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The Inner Heliosphere at Fifty

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Recent observations show that the Sun's magnetic field is flipping, marking one of the weakest sunspot cycle maxima in recent history. Many consequences have been observed and are under study, from a significant diminishing of the upper atmosphere's density [*Solomon et al.,* 2010] to record low levels of geomagnetic activity [*Richardson,* 2013] to the large increase of local galactic cosmic ray fluxes starting in the preceding solar minimum [*Mewaldt et al.,* 2010].

Yet as recently as the 1950s, there was little deep understanding of long-documented connections between the observed sunspot cycle, perturbations in the Earth's surface magnetic field, the occurrence of auroras, the appearance of the Sun's corona during total solar eclipses and in coronagraph images, and occasional white-light solar flares, with their associated radio emissions and ionospheric disturbances. Spectral line information had already indicated that the corona—the upper atmosphere of the Sun—is composed mostly of hydrogen at a temperature of about a million degrees Kelvin with a correspondingly high ionization state, but beyond that, researchers knew little of how the corona influenced Earth or the space around it.

The 1950s was also a period of postwar technological advancements and unprecedented growth of institutions of higher learning. Communications increasingly relied on ionosphere-dependent transmissions, which can be disrupted by solar events. The time had arrived for new investigations concerning our relationship to our star. Following the discovery by George Ellery Hale that sunspots were sites of magnetic fields [*Hale,* 1908], the development of the magnetograph by Horace Babcock and his son Harold was particularly important in spurring interest in solar astronomy in academic circles [*Babcock,* 1953]. Sunspots were established as sites of especially strong magnetic fields on the solar surface, but, in addition, the presence of fields outside of sunspots and their influences over the highly ionized solar atmosphere gained attention. While the emphasis in this era was mainly on the phenomenology observable within the limits of ground-based instrumentation, with colorful names of features such as "disparitions brusque" and "plages" introduced, the stage was set for the next phase in the space age.

The Parker Solar Wind and Emergence of the Field of Heliophysics

By the early 1960s, several theoreticians were using existing information to envision what was present between the Sun and Earth. Eugene Parker proposed that an ionized, mainly hydrogen gas or plasma continuously flowed out from the Sun like a fluid, carrying some of the Sun's magnetic field along with it [*Parker,* 1958]. He made the additional prediction that this "solar wind" was flowing at supersonic speeds (reaching hundreds of kilometers per second or more) because of its origins in the hot corona and the resulting physics of its pressure-driven escape from the Sun's gravitational well. A competing theory invoking a picture more similar to an ionized planetary upper atmosphere was developed around the same time by Joseph Chamberlain [*Chamberlain,* 1960]. Chamberlain's consideration of single particle or kinetic effects, together with the charge and mass differences between the protons and electrons, resulted in much lower outflow speeds. The essential difference between Parker's and Chamberlain's hypotheses concerned the applicability of the fluid theory to the space between the Sun and Earth, which was expected to be a highly rarefied, collisionless medium.

Then instruments successfully detected the solar wind particles and magnetic fields in interplanetary space on the Soviet Union's first three Luna missions and on the United States's Explorer 10 and Mariner 2 missions [*Neugebauer and von Steiger,* 2001]. These measurements established the existence of a solar wind and interplanetary field with properties much like those described by Parker's concept. In particular, the speed of the ionized gas (plasma) was about 400 kilometers per second, and the magnetic field exhibited behavior consistent with a "Parker spiral" configuration (Figure 1a) that arises naturally from picturing streams of fluid ejected from a rotating Sun—the flow is radially outward, but the fluid elements from a particular source location and the source field they carry make a spiral shape as the Sun rotates under them. While a greater appreciation of the nonfluid aspects of solar wind behavior developed later, Parker's picture is the first one that most students of space physics encounter and routinely use.

The field of heliospheric research was thus born and grew rapidly through the 1990s with much success, based on these early paradigms. Important advances made during this time included much more detailed descriptions of the coronal sources of solar wind. The bright, near-equatorial rays or streamers seen in eclipse and coronagraph images obtained during periods of low solar activity led to the first coronal models based on the assumption of a large-scale dipole magnetic field of the Sun (Figure 1b). Streamers were interpreted as sites where hot gas is trapped in topologically "closed" magnetic field arcades rooted in the Sun, which in the dipole case encircles the solar equator (Figure 1b).

