

Solar Wind: Global Properties

The most fundamental problem in solar system research is still unsolved: how can the Sun with a surface temperature of only 5800 K heat up its atmosphere to more than a million K? In fact, the solar atmosphere is so hot that not even the Sun's enormous gravity can contain it. Part of it is continuously evaporating into interplanetary space: the SOLAR WIND. As a highly ionized magnetized plasma it dominates a huge volume around the Sun which is called the heliosphere. Only far beyond the outermost planets is a transition into the interstellar gas flowing through our Galaxy expected to occur.

On the rare occasions of solar eclipses, every observer is stunned 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 plasma heliosphere. Interactions between outflowing streams of different speeds and solar transient phenomena cause further complications. Thus, the solar wind as we see it from the Earth's orbit 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 large impact on the Earth. Some effects even make it down to the ground!

The solar wind proves to be one key link between the solar atmosphere and the Earth. Although the energy transferred by the solar wind is miniscule compared to both sunlight and those energies involved in the Earth's atmosphere, the solar wind is capable of pin-pricking the Earth system until it eventually reacts in a highly nonlinear way.

In this article the chief characteristics of the solar wind in context with its sources in the corona will be presented. The next section first describes the basic properties of the solar wind as observed in the comparatively simple situation around solar activity minimum. Next the corona and inner heliosphere are discussed in their full 3D extent. The fate of the stream structure as it evolves with increasing distance from the Sun is then dealt with. Finally we summarize the current knowledge of the different types of solar wind, ending with the admission that none of them is really explained yet.

The solar wind at 1 AU

Basic properties

The existence of the solar wind was theoretically modeled by E Parker in 1958 and experimentally verified in 1962. Since then, it has been observed throughout wide parts of the heliosphere, as close as 0.29 AU and as far as (by now) 70 AU from the Sun, mainly in the ecliptic plane, but also above both solar poles. Some typical parameters as measured at the Earth's orbit (i.e. at 1 AU distance from the Sun) are given in table 1.

The solar wind flow speed is usually much higher than the local sound and Alfvén speeds, and typical Mach numbers are around 10. This implies that the plasma

Table 1. Typical parameters of the slow solar wind at 1 AU.

Flow speed v_p	350 km s ⁻¹
Proton density n_p	9 cm ⁻³
Flux density $n_p v_p$	3×10^8 cm ⁻² s ⁻¹
Composition	96% protons, 4% He ⁺ ions, minor constituents, plus an adequate number of electrons to maintain nearly perfect charge neutrality
Proton temperature T_p	4×10^4 K
Electron temperature T_e	1.5×10^5 K
Magnetic field B	4 nT

dynamic 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. The curvature is determined by both the flow speed and the distance from the Sun. The average Parker angle between the stream lines and the radial direction to the Sun at 1 AU amounts to about 45°. With increasing distance to the Sun the Parker spiral winds up further and further: from Jupiter's orbit in the direction of the local magnetic field can be considered almost perpendicular to the solar wind flow. Actually, the plasma keeps moving radially, in analogy to the needle in the spiral grooves of an old-fashioned record.

Solar wind stream structure

The solar wind exhibits a remarkable variability, even at times of low solar activity. As a typical example, figure 1 shows the main solar wind parameters obtained near the Earth's orbit during a whole solar rotation. They were recorded in early 1974, i.e. close to a solar activity minimum, and the basic pattern seen then remained almost unchanged through several months:

- For two intervals of some 60° in longitude (corresponding to a durations of several days) the flow speed exceeds 600 km s⁻¹.
- In both these high-speed streams the plasma density is lowest and the proton temperature is highest (while the electrons are somewhat cooler), just opposite to the low-speed regions in between.
- Both high-speed streams are regions of unipolar magnetic fields (indicated by the + and - signs),
- In a short interval in the middle of the figure, interplanetary shock waves went by, characterized by abrupt increases in speed, density, temperature and magnetic field strength (not shown here). This type of shock wave is caused by transient activity on the

