solar magnetic field at very low resolution, in effect, averaging over much of the solar disk [*Scherrer et al.*, 1977]. It was found that such measurements led to quasi-sinusoidal variations in the observed magnetic field polarity that correlated reasonably well with the polarities measured in space. A further attempt to account for the sector structure involved the development of models of the HMF based on the concept of a solar magnetic "source surface" [*Altschuler and Newkirk*, 1969; *Schatten et al.*, 1969]. The basic objective of these models was to derive the sector structure as observed by in-ecliptic spacecraft from the Sun's photospheric magnetic field as observed by Earth-based magnetographs. The basic approach involved extrapolation of the photospheric fields to an outer spherical surface at which a boundary condition was imposed requiring that the field outside this surface be radial (Figure 7). These models are magnetostatic and assume the absence of currents in the coronal shell between the two boundaries so that the field can be characterized by a scalar potential. The distance to the outer source surface was adjusted to give good agreement with the magnetic sector obser-

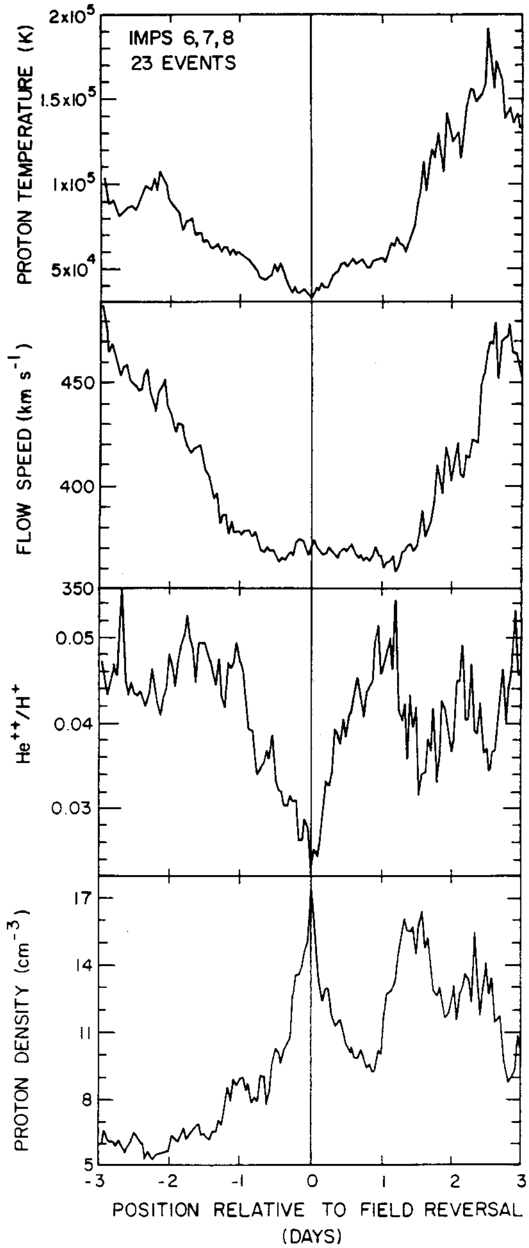

Figure 5. Solar wind properties in the vicinity of the HCS. This superposed epoch plot uses the reversal at the HCS as the "key" day, or day zero. Four solar wind parameters are plotted from top to bottom. At the current sheet the proton density is high while the speed, proton temperature, and helium-to-proton ratio are low. From *Borrini et al.* [1981].

