SOLAR WIND AND INTERPLANETARY MAGNETIC FIELD

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Summary

Space between the Sun and its planets is not empty. It is filled by a tenuous magnetized plasma, which is a mixture of ions and electrons flowing away from the Sun—the solar wind. In fact, the Sun's outer atmosphere is so hot that not even the Sun's enormous gravity can prevent it from continually evaporating. The escaping plasma carries the solar magnetic field along, out to the border of the heliosphere where its dominance finally ends.

The solar wind proves to be one key link between the solar atmosphere and the earth system. Although the energy transferred by the solar wind is minuscule compared to both sunlight and those energies involved in Earth's atmosphere, the solar wind is capable of pin-pricking the earth system until the latter eventually reacts in a highly nonlinear way. There are indications of effects reaching down as far as the troposphere, and our increasingly sophisticated high-tech civilization can indeed notice them and

does, at times, even suffer from them. That is why the role of the Sun and the solar wind as the drivers of space weather have gained particular attention in the recent past.

1. Basic Concepts

The existence of the Sun's extended atmosphere, the corona, has been known ever since mankind has been stunned by the beauty of solar eclipses. Our familiar home star looks so perfectly shaped and never-changing, and yet eclipses reveal its atmosphere to be highly structured and always variable! Photographic images of these rare occultations lead even to the impression of "stream lines" emerging from large regions of the corona (Figure 1). However, not until the 1950s was the existence of continuous particle streams from the Sun first suspected by Biermann from the observations of cometary plasma tails and then theoretically modeled by Parker in 1958. These hypotheses were basically confirmed a few years later when appropriate instruments were installed on interplanetary space probes. In very general terms, it can be said that due to the extremely high temperatures in the corona (1×10^6 K to 2×10^6 K) even the Sun's enormous gravity cannot hold together the Sun's atmosphere completely. Part of it escapes and beyond the critical—or Alfvén—point, it flows away with supersonic speed. This is what was termed in a very visual way the *solar wind.*

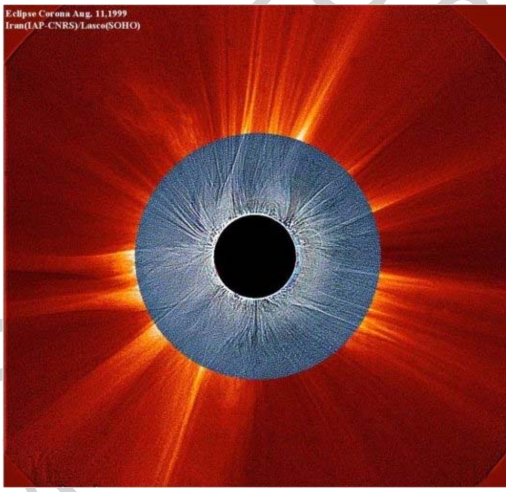

Figure 1.Eclipse image of August 11, 1999, combined with a simultaneously taken coronagraph image (LASCO-C2 on SOHO)
For both images, the contrast was artificially enhanced in order to reveal the large-scale coronal structures and their sources in the lower corona. (Courtesy of S. Koutchmy)

At any eclipse, observers are stunned most by the high degree of structure in the then-uncovered corona. No wonder that the solar wind emerging from there is similarly inhomogeneous and creates a complicated three-dimensional shape of the heliosphere. Interactions between outflowing streams of different speeds and solar transient phenomena cause further complications. Thus, the solar wind as we encounter it in space is characterized by an enormous variability in all its basic properties. It is this very variability that allows the solar wind to have a surprisingly great impact on the earth system (see *Magnetosphere and Its Coupling to Lower Layers*).

No doubt exists about the key role that the interplanetary magnetic field plays for Earth. Of particular significance are those occasions when the generally radially outward pointing field vector swings out of the ecliptic plane and points southward. In such cases, a connection between Earth's intrinsic field and the interplanetary field can occur (by a process of "field line reconnection").

Such a configuration would allow solar wind particles "attached" to their interplanetary field lines to move on and enter the magnetosphere on that same field line that now belongs to Earth.

