A New View of the Coupling of the Sun and the Heliosphere

Thomas H. Zurbuchen

Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, Michigan 48109-2143; email: thomasz@umich.edu

Key Words
magnetic convection, magnetic fields, magnetic field emergence, reconnection, solar winds, stellar winds

Abstract
The structure of the global heliospheric field reflects the physical properties of the low corona. The implied connections between solar and heliospheric evolution have been analyzed by a powerful multisatellite solar and heliospheric observatory that includes the Ulysses and the Solar and Heliospheric Observatory (SOHO) spacecraft. This coordinated investigation yielded unprecedented observational opportunities. Some of these results confirmed predictions by models based on time-stationary conditions of the corona at its lowest energy state. However, there are results that exhibit important contradictions to these models, and limit their applicability, pointing to the importance of photospheric dynamics and small-scale field emergence for the structure of the heliospheric field. The interpretation of these data provides challenges to our understanding of the physics of the energy transport from the convective layers of the Sun into the heliosphere and motivates new theoretical approaches to the evolution of the heliospheric field.
1. INTRODUCTION

The physical processes dominating the extended solar atmosphere are crucial to our understanding of many astrophysical phenomena. Advances in our understanding of the solar magnetic field and its plasma and particle energization processes therefore have crucial implications for our understanding of other stellar environments, accretion disks, and energetic phenomena such as jets and transient electromagnetic emissions.

1.1. The Scientific Challenge

The heliosphere (Figure 1) is a teardrop-shaped bubble in interstellar space that extends from the Sun to beyond 100 times the Sun-Earth distance (1 AU). It is inflated by the solar wind and threaded by magnetic fields that drive the electromagnetic environment of Earth and all the planets. The heliospheric magnetic field extends away from the solar atmosphere, carried by the solar wind, to the magnetic interfaces of our Galactic neighborhood. The closer we get to the outer boundary of the heliosphere, the more it is dynamically affected by the Galactic environment. For example, beyond

**Figure 1**

Artistic view of the heliosphere. Bounded by the solar atmosphere, the corona, and the local interstellar environment, the heliosphere includes the magnetic field, which is determined by the solar atmosphere and the physical processes therein.
10 AU, shocks and solar wind turbulence are strongly influenced by interstellar neutral atoms that originate in our Galactic neighborhood and become charged either via charge exchange with solar wind ions or via UV ionization (Gloeckler 1996, Gloeckler & Geiss 1996, Smith et al. 2006). However, events in the heliosphere inside Jupiter’s orbit, including Earth’s space environment, are dominated by the inner heliospheric boundary, the solar atmosphere, which is at the center of this review.

The interaction between the Sun and its heliosphere provides a benchmark for our understanding of interactions of stars with convective outer layers and their respective stellar spheres. The source of energy for the heliosphere and the corona is the mass motion in the solar convection region where turbulence stresses the magnetic field. These stressed and tangled field lines eventually emerge onto the solar surface and release their energy into the corona. The process of energy transfer and release is highly nonthermal, owing to the magnetic coupling, leading to temperatures much higher than are found at the solar surface itself. Much of the magnetic energy is stored in closed magnetic structures of different sizes. But, owing to the high coronal temperature, solar plasma becomes energized and can escape the Sun’s gravitational field and pull the solar magnetic field into the heliosphere. This portion of the solar magnetic field is commonly referred to as open flux, because it closes at distances of hundreds of astronomical units from the Sun.

The heliosphere and its magnetic field should therefore be understood as the transformation of solar convective energy into a flow field of energized and magnetized plasma. The energy transferred into the corona and its subsequent release is often localized in space and time in spite of the fact that, owing to the large Alfvén speed (∼1000 km s⁻¹), the corona can easily adjust to photospheric forcing that occurs with speeds less than 1 km s⁻¹. The coronal field therefore stores energy through a series of quasi-stationary states, but can explosively change, releasing a large amount of electromagnetic energy and ejecting plasma and the magnetic field into the heliosphere. When the Sun is observed at higher resolution, the abundance of such abrupt energy release processes becomes even more apparent.

Magnetic field emergence occurs through two channels at very different spatial scales. Sunspots and their related active regions have sizes of more than 100,000 km. Their occurrence rate varies dramatically over time, from solar minimum, where there are very few active regions, to solar maximum, when the sunspot number is almost 100 times larger. There is a second process of field emergence that occurs ubiquitously over the entire solar surface at much smaller spatial scales of less than 20,000 km. This small-scale process occurs during all parts of the solar cycle and, with regard to the total emerging flux, actually dominates active regions. In our quest to understand the global heliospheric magnetic field we must therefore understand the roles of both of these field emergence processes—through localized active regions, or through ubiquitous small-scale emergence—for the structure and evolution of this field and its associated solar wind.

It is the purpose of this paper to discuss the results of the Ulysses mission that, as part of a distributed solar-heliospheric observatory, has performed humanity’s first excursion into the polar regions of the heliosphere and hence enabled this global view of the Sun-heliosphere system. Prior to the Ulysses mission, our views were derived
Coronal mass ejection (CME): an explosive ejection of plasma and field from the solar corona, often related to a magnetic restructuring of the corona

Heliospheric current sheet: a global current layer that separates adjacent interplanetary magnetic field with opposite magnetic polarity

primarily from in-ecliptic measurements. This review focuses on the many surprises from *Ulysses* and the theoretical approaches to the solar-heliospheric energy transfer motivated by these data.

### 1.2. History

Our understanding of the heliosphere and its magnetic field has evolved during the past 50 years or so, from the recognition of the existence of a continuous solar wind, based on pioneering interpretations of cometary observations (Biermann 1951, 1957); to the development of the theory of the supersonic solar wind and the embedded heliospheric magnetic field (Parker 1958); to our present theories of open and closed flux, coronal mass ejections (CMEs), and the flip-flopping of the heliospheric current sheets.

Parker pointed out that owing to the high temperature of the solar atmosphere, and its resulting large electric conductivity, magnetic fields and plasma velocity fields are intimately linked. He suggested that the structure of the heliospheric field should primarily be dominated by two important velocity fields. First, the solar wind propagates nearly radially away from the Sun. Second, the Sun rotates during the expansion of the solar wind, and with it rotate the sources of the heliospheric magnetic field.

Based on these considerations, Parker predicted a spiral configuration for the heliospheric field in the equatorial plane of the Sun (Earth's orbital plane, the ecliptic, is tilted \(\sim 7^\circ\) to the equatorial plane). His 1958 theory did not specifically predict the polarity of the magnetic field, but it focused on the evolution of the solar magnetic field as it is carried into the depths of the heliosphere by the solar wind. All of Parker's key predictions were successfully confirmed within 10 years of his pioneering work (Neugebauer & Snyder 1962, Ness et al. 1964, Snyder & Neugebauer 1964; for historic summaries, refer to Parker 2000, 2001).

The polarity of the heliospheric field was first predicted based on the simplest physical model of our magnetic corona, a potential field model (Schatten, Wilcox & Ness 1969). In such models the coronal field can be described as a Sun of spherical harmonics, and hence at large distances only the first few terms matter. These models were very successful at predicting the polarity of the field in the ecliptic based on photospheric magnetic field measurements (Rosenberg & Coleman 1969; Hundhausen 1977; Smith, Tsurutani & Rosenberg 1978). The review by Svalgaard & Wilcox (1978) focused on the many successes of these potential field models. This review should be considered a follow up to that review by comparing those first models to more recent efforts.

The year 1978 is significant for another reason tightly coupled to this review: That is the year the U.S. Congress began the international space mission that became *Ulysses* (Fisk 2005b).

Together with *Ulysses*, many new observations of the Sun and the heliosphere have provided a global view of the Sun. We now see that the Sun and the corona are a highly dynamic and ever-changing structure. Some of these key solar measurements are briefly summarized below. *Table 1* further provides average properties of the heliosphere to simplify comparisons to other astrophysical plasmas.
Table 1  Key average properties of the solar wind plasma near Earth

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_r = 2.5$ nT</td>
<td>Radial magnetic field</td>
<td>Wang &amp; Neubauer 1990</td>
</tr>
<tr>
<td>$B_\phi = 2.4$ nT</td>
<td>Toroidal magnetic field</td>
<td>Wang &amp; Neubauer 1990</td>
</tr>
<tr>
<td>$B_\theta = 1.5$ nT</td>
<td>Latitudinal magnetic field</td>
<td>Wang &amp; Neubauer 1990</td>
</tr>
<tr>
<td>$V = 600$ km/s</td>
<td>Solar wind speed</td>
<td>McComas et al. 1998</td>
</tr>
<tr>
<td>$\rho = 11 \cdot 10^{-21}$ kg/m³</td>
<td>Solar wind mass density</td>
<td>Schwenn 1990</td>
</tr>
<tr>
<td>$T = 120,000$ K</td>
<td>Solar wind temperature</td>
<td>Schwenn 1990</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Derived Quantity</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_A = 32$ km/s</td>
<td>Alfvén speed</td>
<td></td>
</tr>
<tr>
<td>$C_S = 41$ km/s</td>
<td>Sound speed</td>
<td></td>
</tr>
<tr>
<td>$\beta \sim 1$</td>
<td>Plasma beta</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{mfp} \sim 0.2-0.5$ AU</td>
<td>Mean free path of ion Coulomb collisions</td>
<td>Marsch 1990</td>
</tr>
</tbody>
</table>

*These quantities vary near Earth, and also have systematic variability as a function of distance from the Sun.