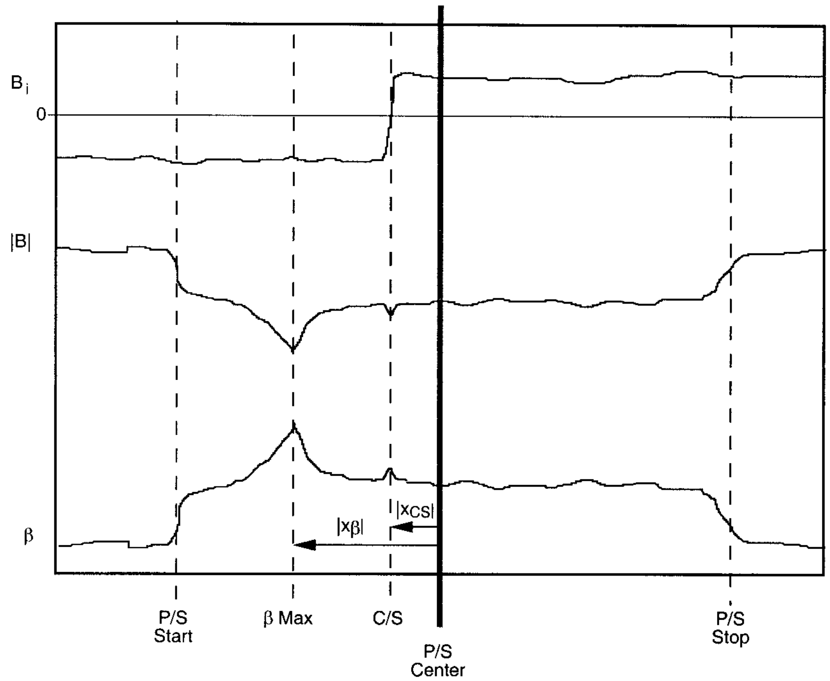

Figure 6. Heliospheric plasma sheet: magnetic field and plasma beta. This sketch shows the variation in three parameters surrounding the HCS (identified as the vertical line marked C/S). The top curve is the field component along the principal direction corresponding to the maximum variance and shows the field reversal at the current sheet. The middle curve is the total field magnitude. The bottom curve is the plasma β (the plasma pressure divided by the magnetic pressure). The dashed lines outline the HPS, which is seen as a region of reduced B and enhanced β. The current sheet does not coincide with the minimum in B, a common occurrence, nor with the center of the HPS (also indicated by a vertical bar). The increase in β which often begins and ends relatively abruptly, can be used to identify the HPS. From *Winterhalter et al.* [1994].

vations. A location of the source surface at 2.5 solar radii appears to be preferred.

The essential feature of the source surface is the presence of a "source surface neutral line" (SSNL) or contour which separates outward from inward fields, along which the radial field vanishes (Figure 8). The location and shape of this neutral line account for the sector structure and are the principal success of source surface models. When the nature of the sector boundary was established, this neutral line was identified with the HCS. The inherent three-dimensional nature of the models provides a representation of the HCS in space. Useful information, such as the inclination of the neutral line/HCS, can then be obtained.

In spite of their successes the source surface models are known to have limitations whose significance depends on how the results are used. Ulysses measurements of the radial field component have been shown to be independent of latitude [*Smith and Balogh*, 1995]. The obvious interpretation is that the strong polar cap magnetic fields are forcing the solar wind equatorward until the magnetic flux is uniformly distributed and equilibrium is established [*Smith and Balogh*, 1995; *Suess and Smith*, 1996]. (Such forcing can also be viewed as arising from the interaction of the field with currents produced in the source region of the solar wind.) Once flux equilibrium is established, the radial field component is independent of latitude, and there are no distributed currents in the solar wind, only the HCS (apart from the radial currents implied by the spiraling of the field caused by the solar rotation [e.g., *Smith et al.*, 1978]). This application of the VB paradigm is obviously quite different than solving an electromagnetic boundary value problem, such as is done in source surface modeling, in which currents distributed along a spherical surface are responsible for the field changes both inside and outside it.

The source surface models, on the other hand, ignore the superradial expansion of the field and solar wind and lead to radial field strengths that vary with latitude rather than being constant. In addition to the currents representing the source surface the nonuniform radial field requires volume currents outside the source surface in the solar wind which are not present. An alternative view of the limitations of the source surface models, expressed in terms of currents rather than the VB paradigm, is presented by *Wang and Sheeley* [1995].

The magnetic stresses in the solar wind source region affect the shape of the HCS, in particular, its extension in latitude. Although the source surface models yield inclinations of the SSNL that agree with in-ecliptic measurements [*Burton et al.*, 1994], observations above the ecliptic by various spacecraft have shown that the maximum latitude of the HCS is typically overestimated by the SSNL. This problem can be alleviated by applying the radial field boundary condition in the photosphere [*Wang and Sheeley*, 1992].

The models also lead to an inadequate representation of the fields adjacent to the HCS. Although the models produce a line contour for the neutral sheet, the field strength increases gradually above and below it, implying a relatively thick current distributed over the source surface rather than a thin current sheet [*Wolfson*, 1985]. Observations in the vicinity of the HCS show that the radial field changes abruptly from one side to the other and is commonly equal on the two sides [*Burton et al.*, 1996].