The door into the usually well-shielded magnetosphere appears to stand open so that the solar wind plasma can directly enter and dump its kinetic energy, or trigger the release of different energies stored at other places within the magnetosphere.

As a consequence, geomagnetic activity may arise with all its typical signatures, such as geomagnetic storms, visible auroras, ionospheric disturbances, and others.

2. Sun and Heliosphere at Times of Solar Activity Minimum

2.1. Typical Solar Wind and its Sources

Some typical solar wind parameters, as measured at Earth's orbit (i.e., at 1 AU distance from the Sun; 1 AU = 150 × 10^6 km), are given here: flow speed ranges 300–800 km s^{-1}: particle number density ranges 3–20 cm^{-3}; the solar wind consists of 96% protons, 4% He^{2+} ions, and some minor constituents, plus an adequate number of electrons; temperature of ions and electrons range 10^4–10^6 K; magnetic field measures ~4 nT.

The solar wind flow speed is usually much higher than the local sound and Alfvén speeds, and typical Mach numbers are approximately 10. This implies that the plasma kinetic pressure is much higher than both the magnetic pressure and the thermal pressure. It also means that the magnetic field is frozen-in in the expanding flow.

The field lines can be regarded as "stream lines" of the flow. Generally, they maintain their identity on their way through the entire heliosphere; since, due to the near absence of collisions in the tenuous plasma, the particles can hardly ever leave their original field lines. All particles move, on the average, radially away from the Sun.

Therefore, the stream lines interconnecting particles emerging from the same source on the rotating Sun are curved like Archimedean spirals (i.e., Parker spirals*)*. The curvature is determined by both the flow speed and the distance from the Sun. The average angle between the stream lines and the radial direction to the Sun at 1 AU amounts to ~45°.

With increasing distance to the Sun, the Parker spiral winds up further and further: from Jupiter's orbit on the direction of the local magnetic field can be considered almost perpendicular to the solar wind flow. Note, however, that the plasma keeps moving radially, in analogy to the needle in the spiral grooves of an old-fashioned record.

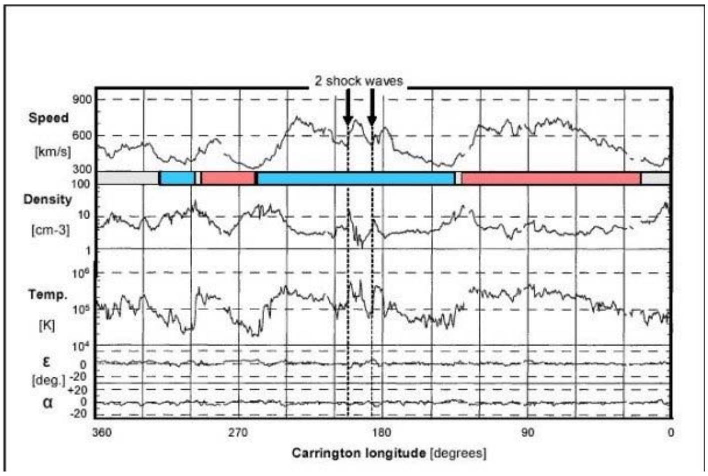

Figure 2.The solar wind proton parameters (flow speed, density, temperature, and flow angles relative to the radial direction) during a full solar rotation in early 1975, as observed by the Helios 1 solar probe close to 1 AU
The colored bars indicate the polarity of the interplanetary magnetic field: blue, inward pointing; red, outward pointing; gray, mixed polarities.

The high variability of the solar wind has been a puzzle since the beginning of the observations. As a typical example, Figure 2 shows the main solar wind parameters obtained near Earth’s orbit during an entire solar rotation. Measurements were recorded shortly before the solar activity minimum in 1976. This basic pattern then remained almost unchanged through several months.

- For two intervals of some 60° in longitude (corresponding to duration of several days), the flow speed exceeds 600 km s^{-1}.

- In both of these high-speed streams, the plasma density is lowest and the proton temperature is highest (while the electrons are somewhat cooler), precisely opposite to the low-speed regions in between.

- Both high-speed streams are regions of unipolar magnetic fields (indicated by the colored bard in Figure 2).