1.3. Temporal Variability

The solar atmosphere evolves on many timescales. There is now an enhanced recognition of the fact that the photospheric field is intrinsically time-dependent, driven by the convective motions of the Sun and their impact on the photospheric field (Schrijver et al. 1997). Small-scale magnetic flux emerges ubiquitously from beneath the photosphere at a rate that leads to a replacement of the entire solar flux over a time period of only 15–40 hours (Schrijver et al. 1998, Schrijver 2005). This replacement time may become even shorter as we look at the Sun with better spatial and temporal resolution. There is also a longer timescale in the system observed to be around 11 years, during which both the heliospheric and solar magnetic fields change polarity. The most visible aspect of this restructuring is the sunspot cycle. Sunspots are locations of large, highly localized emergences of magnetic flux, which have the most dramatic consequences. Through a number of coronal interactions, this field emergence results in episodic expulsions of mass and magnetic field from the Sun in events known as CMEs (e.g., Hundhausen 1993, Gopalswamy et al. 2003b). Most theoretical efforts have focused on the surface variability of the Sun, such as that observed through sunspots (Gilman 2000). But few predictions exist about the manner in which the heliosphere, dominated by topologically open fields, participates in this cycle, and how it relates to the field emergence at large and small scales.

As illustrated in Figure 2, the vast majority of the solar field is closed in the corona; a given field line has an arclike topology, with a length that is short compared to the scale of a solar radius. Plasma on such field lines cannot easily escape into the heliosphere. Conversely, open field lines that stretch far out into the heliosphere are notoriously difficult to observe near the Sun. Much of this open heliospheric magnetic flux originates in coronal holes, which appear dark when imaged in X rays or extreme ultraviolet (EUV) owing to the comparatively low density and temperature there. Coronal...
Coronal hole source regions are usually dominated by a single dominant magnetic polarity, even though it also contains an important and time-variable fraction of the other magnetic polarity field. When solar activity is at its minimum, coronal-hole-associated field lines dominate over 70% of the heliosphere. However, at solar maximum, fast solar wind streams from coronal holes only comprise 20–30% of the heliosphere.

There are two other contributors to the heliospheric plasma and field. The first one has already been mentioned above: CMEs are an increasingly important contribution to the heliospheric field and plasma, by up to 15–20% near solar maximum. They affect an even larger fraction of the heliosphere through dynamic interactions that can be detected far away from CMEs (Gosling et al. 1994; Riley, Gosling & Pizzo 1997; Lugaz, Manchester & Gombosi 2005; Manchester & Zurbuchen 2006). Near solar minimum conditions, less than 5% of the heliospheric magnetic field is explosively expelled.
Contributions to the heliospheric plasmas other than from coronal holes are associated with magnetic structures on a spatial scale of a fraction of a solar radius. These structures extend rather statically, and result in so-called streamers (bright loop-like structures in the outer portion of Figure 2). These streamers can be surprisingly stationary and exist for tens of days and sometimes even a hundred days (Gosling et al. 1981, Koutchmy & Livshits 1992, Wang et al. 1998). They give rise to heliospheric plasma that is often highly structured and has a dynamic variability that by far exceeds the variability associated with the fast, coronal-hole-associated wind streams (Schwenn 1990, Gosling 1997). It is not clear how open fields can emerge from this closed magnetic topology. This solar wind either has to originate the streamer boundary, or its emission mechanism is fundamentally transient. This will be discussed below.

Our physical theories connecting the solar and heliospheric fields must pass two critical test cases. First, they need to explain the topological structure of the magnetic field in the three-dimensional heliosphere and how it relates to the large- and small-scale energy flow through the solar surface. Second, they need to explain the transition and evolution of the large-scale field topology throughout a solar cycle. Heliospheric plasma measurements, interpreted in the context of these theories, will have profound implications for our understanding of the cyclic behavior of the Sun and the heliosphere.

Section 2 develops the theoretical framework in which these themes are going to be addressed. Sections 3 through 4 will address the two science themes at the center of this discussion, including their recent observational constraints. Section 5 interprets these observations in the context of our present theoretical understanding of the heliospheric field, and Section 6 provides a summary and short outlook.

2. THEORETICAL APPROACHES

There are a number of solar and heliospheric processes that are responsible for shaping the structure and topology of the heliospheric magnetic field (Figure 3). The most fundamental of them, addressed in Section 1.1, is the emergence of magnetic fields through the convective layers of the Sun and into the photosphere. These emerging fields are embedded in systematic velocity fields such as differential rotation and meridional flow (Sheeley 2005, Schrijver 2005). Driven by convection, a topologically complex field enters the photosphere, where it expands and, owing to the rapid decrease of the gas pressure with altitude in the solar atmosphere, becomes dominant for the structure of the corona. The small magnetic loops that emerge interact with one another and the plasma on these field lines is successively heated as a result of these interactions, turning them into larger and larger loops. Magnetic loops of various sizes can also interact with the open components of the solar flux through a process called interchange reconnection (Crooker, Gosling & Kahler 2002).

Energy loss in the solar atmosphere occurs through multiple channels and is highly dependent on the magnetic topology (see, e.g., Low 1990). Energy can be released through electromagnetic emissions, it can be conducted back into the photosphere,
Figure 3
Schematic representation of the physical processes that shape the heliospheric magnetic field. The magnetic field emerges through the photosphere in small flux elements that interact with each other and with heliospheric field lines, leading to diffusive transport. Similarly, systematic flows, such as the flows caused by differential rotation, can also be projected into the heliosphere. Direct observations of these effects are difficult owing to the dynamic evolution of the heliospheric plasma caused by stream interactions and turbulent effects.

or it can drive the expulsion of plasma out of the solar potential well and into the heliosphere. The dynamic pressure of the accelerating solar wind flow soon dwarfs the magnetic pressure on open field lines and dynamically affects the magnetic field. Some of these dynamic changes are highly organized, but many of these heliospheric interactions are intrinsically random and affect the intrinsic structure of the heliospheric magnetic field through turbulence (see, e.g., Burlaga 1995; Goldstein, Roberts & Matthaeus 1995).

Owing to the high degree of ionization of the corona and the solar wind, and its resulting large conductivity, the physical behavior of the heliospheric magnetic field is well approximated by the ideal magnetohydrodynamic (MHD) equations,

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \]

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \]

\[ \rho \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p - \rho \nabla \Phi. \]

(1)

MHD:
magnetohydrodynamic
Here, $B$, $v$, $\Phi$, $p$, and $\rho$ denote the magnetic field, the flow velocity, the gravitational potential, the pressure, and the mass density, respectively. The ideal MHD equations are completed with an energy equation. Most commonly, the full energy equation is replaced with a simpler polytropic law, such as

$$\frac{dp}{dt} \frac{\rho}{\gamma} = 0,$$

introducing the polytropic coefficient, $\gamma$. Parker’s 1958 article used isothermal assumptions, i.e., $\gamma = 1$, whereas others have assumed an adiabatic expansion, $\gamma = 5/3$. Numerical global MHD models include a volumetric energy source term $S$ (Mikić et al. 1999, Manchester et al. 2004),

$$\frac{dp}{dt} + \nabla (pv) = (\gamma - 1)(S - p \nabla \cdot v).$$

This simplified energy source term attempts to simulate the effects of coronal heating. More sophisticated energy equations have been studied but not yet fully integrated into global heliosphere models (Hansteen & Leer 1995). In such more-complete models the observed nonisotropic pressure terms are correctly modeled. These terms are neglected in Equations 1–3 and the vast majority of models dealing with the large-scale structure of the heliosphere. In these large-scale models, nonideal characteristics of the fluid, as are necessary to enable reconnection, are controlled by the numeric properties of the codes.

The emerging magnetic field in the photosphere has a profound impact on the overall heating of the open and closed corona and its temporal behavior (Aschwanden, Poland & Rabin 2001; Charbonneau 2005). Here, we focus on its effects in the heliosphere, and hence focus our theoretical descriptions on two regimes: the open flux in the inner heliosphere, and the near-solar corona.

### 2.1. Heliospheric Field Models

There is a set of models that can be useful for investigating the heliospheric consequences of solar dynamics effects where the flow speed is much larger than the Alfvén speed $V_A$, or

$$V^2 \gg V_A^2 = \frac{B^2}{\mu_0 \rho}.$$  (4)

For simplicity, we will also assume that the heliospheric magnetic field is carried out by a radially flowing solar wind of speed $V = V_e$. A spatially varying velocity field near the Sun produces stream-stream interactions that become dominant in the outer heliosphere (Pizzo & Gosling 1994). Near the Sun, at a spherical surface with radius $r_s$, the radial component of the magnetic field is assumed to be $B_r$. The azimuthal and poloidal components of the field at $r = r_s$ are determined by motions of field lines, $u_\perp$ (Hollweg & Lee 1989). If there are motions at speeds well below the Alfvén speed, they propagate into the heliosphere and result in a field component normal to...
Figure 4
Solar motions projected into the heliosphere. (a) Parker field configuration, produced by a rigidly rotating Sun. There is no transport in latitude. (b) The Heliospheric field under the assumption of differential rotation into an asymmetric corona. Adapted from Zurbuchen, Schwadron & Fisk 1997. (c) The effect of random, diffusive motions in the heliosphere. Adapted from Jokipii & Kóta 1989.

the radial direction, $B_\perp$, with

$$B_\perp = -\frac{u_\perp}{r} \left( \frac{r}{r_s} \right) B_r$$

and

$$B_r = B_1 \left( \frac{r}{r_s} \right)^2.$$  \hfill (5)

owing to the conservation of magnetic flux. Note, the $B_\perp$ component includes both poloidal and toroidal terms. Also, the equation applies to any field distribution near the Sun, $B_1$. Hence, Equation 5 can be used to compare useful models of the heliospheric field (Figure 4). It is possible to assume that the entire contribution to $u_\perp$ comes from a rigidly rotating Sun with the rotation speed $\Omega$, $u_\perp = \Omega r \sin \theta e_\phi$. Here, $\theta$ is the polar angle (latitude) of a spherical coordinate system and $\phi$ is the azimuth. Under these conditions, we retrieve Parker’s (1958) solution (Figures 4b).

$$B = B_1 \left( \frac{r}{r_s} \right)^2 e_r - B_1 \frac{\Omega r^2 \sin \theta}{V_T} e_\phi.$$  \hfill (6)

If differential motion is to be included, $\Omega = \Omega(\theta)$, but using the same formalism.
The relevant velocity field is a superposition of two rotations, as can be expected in a differentially rotating corona in a nonsymmetric field expansion (Fisk 1996; Zurbuchen, Schwadron & Fisk 1997; Zurbuchen 2001). In this case the velocity field, \( \mathbf{u}_\perp \), can be described as a sum of two velocity fields, one from the rotation of the Sun, \( \Omega \), and the other from the differential rotation \( \omega \approx (\Omega/4) \), about an axis offset from the solar rotation axis. The heliospheric magnetic field reflects these changes through large-scale excursions in latitude (Figure 4a).