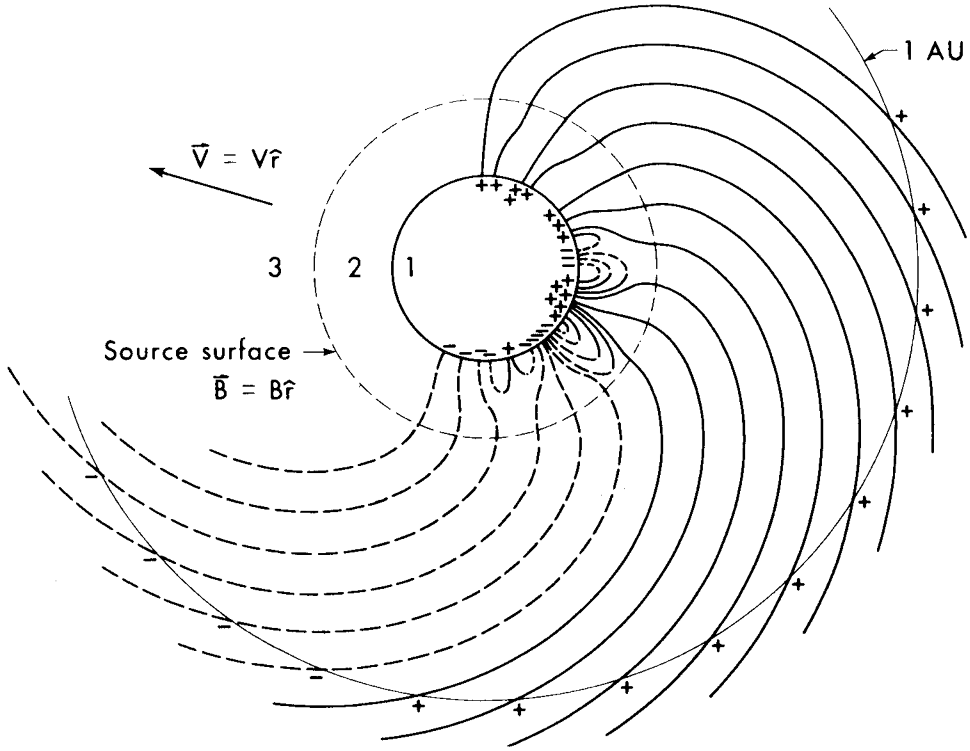

Figure 7. Schematic of the solar wind magnetic field source surface. The photospheric magnetic field, routinely observed by ground-based magnetographs, is extrapolated upward using a magnetic potential to the "source surface" at which the field is required to become radial. The differing magnetic polarities along the photosphere associated with both low- and high-latitude fields are indicated. Only the largest-scale fields reach the source surface. Both positive and negative fields are shown. From *Schatten* [1972].

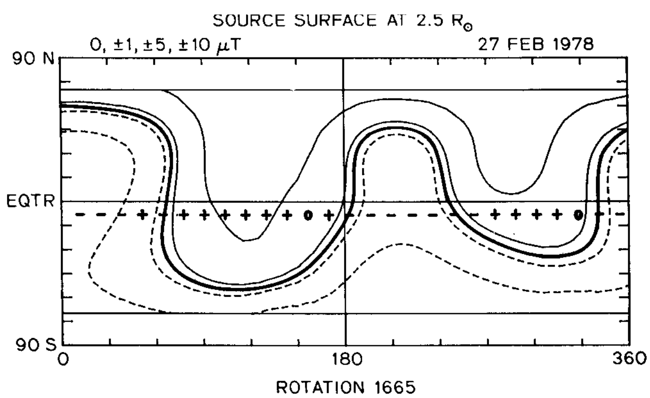

Figure 8. Example of the source surface field. Magnetograph observations obtained over a solar rotation are subjected to a potential field analysis, the magnetic field along the source surface is derived, and a synoptic map is prepared, of which this figure is an example. The dashed lines display negative (predominantly southern) fields, and the thin solid lines represent positive (predominantly northern) fields. The contours identify fields of specific strengths. The heavy contour surrounded by unshaded area is the neutral line along which the field strength is zero. It is a surrogate for the HCS. The neutral line is used to obtain a measure of the HCS inclination, which is simply defined as the difference in the maximum latitudes of the SSNL in the north and south hemispheres. From 1986 magnetograph data and source surface diagrams published by J. T. Hoeksema in Solar Geophysical Reports and available on line from the Wilcox Solar Observatory at http://quake.stanford.edu/~wso/Polar.ascii).

6. Coronal Mass Ejections and the Heliospheric Current Sheet

During minimum solar conditions, coronal mass ejections (CMEs), which originate in closed field regions, tend to occur in or near the streamer belt. Under those circumstances there is a close connection between CMEs and the HCS [*Hundhausen*, 1993]. Near solar maximum, streamers occur all over the Sun, and the connection between CMEs and the HCS is not obvious.