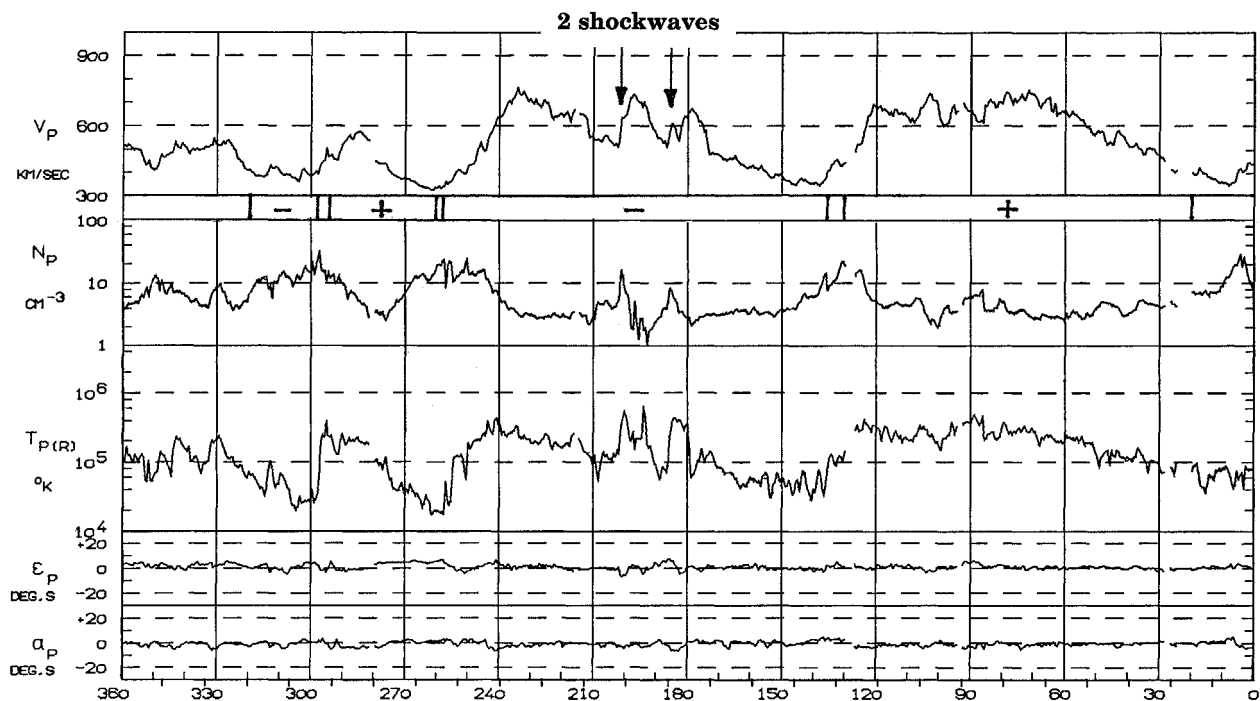


Figure 1. The solar wind proton parameters (flow speed, density, temperature and flow angles relative to the radial direction) during a full solar rotation in early 1975, as observed by the Helios 1 solar probe close to 1 AU. Typical for this phase of minimum solar activity are the two large high-speed streams with the extended compression regions in front. Note also the two transient-related shock waves.

Sun, e.g. SOLAR CORONAL MASS EJECTIONS (CMES). Usually, not more than one such event occurs per solar rotation at solar minimum.

- The left part of the figure 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 about 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 1 revealed that solar wind variability cannot be attributed to just transient disturbances of an otherwise quiet or structureless solar wind. In particular 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 1973–75, 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 stationarily corotating with 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), indicating significantly lower electron densities and temperatures. The boundaries

are remarkably sharp and coincide in detail with those of the high-speed streams properly mapped back to the Sun. Coronal holes mark the regions in which coronal magnetic field lines open freely into interplanetary space (see articles by Kohl and de Forest). At times of low solar activity they cover mainly both polar caps. In contrast, closed loop-like structures are always related with active centers such as SUNSPOTS which most often are located at lower 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.

The solar wind in three dimensions

The 3D heliosphere in terms of the 'ballerina model'

On the basis of these early discoveries, a three-dimensional model of the heliosphere and the stream-structured solar wind emerged. It is most adequately visualized in terms of the ballerina model first proposed by H Alfvén in 1977.

Figure 2 is an artist's view of the inner heliosphere as it may appear immediately before a typical solar activity minimum, e.g. in 1975. 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, the southern hole being negative. One solar cycle later the polarity reverses, of course. Some tongue-like extensions of the coronal holes reach well into the equatorial regions. The Sun's equatorial