Similarly, random coronal motions are also projected into the heliosphere (Jokipii & Parker 1968, Jokipii & Kóta 1989, Giacalone 2001) under certain assumptions regarding the overall properties of these flows. To model this, a divergence-free flow pattern is assumed using an arbitrary generating function, \( \Psi = \Psi(\theta, \phi, t) \), with

\[
\begin{align*}
\mathbf{u}_\perp = & \frac{1}{\sin \theta} \left( \frac{\partial \Psi}{\partial \phi}, \frac{\partial \Psi}{\partial \theta} \right), \\
\mathbf{u}_\perp = & -\mathbf{u}_\perp \times \mathbf{B}.
\end{align*}
\]

For a given choice of \( \Psi \), constrained by solar observations, the velocity field at \( r = r_0 \) can be calculated and, using Equation 5, can be projected into the heliosphere (Figure 4c) using the correct phase relationship, correcting for the solar wind expansion time.

This simple model allows for a discussion of time-dependent effects on the Sun and its consequences for the heliospheric magnetic field. But, it is worth noting that there are important consequences of the solar field expansion that need to be taken into account when relating \( \mathbf{u}_\perp \) to its solar origin in the photosphere (Hollweg & Lee 1989). Furthermore, dynamic interactions in the heliosphere can be added using the process outlined by Pizzo & Gosling (1994).

### 2.2. Quasi-Stationary Coronal Models

Models of the near-solar corona fall into two categories: quasi-stationary models and so-called interchange models. Quasi-stationary models depend on the assumption that the heliospheric field can basically be understood as an approximately time-stationary expansion of magnetic field from the Sun into space (Figure 5) and rely on two approaches. They either assume that the corona is at its minimum energy or they use more complete formulations of the MHD equations (Equations 1–3).

The potential field source surface (PFSS) models, as the first class of models have come to be known, are still much used by the solar and heliospheric community (Wang & Sheeley 1992, Arge et al. 2002, Luhmann et al. 2002, DeRosa & Schrijver 2002). Near real-time PFSS models, with additional empirical elements, are now used for space weather predictions on a daily basis (Wang & Sheeley 1995, Arge & Pizzo 2000). In many ways, these models have therefore evolved into standard models that are used to compare and contrast theoretical approaches.

The PFSS models are characterized as follows: First, the inner boundary is given by a series of remote observations of a single component of the magnetic field observed at the photosphere, at \( r = r_0 \). Establishing this boundary condition is a nontrivial task:
At any given time, we only get useful magnetic field observations within 60° azimuth and we generally have very limited observations of the polar magnetic field (Hoeksema, Wilcox & Scherrer 1982). Second, there is an outer boundary of the corona, the so-called source surface, \( r_s > r_0 \). All field lines that intersect this boundary are radial at \( r = r_s \). Third, the field in the volume bounded by the two spherical surfaces \( r_0 < r < r_s \) is assumed to be current-free (Riley et al. 2006). The magnetic field is then at its lowest energy state and at its simplest geometry (for details, refer to Altschuler & Newkirk 1969; Schatten, Wilcox & Ness 1969).

These models predict a simple extension of the magnetic field from the Sun into the heliosphere. The field-expansion in the corona acts as a low-pass filter, and only the lowest-order multipoles affect the open corona. During solar minimum, the heliosphere is dominated by a single dipole moment (Figure 5a) with a single, almost planar structure. This is known as the heliospheric current sheet, where the polarity of the heliospheric field shifts from being directed away from the Sun to toward the Sun, or vice versa (Figure 5c). Owing to the nonzero curl of the field at this location, and its subsequent expansion into the heliosphere, this current layer extends into the heliosphere as the so-called heliospheric current sheet. During solar maximum conditions, quadrupole and higher-order moments can also become important (Figure 5b), leading to a current sheet that is not well-approximated by a plane (Figure 5d). Note that it is theoretically possible to have multiple current sheets in the heliosphere that are entirely disjointed from each other. Also, the potential assumption prohibits all but one field-line motion, \( \mathbf{u}_\perp \) (Equation 5), the rotation of a rigidly rotating Sun.

There have been a number of mathematical refinements of these models, such as adding the effect of a nonspherical source surface (Schulz, Frazier & Bougher 1978; Schulz 1997), or the effects of current sheets outside the modeling domain (Zhao & Hoeksema 1995). Note that \( r_s \) is effectively a free parameter and different values are used for different purposes. A larger value of \( r_s \) reduces the heliospheric flux and increases the largest dimensions of coronal loops. There is tremendous utility in PFSS models, as demonstrated recently by Antiochos et al. (2007). The topology of open and closed magnetic fields can be discussed in this approximation and strong conjectures about mathematically possible and forbidden configurations can be achieved.

The second approach used to describe the quasi-stationary heliosphere employs a full set of MHD equations. In most cases, modern MHD models solve Equations 1–3 numerically under the assumption of an empirical heating function deduced from

---

**Figure 5**

Solar minimum and maximum corona and heliosphere computed using quasi-stationary models. (a) The quasi-stationary conditions at their lowest magnetic energy state near solar minimum (June 1996) and (b) maximum (November 2000). Colors on the solar surface indicate positive (red) and negative (blue) magnetic fields. (c) The heliospheric current sheet, and (d) the extension of the polarity inversion line on the solar wind source surface. The current sheet persists during the entire solar cycle and stays topologically simple. (e) and (f) show modern magnetohydrodynamic calculations of the same solar conditions as in (a) and (b). Adapted from Riley et al. (2006) and Zurbuchen (2007).
time-averaged conditions, which is used to match some set of solar observations. The inner boundary conditions of the magnetic field are very similar to those used by PFSS models. The vast majority of MHD models of the Sun-heliosphere interface are, like the PFSS models, time-stationary. There are a lot of similarities between the two approaches (Figure 5e and 5f), but some differences are obvious. First, closed magnetic structures are more extended in the MHD solution than in the PFSS model. This extension is caused by kinetic and dynamic pressure terms, because of the gas temperature and flow, respectively, which become important in the outer corona compared with magnetic forces. Similarly, the radial component of the magnetic field, the heliospheric flux density, in the heliosphere is more equilibrated, caused by lateral pressure gradients in the magnetic field. However, the global topology of closed fields is well modeled by PFSS during rather time-stationary conditions (Neugebauer et al. 1998, Linker et al. 1999). Currently, the key limitations to the predictive nature of large-scale MHD models result from our understanding of coronal heating and its dependence on solar observables (Riley et al. 2006, Zurbuchen 2007, Aschwanden et al. 2007).

2.3. Interchange Models

Interchange models of the solar corona and the heliospheric magnetic field are generally motivated by heliospheric observations discussed below (Fisk, Zurbuchen & Schwadron 1999; Fisk 2001, 2005a; Fisk & Schwadron 2001; Fisk & Zurbuchen 2006). These models provide a fundamentally different approach to the description of the heliospheric magnetic field. Instead of the assumption of quasi-stationary conditions, interchange models seek to explain the behavior of open magnetic flux as an intrinsically time-dependent process resulting from a sequence of interactions between topologically open and closed fields (Handy & Schrijver 2001). The open magnetic field on the surface of the Sun, \( B_o \), is then described in a statistical theory as

\[
\frac{\partial B_o}{\partial t} = \nabla^2 (\kappa B_o) - \nabla \cdot (u_{\perp} B_o).
\]

Equation 8 is derived from the induction of Equation 1 using a quasi-linear approximation (for details, refer to appendix A of Fisk & Schwadron 2001). Notice that there is a distinct difference between the mathematical structure of the diffusive term and the structure of regular thermal diffusion. This is further discussed below. There are two transport processes that define the evolution of the open flux \( B_o \). All systematic and uniform convective motions on the surface of the Sun, \( B_o \), are summarized by the velocity field \( u_{\perp} \). The diffusion coefficient, \( \kappa \), describes the statistical behavior of the interchange reconnections ultimately caused by random convective motions, which lead to jumps of footpoints of heliospheric field lines on the solar surface. For a typical jump length of \( \delta b \), and an average time between two successive interactions of a given field line, \( \delta t \), the diffusion coefficient is computed to be (Fisk 2005a)

\[
\kappa = \frac{(\delta b)^2}{\delta t}.
\]
In general, $\kappa$ should be expected to be spatially and temporally variable (Hagenaar 2001; Hagenaar, Schrijver & Title 2003; Abramenko, Fisk & Yurchyshyn 2006). In this case, there is an important difference between Equation 8 and regular diffusion equations (see discussion in appendix B of Parker 1963). Under time-stationary conditions, diffusion equations result in a uniform distribution. For example, the heat equation will predict a constant temperature in the absence of sources. This is not the case for Equation 9. In the absence of convective motions, Equation 9 predicts a temporal evolution toward a state for which $B_0 \propto (1/\kappa)$. Open flux is therefore expected to be unevenly distributed in the photosphere, depending on the spatial distribution of the small-scale emerging flux. These variations in $\kappa$ should lead to the observed differences between coronal holes and active regions, for example. The interchange theory has numerous consequences that differ considerably from those of the quasi-stationary models, as will be discussed below.

3. THE THREE-DIMENSIONAL HELIOSPHERE

Observations of the heliosphere in all three dimensions provide unique test cases of these models. First, they test the models beyond the range of observations that were used to construct them. Second, there are distinct physical differences to the high-latitude heliosphere that are not accessible by observations in the ecliptic. These unprecedented observations and their key results are discussed below.

3.1. The Solar and Heliospheric Observatory

The science topic at hand can only be addressed with a distributed solar and heliospheric observatory that combines in-situ observations throughout the three-dimensional heliosphere with observations of the Sun and its atmosphere. This was first accomplished in the early 1990s through a coincidence of numerous contemporary space missions.