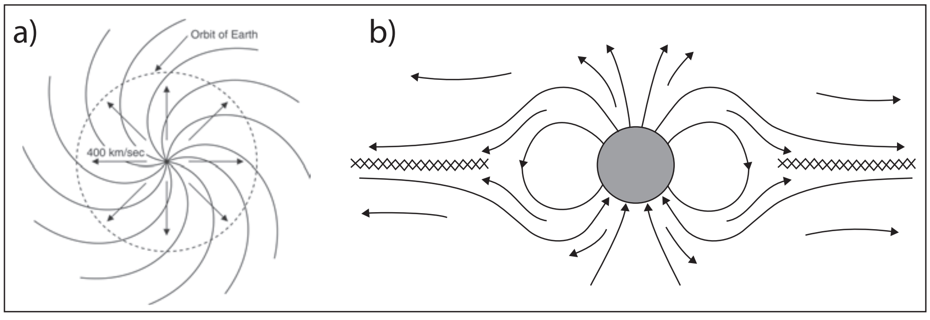

Fig. 1. Depictions of early ideas of heliophysics. (a) The original Parker solar wind and interplanetary magnetic field concepts. (b) The early dipolar corona model with polar coronal hole sources of the solar wind.

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The solar wind flows out along "open" fields in the solar polar regions.

This picture neatly explained the "magnetic sector" structure observed in the solar wind where alternating outward and inward Parker spiral fields were detected—with sometimes repeating patterns on the approximately 27-day time scale of the solar rotation. A tilt or warp of the coronal dipole equator with respect to the ecliptic plane could easily produce such patterns.

Insights From Space-Based Platforms and the Emerging Field of Space Weather

Parallel developments of still newer technologies and increasing access to space-based platforms then led to the next major paradigm shifts. In particular, the soft X-ray telescopes on Skylab (NASA's first space station [see *Eddy,* 1979, and references therein]) had a particularly important impact on heliospheric research because they allowed scientists to observe coronal holes, areas dark in X-ray images that are seen on the solar disk nestled between the arcades of the bright streamers. Moreover, these features changed with time, and the magnetically closed arcades sometimes erupted. These eruptions, a newly defined form of solar activity distinct from flares, were termed coronal mass ejections (CMEs).

Space-based in situ measurements of plasma and field features at both quiet and active times could now be associated with what was observed at the Sun in remarkable detail. For example, a large coronal hole present near the central disk of the Sun would often be followed several days later by especially fast solar wind at Earth. The dark areas were therefore recognized as the footprints of open coronal field channels out of which fast solar wind easily escaped. Notably, these were often not confined to the solar polar regions associated with the dipole corona picture. Instead, coronal holes were often highly irregular in shape and present over a range of solar latitudes (Figure 2). Moreover, their spatial distribution, like that of the bright streamers, changed with the phase of the 11-year sunspot cycle. Computational advances enabled the development of models of the coronal magnetic field based on the solar surface field observations. These often reproduced features resembling both streamers and coronal holes seen in the eclipse, coronagraph, and soft X-ray images, establishing once and for all that the solar magnetic field exerts major control over the structure of the heliosphere.

The identification of CMEs ushered in a new era of space weather research and the possibility of forecasting it. A European twin-spacecraft mission called Helios, which orbited the Sun between the heliocentric distance of Mercury's and Earth's orbits from the mid-1970s to the mid-1980s, captured the plasma and field signatures of CMEs and their effects on the surrounding solar wind as they evolved along their outward paths.

By the late 1990s, *Gosling* [1993] had convinced the research community to accept that the flares observed at the Sun were not the most direct cause of the geomagnetic storms that sometimes followed. If a coronal mass ejection occurred in association with a central or western disk flare, it could be followed within a few days by a shock wave and then several days of enhanced solar wind parameters (density, velocity, and magnetic field) upstream of Earth. Around this time, the first phenomenological models of the proposed coronal eruption process and its interplanetary consequences were introduced (Figure 2).

Detailed Observations of the Heliosphere

In the 1970s, a number of planetary missions traveling away from the Sun, in particular the