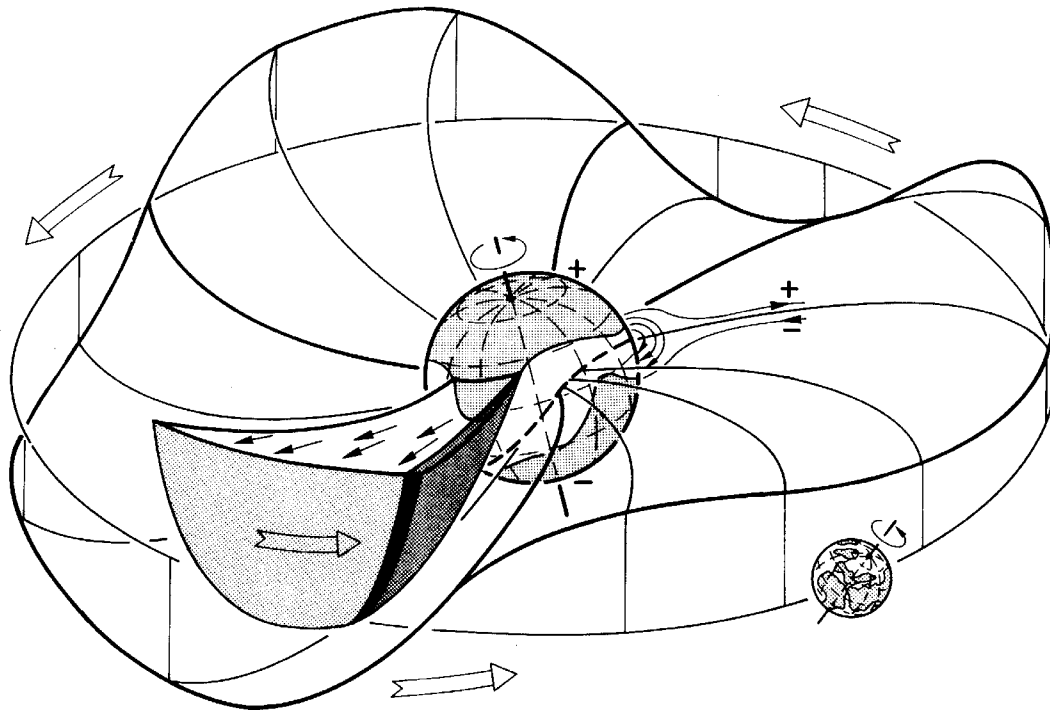


Figure 2. The 'ballerina model' of the 3D heliosphere, according to H Alfvén.

region is governed by bright active centers (including some sunspots left over from the past cycle) 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 the 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 the earth, he would notice a polarity switch and call it a crossing of a 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 (for more details see the article SOLAR WIND: MAGNETIC FIELD).

The heliospheric current sheet: shape and origin

The coronal holes are the sources of high-speed solar wind. The emission of slow solar wind is sharply confined to a belt centered at the warped current sheet of about 40° width in latitude. 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 some high-speed streams to extend to low latitudes so that they become observable

at times even in the plane of the ecliptic. This occurs preferentially in the 2 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.

At times of minimum solar activity there are almost no warps left in the current sheet which is then planar like a disk lying very close to the plane of the heliographic equator. This is demonstrated in figure 3 where two images registered by the LASCO coronagraphs on board SOHO 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 solar activity minimum have revealed that:

- 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,

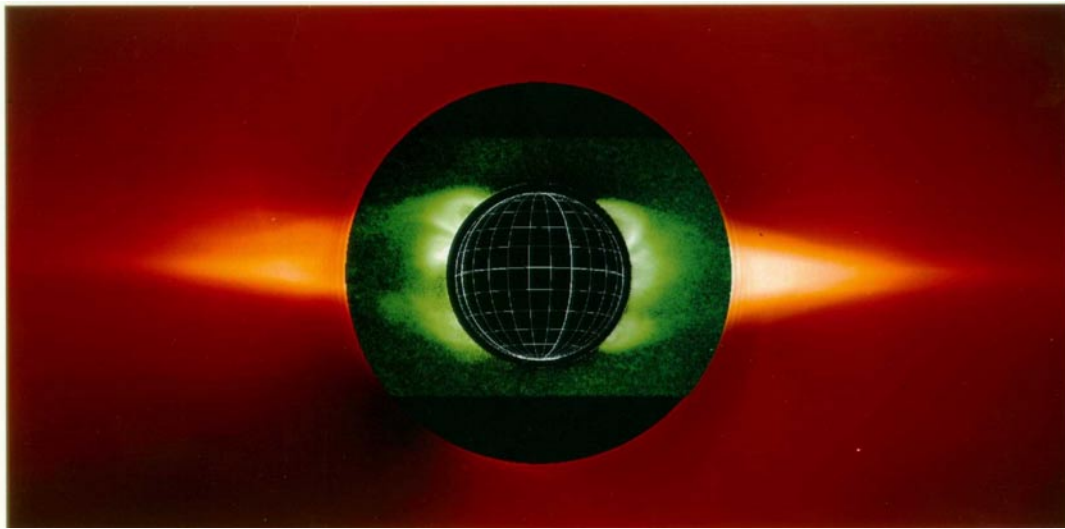


Figure 3. A coronagraph view of the extended minimum corona (on 1st February 1996), composed by a green-line emission image and a white-light image taken by the LASCO coronagraphs on-board SOHO. **This figure is reproduced as Color Plate 54.**

- 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, not even at the comparatively quiet minimum phase. Higher-order multipole components are always involved. A coronal image like figure 3 leads to the immediate impression that there are several magnetic loop systems anchored at the Sun. As a consequence, 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 3 with photospheric magnetograms shows that the mid-latitude loop systems are located well on top of magnetic neutral lines which often reach all around the visible half of the Sun. This is also the location of polar crown filaments 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 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 1 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 mid-latitude streamers. In other words, the current sheet is determined by mid-latitude phenomena rather than by streamers above the near-equatorial activity belt. The mid-latitude streamers are apparently bent towards the equator by the more than radially expanding polar coronal hole magnetic field and high-speed plasma flow. 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!