The most important elements of this observatory are two missions jointly developed by the ESA and NASA—Ulysses and the Solar and Heliospheric Observatory (SOHO). Ulysses was launched on October 6, 1990 (Wenzel et al. 1992; Balogh, Marsden & Smith 2001). After a gravitational assist from Jupiter in February 1992, Ulysses has been on a near-polar trajectory about the Sun. To date, it has performed two full orbits over both poles of the Sun, providing hitherto unavailable insights into the three-dimensional heliosphere. The Ulysses orbit has an eccentricity of $e = 0.6$ and an orbital period of approximately 6.2 years. During one orbit, the spacecraft spends 234 days above 70° solar latitude, culminating at 80.2° solar latitude. Ulysses is superbly instrumented to address the science topics at hand, including a complete plasma and field package, a solar wind composition instrument, and high-energy particle instruments. The magnetic field instrument and the solar wind composition sensor are the most important for the conclusions in this review.

The magnetic field instrument provides measurements of the heliospheric magnetic field with unprecedented accuracy. It consists of two sensors, a vector helium magnetometer and a fluxgate magnetometer, which measure the heliospheric field on
Figure 6
Ulysses orbit as a function of time and solar cycle. (a) Ulysses heliocentric distance in AU and heliospheric latitude. (b) Sunspot number during the Ulysses mission. Also shown are key missions operating in the ecliptic, Solar and Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE) at the first Lagrange point (L1), and Wind near Earth. Figure courtesy of the Ulysses project.

ACE: Advanced Composition Explorer

a deployed boom on the spinning spacecraft. The quality of the magnetic field data is excellent owing to the strict magnetic cleanliness management at the spacecraft level, and the measurement redundancy obtained through two independent technological approaches for the magnetometer providing independent measurements of the same heliospheric field (Balogh et al. 1992). In addition, the Solar Wind Ion Composition Spectrometer (SWICS; Gloeckler et al. 1992) is the first successful
Solar photosphere: the visible surface of the Sun, between the solar convection zone and the solar atmosphere

3.2. The Solar Minimum Heliosphere: Expectations and Observations

During its first high-latitude pass in 1994, Ulysses transformed our understanding of the heliospheric magnetic field near solar minimum conditions. Previous expectations were largely motivated by models that were found to be successful near the ecliptic (see contributions in Fisk & Axford 1976, Marsden 1985). PFSS models, for example, had been shown to be highly successful at predicting both the polarity and the strength of the magnetic field at low heliospheric latitudes (Mariani & Neubauer 1990). Similarly, in spite of large deviations, the average magnetic field direction was well predicted by Parker’s (1958) theory. As a consequence of this theory (Equation 6), heliospheric magnetic field lines were expected to be wrapped less tightly, moving closer to the radial direction, as Ulysses propagated to higher latitudes. Furthermore, there was an expectation of latitudinal gradients in the normalized magnetic flux density, $B_r$ (Equation 5). There were different reasons for that expectation. Naturally, PFSS models predicted an increase of the magnetic flux with increasing latitude (Hoeksema, Wilcox & Scherrer 1994). But there were also MHD solutions (Suess et al. 1977) that predicted a measurable, although reduced, gradient in the radial component of the magnetic field as a function of latitude based on certain assumptions of an acceleration profile and kinetic pressure, which were thought to be balanced.
Table 2  Heliospheric observations by Ulysses

<table>
<thead>
<tr>
<th>Section</th>
<th>Heliospheric Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>1. The heliospheric flux density is constant as a function of latitude.</td>
</tr>
<tr>
<td></td>
<td>2. The high-latitude magnetic field is systematically underwound relative to the predictions of Parker (1958).</td>
</tr>
<tr>
<td></td>
<td>3. Low-frequency directional variations of the magnetic field appear quasi-static, as caused by footpoint motion on the Sun. They have a $1/f$ power spectrum.</td>
</tr>
<tr>
<td>3.3</td>
<td>4. Coronal-hole-associated wind is fast and has a composition consistent with remote observations of the Sun.</td>
</tr>
<tr>
<td></td>
<td>5. Slow wind is highly variable and has a substantially different composition compared with fast wind. It is geometrically and compositionally associated with topologically closed coronal structures such as coronal streamers.</td>
</tr>
<tr>
<td></td>
<td>6. Energetic particles reveal global-scale field deviations from Parker’s (1958) predictions, indicating substantial footpoint motion.</td>
</tr>
<tr>
<td>4.1</td>
<td>7. Within error bars, the measured field direction is consistent with Parker’s predictions throughout the solar cycle (with exception to 2).</td>
</tr>
<tr>
<td></td>
<td>8. The magnetic flux in the heliosphere remains approximately constant during the entire solar cycle.</td>
</tr>
<tr>
<td></td>
<td>9. The heliospheric current sheet retains its character during the entire solar cycle.</td>
</tr>
<tr>
<td></td>
<td>10. The large-scale properties of the current sheet during the solar cycle are well approximated by a flipping dipole model.</td>
</tr>
<tr>
<td></td>
<td>11. During the entire solar cycle, the topology of the heliospheric field apart from CMEs is open and not loop-like.</td>
</tr>
<tr>
<td>4.2</td>
<td>12. Heliospheric field lines exhibit large-scale deviations from Parker’s (1958) field predictions.</td>
</tr>
<tr>
<td></td>
<td>13. The dichotomy of solar wind sources retains its character during the entire solar cycle.</td>
</tr>
<tr>
<td></td>
<td>14. There are direct and indirect observations of reconnection in the corona associated with the heliospheric plasma.</td>
</tr>
<tr>
<td></td>
<td>15. CMEs appear to add magnetic field to the heliosphere, but the overall heliospheric flux does not increase proportionally.</td>
</tr>
<tr>
<td>4.3</td>
<td>16. There is a persistence of preferred solar longitudes of solar wind over several solar cycles. The solar cycle seems to have a memory.</td>
</tr>
<tr>
<td></td>
<td>17. There are significant periodicities at timescales between a solar rotation and a solar cycle timescale, in particular with a period of 1.3 years.</td>
</tr>
</tbody>
</table>

by lateral magnetic pressure gradients (Equation 1). These predictions were crucial for one of the critical science objectives for Ulysses (Simpson 1989): Due to their high energy, the propagation of galactic cosmic rays is highly sensitive to large-scale gradients in the heliospheric field (Jokipii & Levy 1977). The significant reduction of the curvature in the overall magnetic field at high latitude would allow direct access of cosmic rays over the poles of the Sun, with much reduced modulation. The polar regions of the heliosphere therefore would become windows to the low-energy
component of galactic cosmic rays. However, Jokipii & Kóta (1989) indicated the possible importance of random fluctuations at high latitudes (Equation 7). Transverse fluctuations (to the radial) scale $\propto (1/r)$ (Equation 5), whereas, near the pole, the background magnetic field (which Parker's model predicts should be radial) should drop much faster, $\propto (1/r^2)$ (Equation 6), thus making the transverse component of the field dominant in the polar regions.

In 1992 Ulysses started to climb toward the polar regions of the heliosphere. Until it reached mid-latitudes, $\theta \approx 45^\circ$, the observations were roughly as predicted as far as the magnetic field was concerned: The polarity appeared to be reasonably well predicted by PFSS models, and the field direction was in approximate agreement with Parker's prediction (Figure 5c). At high latitudes, however, a new three-dimensional picture of the heliosphere started to reveal itself (Balogh et al. 1995, Forsyth et al. 1996b, Smith et al. 1997). First and foremost, the radial magnetic field strength in the heliosphere was found to be roughly constant with latitude (Figure 7), contrary to previous expectations. Indeed, within the error bars the total normalized magnetic flux density, $r^2B_r$, was found to be identical near the ecliptic all the way up to the near-polar regions. The polarity of the magnetic field was well predicted by PFSS models—there was a single current sheet that separated outward and inward magnetic polarities (Figure 5a and c). By completing two subsequent polar passes during and near solar activity minimum, these findings were confirmed, but with an interesting complication: The strength of the field in the positive and negative sectors was found to be different, indicating that the solid angle of the positive sector was slightly larger than that of the negative sector owing to the fact that the magnetic field is divergence-free (Smith et al. 2000). There were more surprises (Figure 7b): Ulysses found systematic deviations from Parker's predicted field orientation at higher latitudes. At the very highest latitudes during the solar minimum pass in 1994–1995, the magnetic field was found to be less wound than expected by Parker’s predictions. During the first polar pass in 1994 there was also an indication that a significant fraction of field lines near the poles were systematically overwound as compared to Parker’s model (Forsyth et al. 1996b). Even though we focus here on the surprising deviations from Parker’s model, we stress again that Parker’s field model basically correctly predicted the zeroth-order behavior of the magnetic field at its largest scale.

Similar high-latitude deviations from the expected Parker configuration were also found in the $\theta$-direction: There is a systematic nonzero meridional component, directed toward the equator (Forsyth et al. 1996a).

We have already mentioned that PFSS models were found to be relatively successful in their predictions of the heliospheric current sheet. But, the limitations of PFSS models owing to the lack of measurements of the global photospheric fields also became painfully clear: Solar magnetic fields are only observed from the ecliptic, near Earth, and there are severe limitations with regard to observations of the solar polar regions that most seriously affect the heliosphere where Ulysses makes its most important measurements (Neugebauer et al. 2000).