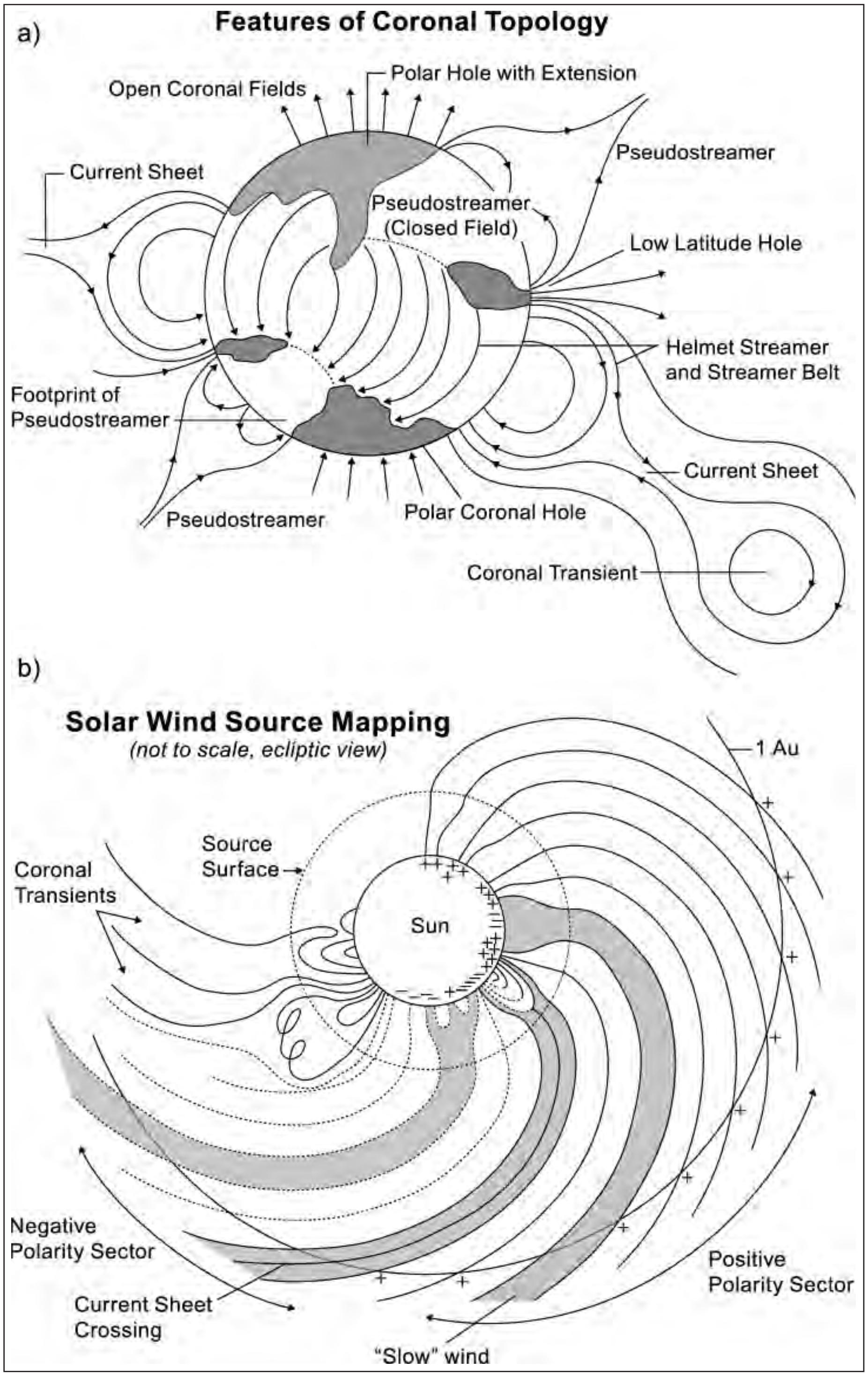

Fig. 2. Depictions of the current understanding of heliophysics. (a) A modern illustration of the corona, including the complications realized after 5 decades of technology and theoretical/modeling developments and observations. (b) The solar wind structure consequences of the modern coronal picture, also constrained by observations and, to a degree, by detailed, physics-based numerical simulations.

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Pioneer 10 mission to explore Jupiter's space environment followed by the twin Voyager spacecraft, made interplanetary measurements of the solar wind and its variations beyond Earth's orbit that extended Parker's basic picture as far as human-made robots ventured in space. During this period the practical aspects of this science of heliospheric physics were also realized in the support of the human space exploration program because flare watching was no longer sufficient to ensure astronaut safety. Potential solar energetic particle radiation hazards related to CME-driven shocks were recognized as something to be considered in both human and robotic mission design and operations. It would have seemed to many an outside observer that the understanding of the heliosphere and its connections to the Sun were nearly complete.

With the 1990s came the European-led Ulysses mission, the first opportunity to venture far out of the ecliptic plane and observe the Sun. At the same time, major developments in computing and numerical simulation techniques began to allow increasingly sophisicated physics-based modeling of the corona and heliosphere. The possibilities for space weather prediction from the Sun to Earth became more realistic. In addition, progress in helioseismology, the diagnosis of the Sun's internal structure and dynamics from its surface oscillations, opened minds to the connections of the solar interior to the structure of, and events in, the corona.