- In a short interval in the middle of Figure 2, interplanetary shock waves went by, characterized by abrupt increases in speed, density, temperature, and magnetic field strength (not shown). This type of shock wave is caused by transient activity on the Sun. On average, not more than one such event occurs per solar rotation at solar minimum.

- The left part of Figure 2 shows a less well-ordered pattern of flow speeds and polarities.

- The flow angles ε_P (out of the ecliptic) and α_P (azimuthal) fluctuate within approximately 10° around the radial direction. More pronounced deflections are observed in compression regions ahead of high-speed streams and at shock waves.

Observations as shown in Figure 2 revealed that solar wind variability cannot be simply attributed to transient disturbances of an otherwise quiet or structureless solar wind. Specifically, the persistent occurrence of high-speed streams with flow speeds up to 800 km s^{-1} was realized to be an intrinsic feature of the solar wind phenomenon. With decreasing solar activity in the years 1973–1975, these high-speed streams developed into stable large-scale structures. Some of them were observed at the same solar longitude for several months (i.e., they were corotating, stationary in relation to the Sun, through several solar rotations).

In the Skylab era, the coronal sources of the high-speed streams could be identified: these are regions of diminished brightness at soft X-ray and EUV wavelengths (so-called coronal holes). In Figure 3, a large coronal hole can be seen to cover the south polar cap. The sharp edges of this coronal hole transform strikingly well into the outer corona. Much further out, they can still be recognized as sharp boundaries between fast and slow solar wind streams.

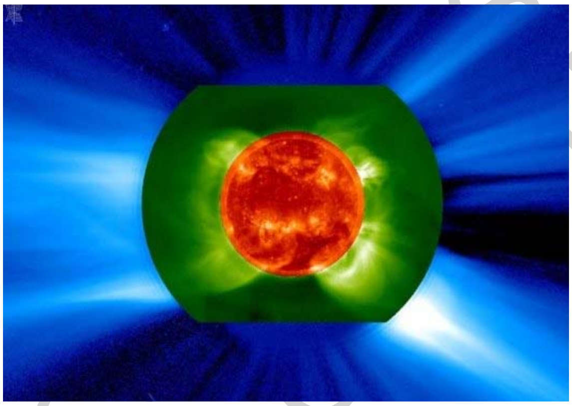

Figure 3.Montage of images from three different telescopes on SOHO: from EIT, the EUV disk image (at 19.5 nm); from LASCO-C1, the inner corona (at 530.3 nm); from LASCO-C2, the outer corona (in white light)
Note, in particular, the dark area on the disk near the south pole which is a good example of a large coronal hole.

Coronal holes mark the regions in which the magnetic field lines open directly into interplanetary space, and the solar wind can flow along unimpeded. At times of low solar activity, they are often located above both polar caps. In contrast, closed loop-like structures are always related with active centers such as sunspots, which most often are located at low heliographic latitudes. Coronal holes and the high-speed streams emerging from them have to be regarded as features of the *quiet* Sun, not the *active* Sun. In fact, careful analysis proved that if there is a "quiet" solar wind at all, it is more likely to be found in the fast wind rather than in the slow wind.

2.2. The Ballerina Model

On the basis of these discoveries, a new three-dimensional model of the heliosphere and the stream-structured solar wind emerged that is most adequately visualized in terms of the "ballerina" model first proposed by Alfvén in the 1970s.