The heliospheric polar regions, in spite of being overall unipolar, were found to be variable on all timescales. Indeed, the variance of the magnetic field was found to have a strong dependence on latitude—the high-latitude heliosphere ($\theta > 60^\circ$) was found...
Figure 7
Global heliospheric field during solar minimum as measured by Ulysses. (a) Within a given sector, the magnetic field is constant and independent of latitude. (b) The average winding angle observed by Ulysses is typically underwound relative to Parker's predictions. (c) The relative variability of the magnetic field vector (upper curve) and its magnitude (lower curve) is a strong function of heliographic latitude. Adapted from Balogh et al. (1995) and Smith et al. (1997).

to have a fluctuating field over three times the value found at lower latitudes (Balogh et al. 1995, Jokipii et al. 1995) (Figure 7c). The radial scaling of these fluctuations depends strongly on the timescale in question. Over short periods of time (<1 day), the variation looks like turbulence with an approximate $\propto r^{-3/2}$ amplitude scaling predicted by Wentzel-Kramers-Brillouin theory. Over longer timescales (>1 day), it changes character. It is quasi-static and is observed to have a $\propto r^{-1}$ scaling, as predicted by footpoint motions (Equation 5) on the Sun (Jokipii et al. 1995).
Some of these fluctuations appear to be highly systematic and have been analyzed in detail. For example, there were large deviations from the observed heliospheric field, which are not easily explained by heliospheric, turbulent effects. During these events the magnetic field turns in an almost radial direction for time periods of several hours. Clearly, these deflections had to originate in the corona, perhaps indicating footpoint motion on the Sun as described by Equation 5 (Murphy, Smith & Schwadron 2002), or the dynamic effects of reconnection (Gosling & Skoug 2002).

3.3. Other Constraints on the Heliospheric Magnetic Field

There are a number of auxiliary observations by Ulysses and SOHO that have added to the puzzle of the heliospheric magnetic field.

First, Ulysses observations, together with SOHO data, clearly established the bimodal nature of the solar wind (Figure 8a), which had been discovered based on near-ecliptic observations (Gosling et al. 1981, Schwenn 1990 and references therein): Slow solar wind is associated with coronal streamers and fast solar wind streams are associated with coronal holes (Figures 2 and 8a). Ulysses added important information about this dichotomy and physical constraints that were not previously known (McComas et al. 1998). Most importantly, the two solar wind types have different compositions (Geiss et al. 1995). The ionic composition, which freezes-in near the solar corona as the solar wind accelerates in the heliosphere, reflects significant electron temperature differences in solar wind regions. Clearly, the slow solar wind does not originate in coronal holes, as had been advocated by some (e.g., Bravo & Stewart 1997, Wang 1994)—its frozen-in charge states reflect electron temperatures much higher than remotely measured temperatures within coronal holes, but lower than the temperatures measured in active regions. This conclusion is even more obvious when looking at the elemental composition of the wind. It had been known prior to Ulysses that there is a significant elemental fractionation of solar wind plasma relative to that of the photosphere (e.g., Geiss & Bochsler 1985). This fractionation scales with the first ionization potential (FIP). Metallic ions, with low FIP, are more abundant in the solar wind than mid- or high-FIP elements, when compared with their photospheric compositions (von Steiger, Geiss & Gloeckler 1997). Ulysses revealed that there was a systematic difference in the degree of fractionation depending on the solar wind type. Coronal-hole-associated fast wind has a composition similar to the photosphere, whereas there is a substantially larger degree of fractionation in the slow, streamer-associated wind (von Steiger et al. 2000). This dichotomy between the composition of slow and fast wind and their respective sources was also shown to be consistent with measurements based on coronal spectroscopy (Raymond et al. 1997; Feldman, Widing & Warren 1999; Raymond 1999; Feldman, Landi & Schwadron 2005).

The Ulysses mission therefore showed that the quasi-stationary heliospheric magnetic field has two different solar sources. The magnetic field embedded in the fast solar wind originates in coronal holes and fills over 60% of the heliosphere near solar minimum. The field in the slow solar wind originates from coronal streamers that, on first investigation with a PFSS model, appear to be magnetically closed, but from which plasma clearly escapes into space. These two sources are compositionally
Solar wind observations of the solar minimum and solar maximum pass. (a) Solar wind speed and magnetic polarity as a function of heliospheric latitude, overlaid on three images from Extreme Ultraviolet Imaging Telescope, and coronagraph images of Mauna Loa and SOHO’s Large Angle and Spectrometric Coronagraph Experiment. The color indicates the polarity of the field. The solar wind is well ordered in polarity, as predicted in the models presented in Figure 5d. A band of slow solar wind straddles the heliospheric current sheet; at high latitude the solar wind is uniform. (b) Same format as a, but at solar maximum. Fast and slow streams occur at all latitudes, as the current sheet extends to all latitudes. Adapted from McComas et al. (2003).

distinct. Furthermore, the transition between these two wind types is rather abrupt (Wimmer-Schweingruber, von Steiger & Paerli 1997; Zurbuchen et al. 1999b; Posner et al. 2001). There is also a transient source of heliospheric field in the form of CMEs (Zhang and Low 2005). The magnetic field in CMEs has a tendency to be loop-like to heliospheric distances of 5 AU and therefore should add magnetic flux to the heliosphere. This is discussed in detail in Section 4.
Ulysses also provided important constraints on the topology of the heliospheric field through its measurements of so-called suprathermal electrons that are well tied to the heliospheric field. These electron populations have energies from ∼70 eV to several keV, much higher than the typical energy of thermal electrons in the heliosphere, which is around 10 eV or less (Gosling et al. 1987). The field-aligned portions of this particle population are very useful measures of the overall field topology. Open magnetic flux is identified by a single field-aligned beam directed away from the hot solar corona. Heliospheric field lines with loop-like topology—such as found in CMEs—have electron beams streaming in both directions along the field, away from a pair of footpoints that are rooted in the hot corona (e.g., Gosling, Birn & Hesse 1995). Field lines disconnected from the Sun show an absence of such electron beams in either direction (McComas et al. 1989).

Care has to be taken in the interpretation of the suprathermal electron data in order to identify correctly the effects associated with particle collisions or magnetic connection to large-scale heliospheric structures, which might also lead to a reduction of electron flow, or introduce a secondary electron distribution streaming along the field (Lin & Kahler 1992; Gosling, Skoug & Feldman 2001; Crooker et al. 2003; Pagel, Crooker & Larson 2005). The Ulysses and in-ecliptic measurements showed that both slow and fast winds are composed of predominantly open field lines with a simple open topology. Loop-like topologies, as identified by the flow characteristics of these electrons, are associated primarily with CMEs (Gosling et al. 1995, McComas et al. 2003). Furthermore, no regions were found in the heliosphere where magnetic flux is systematically disconnected. Such disconnections occur on rare occasions.

Another constraint on the heliospheric magnetic field comes from recurrent particle enhancements that were observed up to the highest latitudes sampled during the first solar pass (Lanzerotti et al. 1995, Simnett et al. 1995). Particle enhancements with a 26-day periodicity are common near the ecliptic beyond 2–3 AU heliospheric distances. There, they are accelerated in compression regions corotating with the Sun, as slow and fast wind streams originating from the Sun exist at the same solar latitude, but different longitudes dynamically interact, leading to particle acceleration (Gosling 1996, Simnett & Roelof 1995). In 1993–1994, these corotating interaction regions were confined to ∼30° latitude, consistent with the magnetic structure calculated in quasi-stationary models. Owing to the relatively small energy of these particles (38–315-keV electrons, 0.5-MeV protons) and subsequently their relatively small gyroradius, their cross-field transport should be expected to be very small (Fisk & Jokipii 1999). Also, local turbulent effects cannot account for magnetic field connections over many astronomical units in distance without violating observational constraints on this turbulence (Zurbuchen et al. 1999a).

These particles thus are tied to magnetic field lines, and their observed presence in the polar heliosphere demonstrates the existence of global-scale magnetic connections from low to high latitudes. These connections are only possible if there are systematic or random motions at the footpoints of heliospheric field lines (Figure 4a and 4c).

Galactic cosmic rays provide a very important measure for the overall field configuration. Their flux observed in the heliosphere had been predicted to increase in polar regions, very similar to the auroral regions on Earth, where high-energy
radiation preferentially enters. However, the latitudinal gradients were remarkably small, <0.5° (McDonald et al. 1997), much smaller than the predictions prior to Ulysses (Fisk & Axford 1976) that assumed a Parker field configuration.

3.4. Summary
At a global scale the average heliospheric field was found to be in good agreement with Parker’s predictions. However, the Ulysses mission has revealed a first view of the global heliosphere with properties that appear to contradict several of the expectations from solar models: The heliospheric magnetic fields originate from three distinctly different locations. There are fields rooted in coronal holes, but there are also heliospheric fields embedded in the slow solar wind that are associated with coronal streamers. Furthermore, there are transient ejections of field lines within CMEs that appear to be loop-like. At near-stationary conditions, the open corona is magnetically dominated, and large-scale and distributed currents and their dynamic effects play a major role. See summary in Table 2.

4. THE HELIOSPHERE DURING THE SOLAR CYCLE
The extension of the Ulysses mission, which was fortuitously agreed upon by ESA and NASA, allowed for an analysis of an 11-year solar cycle using the full power of the distributed observatory discussed above.

4.1. Expectations and Observations
During times of elevated solar activity the rate at which magnetic flux emerges in the form of large active regions (Figure 2) increases dramatically, enhancing the total energetic output of the solar atmosphere. This emergence typically occurs on short timescales compared to a solar rotation (Schrijver & Title 2001, Schrijver 2005). Active regions also increase in topological complexity, which leads to substantial increases of magnetic energy in the corona. The coronal magnetic field configuration is therefore far from its lowest energy state and it can become unstable, resulting in explosive ejections of magnetic flux and plasma into the heliosphere in CMEs. Indeed, the CME rate increases by close to one order of magnitude as the Sun moves from minimum to maximum conditions (Gopalswamy et al. 2003b). During the entire solar cycle, the spatial distribution of CME source regions strongly tracks the global structure of the heliosphere (Hundhausen 1993), with a latitudinal distribution reflective of that of large-scale magnetically closed regions, such as the bases of coronal streamers. As the Sun evolves toward increased activity these streamers reach to higher latitudes, leading to the disappearance of the polar coronal holes that dominate the heliosphere during solar minimum conditions (Harvey & Recely 2002, Bilenko 2004). Smaller, shorter-lived coronal holes now appear at all latitudes, with a rapidly changing polarity distribution, eventually reversing the polarity of the polar regions (Miralles et al. 2001; Miralles, Cranmer & Kohl 2004). This process is directly
reflected in the CME activity at high latitudes (McComas et al. 2002, Gopalswamy et al. 2003a).