In view of the large number of CMEs occurring when solar activity is high, it might be supposed that the sector structure, and the current sheet, would become disrupted. In fact, the sector structure is very persistent (Figure 9) and only changes slowly even near sunspot maximum [*Smith et al.*, 1986]. However, further study was required to establish the presence of a global current sheet during solar maximum [*Hundhausen*, 1992]. Histograms of hourly averaged azimuth angles between 1978 and 1982 showed that the Parker spiral was maintained throughout solar maximum [*Zhao and Hoeksema*, 1996]. This study also revealed a continuing correspondence between the SSNL and the current sheet crossings observed by ISEE 3. The effect of CMEs on the spiral structure and on the HCS was also examined directly. The results suggested that the coronal streamer belt was disrupted locally by a CME but reformed near the previous location of the helmet streamer in a time that was short compared to the duration of the HCS. Thus the HCS is maintained near solar maximum even when CMEs are occurring frequently.

Figure 9. Sector structure before, during, and after solar maximum. A customary display of sector structure, in which two pound signs signify positive polarity on a given day while a pair of negative signs indicate a negative polarity. Blank spaces indicate missing data or days when the sector structure could not be determined. The column on the left is obtained from data taken at 1 AU by IMP 8 and ISEE 3 from 1973 to 1982. The column on the right shows sectors identified in Pioneer 11 data. The year numbers are given in left and right columns outside the sectors. The second column on the left shows the numbers of the Bartels rotations (BR) that begin each year. The column to the right of the Pioneer sectors shows the latitude of the spacecraft. The latitude was changing as Pioneer approached a rendezvous with Saturn in 1979. Solar maximum occurred in the center of both plots. Two features are noteworthy. There is general agreement between the sectors at the two locations in spite of Pioneer being near 10 AU at this time. Neither pattern shows a significant disruption in spite of large numbers of CMEs being emitted by the Sun. From *Smith et al*. [1986]. (Reprinted with kind permission from Kluwer Academic Publishers. Copyright © 1986 by Kluwer Academic Publishers.)

Evidently, the sector structure continues to represent the largest-scale structure of the solar field and is dominated by the equatorial dipole component. In spite of the relatively large number of solar transients the solar wind and HMF still originate predominantly in open field regions at midlatitudes or low latitudes. Such regions can persist for several solar rotations, so that their contribution is significantly larger than whatever magnetic flux the CMEs may contribute.

The solar features associated with the coronal holes and open field regions are unipolar magnetic regions (UMRs) which appear on the source surface and can be traced back to the photosphere. At low latitudes they are the remnants of sunspot magnetic fields which spread out while drifting gradually poleward. They are present throughout the solar cycle. During the declining phase and minimum, UMRs are evident as the large polar cap coronal holes. During the ascent phase, UMRs from the trailing sunspots in each hemisphere are thought to travel to high latitudes and erode the polar cap fields, which have the opposite magnetic polarity, causing their disappearance and eventual reversal. A multiplicity of UMRs are present at the solar surface throughout solar maximum.

The dynamics of the interaction between the HCS and CMEs has also been the subject of ongoing investigation. In the absence of the HCS it is expected that the CME, having a limited longitudinal extent, would simply displace the HMF, causing it to drape around the CME and close behind it. Several cases have been identified in which the fields behind the CME tend to be radial, as predicted by such a model [*McComas et al.*, 1988]. In fact, the magnetic stress exerted on the CME by the draped fields appears to cause a deflection of the CME in longitude or azimuth which is large enough to be detected in plasma measurements. When the HCS lies in the path of a CME, it might be supposed that it would be deflected sideways. If the CME can travel directly along the HCS, the fields normally adjacent to the current sheet could be pushed apart to lie on opposite sides of the CME, in which case the HCS would effectively be disrupted locally. Multiple spacecraft observations at proper locations relative to the CME are required to sort these possibilities out. It seems certain that whatever the interaction, the current sheet cannot penetrate inside the CMEs, which have their own unique magnetic topology.

7. Fine Structure of the HCS

The transit of the HCS across a spacecraft can vary between a few seconds to a few hours although rapid crossings in a few minutes are more common. At least some of the differences are due to the local inclination of the HCS, which leads to a slantwise path through the current sheet. As a result, it is essential to know the orientation of the current sheet locally. It is customary to assume a plane current sheet and to subject high–time resolution magnetic field measurements to a minimum variance analysis. This analysis determines the direction of the minimum magnetic field variation, which is taken to be the desired normal. When combined with the measured speed of the solar wind, the current sheet thickness can be derived. Statistical studies reveal that at 1 AU the current sheet is typically ~10,000 km wide. The width of the surrounding plasma sheet/HPS is ~320,000 km, or a factor of 30 larger [*Winterhalter et al.*, 1994]. The width of the HCS increases with heliocentric distance and is approximately proportional to distance.