More information can be found in the articles CORONAL LOOPS, CORONAL STREAMERS, and FILAMENTS.

Solar wind stream boundaries

Coronal holes attract attention not only by their surprisingly sharp boundaries. The high-speed solar

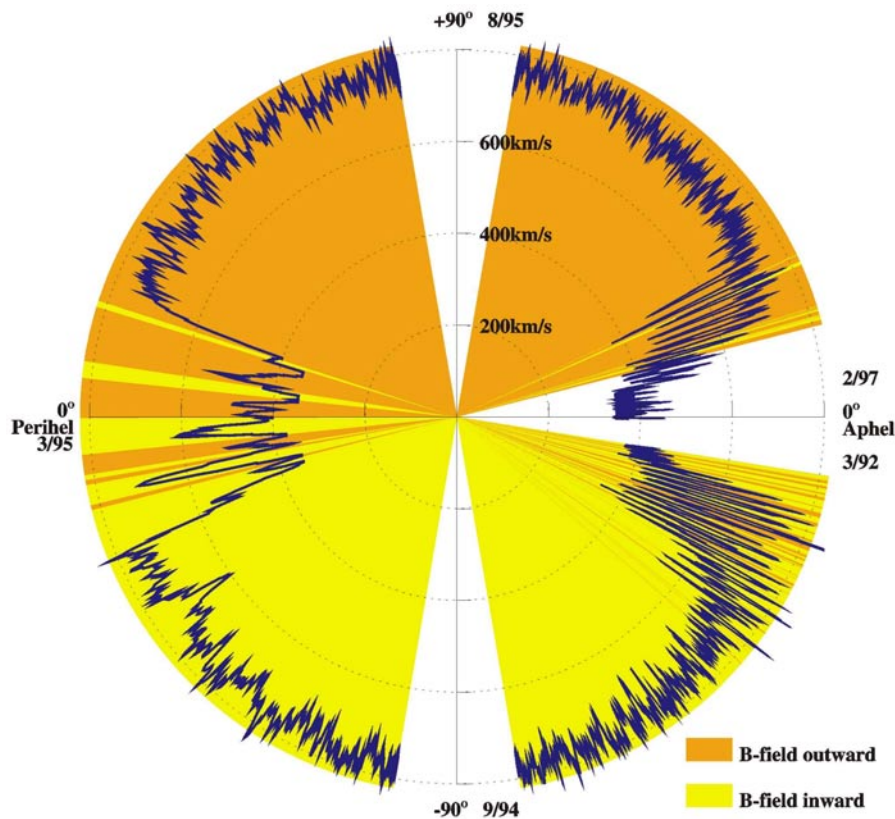


Figure 4. Solar wind and magnetic field polarity observations during the passage of Ulysses across both solar poles. (Courtesy of J Woch, Max-Planck-Institute für Aeronomie.)

wind streams emerging from them are also very distinctly separated from adjacent slow flow. The boundary layer between high-speed wind at 600 km s^{-1} and slow wind at 300 km s^{-1} is often found to be less than 1.5° with respect to heliographic latitude! In longitude, mutual interactions between flows of different speeds tend to smooth the originally steep profiles with increasing distance to the Sun. Only when the Helios solar probes approached the Sun as close as 0.29 AU were similarly thin boundary longitudinal boundary layers confirmed and a ‘mesa-like’ shape of high-speed streams was recognized. In high-speed wind, remnant signatures of the coronal network could be identified, proving its originally filamentary nature. Close to the Sun, all the transition from slow to fast wind was observed to occur apparently as the transition from one flux tube to the next! These discoveries led to the conclusion that high- and low-speed wind are very different in nature, emanate from well-separated sources in the corona, and are due to basically different acceleration mechanisms.

Figure 4 is an impressive experimental confirmation of what has been said in this subsection. This unusual polar plot shows the solar wind speed as measured from the Ulysses space probe during its passage across both solar poles in the years 1992–97. The magnetic

polarity is also indicated. Clearly, high-speed wind is encountered predominantly at latitudes beyond 20° in either hemisphere. During the fast passage through the ecliptic plane (left part of figure 4) abrupt changes from fast to slow and wind and back occurred. In contrast, the rather slow orbital motion of Ulysses away from and towards the ecliptic (right part) allowed mid-latitude fast streams and interstream slow flow to be observed alternately for many solar rotations. Beyond about 35° no slow wind and no ‘wrong’ sector polarity were found any more. For more details about Ulysses see the article SOLAR WIND: ULYSSES.