These coronal reconfigurations are accompanied by important changes to the electromagnetic emissions from the Sun. During the solar evolution from minimum to maximum conditions, the coronal EUV and X-ray fluxes increase by factors of 2–5 (Lean 1991, Woods et al. 2004) and become highly variable owing to explosive energy releases in excess of $10^{32}$ ergs in the solar corona, in connection with flares and CMEs. These transient electromagnetic emissions occur on many different scales, down to the smallest events currently observable, which have energies around $\sim 10^{17}$ J (Benz & Krucker 2002).

This evolutionary transition from solar minimum to solar maximum is also observed in the heliosphere (McComas et al. 2003) (Figure 8). In addition to the rapid evolution of the coronal source of the heliospheric magnetic field, the dynamic interactions of transients in the heliosphere become increasingly important. Numerical calculations demonstrate that a single CME can dynamically alter a large fraction of the heliosphere, leading to compression and angular deflections of its magnetic field (Odstrcil, Pizzo & Arge 2005; Manchester & Zurbuchen 2006). A given observation of a field-deflection, for example, can thus be caused by an eruption over 90° longitude away from the observer’s longitude. Even in the absence of CMEs, the observed behavior of coronal-hole-associated wind is difficult to interpret because of substantial dynamic modifications that occur in the heliosphere owing to the smaller geometric scale of isolated coronal holes and their associated streams (Gosling 1996). These spatial and temporal variations are almost impossible to separate based on single measurements in space: Without additional constraints, an observed temporal variability of the expanding solar wind can be interpreted as either a temporal change of the solar wind or as the signature of a spatial structure sweeping over the spacecraft.

Despite all anticipated and also observed complexities in the heliosphere, it is the simplicity of some important heliospheric observables during solar maximum that constitute perhaps the biggest surprise discovered by Ulysses (Figure 6, for observation details). First and foremost, a number of key observations of the large-scale heliospheric field found near solar minimum roughly persisted throughout the solar cycle (Smith et al. 2003, Smith & Marsden 2003). During a large fraction of the 11-year cycle, the overall magnetic topology of the corona remains dominated by a magnetic dipole-moment, leading to a single, often warped current sheet (Figure 5d). During its progression from solar minimum to solar activity maximum, the heliospheric current sheet simply rotates from one nearly equatorial state—near solar minimum—to the next equatorial state in reverse orientation (Jones & Balogh 2003; Jones, Balogh & Smith 2003; Sanderson et al. 2003) (Figure 9a). This is only a very rough approximation: During this tilting motion, the current sheet is also warped owing to the relative importance of higher-order moments in the solar field (Figure 5d). Second, this large-scale motion is rather step-wise, often associated with major bursts of activity and resulting CMEs (Riley, Linker & Mikic 2002). This has important consequences for the near-ecliptic identification of such transitions and their impact on the modulation of Galactic cosmic rays (Jokipii & Kota 2000, Burlaga et al. 2003).
Figure 9

Global heliospheric field during solar maximum conditions as observed by Ulysses. (a) Magnetic field strength, as compared to Advanced Composition Explorer data at 1 AU indicating the lack of latitudinal gradient. (b) Tilt angle of the dipole axis for the same period. Periods shaded in darker gray indicate measurements at too low of a latitude to accurately measure the dipole tilt angle. The series of vertical lines indicate dipole tilt angles where only a range of angles could be derived. During solar maximum, the heliosphere current sheet approximately flips over, resulting in a change of polarity in each hemisphere. Figure adapted from Jones, Balogh & Smith (2003) and Smith et al. (2001).

The direction of the magnetic field observed by Ulysses also seemed to be in reasonable agreement with Parker’s predictions. Note, however, that owing to the large degree of structure resulting from waves, turbulence, and dynamic interactions in the heliosphere, systematic deviations from a Parker configuration are more difficult to identify during solar maximum conditions (Smith et al. 2001). Within measurement errors, the strength of the magnetic field in the heliosphere is found to be approximately constant to within a factor of 2 and uniform throughout in the entire heliosphere as during solar minimum (Figure 9b).

4.2. Other Constraints

The overall magnetic topology of the heliospheric field remains topologically open, apart from CMEs discussed below, and thus comparable to solar minimum conditions. Even though there are some observations of flux disconnections (Gosling et al. 2005), there are no indications of the presence of extended heliospheric regions where magnetic field is systematically removed from the Sun (Pagel, Crooker & Larson 2005). Furthermore, the heliospheric current sheet remains well-defined during all phases of the solar cycle (Smith 2001), which would not necessarily be the case if substantial magnetic flux elimination occurred at this location.

There is an interesting puzzle related to CMEs and their effect on the total magnetic flux in the heliosphere: Many of the CMEs observed in the heliosphere are topologically closed, or loop-like, and approximately retain their topological properties out to 5 AU heliospheric distance. The active Sun thus adds magnetic flux into
the heliosphere through the transient addition of a CME-associated field (McComas et al. 2003). However, the overall heliospheric flux does not accumulate at the rate suggested by observations of CMEs and their magnetic topology (Figure 9b). This suggests the presence of a reconnection process in the corona, as discussed below (Owens & Crooker 2006). This process might be active until several days after the coronal ejection.

There is surprisingly little effect on the total momentum flux of the solar wind during the solar cycle (Schwenn 1990; Bruno, Villante & Stecca 1994), considering the dramatic transitions of its solar source in both field topology and emissions of the solar corona. Solar wind during solar activity minimum is faster, but the slow, streamer-associated wind has a higher average density. When analyzed in detail, solar wind observations are consistent with a temporally dependent and/or spatially highly structured solar wind source. Some of the observed structure is time-stationary on a temporal scale of a solar rotation; some structure is highly transient, such as in CMEs. Owing to the dynamic interactions of streams of different speeds, single-point observations of the heliosphere can look extremely complicated (Figure 8b). Simple model calculations have been shown to be very effective at putting such single-point observations into their global coronal contexts, especially when adding observational constraints, such as ionic charge state measurements and the observed magnetic polarity (Neugebauer et al. 2002; Liewer, Neugebauer & Zurbuchen 2004).

The solar wind’s ionic and elemental composition during solar maximum has been measured by ACE and Ulysses. On average, the solar wind ionic charge states become hotter, reflecting the temperature increase of the corona. The solar wind speed distribution evolves from a rather bimodal state (Figure 8a) to a continuum of dynamic states (Figure 8b). However, the elemental composition of the solar wind retains its bimodal character roughly consistent with solar minimum values (von Steiger et al. 2000, Zurbuchen et al. 2002). Observed solar wind structures can thus again be associated with coronal holes and with streamers, even though both become shorter-lived. Furthermore, the streamer-associated solar wind is compositionally structured, with statistical properties that would be expected from time-dependent and distinct sources with varying source properties (Zurbuchen et al. 2000; Gloeckler, Zurbuchen & Geiss 2003).

The initial discussion of the solar wind structure focused on the question of whether it is mostly spatial or temporal in nature. There is now evidence from many different observations that the structure is indeed temporal, pointing to localized events, such as reconnection. Indeed, there is new and increasing direct observational evidence for reconnections in the corona and also in the heliosphere: Remote observations of the outer corona reveal coordinated signatures consistent with reconnection features (Sheeley & Wang 2001, Wang & Sheeley 2006). Furthermore, reconnection is now also observed in situ (Gosling et al. 2005; Gosling, Eriksson & Schwenn 2006). There are also indirect observations for coronal reconnection processes and their effects on the transient solar wind. Suprathermal electron observations reveal signatures of bursts, which indicate time-dependences at the solar wind source (Gosling, Skoug & McComas 2004 and references therein). There are also important constraints based on the analysis of the low-frequency turbulence (for
At these intermediate scales—between the large scales imposed by solar rotation and the turbulent high frequencies—the magnetic turbulence has a spectral shape as a function of frequency \( \propto 1/f \), consistent with plasma released by reconnection processes and possibly other statistical processes (Matthaeus & Goldstein 1986). There are also sheetlike spatial structures identified in Ulysses data, again reminiscent of a highly structured or temporally dependent source in the corona (Jones & Balogh 2000).

One of the most dramatic heliospheric transitions from solar minimum to activity maximum occurs in the high-energy particle component. Near solar maximum, the energetic particle environment around 1–50 MeV/nuc is dominated by energetic particles accelerated near the Sun. Similar to the energetic component observed during solar minimum, solar energetic particles are again tracing the magnetic field lines in the heliosphere. The width of rather localized solar particle events is therefore an important measure of the three-dimensional spread of these events. In many cases, the approximation of localized acceleration is not appropriate, and the measured width of the particle event represents an upper limit on the spreading of the magnetic field. The angular width of very large energetic particle events is observed to be up to \( \pi \) sr, mostly reflecting the angular width of shocks driven by CMEs (Emslie et al. 2004, Lario et al. 2006).

But, it is the small particle events that provide direct insights into the structure of the heliospheric magnetic field. These particles originate from a highly localized source and follow the heliospheric magnetic field into the heliosphere (Mazur et al. 2000, Gosling et al. 2004). Heliospheric magnetic field lines have imprinted on them the history of footpoint motion on the surface of the Sun (Figure 4). From a given location in the heliosphere, these motions are then detected as a series of apparent disruptions and can be interpreted as a very specific and well-defined temporal and energy-dependent profile of these escaping particles. The statistical properties of such behavior are very well modeled by footpoint motion on the Sun as described by Equation 7 (Giacalone, Jokipii & Mazur 2000).