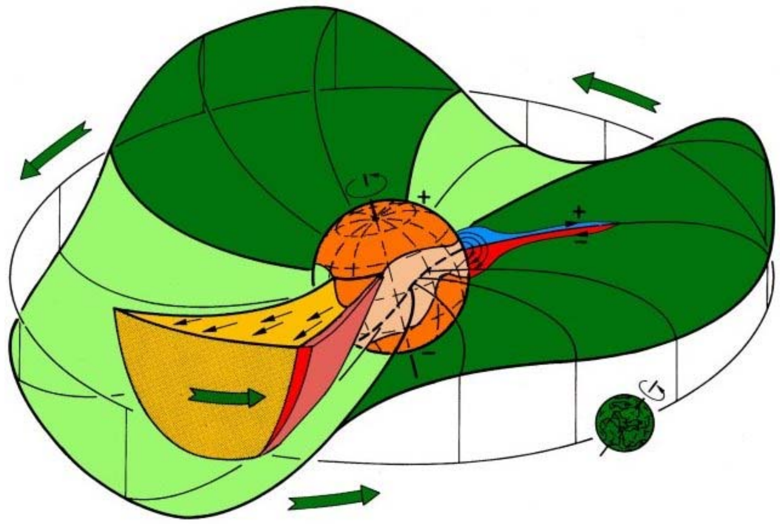

Figure 4.The “ballerina model” of the inner heliophere as suggested by Alfvén in 1977

Figure 4 is an artist's view of the inner heliosphere as it might appear immediately before a typical solar activity minimum (e.g., in 1996). We find the Sun's poles to be covered by large coronal holes. They are areas of open magnetic field lines, the northern hole being of positive (outward directed) polarity, and the southern hole being negative. Some tongue-like extensions of the coronal holes reach well into the equatorial regions and give the Sun the appearance of a tilted magnetic dipole.

The Sun's equatorial region is governed by a few remaining bright active centers (including sunspots) and their loop-like and mainly closed magnetic structures. What looks like the skirt of a spinning ballerina is the warped separatrix between positive and negative solar magnetic field lines "dragged" out into interplanetary space by the radially outflowing solar wind plasma.

This heliospheric current sheet is formed on top of closed magnetic structures at the transition between closed and open flux tubes (i.e., generally in the middle of the near-equatorial belt of activity). If the spinning skirt passes an observer sitting, say, at Earth, a polarity switch would be noticed, which is referred to as crossing of an magnetic sector boundary. The size and number of magnetic sectors is closely related to the structure of the underlying corona (i.e., the shape of the activity belt and the coronal holes, respectively).

The coronal holes are the sources of high-speed solar wind, while the emission of slow interstream-type solar wind is confined to the equatorial region. The warps of both the current sheet (which can be taken to be the heliomagnetic equator) and the coronal hole boundaries with respect to the heliographic equator allow high speed streams to extend to low latitudes so that they become observable even in the plane of the ecliptic.

This occurs preferentially in the two years before activity minimum, when the large-scale coronal structure is rather stable and high-speed streams reappear at the same heliographic longitudes for many solar rotations.

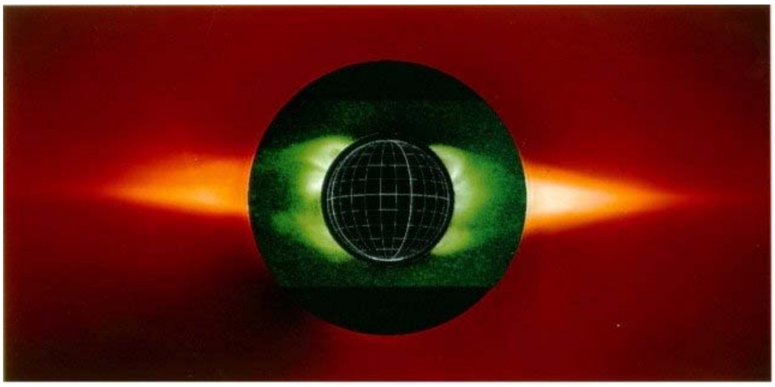

Figure 5.A coronagraph view of the extended minimum corona (on February 1, 1996), composed of a green-line emission image and a white-light image taken by the LASCO coronagraphs C1 and C2 onboard SOHO.

At times of minimum solar activity, there are almost no warps left in the current sheet that is then planar like a disk lying very close to the plane of the heliographic equator. This is demonstrated in Figure 5, where two images registered by the LASCO (large-angle and spectrometric coronagraph) coronagraphs on board SOHO (Solar and Heliospheric Observatory) in early 1996 were merged. They give a very typical example of the appearance of the extended corona at the most recent activity minimum. The inner part was taken in the light of the green corona line at 530.3 nm produced by Fe XIV ions at temperatures of 2×10^6 K. This spectral line is particularly well suited to outline hot magnetic structures in the inner corona. The outer part taken in white light shows the larger scale electron density distribution.