Further signatures of stream structure

There are some more signatures indicating the basically different nature of high-speed wind from coronal holes and low-speed flow in the streamer belt. They are mainly associated with constituents other than protons and their ionization states (for details see the article SOLAR WIND: COMPOSITION).

- The helium abundance is 3.6% in high-speed wind, very constant in time and almost identical for all streams. In slow wind the abundance is only 2.5% and highly variable. This is one strong indication that high-speed wind is released at lower altitudes in a gravitationally stratified corona.

- The ionization state of heavy ions is significantly lower in fast flow, indicating a lower coronal temperature in its source region.
- In the slow solar wind there is a much more pronounced first ionization potential (FIP) effect, i.e. the elements with a FIP of less than 10 eV are significantly overabundant in comparison to photospheric values (see the article by von Steiger).
- The angular momentum carried away by the solar wind from the rotating Sun is almost completely contained in the slow flow. This is another strong indication that the fast wind starts from rather close to the solar rotation axis, while the slow wind is released only beyond $30 R_s$.

On the other hand, there are also some stunning similarities between the two types of solar wind:

- The momentum flux density $n_p v_p^2 m_p$ does not differ by more than 5%. Using this quantity alone no stream structure at all would be discernible! That means that both types of wind put identical dynamic pressure on any obstacle, e.g. planetary magnetospheres or the pouring up interstellar gas, implying important consequences for the 3D shape of the heliosphere as a whole.
- Similarly, the total energy flux density summoned by the Sun in order to release the solar wind is equal all around the Sun. Of course, the fast flow carries more kinetic energy $n_p v_p^3 m_p$, with it, but the Sun has to bring up much more energy $n_p v_p G m_p M_s / R_s$, in order to lift the high density slow wind out of its gravitational field, and the sum of both remains constant.

There is no conclusive answer yet as to whether these invariances happen by chance, whether they are intrinsic solar phenomena, or are the result of global rearrangement of the different flows beyond the corona. The solution of this problem might hold a key to the understanding of the corona and the generation of the solar wind.

Solar wind streams on their way out into the heliosphere

Solar wind streams and their interactions

A fast stream may follow a slow one if the coronal hole boundary is inclined by some angle to the Sun's rotation axis which is almost perpendicular to the equatorial plane. These two types of plasmas flow side by side in the first place, but start interacting with each other with increasing distance from the Sun. The Parker spiral of a fast plasma stream is less tightly wound up and thus pushes the slow plasma with the more strongly curved field lines. Compression and deflection of the plasma on both sides of the stream interface finally yields the typical profiles found at 1 AU as shown in figure 1. The transition from slow to fast flow in these corotating interaction regions (CIRS) now extends over some $10\text{--}30^\circ$ in longitude (see SOLAR WIND: COROTATING INTERACTION REGIONS). In many cases,

the stream interface survives as a tangential discontinuity which allows us to still recognize what was originally fast and slow flow. The total range filled with plasma affected (i.e. compressed and deflected) by these interactions amounts to some 30° at 1 AU. However, the plasma packed into that range stems from coronal source regions originally spanning some 90° in longitude! Generally, at about 1 AU distance from the Sun all solar wind in the ecliptic plane will have undergone some processing due to stream-stream interactions. In other words: no longer will there be any solar plasma in its original state, and primordial coronal imprints on the plasma will be lost by then. For this reason, one may draw a borderline between the inner and the outer heliosphere near 1 AU.

At the backside of fast streams no interaction of the flows occurs and no CIRs develops since here the different Parker angles lead to a separation of the flows rather than a compression. The stream boundaries are found to extend over some 60° at 1 AU (see, e.g., the stream in figure 1 on the right-hand side). However, mapping back the flow to the Sun assuming a strictly radial flow at the locally measured speed, the original rectangular profile at the Sun is nicely reconstructed!

At even larger distances from the Sun, the compression waves at the CIRs steepen to finally form corotating shock waves. There are fast forward shocks at the frontside, i.e. traveling to the slow wind side, and fast reverse shocks traveling seemingly backward, i.e. into the fast wind coming from behind. Thus, the originally steep stream profiles are further eroded (see also the article SOLAR WIND: COROTATING INTERACTION REGIONS). The corotating shocks at CIRs, similar to transient-related interplanetary shock waves, can accelerate ionized particles to considerable nonthermal energies, as explained in the article SOLAR WIND: ENERGETIC PARTICLES.

Beyond several AU, the CIRs themselves interact and merge by a variety of processes to form merged interaction regions (MIRS). They may be purely corotating MIRs (CMIRs), or include ejecta and shocks from CMEs to form global MIRs (GMIRs). After all, there is an increasing loss of detail of the solar source conditions with further increasing distance from the Sun, such that even the signatures of the solar rotation are lost beyond about 40 AU. At much larger distances, by interaction with the local interstellar medium the solar wind undergoes the termination shock of the heliosphere where it is diverted and decelerated. This region of subsonic flow, the heliosheath, is separated from the impinging interstellar plasma at the heliopause. Inside, the solar wind flow is diverted into the heliotail which is many thousands of AU long. On the upstream side, outside the heliopause, a bow shock may form to divert the interstellar material around the heliospheric obstacle. For details see the article SOLAR WIND: INTERACTION WITH THE LOCAL INTERSTELLAR MEDIUM.

