The Quasi-Stationary and Transient States of the Solar Wind

M. NEUGEBAUER

There are two states of the solar wind: quasi-stationary and transient. After 30 years of measurements by interplanetary spacecraft, the differences in the physical properties of the two types of wind are fairly well determined, but the physical processes involved in their accelerations are not yet understood in detail. The solar wind exists in part because the upper solar atmosphere, called the corona, is very hot, but the heating mechanisms are also not well understood. Recent research suggests a link between the heating and acceleration mechanisms.

THE SOLAR WIND IS THE EXTENSION OF THE SUN'S ATMOSPHERE that pervades interplanetary space. As its name implies, it is a wind rather than a static atmosphere, and it flows approximately radially outward from the sun with speeds that vary from 250 to 2000 km s^{-1}. It is a highly ionized plasma, the principal constituents of which are protons and electrons. Near the orbit of Earth, its average density is ~8 ion-electron pairs per cubic centimeter. Its electrical conductivity is so high that magnetic fields generated within the sun are trapped in the flow and dragged out into space with the wind.

The existence of a continuously blowing solar wind was first suggested to account for the nearly antisolar orientation of the plasma tails of active comets (*1*). In 1958, Parker (*2*) explained that, in the absence of a high pressure in the interstellar medium or any other restraining force, such a continuous outflow was a necessary consequence of the 1×10^6 to 2×10^6 K temperature of the corona (the part of the solar atmosphere above ~4000 km in altitude). Although understanding of the acceleration of the solar wind has matured considerably since Parker's landmark paper and the confirmatory observations by spacecraft in the early 1960s, the solar wind is still an area of active research. Parker was not originally concerned with how the corona is heated. In recent years, however, it has become clear that the problems of heating the corona and accelerating the wind are not so readily separated as was first assumed.

There are two types of solar wind that must be explained: the quasi-stationary and the transient. The term quasi-stationary describes flows for which large-scale features change over periods of many days to several months. High-speed quasi-stationary streams have their origin in features called coronal holes, which are large, low-density regions of the corona from which single-polarity, weak magnetic fields open out into interplanetary space. There are other regions of the corona where plasma is confined by closed magnetic structures with field lines emerging from the photosphere (the visible surface of the sun) and reentering it after extending no more than one or two solar radii above the surface. The transient wind results from the explosive release and ejection of this magnetically confined plasma.

This review covers current ideas of how the corona is heated, how the quasi-static solar wind is accelerated, and how the transient wind differs from the quasi-stationary wind and offers some suggested interpretations of those differences. The final section gives a glimpse of future work.

Heating the Corona

It is generally agreed that magnetic fields must be responsible for coronal heating. Some of the kinetic energy of convective motions in the outer part of the sun is converted to magnetic energy near the solar surface and then is converted to thermal motions of the plasma in the corona. The magnetic field emerging from the surface of the sun is different from the relatively uniform field emerging from Earth's surface in that it is concentrated in a few small-scale regions of high field strength. The convection cells, called granules, are organized into supergranules, each of which is approximately 30,000 km across and has a lifetime of about 1 day. The magnetic field is concentrated on the periphery of the supergranules. Small flares, termed microflares, have been observed to occur at small bipolar structures within this magnetic network (*3*), especially at the corners where supergranules meet. Approximately 10^3 microflares occur somewhere on the solar surface each second (*4*), each releasing on the order of 10^{26} erg. That is approximately the amount of power required to heat the corona and accelerate the wind.

Solar convection causes constant motion of the field lines. On open field lines, the shuffling of the magnetic footpoints (the locations where the magnetic field lines cross the visible solar surface) creates hydromagnetic waves that move out along the field lines into the corona. The microflares are probably an additional source of waves. Some wave modes are readily damped, and the absorption of their energy can contribute to the heating of the corona. The common Alfvén mode wave (a propagating fluctuation in the direction but not in the magnitude of the field) is less easily damped, and a substantial flux escapes to be detected in the wind. There are circumstances, however, in which energy and heating can be extracted from those waves too; for example, they can be converted to other wave modes in magnetic fields that are significantly inhomogeneous or curved on scales of the order of the wavelength. A recent study of the propagation of waves in a model coronal hole (*5*) indicates that Alfvén waves with periods equal to or less than ~5 min, which is the period corresponding to the peak energy in the convective motions, are strongly reflected back toward the sun (that is, they are trapped) if the coronal temperature is below ~10^6 K, but they escape into the wind if the temperature is higher. This suggests that Alfvén waves may be important in heating the plasma in coronal holes.