The results of the variance analysis have other uses. The direction of the normal provides a measure of the local inclination of the current sheet. Good agreement is found between the HCS normals and the directions predicted for the SSNL by source surface models, especially when transients are avoided [*Burton et al.*, 1994]. The tilting of the normals also tends to be transverse to the average spiral field direction as would be anticipated.

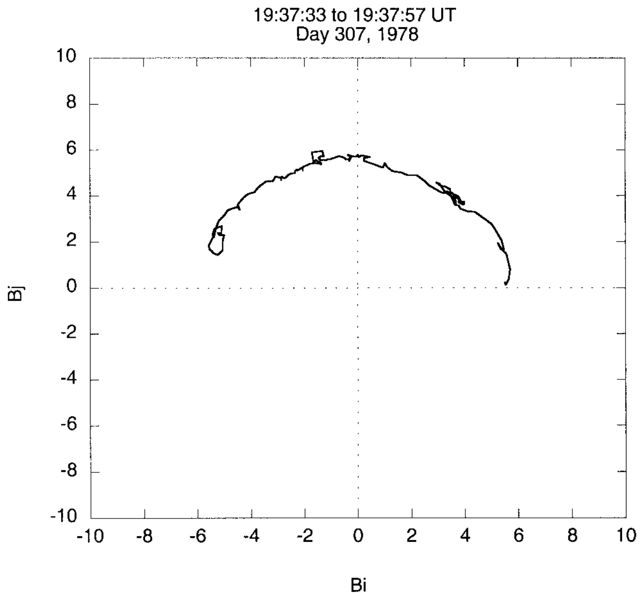

Figure 10. Change in the magnetic field as the HCS is crossed. This figure is typical of large numbers of examples in which the vector fields above, within, and below the HCS are subjected to a minimum variance analysis, the principal directions are determined, and the data are transformed into principal axis coordinates. In this figure, the field is shown in the principal plane formed by the directions (eigenvectors) of the two largest variances (eigenvalues). The field begins on the left side and rotates through ≈180° in a clockwise sense. This behavior is typical of the change in field and implies a rotation of the current streamlines as well as of the field. A simple decrease in field strength with the field direction remaining constant is rare. From M. E. Burton (unpublished manuscript, 1990).

The three directions given by the eigenvectors obtained from the variance analysis constitute the principal axes and provide the natural coordinate system in which to examine how the magnetic field changes during the crossing. This application is basically the same as that which has proven highly successful in studies of interplanetary/heliospheric discontinuities.

The simplest concept of a current sheet is that the field is unidirectional and decreases monotonically to zero and then reappears with the opposite sign. This behavior is a special case of a tangential discontinuity (TD), in which the decreased magnetic pressure inside the current sheet is compensated by an increase in plasma pressure (density and/or temperature). However, such behavior is rarely, if ever, seen at HCS crossings. It is typical of the field to rotate from one side to the other while more or less preserving magnitude (Figure 10). This property is reminiscent of a rotational discontinuity (RD), in which the plasma properties are the same on both sides, with correlated changes in magnetic field direction and plasma velocity. However, tangential discontinuities do not exclude rotated (or sheared) fields, so this aspect of the current sheet structure is common to both types of discontinuities, rendering an identification on this basis ambiguous. An essential distinction is whether or not there is a component of the magnetic field along the current sheet normal. (A rotational discontinuity has helicity as an essential property. That makes an RD like the handrail of a spiral staircase, whereas TDs are like the steps.)

The existence of a normal component is also important as an indicator of possible reconnection or magnetic merging across the current sheet. In a simple two-dimensional (2-D) model the field would cross the current sheet and have a component along the direction of the normal. In 3-D, however, the fields adjacent to the current sheet can be skewed relative to one another, so that the component in the current sheet could be slanted with respect to the normal and, although the field inside the current might be reasonably large, the normal component could still be small. These limitations need to be considered when analyzing the data in principal axis coordinates to determine whether a normal component is present or not. Depending on the field variability near and inside the current sheet, there is a limit to how small a normal component can be detected reliably. There is always a class of crossings that must be categorized as ambiguous.

These comments are offered because of the potential importance of reconnection. Many theorists expect reconnection to occur at current sheets. However, very few, if any, cases of reconnection have actually been documented, especially in magnetic field data. Studies of the normal field have generally led to very small components consistent with a null result (Figure 11).

Potential reconnection sites have been identified as places in the current sheet where the solar wind heat flux experiences "dropouts" [*McComas et al.*, 1989]. A large electron heat flux is indicative of connection to a source of hot electrons, usually presumed to be the solar corona. A dropout could then indicate the absence of such a magnetic connection when neither end of the field line is attached to the Sun. A problem in accepting such an argument is that there are other interpretations of the dropouts [*Fitzenreiter and Ogilvie*, 1992; *Crooker et al.*, 1996].