Radial variations of average solar wind parameters

The radial profiles of the basic solar wind plasma parameters are of special importance in that they narrow

down the degrees of freedom available for modeling solar wind expansion. In-situ measurements as close as 0.29 AU (i.e. $60 R_s$ from Sun center) have recently been complemented by optical observations from close to the Sun's limb out to $32 R_s$. On the other hand, the Pioneer and Voyager spaceprobes are currently expanding our knowledge of heliospheric signatures to beyond 70 AU. In the inner heliosphere, the local properties of the flow and its radial expansion are basically determined by the coronal sources and their topology. From about 1 AU distance on, stream-stream interactions and local plasma processes begin playing a dominant role in the solar wind's radial evolution.

- The flow speed profile of the slow wind close to the sun has been inferred from the coronagraphs on SOHO: small density blobs could be traced which are thought to float along with the flow. It begins to accelerate from about $3 R_s$ only, and by $10 R_s$ it is barely faster than 250 km s^{-1} . This profile is consistent with an isothermal expansion at a temperature of about 1.1 MK and a sonic point near $5 R_s$, in good agreement with the simple Parker model. There is a further speed increase of about 50 km s^{-1} until about 1 AU.
- The UVCS instrument on SOHO by applying the Doppler dimming technique was able to determine the fast wind acceleration profile. This type of flow starts in the very low corona and attains a speed of 300 km s^{-1} at $3 R_s$ and 800 km s^{-1} at $10 R_s$. From there on it travels at constant speed. Further details of solar wind acceleration and expansion in the sun's vicinity are found in SOLAR WIND: CORONAL ORIGINS.
- In the outer heliosphere, the speed differences between fast and slow flows are wiped out, and the heliospheric plasma expands at an average constant speed of 400 to 500 km s^{-1} . A slowdown of the solar wind by action of the interstellar gas has not yet been noted.
- The density is consistently found to drop off as R^{-2} as would be expected for a medium which expands spherically at constant speed. However, inside 1 AU the average gradient is $R^{-2.1}$, according to the mentioned speed increase of the slow wind. Also, there is a slight relative over-expansion of the slow wind (by some 10%), at the expense of a commensurate fast wind compression.
- The proton flux density goes most accurately as R^{-2} , on the grand average, from at least 0.3 AU on outward. However, inside 1 AU, the mass flux in fast streams grows by some 15% and decreases accordingly in slow wind. The conclusion is that flux tubes carrying the fast, low-density wind are compressed by some 15% in cross section by the flux tubes carrying the slow, high-density plasma.
- UVCS measured strikingly large line widths of O^{5+} lines in fast flow from polar coronal holes. If interpreted in terms of kinetic ion temperatures,

values of more than 100 MK would be obtained! Also, there is an extreme temperature anisotropy, i.e. the temperature perpendicular to the magnetic field directions is much higher than that parallel to it. These findings support the concept of ion cyclotron heating in this type of solar wind inferred from in-situ observations at 0.3 AU from the Helios solar probes

- The proton temperature in slow wind drops with distance from the sun as $R^{-1.33}$. That is exactly what would be expected for an adiabatic expansion. Extrapolation back to the corona leads right to the observed coronal temperatures of about $2 \times 10^{-6} \text{ K}$. That means that this type of solar wind escapes wave heating by originating from sources with closed magnetic fields without intense MHD-wave emission. In contrast, the fast wind cools off as $R^{-0.78}$, thus indicating substantial additional heat input beyond the corona due to heat conduction and local dissipation of convected wave energy. In the range between 1 and 20 AU temperature variations of $R^{-0.5}$ to $R^{-0.7}$ were reported. Apparently, that is a result of compression heating caused by stream-stream interactions.
- The electron temperature falls off, by and large, significantly slower than expected for adiabatic and isotropic expansion. For details the reader is referred to SOLAR WIND: KINETIC PROPERTIES and the specialized literature.

Signatures of what is affecting the earth system

Generally, the solar wind flow is diverted around the Earth by its magnetosphere which is maintained by the Earth's intrinsic magnetic field (see MAGNETOSPHERE OF EARTH). Solar wind particles cannot enter, unless there occurs a MAGNETIC RECONNECTION of interplanetary and planetary field lines. That may happen if the northward pointing Earth field on the front of the magnetosphere is hit by solar wind carrying a southward pointing interplanetary field. In such cases, significant geomagnetic disturbances of various kinds are initiated (see, e.g. the article SOLAR-TERRSTRAL CONNECTION: COUPLING BETWEEN SOLAR WIND, MAGNETOSPHERE, IONOSPHERE, AND NEUTRAL ATMOSPHERE, MAGNETOSPHERE OF EARTH: GEOMAGNETIC STORMS AND SOLAR WIND ORIGINS and others).