The author is a Senior Research Scientist at the Jet Propulsion Laboratory of the California Institute of Technology, Pasadena, CA 91109.

A different heating mechanism may occur in regions of closed field lines, where the convective shuffling of both ends of a magnetic loop twists or braids the field lines. Parker (*6, 7*) believes, and computer modeling tends to confirm, that the field arranges itself into regions of relatively uniform field separated by localized current sheets at what are called tangential discontinuities. With further shuffling and twisting, the fields are stressed until they reconnect across the discontinuities and release energy in what Parker calls nanoflares. With each nanoflare releasing 10^{24} erg, it is possible to produce the 10^7 erg cm^{-2} s^{-1} necessary to maintain the hot, bright corona seen in x-ray observations of closed field regions. Although the detection of individual nanoflares is beyond the present capability of Earth-based solar observatories, there is some evidence from space observations that coronal heating may indeed occur impulsively.

Acceleration of the Quasi-Stationary Solar Wind

Parker's theory (*2*) dealing with the quasi-stationary solar wind can be summarized by consideration of the equations of motion and continuity for a steady-state, spherically symmetric flow as follows:

$$nmv \frac{dv}{dr} = -\frac{d}{dr}(2nkT) - \frac{nmMG}{r} \qquad (1)$$

$$\frac{d}{dr}(nvr^2) = 0 \qquad (2)$$

where n is the number of proton-electron pairs per unit volume, m is the proton mass (electron mass can be neglected), v is velocity, r is the distance from the sun, k is Boltzmann's constant, T is temperature, M is the mass of the sun, and G is the gravitational constant. The factor of 2 in the pressure gradient accounts for the fact that both the protons and the electrons exert pressure. By assuming that temperature is uniform throughout the corona and then drops to a low value, Parker obtained the solar-wind velocities required by the observations of comet tails.

Since the early 1960s, a series of increasingly sophisticated space instruments has obtained detailed information about the physical properties of the solar wind over solar distances ranging from 0.3 to 50 AU. The observational effort has been accompanied by many attempts to improve the theory to explain those data. The first improvement was to replace the assumption concerning $T(r)$ with an energy equation;

$$nv\left(\frac{mv^2}{2} - \frac{mMG}{r^2} + \frac{5}{2}kT\right) - \kappa\frac{dT}{dr} = \text{energy input} \qquad (3)$$

where κ is thermal conductivity. Equations 1 to 3 underlie most theoretical studies, with various simplifications made or other terms added for exploration of the importance of different processes. Separate equations can be written for protons and electrons, allowing them to have different temperatures. Three-fluid equations have been used to account for the effect of He^{2+} ions. Other studies have included magnetic forces and the ways in which the magnetic field can modify thermal conduction. In the mid-1970s, however, the solar wind took on characteristics that could not be explained by minor tinkering with these equations.

As seen from Earth, the sun rotates once every ~27 days. The solar wind speed v, He (α particle) abundance n_a/n_p, and proton density n_p for two solar rotations when the solar wind was unusually stationary are shown in Fig. 1. Each of two long-lived, high-speed streams were observed twice during this period of two solar rotations. Those two streams came from two large coronal holes. A phenomenologic model of the quasi-stationary solar wind is shown in Fig. 2; in the lower corona, the flow expands out of the coronal holes around regions where the magnetic tension of closed field loops is sufficient to inhibit the wind. The geometry demands relaxation of the assumptions of spherical symmetry and radial expansion. Although some theoretical models indicate that the effect of nonradial flow is not large, the solar wind speed at 1 AU does appear to depend on the extent to which the magnetic field spreads out between the base of the corona and 1 AU.

The principal problem is explaining the velocity and density in the flow from coronal holes. None of the theories mentioned above can do it. Additional sources of energy and momentum are required. Furthermore, to obtain high speeds at 1 AU without reducing the density to unrealistically low values, it is necessary to add this energy and momentum high in the corona, above the critical point where the flow becomes supersonic.

One mechanism that has been investigated in some detail is acceleration by the remnant Alfvén waves that are not damped in the process of heating the corona. The effect of those waves would be to add a pressure term $-d < |\delta\mathbf{B}|^2/8\pi > /dr$ to Eq. 1, where $\delta\mathbf{B}$ is the perturbation of the vector magnetic field. Although it is still questionable whether there are enough waves to account quantitatively for the properties of the fast wind, several features suggest the importance of waves in the flow of plasma from coronal holes. One of the more intriguing oddities is that the α particles and other heavy ions flow away from the sun with speeds that exceed the speeds of protons by approximately the Alfvén speed (the speed of Alfvén waves) despite the fact that their greater masses make escape from the sun more difficult. This phenomenon has not been satisfactorily explained, however, even if the waves are taken into account. Another probable manifestation of waves in coronal hole flow is the observation that the minor ion species usually have equal thermal velocities rather than equal temperatures, which is consistent with their reaching equilibrium by collisions with propagating magnetic structures or waves rather than by Coulomb collisions with other ions.