Another approach has been to examine the HCS and sector structure at large distances from the Sun using Pioneer 10/11 and Voyager observations. The very weak fields and the continued presence of field variations on all scales (and the presence of data gaps caused by the lack of spacecraft tracking) can make assigning a magnetic polarity on any given day very difficult. The usual sector plots end up with a large number of ambiguous or uncertain identifications, which have occasionally been interpreted as evidence that the HCS is becoming "tattered," presumably as a result of patchy reconnection. However, when the measured spiral angles are assembled into distribution functions (histograms) over a solar rotation or longer, their shapes compare favorably with those obtained in the inner heliosphere. In particular, there is no evidence of any "filling in" of the valleys between the two peaks corresponding to the inward and outward polarities. Thus there is little indication of any fundamental change in the HCS with distance that might be attributed to "tearing" or field merging. Since a basic feature of the HCS is the gradual rotation of the field through the current sheet, there are actually no adjacent fields that are opposite or nearly opposite in direction. This behavior may preclude reconnection.

Irrespective of the presence or absence of a steady component perpendicular to the current sheet, the field rotation at constant magnitude is easily simulated mathematically. The two components in the current sheet have equal magnitudes but are out of phase by 90°. The current, derived from curl **B**, is parallel to the field and rotates along with it. Since **J** × **B** is then zero, the configuration corresponds to a force-free field. (The constant magnitude without curvature or twisting also implies the absence of stress.) There are no oppositely directed adjacent fields to reconnect.

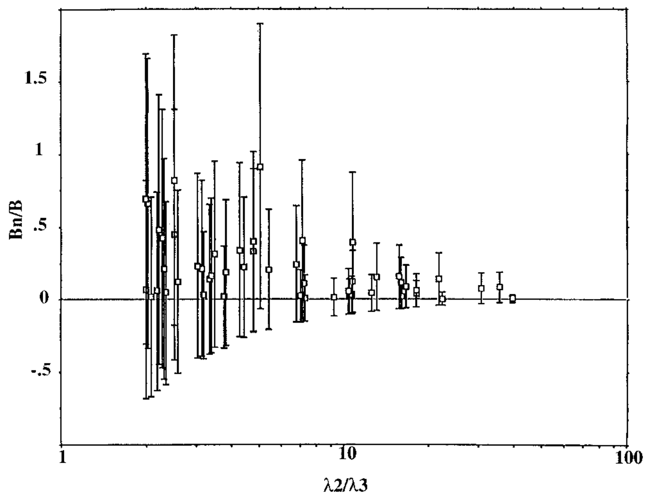

Figure 11. Component of the magnetic field perpendicular to the HCS. This figure is the result of minimum variance analyses of numerous current sheet crossings. The field component along the minimum variance direction, identified with the current sheet normal, is determined and divided by the average field magnitude for each case. The ratio is plotted as a function of the ratio of the intermediate eigenvalue λ_2 to the smallest eigenvalue λ_3. The error bars were obtained from the formulation developed by B. Sonnerup. They are largest, as expected, for small eigenvalue ratios and decrease as the ratio increases. The definition causes all values of the normal component to be ≥ 0, so no significance should be attached to all the values, represented by squares, lying on or above zero. The important point is that the error bars for all the values of B_N/B include zero. There is no statistically meaningful normal component associated with any of the crossings. From M. E. Burton (unpublished manuscript, 1990).

A curious detail of many current sheet crossings can be seen when the field is projected into the principal plane defined by the eigenvectors corresponding to the two largest eigenvalues (the intermediate and maximum variances) to produce a hodogram. In addition to rotating from the above orientation to the below orientation, the endpoint of the field traces out an "S-shaped" curve so that the field is actually not constant during the rotation (Figure 12).

The S-shaped variations in the field magnitude parallel to the current sheet imply the presence of magnetic stresses. In a steady state configuration these stresses are compensated by out-of-phase changes in plasma pressure, whose profile is also S-shaped. Since the plasma pressure is higher on one side of the midplane than on the other, an asymmetry is present. This asymmetry may be the cause, rather than the effect, of the S-shaped field.

Alternatively, a feature like this has often been reproduced in simulations of rotational discontinuities [*Lee et al.*, 1989; *Goodrich and Cargill*, 1991; *Omidi*, 1992]. Since the RD is basically a large-amplitude Alfven wave, the appearance of the "S" has been attributed to the effect of dispersion. The abrupt discontinuity then broadens into a front of finite thickness. The problem in applying this possible interpretation to the HCS is a matter of scale. Alfven waves are nondispersive except for frequency or spatial scales in the vicinity of the proton gyrofrequency or, alternatively, the gyroradius. The scales associated with the HCS and the S-shaped change are many gyroradii, and it is not evident that finite gyroradii effects can be invoked.