In the present context it is important to discuss by which means the usually radially pointing interplanetary field can be tilted in such an abnormal way.

- Compression and deflection of the solar wind flow in CIRs has important consequences for its magnetic field, too. Naturally, it undergoes the same compression and participates in the deflection process. Thus, there may arise enhanced out-of-the-ecliptic field components, particularly in the vicinity of magnetic sector boundaries which often happen to be embedded in CIRs at 1 AU. The action of potential magnetic reconnection is enhanced by the pressure pulse from the compressed plasma.

- High-speed streams are also characterized by the occurrence of large amplitude transverse Alfvén fluctuations. They are easily recognizable by large excursions in the directions of both the interplanetary magnetic field (including geo-effective southward excursions) and the plasma flow. The field magnitude and the plasma density remain about constant. Typical fluctuation periods at 1 AU range from fractions of a minute to a few hours. Probably, these waves are remnants from coronal activity since they travel outward only, without evidence for local damping (for details see the chapters by Roberts and Gurnett). There is a close correspondence between the southward pointing of the interplanetary magnetic field in the course of Alfvénic fluctuations and geomagnetic activity, leading to clear association between medium-level geomagnetic activity and high-speed solar wind.

The recurrence of this particular type of geomagnetic activity every 27 d, i.e. exactly in the rhythm of solar rotation, had led J Bartels to postulate the existence of M regions on the Sun already in the 1930s. He thought they were long-lived stable regions on the Sun which emit certain particles capable of stirring geomagnetism. After all, he was strikingly right except for one aspect: these M regions are not to be sought in active regions on the Sun, as he thought, but rather in the inactive parts: the M regions are to be associated with the coronal holes representative of the inactive sun, and the geomagnetism is stirred by the streams of high-speed plasma emanating from them.

The major geomagnetic storms are also due to large southward excursions of the interplanetary field, but these are caused by transient processes on the Sun, e.g. coronal mass ejections and their interplanetary counterparts. The interested reader is referred to the articles on CMEs and geomagnetic effects, and SOLAR–TERRESTRIAL CONNECTION: SPACE WEATHER PREDICTIONS.

Slow variations during the solar activity cycle

What does the interplanetary medium sense from changes in solar activity during the solar cycle? That can best be described using the ballerina model (figure 2). It shows the slightly warped heliospheric current sheet separating inward and outward going magnetic field lines around activity minimum. Starting from this state the warps in the skirt begin to grow with increasing activity. They finally break up and turn over at activity maximum. Then, the current sheet begins reorganizing itself according to the overall magnetic field of the Sun which has just undergone a global polarity reversal. The warping diminishes, and at the following minimum the ballerina skirt is flat again; just the magnetic polarity is reversed. Thus, a full magnetic cycle of the Sun (called the Hale cycle) takes 22 yr, i.e. two activity cycles. This is described in more detail in the article SOLAR WIND: MAGNETIC FIELD.

According to the structural changes of the corona, the solar wind also changes. The remarkably stable shapes

of both coronal holes and solar wind high-speed streams in the years before minimum activity are replaced by increasingly irregular patterns. The few remaining fast streams are smaller in size and amplitude, and they come from small, isolated, transient coronal holes.

Almost all around the Sun now emits slow wind. That applies to the poles as well, as indirect measurements using interplanetary scintillations of radio pulsar signals have shown. It is hard to conceive that this can be the same type of slow flow as is found in the streamer sheet at solar minimum. This ‘maximum type’ slow solar wind is found to emerge from substantially larger areas often located far from any current sheet. It is highly variable and usually contains some 4% of helium, thus indicating its release at lower altitudes in the corona than the ‘minimum type’ slow wind.

The whole structure is additionally confused by abrupt disturbances due to interplanetary shock waves driven by CMEs. (see articles on CMEs and SOLAR WIND SHOCK WAVES AND DISCONTINUITIES). Naturally, the occurrence rate of big solar transients follows solar activity very closely, and one would expect to find considerable variations of the average solar wind’s properties going in parallel. It turns out, though, that this is actually not the case, at least not for the plane of the ecliptic where most long-term observations were made so far. There is not much change: the average speed drops from some 500 km s^{-1} at minimum to 400 km s^{-1} at maximum. Other quantities such as particle densities, and the fluxes of mass, momentum, and energy are modulated by not more than about 20%. It is interesting to note that they all reach their minima at activity maximum, despite the many CME and shock events at that time!