The densities and speeds observed in coronal hole flow have been

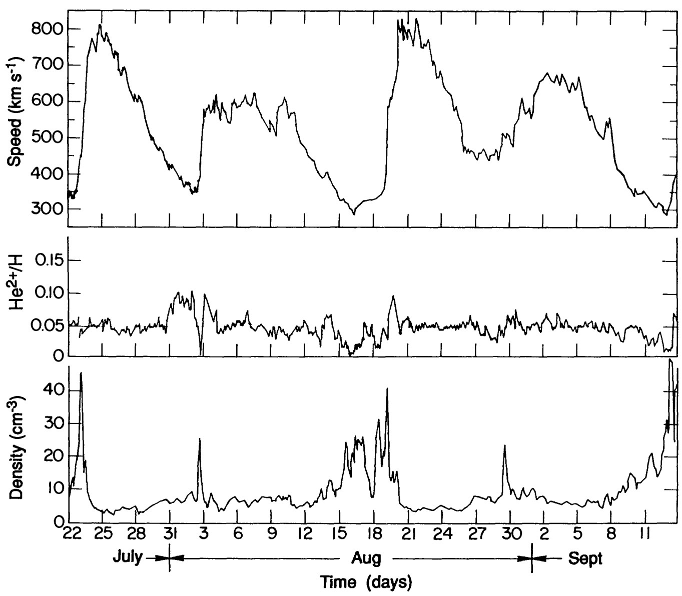

Fig. 1. Three-hour averages of the solar wind speed, ratio of He to H densities, and proton densities observed by the IMP spacecraft (1974). [Reprinted from (*12*) with permission, © American Geophysical Union]

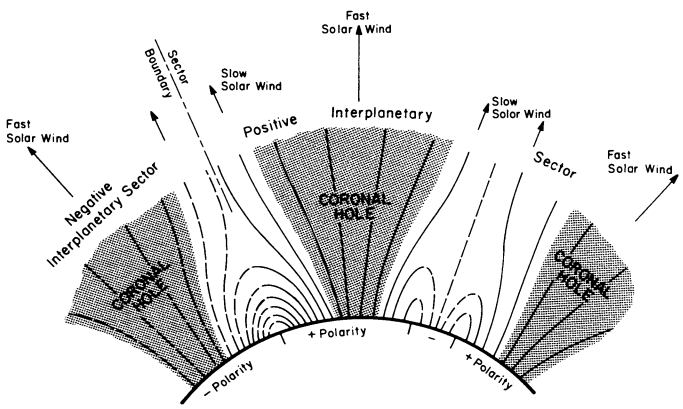

Fig. 2. Sketch of the magnetic structures associated with the flow of the solar wind from coronal holes. [Adapted from (*13*) with permission]

calculated for idealized conditions by considering the effect of the heat flux carried by superthermal electrons (*8*). Although parts of those calculations have been criticized (*9*), the possible importance of the modification of the electron heat flux by superthermal electrons cannot be ruled out.

It has also been suggested that the acceleration of the quasi-stationary solar wind may depend on small-scale, nonstationary events close to or below the current limits of observation from a distance of 1 AU. The chemical composition of the solar wind differs from that of the photosphere. The relative overabundance of elements with first-ionization potentials <10 eV has been interpreted as evidence that, in the region where the wind forms, the separation of plasma from neutral gas occurs in structures with scale sizes on the order of only 10 km (*10*). On a larger scale, in coronal holes structures called macrospicules rise to altitudes of 5,000 to 40,000 km before becoming so tenuous that they disappear. Small bipolar field structures continuously emerge from the surface and disappear in bursts of energy called x-ray bright points. Extreme ultraviolet views of the sun show explosive events, jets, and coronal bullets that shoot upward with speeds of up to 400 km s^{-1}. These features may be the result of magnetic reconnection in microflares. Once launched by a microflare, a jet of plasma could be further accelerated in the diverging magnetic field by what has been descriptively called the melon seed effect. If spatially limited, impulsive events are in fact the source of the quasi-stationary solar wind, then it is necessary to understand how they merge to yield the relatively featureless wind observed at $r \geq 0.3$ AU.