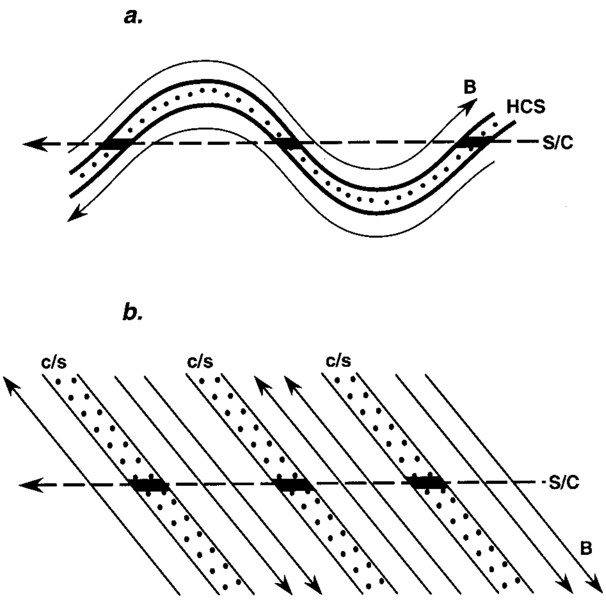

Figure 13. Diagram of alternative interpretations of multiple HCS crossings. (a) The observing spacecraft shown as passing through a wavy HCS (dotted region). (b) A series of current sheets (aligned parallel to one another for simplicity) being penetrated successively by a spacecraft.

8. Scientific Questions

A series of questions are related to the properties of the HCS during solar maximum. Source surface models characteristically predict that the HCS is nearly vertical near sunspot maximum [*Hoeksema*, 1992]. The SSNL typically passes between low-latitude coronal holes having opposite polarities. Occasionally, unipolar regions develop that are surrounded by a more or less circular neutral contour. They could represent a "tube-like" current sheet detached from the main HCS; that is, multiple current sheets may be present. A general question is the following: How faithfully do the source surface models describe the HCS at high latitudes near solar maximum? With the Ulysses spacecraft now en route to the solar poles during the current solar maximum, the answer may soon be known.

A long-standing issue has been the nature of multiple crossings of the HCS. It is common to observe several HCS crossings within minutes, hours, or days. The earliest interpretation was that multiple crossings were caused by "warps" on the current sheet, associated with structure of the solar field, or propagating along the HCS as waves (Figure 13a). A possible origin for such waves would be velocity shears, i.e., differences in speed or direction of solar wind flow along the current sheet boundary. Large enough shears, e.g., with speed differences exceeding the Alfven speed, are expected to be unstable and to lead to the growth of waves traveling along the surface. There are other instabilities that could lead to the production of surface waves. In addition, fast-slow stream interactions can deform the shape of the HCS locally.

An alternative explanation is that the multiple crossings represent spatial structure internal to the current sheet (Figure 13b). Since the HCS is thought to originate in or near coronal streamers, complex streamer or magnetic arcade structure could be reflected in the current sheet structure. One example that has been provided is the presence at the Sun of multiple magnetic loops located side by side [*Crooker et al.*, 1993]. If these loops are stretched out into space to become the HCS at larger distances, the sign of the magnetic field could reverse several times when the HCS was crossed, reproducing the appearance of multiple crossings of a single current sheet.

Either or both of these circumstances are possible. If both occur, the question then arises as to what the relative rates of occurrence are. Although the questions related to multiple crossings have been known for many years, progress in answering them has been slow. The separation of spatial from temporal variations is no easy matter and is very unlikely with observations made at a single point or by a single spacecraft. Even observations by multiple spacecraft may not provide a definitive answer. The measurements may be made at different locations, and information about the scale over which variations can occur over the current sheet is still uncertain. A careful study of HCS structure and variability using two or more nearby spacecraft has yet to be carried out.

The recent discovery and confirmation that the HCS may be displaced from the solar equator by as much as 10° (Figure 14) raises a host of questions. The north-south asymmetry associated with the HCS displacement was discovered in galactic