Outside the ecliptic plane and especially at very high solar latitudes the solar cycle modulation can be expected to be completely different. At solar minimum there is only fast wind characterized by its high speed and very low density. With increasing activity and the associated disappearance of the polar coronal holes the share of slow type solar wind grows, with its high values of particle and mass flux densities. Thus, the modulation of the average solar wind properties at high latitudes is expected to be much more pronounced than in the ecliptic plane. We will certainly learn more details once the spaceprobe Ulysses has performed its second run across the Sun’s poles.

Summary

In conclusion, it can be stated that the ballerina model (see figure 2) as conceived in the mid-1970s describes the 3D heliosphere at activity minimum in connection with the solar corona fairly well.

It is now well established that there are two basic types of quasi-steady solar wind which differ markedly by their main properties, the location and magnetic topology of their sources in the corona, and probably in their acceleration mechanism. Therefore, in table 2 the more specific values are given separately for both types:

Table 2. Average solar wind parameters at 1 AU, for the time around solar activity minimum.

	Slow wind	Fast wind
Flow speed v_p	250–400 km s ⁻¹	400–800 km s ⁻¹
Proton density n_p	10.7 cm ⁻³	3.0 cm ⁻³
Proton flux density $n_p v_p$	3.7×10^8 cm ⁻² s ⁻¹	2.0×10^8 cm ⁻² s ⁻¹
Proton temperature T_p	3.4×10^4 K	2.3×10^5 K
Electron temperature T_e	1.3×10^5 K	1×10^5 K
Momentum flux density	2.12×10^8 dyn cm ⁻²	2.26×10^8 dyn cm ⁻²
Total energy flux density	1.55 erg cm ⁻² s ⁻¹	1.43 erg cm ⁻² s ⁻¹
Helium content	2.5%, variable	3.6%, stationary
Sources	Streamer belt	Coronal holes

Some further characteristics of different solar wind types at solar activity minimum are:

- The *fast solar wind* emerges from magnetically open coronal holes which are representative of the inactive Sun, i.e. the ‘quiet’ Sun. Consistently, the ‘quiet’ type solar wind is found in high-speed streams. Although the major coronal holes usually cover the polar caps at latitudes beyond 40–60°, the solar wind emerging there over-expands significantly and fills up all heliosphere except for the 40° wide streamer belt close to the heliomagnetic equator.
- The *slow solar wind of the minimum type* originates from above the more active regions on the Sun. It is constrained to the warped streamer belt and comprises the large-scale heliospheric current sheet. The low helium content in this type of solar wind indicates a larger release height. It is not clear yet how slow solar wind can be released at all. The transition from closed loops down below to an open field topology of the free solar wind flow above requires some kind of reconnection, be it in a steady-state mode or involving transient phenomena. It is conceivable that the slow solar wind might be released in a transient mode, in analogy to water drops dripping from the ceiling of a limestone cavern. (A thorough discussion of solar wind acceleration processes can be found in the articles SOLAR WIND: THEORY and SOLAR WIND ACCELERATION.)

Note that there is no continuous transition between these two types. Rather, the boundary layers between them are very thin close to the Sun and correspond in detail to the boundaries of the coronal holes.

There are two additional types of solar wind which can be considered products of the active Sun rather than the quiet Sun:

- the *slow wind of the maximum type* emerges from substantially larger areas distributed all over the Sun and often located far from any current sheet. It contains twice as much helium than the minimum type,
- *plasma clouds* released in huge eruptions at the sun can often be discerned by the unusually high helium

percentages (up to some 30%) and other signatures (see the article SOLAR WIND: MANIFESTATIONS OF SOLAR ACTIVITY). Around activity maximum, these clouds contribute about 10% to the total solar wind flow, on the average.

In conclusion, it is only fair to state that for none of the mentioned types of solar wind is there a unique and generally accepted theoretical model. At present, existing theories are highly controversial. For example, an exciting alternative model for generating the fast or even all solar wind is acceleration in the form of numerous smallest-scale high-velocity jets (other terms in use: microflares, nanoflares, coronal bullets) that were discovered in very high resolution UV observations of the Sun (see TRANSITION REGION: EXPLOSIVE EVENTS). Apparently, such a model is in extreme contrast to Parker’s classical thermal expansion model and its derivatives. This clearly illustrates that the understanding of solar wind acceleration is not yet on firm ground, and further research is needed.

Bibliography

- Burlaga L F 1995 *Interplanetary Magnetohydrodynamics* (New York: Oxford University Press)
- Cravens T E 1977 *Physics of Solar System Plasmas* (Cambridge: Cambridge University Press)
- Golub L and Pasachoff J M 1997 *The Solar Corona* (Cambridge: Cambridge University Press)
- Schwenn R and Marsch E (ed) 1990/1991 *Physics of the Inner Heliosphere* vols I and II (Berlin: Springer)
- Vial J C, Bocchialini K and Boumier P (ed) 1998 *Space Solar Physics (Lecture Notes in Physics)* (Berlin: Springer)

Rainer Schwenn