There is no shortage of suggestions about the mechanisms responsible for the acceleration of the quasi-stationary flow from coronal holes. The problem is to decide the relative contributions of wave acceleration, superthermal electron heat flux, and jets or other small-scale sources of momentum and energy. Each of these three mechanisms is intimately related to one or more of the processes that may be important in heating the corona.

This discussion of the quasi-stationary solar wind has focused on the acceleration of the high-speed flow from coronal holes, but there are also long-lived, low-speed flows between the high-speed streams, as can be readily seen in Fig. 1. Some of the slow quasi-stationary wind comes from regions above closed magnetic loops as sketched in Fig. 2. Note the reversal of the direction of the magnetic field above the loop; such field reversals, called magnetic sector boundaries or heliospheric current sheets, are almost always embedded in a stream of slow, dense plasma with cooler than average temperature and lower than average abundance of He^{2+} ions. These streams can be traced back to bright solar features called coronal streamers. Even so, not all the slow wind is associated with streamers and sector boundaries; the rest of it may come from the edges of coronal holes or perhaps from the quiet corona associated with neither holes nor streamers. Although the source is uncertain, the acceleration of the low-speed, quasi-stationary wind has not been an issue because its velocity and density are consistent with predictions based on Eqs. 1 to 3 without invoking additional processes such as wave acceleration or jetting. It does not necessarily follow, however, that those processes do not occur in the acceleration of the low-speed wind. Once the source regions of the low-speed quasi-stationary solar wind have been identified, its acceleration should be reconsidered.

The Transient Solar Wind

Once every 0.5 day to once every 3 days, depending on the phase of the solar cycle, the quasi-stationary solar wind is somewhere interrupted by a transient event. The sequence of pictures of the solar corona in Fig. 3 shows the launching of one such disturbance. Large events, like the one in Fig. 3, typically consist of an outer expanding bright shell (upper left), inside of which is a dark region that contains a second bright feature (seen best in the frames in the upper right and lower left). These events, called coronal mass ejections (CMEs), are visible manifestations of the source of the transient solar wind.

The inner bright feature in Fig. 3 corresponds to an erupting solar prominence. Before eruption, quiescent prominences are relatively dense (10^{10} to 10^{11} cm^{-3}), cool (5000 to 8000 K), long-lived (months) structures, $\sim 2 \times 10^5$ km long that can be seen arching some 5×10^4 km above the limb of the sun. They are believed to be supported against gravitational forces and, at the same time, to be prevented from moving out into the solar wind by magnetic forces. The exact nature of the magnetic configuration is a subject of current research.

It is commonly believed that a CME begins when the large-scale magnetic structure that contains the prominence suddenly becomes

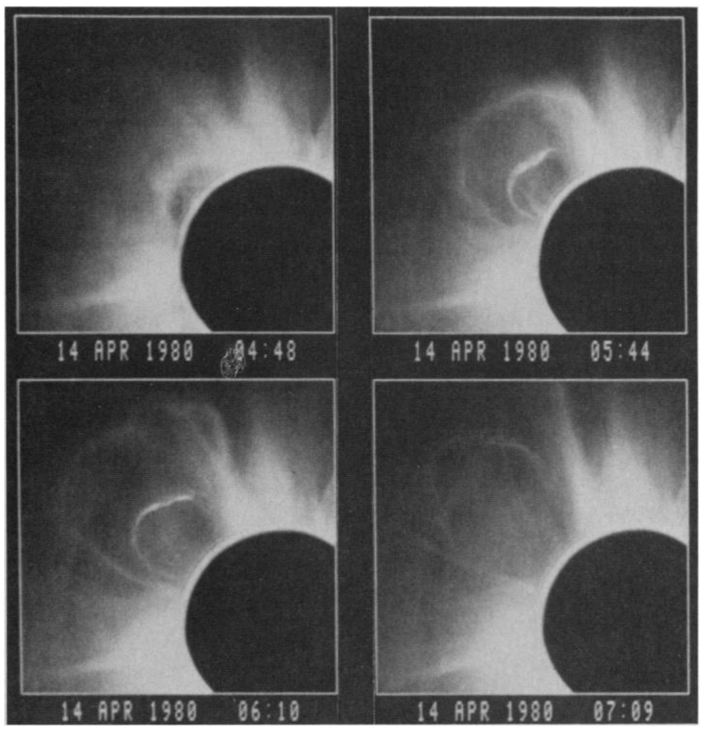

Fig. 3. A time sequence of four images obtained by the Solar Maximum mission on 14 April 1980. [Courtesy of A. Hundhausen, National Center for Atmospheric Research]

unstable; the details of this process are not yet understood. In some events, the outer bright shell exists before the start of the CME, whereas in other events it is thought to result from compression of the corona as the newly released material plows through it. The prominence itself starts moving outward shortly thereafter. A minority of CMEs are associated with solar flares rather than with erupting prominences, but the initiation of the CME apparently precedes the start of the flare. In other words, prominence eruptions and flares are probably the results rather than the causes of CMEs.