Images of this type taken during the months around the solar activity minimum have revealed the following:

- The appearance is nearly symmetric about the solar axis, with a flat high-density sheet right in the equatorial plane.

- The green (inner) patterns merge well into the white (outer) patterns, indicating that hot magnetic loops are closely associated with high-density streamers on top.

- The dense sheet emerges from bright, apparently closed-loop systems (called helmet streamers) centered at latitudes of 30°–45° in both hemispheres; the loop tops usually reach out to about 1.5 R_s, in some cases to well beyond 2 R_s; their helmet-like outer extensions are clearly bent towards the solar equator.

- Around the equator, there is a more diffuse bright pattern, clearly separated from the high-latitude loops and strongly varying with time.

- There is no detectable green-line emission above either of the poles, confirming that the density and temperature in polar coronal holes is rather low; their edges appear to be sharp and well defined and remain stable on time scales of several days.

The structure of the corona is governed by the solar magnetic field. The magnetic topology is not just that of a simple magnetic dipole. Higher order multipole components are also involved. A coronal image like Figure 5 leads to the immediate impression that there are several magnetic loop systems anchored at the Sun.

Consequently, there must be a series of polarity changes around the limb, apart from the global polarity switch from "positive" at the northern coronal hole to "negative" in the south. The radial extent of these multipole moments is much more limited than that of the overall magnetic dipole centered in the polar coronal holes.

Comparison of coronal images like Figure 5 with photospheric magnetograms shows that the midlatitude loop systems are located well on top of magnetic neutral lines that often reach all around the visible half of the Sun. This is also the location of polar crown filaments, which are well known from H-alpha observations.

The near-equatorial magnetic features are more variable, both with space and time, due to the dynamics of some remaining active regions. They cause the green-line corona to vary in intensity by a factor of 10 and more. This variability in conjunction with the smaller scale, and often with inclined magnetic structures, may be the reason for the more diffuse appearance in the equatorial regions.

The formation of antiparallel magnetic fields beyond the closed loops would require the existence of current sheets. Since large streamers coexist at different latitudes, multiple current sheets must also exist, unless they merge somewhere. They form a streamer sheet of initially one solar diameter width. Processes still to be explored may eventually lead to the formation of the large-scale interplanetary heliospheric current sheet imbedded in a flow of slow solar wind. Note that the transition from closed to open magnetic topology at the top of a streamer is generally not yet understood, nor is the release of slow solar wind from these regions.

The flatness and stability of the distant heliospheric current sheet(s) is probably due to the persistence of the midlatitude streamers. In other words, the current sheet is determined by midlatitude phenomena, rather than by streamers above the near-equatorial activity belt. The midlatitude streamers are apparently bent toward the equator by the overexpanding solar wind flow from the polar coronal holes. After all, that would mean that the heliospheric current sheet close to the Sun's equator is being shaped by forces originating in the Sun's polar regions!

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Biographical Sketch

Prof. Dr. Rainer Schwenn obtained his doctorate in experimental plasmaphysics in Munich at the Institut für Plasmaphysik in Garching in 1969. From 1971 to 1978 he worked at the Max Planck Institut (MPI) für Extraterrestrische Physik in Garching as coinvestigator and technical manager of the plasma instruments for the Helios solar probes. Since then he has been employed at the MPI für Aeronomie in Lindau. His scientific work concentrated on solar wind, coronal transients, and other heliospheric subjects. He was lead scientist of the German contribution to the Giotto ion mass spectrometer. As CoI and project scientist of the large-angle and spectrometric coronagraph on SOHO, he and his team developed a new type of coronagraph which worked successfully. From 1982 to 1986 he was a member in the ESA Science Team for Definition of the SOHO project. During 1983/1984 he acted as member in the Topical Team on Solar and Heliospheric Physics for development of the ESA cornerstone program "Horizon 2000." During 1984/1985 he spent a sabbatical year at the Los Alamos National Laboratory. In 1994 he obtained *venia legendi* at the Universität Göttingen and was appointed "Außerplanmäßiger Professor" of astronomy and astrophysics in 1998. From 1998 to 2000 he served in the ESA Solar System Working Group.