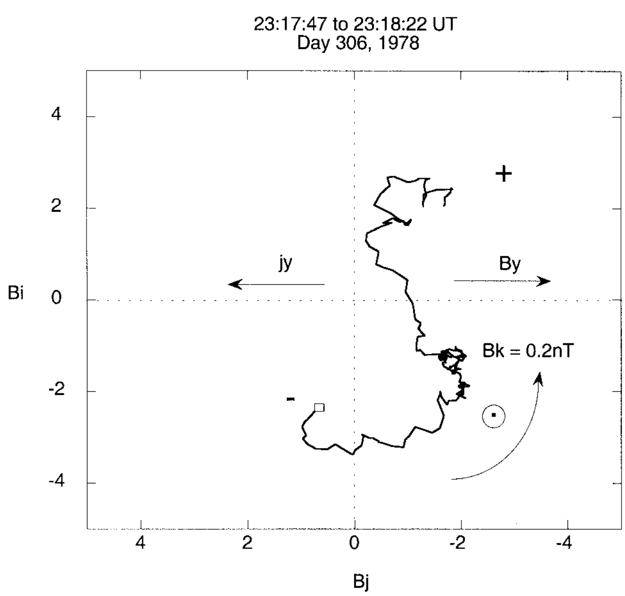

Figure 12. Example of an S-shaped field rotation across the HCS. This display is also in the principal plane perpendicular to the minimum variance or normal direction. It is common to see the rotation, which is counterclockwise in this case, depart from a circle to follow a contour shaped like the letter S. The same feature can be seen in many simulations of rotational discontinuities. From M. E. Burton (unpublished manuscript, 1990).

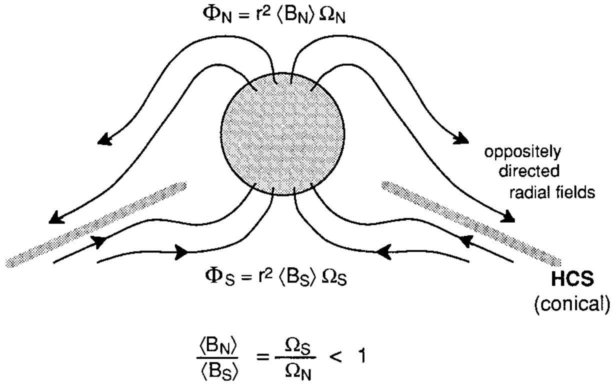

Figure 14. Diagram of the offset or asymmetric HCS. The Sun is shown with the current sheet extending downward (southward) all around the Sun in the form of a cone or skirt. The HCS (shaded linear regions) and the magnetic fields at large distances are radial. The formulas relate the magnetic flux from the north and south poles Φ to the radial field components B_N and B_S and to the solid angles Ω north and south of the HCS. If the flux is the same, the radial field components must differ in the two magnetic sectors, and for a southward displacement of the HCS as shown here and as observed by Ulysses, B_N is ~30% smaller. Although the magnetic and rotation axes are shown here as aligned for simplicity, the HCS could be higher on one side and lower on the other without changing the model significantly. From *Smith et al.* [2000].

cosmic ray observations on Ulysses as the spacecraft transited between ±80° latitude [*Simpson et al.*, 1996; *Heber et al.*, 1996]. It was evident as a difference in particle intensities in the two hemispheres. The asymmetry was also seen in Ulysses measurements of anomalous cosmic rays [*Trattner et al.*, 1997]. An associated asymmetry in the SSNL was noted, and the offset of the HCS was confirmed by simultaneous magnetic measurements made in the ecliptic by the Wind spacecraft [*Smith et al.*, 2000]. The discernable effect on the cosmic rays shows that the HCS asymmetry can have important consequences for the global topology of the heliosphere. A number of issues need to be addressed, and such an symmetry needs to be incorporated into available solar wind and heliospheric models in order to explore the consequences. Why is the HCS displaced? Is it simply the result of an axial displacement of the Sun's magnetic dipole (equivalent to the development of a strong quadrupole) as suggested by *Wang* [1996] and *Smith et al.* [2000]? What influence do the north and south polar coronal holes have? What are the consequences for the solar wind? How often does this configuration arise? Is it favored during one of the phases of the solar cycle?

An area of research that is receiving increased attention involves questions relating to the interaction between the HCS and CMEs or magnetic clouds [*Crooker et al.*, 1998]. Some of the key issues involved were mentioned in section 6. Advances in understanding can be expected during the current solar maximum when a network of heliospheric and interplanetary spacecraft (SOHO, ACE, Wind, Ulysses, and Cassini) will be making simultaneous observations while the rate of occurrence of CMEs is peaking.

9. Epilog

For an "object" that might be considered of secondary importance, the heliospheric current sheet has proven to be of enduring scientific interest and has stimulated a considerable body of research. If the past is indicative of the future, the HCS will continue to provide novel observations and raise significant scientific questions. A particularly fruitful approach in the future would appear to be multispacecraft observations capable of revealing HCS structure and dynamics on a variety of spatial and temporal scales.

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E. J. Smith, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 169-506, Pasadena, CA 91109-8099. (esmith@jplsp.jpl.nasa.gov)

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