An example of a CME that moved through the corona with sufficient speed that it was preceded by an interplanetary shock can serve to illustrate some of the differences between the quasi-stationary and the transient solar winds. Figure 4 shows the changes in several plasma parameters as the ISEE-3 spacecraft encountered a boundary between quasi-stationary and transient plasmas. From top to bottom are plotted the proton density (n), velocity (v), and temperature (TK); the ratio of the proton temperatures parallel ($T_{\|}$) and perpendicular ($T_{\perp}$) to the magnetic field; the ratio of the densities of He to H ions; and the magnitude (β), solar-ecliptic longitude (ϕ), and latitude (θ) of the magnetic field. At the start of the interval, those parameters were typical of flow from a small coronal hole. The passage of two interplanetary shocks (at 2040 UT, 28 September 1978, and ~0230 UT, 29 September 1978) presaged the arrival of a transient flow that swept over the spacecraft starting at ~0813 UT, 29 September 1978. Geomagnetic data and data from other spacecraft were used to estimate the time of the second shock (*11*).

Note that the proton temperature changed from $\sim 2 \times 10^5$ K in the undisturbed coronal-hole flow, to more than 10^6 K in the shocked plasma, to 7×10^4 K in the transient wind. The low proton

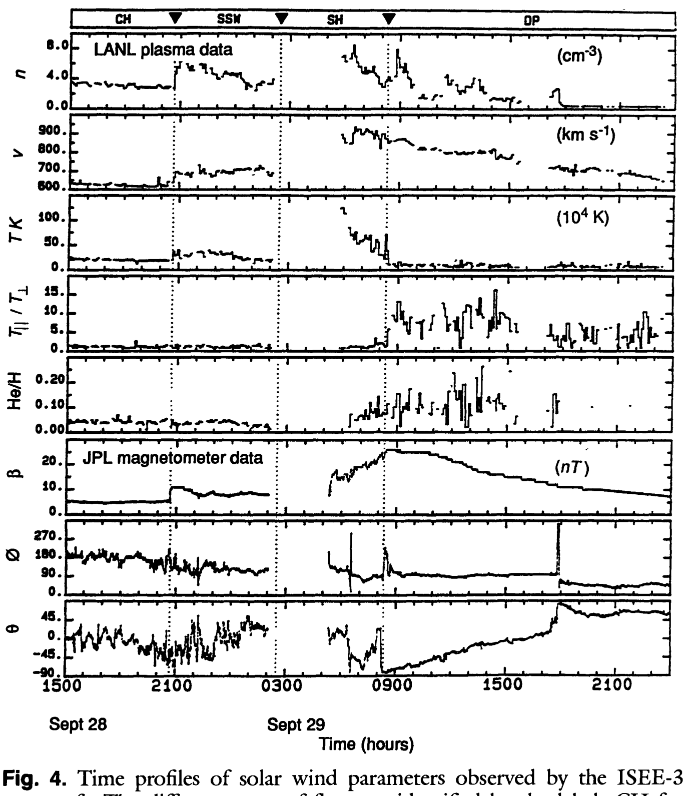

Fig. 4. Time profiles of solar wind parameters observed by the ISEE-3 spacecraft. The different types of flow are identified by the labels CH for coronal hole, SSW for shocked solar wind, SH for sheath (the region between a shock and the high-speed plasma that drives it), and DP for driver plasma (called the transient flow in the text). (See text for identification of the contents of each panel.) [After Galvin *et al.*; adapted from (*11*) with permission, © American Geophysical Union]

temperature typical of the transient wind has been interpreted as evidence for strong expansion of the plasma between the sun and the point of observation near 1 AU. The electron temperature T_e is also often lower in the transient wind than its average value of $\sim 1.5 \times 10^5$ K in the quasi-stationary wind. The relatively low temperatures of the transient wind are, at least qualitatively, consistent with expansion of the plasma from a radial extent of 1 solar radius or less to the 20 to 40 solar radii calculated from the product of the observed speed and the time it takes the plasma from the CME to pass a spacecraft at 1 AU.