In a somewhat ironic twist, the limitations of the Parker picture of the heliosphere also became more apparent. The heliolatitude gradients in solar wind properties inferred earlier from interplanetary scintillation measurements that were confirmed by Ulysses, combined with continuous imaging of the corona on the European Space Agency (ESA)/NASA Solar and Heliospheric Observatory (SOHO) spacecraft, found that the Parker wind concept most closely applies to solar wind coming from the central portions of coronal holes. However, a large fraction of the ecliptic solar wind, and much of the solar wind at all latitudes during active periods of the solar cycle, is much more complicated in its origins and characteristics. Even at quiet times, some of the solar wind that is experienced at Earth consists of CMEs that leave the Sun at speeds less than typical solar wind speeds and are caught up in the flow but are not distinguishable as specific events or disturbances.

There is also a smaller-scale transient outflow that appears in coronagraph images as blobs or layers peeling off of coronal streamers. Though not surprising considering that coronal structure is always adjusting to the evolving magnetic field of the solar surface at its base, this "transient" solar wind source, like the slow CMEs, departs from the original picture of typically steady coronal outflows.

The Next 50 Years: What's Ahead for the Heliosphere

In the past half century, the wealth of new observations of the Sun and the solar wind has provided much fodder for the growth of heliophysics as a more exact fundamental and applied science. It is no longer usual for a dipole field to be used to describe the corona and solar wind sources.

Following Ulysses, researchers have imaged the three-dimensional Sun with combined data from SOHO, the Solar Dynamics Observatory, and the Solar Terrestrial Relations Observatory, forever changing scientists' perspectives and society's reliance on any single scientific platform for monitoring the Sun. The solar field complexity on a wide range of scales, the couplings between those different scales, and their interplanetary consequences characterize much of heliophysics research in its fifth decade. Everything from theories and observations of coronal heating and solar wind acceleration to the initiation and properties of coronal mass ejections depends on scientific understanding of the solar magnetic fields—observations of which are continually improving.

Understanding solar magnetic fields is irrevocably tied to the understanding of stellar dynamos. Improved space- and ground-based helioseismology measurements tell us that the Sun has several different regions where dynamo activity can occur, including a shear layer between the Sun's rigidly rotating radiative core, the convection zone that fills most of the solar interior above it, and a relatively narrow layer at the surface where motions on the small scale of the solar granulation seen in high-resolution images are present. These various dynamo regions generate magnetic fields that interact and evolve to produce phenomena at the Sun's surface, in the corona, and in the heliosphere. Similarly, high spatial resolution images in extreme ultraviolet wavelengths, together with high time cadence field observations—sometimes in full vector form—have inspired numerical simulations of coronal eruptions of unprecedented realism. Nonetheless, researchers still lack the ability to reproduce an accurate, physically self-consistent quiet corona and solar wind model, let alone a fully described coronal and interplanetary transient.

The good news is how far the field has come in 50 years, with scientists much closer to understanding how and why the solar corona behaves the way it does and the larger heliospheric consequences. A level of predictive capability for conditions that affect Earth, the planets, and human technologies in space and on the ground is now in its early phases and widely available (e.g., http://swrc.gsfc.nasa.gov and http://www.swpc.noaa.gov/wsa-enlil). Fundamental understanding of how the solar magnetic field comes about, while not heliophysics per se, is an imminent frontier essential to completing the picture above. Many important details still need to be fleshed out, such as the question of how the Sun's energy flux from its interior, which is largely radiative and mechanical, is in part transformed to coronal heating and solar wind acceleration in all its forms.

Toward these goals, ESA's proposed Solar Orbiter mission, scheduled to launch in 2017, will finally obtain images of the Sun and its surface magnetic field from a high-latitude perspective, and NASA's Solar Probe will venture to within an unprecedented 10 solar radii (about 0.05 astronomical units) of the solar surface to make in situ diagnostic measurements of solar wind and coronal transient processes and structures early in their evolution. Its 2018 launch should get it there by 2024 (http://solarprobe.jhuapl.edu), something to look out for in the news media—or perhaps on your space weather app (e.g., http://www.nasa.gov/centers/goddard/news/releases/2012/12-20.html).

In short, the physics of the inner heliosphere at the 50-year mark remains full of interest and promise, limited by the resources made available and the technologies capable of allowing scientists to probe its physics. It remains the only case known where a stellar atmosphere and its consequences are a great source of curiosity and interest for the beings living with their star.

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