### 4.3. The Heliosphere and the Solar Dynamo

It is the purpose of this section to summarize heliospheric observations with relevance to our understanding of the solar dynamo. Traditional solar dynamo theories seek to explain the solar activity or sunspot cycle, and its observational consequences as a result of self-consistent velocity structures on and below the solar surface (Gilman 2000, and references therein). Since the development of helioseismic measurements in the 1980s, the focus of these theories has been on two shear-layers that were revealed by these new observational tools. The first layer is right below the photosphere, and the second layer, the so-called tachocline, is at the base of the convection zone. There are other large-scale velocity flows, such as poleward meridional motion, previously observed in the photosphere, which extend half-way through the convection zone (Braun & Fan 1998). Much effort has gone into tuning the dynamo models, focusing on these large-scale motions and their implications for the magnetic field (see Charbonneau 2005). But, there are important interactions between the turbulent fluid motions in the
convection zone and the magnetic field that affect dynamo models and their dependence on fluid motions (Parker 1982; Cattaneo, Hughes & Kim 1996). Most modern dynamo models do not discuss heliospheric consequences, or provide predictions that can be tested in the heliosphere, even though heliospheric tests may prove to be very powerful (see, e.g., Scherer & Fichtner 2004; Schrijver, DeRosa & Title 2002).

Studies of the solar wind and its embedded fields have revealed the persistence of “preferred longitudes” over many solar cycles. Solar wind speed and radial magnetic field measurements over more than three solar cycles show persistence with a synodic solar rotation period of 27.02 days, indicating memory effects of dynamo processes in the Sun (Neugebauer et al. 2000, Ruzmaikin et al. 2001). This may be a heliospheric signature of the deep solar interior, but there is currently no theoretical explanation for it.

Time-series analyses of heliospheric magnetic field measurements have revealed periodic changes on temporal scales intermediate to the solar rotation period and the length of a solar cycle. A periodic variation of 1.3-years duration is found in the latitudinal component of the heliospheric field, as well as in the solar wind speed (Richardson et al. 1994; Szabo, Lepping & King 1995). The 1.3-years variability in the solar wind speed is particularly astonishing: Using a 50-day boxcar average, the 1.3-day variability has amplitudes of 50–100 km s\(^{-1}\). Similarly, there are reports of the transmission of low-frequency modes from the Sun through the heliosphere (Thomson, Maclennan & Lanzerotti 1995).

It has been argued that CMEs can play a very important role in the transition of the heliosphere from one polarity to the next, particularly relative to its magnetic helicity. Magnetic helicity is a topological measure of total linkage or twist imposed by noninertial forces on the Sun, and is conserved in closed systems (Bieber & Rust 1995). It has been suggested that CMEs may be important agents of helicity transport away from the Sun (Low 1990, 2001). This motivated a study of such transport; by analyzing CMEs observed in situ (Lynch et al. 2005), it was found that the helicity transport appears to track the solar cycle. This is not expected in current dynamo models.

4.4. Summary

The heliospheric observations during solar maximum are greatly complicated by the quickly evolving solar wind sources and the occurrence of transients from the active Sun. But, the heliosphere retains several of its key properties observed during solar minimum, as summarized in Table 2.

5. PHYSICAL PROCESSES COUPLING THE SUN AND THE HELIOSPHERE

Observations of the global heliospheric field have identified important constraints on the processes by which the Sun determines the magnetic structure and evolution of the heliosphere. Even though many predictions based on stationary models were indeed confirmed, there are new aspects to the heliosphere we did not previously know or appreciate sufficiently.
5.1. Successes of Quasi-Stationary Models

As discussed earlier, quasi-stationary models represent the field-emergence at large spatial scales. There are a number of successes of quasi-stationary models in their ability to predict quantitatively how the heliospheric field relates to its source (Table 2). Most of the successes relate to predictions of the large-scale properties of the corona. For example, PFSS models were very successful at establishing the overall magnetic topology of the heliosphere, in particular in the prediction of the location of the heliospheric current sheet throughout the solar cycle (Neugebauer et al. 2002; Riley, Linker & Mikić 2002) (Table 2, Observations 9 and 10). This prediction is very robust, and advanced MHD calculations provide results comparable to PFSS models, which are much simpler (Figure 5). Well-documented deficiencies of their success in predicting the heliospheric current sheet are likely due to our lack of observations of the global solar magnetic field: We do not have direct magnetic field measurements in the polar regions of the Sun, and we only observe roughly one-third of all solar longitudes at a given time.

Potential field models have also been successful in their prediction that the open heliospheric flux should be much less than the total magnetic flux of the Sun (Wang & Sheeley 2002) (Table 2, Observation 8). There is a simple reason for that: higher-order multipoles of the solar magnetic field drop very quickly with radius, rendering dipole and quadrupole terms dominant at the source surface. These terms do not vary by orders of magnitude as we go from solar minimum to activity maximum, even though high-order multipoles do. But, the observed flux-variability, even though non-vanishing, is smaller than the computed variability (Schatten 1971, or by comparing Ulysses results in Figures 7 and 9 with PFSS predictions by Wang & Sheeley 2002). Note that there may not be a causal relationship between the time-varying multipoles and the observed in-situ variability of the flux. The changing solar flux may be due entirely to flux-transport of CMEs (Owens & Crooker 2006).

PFSS models cannot explain the coronal expansion that leads to an approximately constant magnetic flux density as a function of latitude (Table 2, Observation 1). This equilibration is likely caused by the solar wind expansion in a magnetically dominated corona with a thin global current sheet. These pressure forces are related to currents, which are excluded in PFSS models, but which, in principle, are well modeled in time-stationary MHD models (Suess et al. 1996). MHD models can also successfully model the observed “underwinding” of the heliospheric magnetic field at solar minimum (Banaszkiewicz, Axford & McKenzie 1998) (Table 2, Observation 2). This underwinding is a direct consequence of the solar differential rotation that leads to a more radial field compared to a Parker (1958) model that uses rigid rotation (Equation 5).

Quasi-stationary models also correctly associate fast solar wind with coronal holes on the solar surface (Table 2, Observation 4). They are also very successful at modeling the overall stationary behavior of coronal streamers (Riley et al. 2006). But, they do not have a natural explanation for streamer-associated wind with different composition and larger dynamic variability as compared to coronal-hole-associated fast wind (Table 2, Observation 5).
5.2. Heliospheric View of the Sun-Heliosphere Coupling

The observational constraints in Table 2 imply important transport of footpoints on the solar surface, at smaller scales. This transport occurs during the entire solar cycle and maintains its character without relying on the presence of active regions (Table 2, Observations 6 and 12). The most likely candidate for this transport is footpoint motion caused by successive interactions of the heliospheric field with small-scale flux elements through reconnection, as pointed out many years ago (Jokipii & Parker 1968).

Before returning to the discussion of Table 2, consider two very different geometries of reconnection in the corona. In any magnetic reconnection process, magnetic field lines interact and exchange their respective footpoints (Battarjee 2004). If reconnection occurs between two loops, it will result in loops with different sizes (Figures 10a and 10b). This process is crucial to the evolution of magnetic flux near the photosphere (Handy & Schrijver 2001). A similar reconnection can happen between an open and a closed field line (Figures 10c and 10d). The reconnection process has two important consequences. First, the open field line moves to a new

![Figure 10](https://www.annualreviews.org/doi/10.1146/annurev.astro.45.091305.134934)

**Figure 10**

Reconnection processes of emerging magnetic flux involve two types of topologies. (a,b) Sketches of two interacting loops. The two loops interact and exchange footpoints, generally leading to loops of different sizes. (c,d) The identical process for a loop interacting with an open, heliospheric field line. Due to the process, the open field line moves a distance that is determined by the size of the interacting loop. Adapted from Fisk (2001).
location as its original footpoint is exchanged with a footpoint initially connected to
the closed loop, and second, the magnetic footpoint originally associated with the
open field line becomes part of the new closed loop. Similar processes can happen
in the heliosphere (Gosling et al. 1995). If a loop-like magnetic field emerges into
the heliosphere and interacts in the low corona, magnetic flux can be eliminated
from the heliosphere. This process, during which the topology of interacting fields is
exchanged, is generally referred to as interchange reconnection. In principle, reconnec-
tion can occur also between two open field lines. Such an interaction would result
in a loop and the presence of disconnected flux, a U-type structure opening toward
the heliospheric boundary. Such disconnection events do indeed occur, but are rare

Interchange reconnection with small-scale magnetic fields may indeed be a crucial
process for the overall structure and dynamics of the heliosphere. Such processes, if
occurring in sequence, can result in random footpoint motions (Equation 7) while
maintaining open field topology (Table 2, Observations 6 and 11). Reconnection
processes like this have recently been observed, and their presence is implied by
many observations (Table 2, Observation 14).

Random footpoint motion simultaneously explains the ease of latitude transport of
energetic particles during solar minimum (Table 2, Observation 6), energetic particle
transport observed during the entire solar cycle (Table 2, Observation 6 and 12), and
the radial scaling of low-frequency directional variations in coronal holes (Table 2,
Observations 6 and 3) (Jokipii et al. 1995; Köta & Jokipii 1995; Giacalone, Jokipii &
Mazur 2000). Remarkably, the actual quantitative value for the footpoint motion is
roughly the same for all these solutions.

Such interactions, perhaps with larger loops in the corona, can also account for the
escape of slow solar wind from coronal streamers. Slow solar wind gets successively
released through interchange reconnections. Such a model would be qualitatively
consistent with compositional observations of slow solar wind and its high variability
associated with the distribution of its sources in the solar corona (Table 2, Observa-
tions 5 and 13) (Zurbuchen et al. 2000). This has been proposed previously based on
in-ecliptic observations of the 1/f spectrum at low frequencies (Table 2, Observation
3). It can be shown that this spectral shape can be derived if the solar wind turbu-
rence consists of a superposition of uncorrelated samples of surface turbulence that
have log-normal distributions of correlation lengths. This can be accomplished if the
solar wind indeed originates from individual sources and is released by reconnection
(Matthaeus & Goldstein 1986).

The approximate magnetic flux balance in the heliosphere (Table 2, Observation
8) deserves a detailed comment. CMEs observed in the heliosphere provide a
net-addition to the heliospheric flux, because their topology is loop-like (Table 2,
Observation 15). Based on the observational constraint that excludes systematic dis-
connections of open fields, interchange reconnection may in fact be the dominant
process by which the heliospheric magnetic field sheds that added flux (Reinard &
Fisk 2004). Based on a quantitative analysis of global magnetic flux transport through
CMEs, and the long-term behavior of heliospheric flux, the interchange reconnec-
tion time can be estimated to be 50 days (Owens & Crooker 2006). There is therefore
no need to interpret apparent increases of open flux in the context of quasi-stationary models.