As the solar wind expands away from the sun, the strength of the magnetic field B decreases, and conservation of the magnetic moment ($T_{\perp}/B$) leads to a decrease in the temperature $T_{\perp}$ of the ions and electrons perpendicular to the magnetic field. In the quasi-stationary wind, instabilities generate waves that interact back on the protons to keep the anisotropy $T_{\|}/T_{\perp}$ from growing much larger than ~2.0. In the dense, low-speed quasi-stationary solar wind, Coulomb collisions further limit $T_{\|}/T_{\perp}$ to a value close to 1.0. Figure 4 shows that $T_{\|}/T_{\perp}$ was as high as 10 in the transient flow of 29 September 1978. This difference between the quasi-stationary and the transient winds can perhaps be partially explained by a greater degree of expansion of the transient wind, but it probably also depends on the low level of wave activity often found in the transient wind. Common signatures of transient flows are high field strength, low magnetic field variance, and low velocity variance. Notice in Fig. 4 that the high-frequency fluctuations in the direction angles of the field are much smaller in the transient wind than in either the undisturbed quasi-stationary wind or the shocked plasma.

Another probable effect of the difference in wave levels is the difference in the differential streaming of Fe ions such that in the 28 to 29 September 1978 event the ratio $|\mathbf{v}_{Fe} - \mathbf{v}_p|/v_A$ (where $\mathbf{v}_{Fe}$ and $\mathbf{v}_p$ are the iron-ion and proton velocities and v_A is the Alfvén speed) varied from ~1 before the shock, to ~2 behind the second shock, to ~0 in the transient flow. Except for this one example, however, there has been no comprehensive study of how the heavy ion velocities and temperatures differ between the quasi-stationary and transient winds.

Why is the wave amplitude so small in the transient wind? It was suggested above that disturbances caused by the convective shuffling of the footpoints of the field would be carried off by waves if the field lines were open to space but would lead to tangential discontinuities and nanoflares if the field lines were closed. That explanation is supported by the fact that tangential discontinuities are more frequently observed in transient flows than in the wind from coronal holes. Some of the waves in the quasi-stationary wind, however, are probably generated in interplanetary space by instabilities arising from velocity shears and from anisotropies in the plasma. Strong fields tend to inhibit the development of the instabilities that cause the waves. The level of fluctuations in space plasmas in general, be they in the solar wind or in Earth's magnetosphere, appears to depend on the parameter $\beta = 8\pi nkT/B^2$, which is the ratio of the thermal to the magnetic energy densities. Because of its strong fields and low temperatures, the transient wind often exhibits unusually low values of β compared to the values observed in the quasi-stationary solar wind.

One of the first things noticed about the solar wind after large solar flares was an increase in the abundance of He ions. In the quasi-stationary wind, the ratio of He to H densities increases with the speed of the wind up to a maximum of ~0.05 in the fastest coronal hole flows. The fifth panel of Fig. 4 shows that n_a/n_p increased to 0.10 to 0.20 in the transient wind of 29 September 1978; at the same time, the abundance of Fe ions increased by a factor of ~3 (*11*). Although enhanced relative abundances of heavy

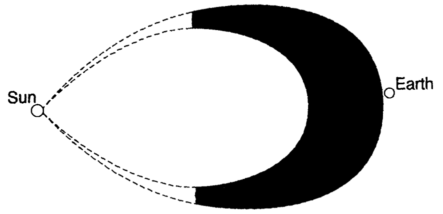

Fig. 5. A flux rope representation of a magnetic cloud. The pitch of the helical magnetic field increases outward from the center of the flux rope. A spacecraft near Earth would sample a linear cut through the structure as it expands away from the sun. [Reprinted from (*14*) with permission, © American Geophysical Union]

ions are commonly observed in the transient wind independent of whether or not a flare occurred, more data are required to determine the dependences of the enhancements on first-ionization potentials and other parameters and to understand the causes of the differences between the ion abundances in the quasi-stationary and transient winds.

The charge states of the ions in the transient wind are also often highly unusual compared to those in the quasi-stationary solar wind. The degree of ionization of ions in the solar wind is largely determined by ion-electron collisions within the first few solar radii; beyond that distance collisions become increasingly rare, and the ionization state is frozen at the value attained in the collisional regime. Typical ionization temperatures T_c are $<2 \times 10^6$ K. In the transient wind, however, T_c is often higher by a factor of 2 to 3, which suggests that the ions come from a hotter region of the corona. Photoionization by flare x-rays is also a possibility. Unusually low ionization states are also sometimes observed in the transient wind. Most startling was the detection of singly ionized He ions with a relative abundance three orders of magnitude greater than that expected to exist in a 10^6 K plasma; those observations have been interpreted as encounters with the plasma from the prominences themselves, which must sometimes move from the sun to 1 AU without coming to thermal equilibrium with the surrounding plasma. A further complication is that both high and low charge states of an ion species are sometimes observed simultaneously.

Consider next the variation of the magnetic field in Fig. 4. There was a sudden change in the direction of the field at the leading edge of the transient wind that was followed by a slow rotation over the next 10 hours. This type of structure, called a magnetic cloud, can be modeled as an expanding magnetic flux rope, as illustrated in Fig. 5. The structure of the trailing edge is indicated by dashed lines because of the present uncertainty about the magnetic topology of that region.

A related noteworthy difference between the quasi-stationary and transient winds is the direction of the electron heat flux and the streaming of energetic particles. In the quasi-stationary wind, the electron distribution function has a field-aligned high-energy tail that carries the electron heat flux outward, away from the sun. A prominent feature of the transient wind, however, is a two-tailed distribution that can be interpreted as heat fluxes moving in both directions, toward and away from the sun. Such bidirectional streaming could arise if both ends of the field line were attached to the hot corona, as sketched in Fig. 5. Bidirectional streaming of energetic protons has also been observed in the transient wind, although the proton and electron events do not always occur simultaneously. An alternative configuration to that in Fig. 5 that could also explain the bidirectional streaming is the reconnection of the field lines behind the plasma from the CME to form a plasmoid that is magnetically disconnected from the sun. Reconnection must occur eventually to prevent a continuous increase in the number of field lines reaching out into space, but the reconnection might be to other field lines if the loop does not close on itself.

The speeds of CMEs near the sun cover a large range, from ~20 to ~2000 km s^{-1}. Although interplanetary shocks, which can be easily identified in solar wind data, form ahead of the fastest ejections, material from the more common, slower CMEs has no such signal to warn of the shock's approach. Thus there is a bias that favors the study of strong, fast events, but those slower events that have been studied do show many of the same features.

There is, however, a great diversity among the transient events independent of their speed. Not all the features outlined above (that is, low T_p, low T_e, high $T_\parallel/T_\perp$, strong, steady fields that sometimes have a flux rope geometry, low β, increased heavy ion abundances, unusual ionization states, and bidirectional streaming) occur in every event. For example, in one study flux rope geometry could be discerned in only 30% of a set of bidirectional electron streaming events (*15*). When features characteristic of the transient wind do occur, they are often patchy. High He abundance, for example, sometimes occurs simultaneously with strong, steady fields (as in Fig. 4) and sometimes precedes or follows an interval of strong field.

Conclusions

What do the many differences in the properties of the quasi-stationary and transient winds tell us about the processes of coronal heating and solar wind acceleration? The observation of stronger magnetic fields in the transient wind is consistent with the idea that this plasma is originally confined by magnetic forces strong enough to prevent the expansion of the wind. The differences in the fluxes of hydromagnetic waves are also important. Recall that, in the quasi-stationary wind, not only is the magnetic field more variable than in the transient wind but there are many indirect manifestations of wave activity, such as lower values of $T_\parallel/T_\perp$, differential flow between heavy ions and protons with a magnitude dependent on the Alfvén speed, and a tendency for different ion species to have equal thermal speeds rather than equal temperatures. The waves may be an important contributor to the acceleration of the wind from coronal holes. Because of the stronger magnetic field and the different magnetic geometry in the closed magnetic field regions that are the source of the transient wind, any waves created by mechanical motions of field lines or by plasma jets created in nanoflares are probably trapped and absorbed, thereby heating the plasma further. The wave energy is stored as thermal energy and then converted to bulk flow energy only when the confining field becomes unstable and the plasma is suddenly ejected into space.

The difference in the plasma temperatures of the two types of wind is interpreted as evidence that the transient wind undergoes greater expansion between the sun and 1 AU than the quasi-stationary wind. A possible explanation is that a quasi-stationary solar wind stream flows in a quasi-stationary channel and that its lateral expansion is limited by the presence of neighboring streams with which it is presumably in a state of pressure balance. The transient wind, on the other hand, is evidently released at a sufficiently high pressure that it can push aside preexisting streams and expand in three dimensions.