In summary, the behavior of the heliospheric field shows evidence of transport owing to interchange reconnection and therefore is fundamentally transient. Such transport is implied by many independent observations. But, it has no analog in quasi-stationary solar models that have been successful in explaining many problems in solar physics.

5.3. The Debate

There is currently no agreement between the solar view of the Sun-heliosphere coupling and the heliospheric view of the same process. Quasi-stationary models imply a more variable heliospheric flux that is adjusted through expulsion of loop-like structures similar to CMEs, or magnetic disconnections at substantial value, inconsistent with heliospheric data.

This has recently been demonstrated in one of the most advanced and time-dependent MHD simulations of a differentially rotating corona near solar minimum (Lionello et al. 2006). During solar minimum, coronal holes rotate quasi-rigidly (Schulz 2001), and closed flux therefore has to interact with open field lines. The MHD simulation is successfully reproducing many characteristic solar observations associated with this problem: Magnetic flux opens on one side of the coronal hole extension and closes back down on the other side. The simulation actually does find interchange reconnection in both locations, consistent with heliospheric data. But, it also finds systematic flux disconnections from the Sun at these boundaries and expanding loop-like structures. Both of these findings appear to be inconsistent with heliospheric observations at these boundaries.

During this field configuration systematic flux-transport between heliospheric latitudes can occur to explain the recurrent low-energy particles at high latitudes (Simnett & Roelof 1995), as shown in Figure 4b, which could possibly lead to a very solid experimental test. The model assumes that the solar magnetic field expands into an asymmetric coronal hole that rigidly rotates (Fisk 1996). All random surface motions were neglected. This model is interesting because of its ability to provide a set of independent predictions, which were tested and resulted in differing conclusions (Zurbuchen, Schwadron & Fisk 1997; Forsyth, Balogh & Smith 2002), limited by the statistical accuracy of the experimentally deduced field variations caused by the overwhelmingly large variance of heliospheric field (Figure 7b). The effects of this field have been successfully included into a cosmic ray transport code, with promising results (Burger & Hitge 2004). In conclusion, this test has not resulted in a clear answer to this central question.

Interchange models, on the other hand, have been very difficult to insert into solar models. The theoretical formulation of transport properties by interchange models is done by modeling stochastic equations that introduce transport properties not easily modeled in perfect MHD (Equation 8). Furthermore, interchange models in the current formulation appear inconsistent with some successful predictions of quasi-stationary models. For example, interchange models predict that coronal holes
occur at locations on the Sun with less random transport, or smaller $\kappa$ (Equation 9). In quasi-stationary models, coronal holes appear in magnetically open areas defined by the large-scale geometry of the corona. The predicted $\kappa$ variations near coronal holes were indeed found (Abramenko, Fisk & Yurchyshyn 2006), but the observed reduction in $\kappa$ may have entirely different reasons.

A test for the validity of interchange models might come from a quantitative analysis of coronal heating and solar wind acceleration resulting from energy released by this reconnection. Open flux can be considered the open-field equivalent of a process proposed by Parker (1988) to explain the heating of closed magnetic structures. In the case of an open field, the churning of the heliospheric footpoints forces successive interactions of loops and leads to the release of energy. Even though interchange models can provide constraints on the abundance of such interactions, the distribution of energy is not self-evident from these models (Axford & McKenzie 1997). Simplifying assumptions have been proposed, using one-dimensional energy transport (Fisk et al. 1999, Fisk 2003, Suzuki 2006). But, interchange reconnection should be expected to be a stochastic, three-dimensional process and be handled as such when calculating the scaling laws that determine how energy dissipation occurs and how it leads to the acceleration of the solar wind (Hollweg 2006; Verdini, Velli & Oughton 2005).

6. SUMMARY AND OUTLOOK

One of the most important problems in astrophysics is the coupling between astrophysical objects and their magnetic field. For example, the interpretation of observed energetic phenomena near astrophysical objects, such as neutron stars, accretion discs, black holes, and stars with flares and activity cycles, relies on a solid understanding of the processes that control energy transmission from these objects into their surrounding magnetic field. This surrounding magnetic field can store large amounts of energy. It eventually releases it through the acceleration of a plasma to form a wind or a jet, or through transient phenomena observable throughout our Galaxy.

Many of the mechanisms that control the coupling to the magnetic field are revealed in solar heliospheric interactions, which have the advantage of being highly constrained by observations of the Sun and the global heliosphere. These observations have led to a transformation of our understanding of the three-dimensional structure of the magnetic heliosphere: The structure of the heliospheric magnetic field is determined by two field systems. Active solar regions determine the overall structure of the heliospheric current sheets and are associated with CMEs, especially during the solar cycle. However, many characteristics of the heliospheric field appear to be independent of active regions (Table 2) and implicate the importance of interactions with small-scale field elements that are ubiquitous.

The solar and heliospheric communities are now at a junction of their understanding of the processes coupling the Sun and the heliosphere and of their interpretation of the importance of both systems and their interrelation. This dialogue may be fundamental to many other problems relating celestial objects to their space environment, especially those with small-scale velocity fields: The interaction between random convective flows and a magnetic field leads to a very uneven distribution of
field concentrations in localized areas. These concentrations convect with the turbulent flow and randomly interact, resulting in magnetic restructuring and also the energization of plasma. In addition, even though the most important energetic events of these bodies may be associated with extended active regions, it is the granular and ubiquitous distribution of small-scale elements that may be responsible for key properties of the plasma environment of these bodies.

The importance of understanding these physical processes for making advances in explaining properties of other skies, accretion discs, and jets cannot be overstated: Magnetic fields at large scales are strongly affected by plasma interactions at their smallest scales.

**SUMMARY POINTS**

1. The transport of energy from the Sun into the heliosphere occurs through processes that are magnetically dominated and temporally and spatially intermittent owing to intrinsic time-dependences of the solar source given by large-scale motions, such as differential rotation, and owing to emergence of magnetic flux on multiple scales.

2. Active regions dominate the organization of heliospheric magnetic flux and the location of the heliospheric current sheet. They also are associated with CMEs, especially during activity maximum.

3. This dynamic behavior of the solar corona is driven by the distribution of magnetic flux at small spatial scales during all times in the solar cycle and apparently relatively independent of active regions.

4. During solar minimum, the heliosphere originates from magnetically open coronal holes and from streams associated with streamers. There are indications of global equilibration and magnetic field transport on the surface of the Sun, moving the corona away from its lowest energy state.

5. The transition of the heliosphere through the solar cycle occurs in a way that is well approximated by a tipping dipolar configuration, which remains globally equilibrated. There is evidence of important transport of the heliospheric field routed in the solar atmosphere.

**FUTURE ISSUES**

Future progress in this research field will be achieved through a three-pronged approach.

1. The quantitative characterization of transport processes of heliospheric field on the Sun, which may be random or organized. This will lead to better determinations of magnetic transport with testable consequences. Indeed, novel solar observatories, such as the recent space missions *Hinode* and *Stereo*, will have important impact on this problem.
2. Theoretical analysis of topologically complex magnetic configurations in potential field models as well as in MHD. These analyses will provide important views to translate approximated interaction-scenarios (Figure 10) into quantitative cases that are comparable with interchange models.

3. Novel and improved observations of the magnetic vector field in the extended solar atmosphere will provide constraints for the models under consideration.

ACKNOWLEDGMENTS

We thank NASA and the NSF for their support of this work through various research and analysis programs. We especially thank NASA for funding a focused study on the heliospheric magnetic field through their Living with a Star (LWS) program. We thank all the individuals of the Ulysses, SOHO, ACE, and Wind missions who, through their work in building and operating these spacecraft, have enabled this research. We further thank the following individuals for their inputs and comments to this review: in alphabetical order, S. Antiochos, A. Balogh, L.A. Fisk, J. Giacalone, J. Gilbert, G. Gloeckler, J. Gosling, M. Guhathakurta, J.R. Jokipii, S. Lepri, J. Linker, W.B. Manchester, R. Marsden, and R. von Steiger. Oscar Grimm of Paper Cardinal Design has helped in the preparation of all the figures in this review. Debbie Eddy has helped with the editorial process. Thanks to the team of the International Space Science Institute in Bern, Switzerland, where a significant fraction of this review has been written. Finally, I want to thank Gene Parker whose influence on this research cannot be overstated. I have been privileged to know him and admire his clarity of thought and the excellence in his approach to science toward which we all strive.

LITERATURE CITED

Axford WI, McKenzie JF. 1997. See Jokipii, Sonett & Giampapa 1997, p. 31
## Contents

An Accidental Career  
*Geoffrey Burbidge*  
1

The Beginning of Modern Infrared Astronomy  
*Frank J. Low, G.H. Rieke, and R.D. Gebriz*  
43

Infrared Detector Arrays for Astronomy  
*G.H. Rieke*  
77

Heating Hot Atmospheres with Active Galactic Nuclei  
*B.R. McNamara and P.E.J. Nulsen*  
117

Physical Properties of Wolf-Rayet Stars  
*Paul A. Crowther*  
177

The Search for the Missing Baryons at Low Redshift  
*Joel N. Bregman*  
221

Irregular Satellites of the Planets: Products of Capture in the Early Solar System  
*David Jewitt and Nader Haghighipour*  
261

A New View of the Coupling of the Sun and the Heliosphere  
*Thomas H. Zurbuchen*  
297

Cold Dark Clouds: The Initial Conditions for Star Formation  
*Edwin A. Bergin and Mario Tafalla*  
339

Statistical Properties of Exoplanets  
*Stéphane Udry and Nuno C. Santos*  
397

Relativistic X-Ray Lines from the Inner Accretion Disks Around Black Holes  
*J.M. Miller*  
441

Toward Understanding Massive Star Formation  
*Hans Zinnecker and Harold W. Yorke*  
481

Theory of Star Formation  
*Christopher F. McKee and Eve C. Ostriker*  
565