The higher state of ionization of heavy ions in the transient wind reveals that the transient plasma is hotter than the quasi-stationary wind at the solar distances where collisions are important, despite the opposite, expansion-caused difference in the temperatures of the two types of wind at 1 AU. A possible interpretation is that the magnetic structure that destabilizes to produce a CME is large enough to include the collision-dominated region, which extends to a few solar radii. The patchiness of the plasma composition, of the state of ionization, and of β suggests that the structure also includes various distinctive substructures; the flux rope feature illustrated in Fig. 5 is one type of substructure. The inhomogeneity of the transient wind is in contrast to the relative uniformity of plasma parameters across a high-speed stream from a coronal hole.

Future Directions

In summary, the quasi-stationary wind is driven by energy and momentum arising from solar convection that are deposited throughout a region extending from the base of the corona to beyond the critical point where the flow becomes supersonic. Research is currently focused on determining the relative contributions of heating and acceleration by waves, heating high in the corona by superthermal electrons, and direct deposition of mass, momentum, and energy by small-scale structures and events such as microflares. Solar convection is also the ultimate source of the energy for the transient wind, but because of the different magnetic configuration all the energy is used to heat rather than to accelerate the plasma. There are many unanswered questions about transient flows. What are the nature and origin of the large-scale magnetic structures as well as of the inhomogeneous (patchy) substructures within them? What is the destabilization mechanism; how, where, and when does it occur? What are the systematics of the highly variable ion abundances in the transient wind, and how are they to be interpreted? What is the topology of the magnetic field behind the ejected plasma?

Progress in addressing those questions requires more theoretical work, more complete analysis of data already in hand, and better observations. Several future space missions are expected to make significant contributions. The Ulysses (launched in 1990) and WIND (currently scheduled for launch in 1992) missions will add to our database on solar wind variations, including improved measurements of ion abundances and charge states. The joint NASA–European Space Agency SOHO mission (launch planned for 1995) will map solar spectral features, from which we can calculate densities, temperatures, and velocities in the region of coronal heating and solar wind acceleration, at the same time that it measures ion abundances and charges at 1 AU. A soft x-ray telescope to be flown on the Japanese-American Solar-A mission late this year should shed new light on the role of microflares in heating the corona. NASA's yet-to-be-approved Orbiting Solar Laboratory will be able to image solar features as small as 100 km, thus testing some of the current ideas about the role of small-scale structures. Perhaps the ultimate mission for studying the acceleration of the solar wind is the Solar Probe, now in the planning stages, which would fly through the corona down to an altitude of only 3 solar radii.

REFERENCES AND NOTES

1. L. Biermann, *Z. Astrophys.* **29**, 274 (1951).
2. E. N. Parker, *Astrophys. J.* **128**, 664 (1958).
3. J. G. Porter, R. L. Moore, E. J. Reichmann, O. Engvold, K. L. Harvey, *ibid.* **323**, 380 (1987)
4. J. G. Porter and R. L. Moore, in *Solar and Stellar Coronal Structure and Dynamics*, R. C. Altrock, Ed. (National Solar Observatory, Sunspot, NM, 1988), p. 125.
5. R. L. Moore, Z. E. Musielak, S. T. Suess, C.-H. An, in preparation.
6. E. N. Parker, *Astrophys. J.* **318**, 876 (1987).
7. ——, *Geophys. Res. Lett.* **17**, 2055 (1990).
8. S. Obert, in *Solar Wind Five*, M. Neugebauer, Ed. (NASA Conf. Publ. 2280, National Aeronautics and Space Administration, Washington, DC, 1983), p. 149.
9. E. C. Shoub, in *Proceedings of the Sixth International Solar Wind Conference*, V. J. Pizzo, T. E. Holzer, D. G. Sime, Eds. (NCAR/TN-306 + Proc, National Center for Atmospheric Research, Boulder, CO, 1988), p. 59.
10. R. von Steiger and J. Geiss, *Astron. Astrophys.* **225**, 222 (1989).
11. A. B. Galvin *et al.*, *J. Geophys. Res.* **92**, 12069 (1987).
12. S. J. Bame, J. R. Asbridge, W. C. Feldman, J. T. Gosling, *ibid.* **82**, 1487 (1977).
13. A. J. Hundhausen, in *Coronal Holes and High Speed Wind Streams*, J. B. Zirker, Ed. (Colorado Associated Univ. Press, Boulder, 1977), p. 225.
14. L. F. Burlaga and R. P. Lepping, in *Physics of Magnetic Flux Ropes*, C. T. Russell, E. R. Priest, L. C. Lee, Eds. (American Geophysical Union, Washington, DC, 1990), p. 373.
15. J. T. Gosling, in *ibid.*, p. 343.

16. I thank the Institute of Geophysics and Planetary Physics of the University of California, Los Angeles for hospitality during the period when much of the material for this article was prepared. This article also presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.