NEW INSIGHTS INTO SOLAR WIND PHYSICS FROM SOHO

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ABSTRACT
The Solar and Heliospheric Observatory (SOHO) was launched in December 1995 with a suite of instruments designed to answer long-standing questions about the Sun's internal structure, its extensive outer atmosphere, and the solar wind. This paper reviews the new understanding of the physical processes responsible for the solar wind that have come from the past 8 years of SOHO observations, analysis, and theoretical work. For example, the UVCS instrument on SOHO has revealed the acceleration region of the fast solar wind to be far from simple thermal equilibrium. Evidence for preferential acceleration of ions, 100 million K ion temperatures, and marked departures from Maxwellian velocity distributions all point to specific types of collisionless heating processes. The slow solar wind, typically associated with bright helmet streamers, has been found to share some of the nonthermal characteristics of the fast wind. Abundance measurements from spectroscopy and visible-light coronagraphic movies from LASCO have led to a better census of the plasma components making up the slow wind. The origins of the solar wind in the photosphere and chromosphere have been better elucidated with disk spectroscopy from the SUMER and CDS instruments. Finally, the impact of the solar wind on spacecraft systems, ground-based technology, and astronauts has been greatly aided by having continuous solar observations at the Earth-Sun L1 point, and SOHO has set a strong precedent for future studies of space weather.

Key words: solar corona – solar wind – SOHO – MHD waves – plasma physics – UV spectroscopy

1. INTRODUCTION
If the Sun is a benchmark for stellar astrophysics, then the solar wind is even more of a necessary reference for the study of stellar winds. The Sun is special because of its proximity; the solar wind is unique because we are immersed in it and its plasma can be accessed directly by space probes. Despite all that has been learned by the in situ detection of particles and fields, though, we have learned the most about how the solar wind is produced from good, old-fashioned astronomical imaging and spectroscopy. This paper summarizes the most recent results of this kind from the past decade of observations with the SOHO spacecraft. (A top-ten list of reasons “Why stellar astronomers should be interested in the Sun” is given in an article with that title by Schmelz 2003).

2. BRIEF HISTORY (PRE-SOHO)
Sightings of the solar corona and the shimmering aurora (i.e., the beginning and end points of the solar wind that encounters the Earth) go back to antiquity. The first scientific understanding of the outer solar atmosphere came as spectroscopy began to be applied to heavenly light in the late 19th century. In 1869, Harkness and Young first observed the 5303˚ A coronal green line during a total eclipse. Soon after, in the very first issue of Nature, J. Norman Lockyer (the discoverer of helium) reported that these observations were “...bizarre and puzzling to the last degree!” The chemical element responsible for the green line went unidentified for 70 years, after which Grotrian and Edlén applied new advances in atomic physics to show that several of the coronal emission lines are produced by very high
ionization stages of iron, calcium, and nickel. The puzzle then shifted to explaining what causes the outer solar atmosphere to be heated to temperatures of more than $10^6$ K. Despite many proposed theoretical processes, this “coronal heating problem” is still with us today because there are no clear observational constraints that can determine which if any of the competing mechanisms is dominant.

Knowledge about an outflow of particles from the Sun was starting to coalesce at the beginning of the 20th century. Researchers came to notice strong correlations between sunspot activity, geomagnetic storms, auroral appearances, and motions in comet tails. Parker (1958, 1963) combined these empirical clues with the earlier discovery of a hot corona and postulated a theoretical model of a steady-state outward expansion of gas from the solar surface. Figure 1 shows analytic solutions to Parker’s isothermal solar wind equation, as well as other solutions including the case of spherical accretion found earlier by Bondi (1952). Traditionally this equation was believed to be unsolvable explicitly for the outflow speed, but Cranmer (2004) showed how a new transcendental function (the Lambert W function) can be used to produce exact closed-form solutions of this equation.

Parker’s key insight was that the high temperature of the corona provides enough energy per particle to overcome gravity and produce a natural transition from a subsonic (bound, negative total energy) state near the Sun to a supersonic (outflowing, positive total energy) state in interplanetary space. An initial controversy over whether Parker’s “transonic” solution or Chamberlain’s always-subsonic “breeze” solutions were most physically relevant was dispelled when Mariner 2 confirmed the existence of a continuous, supersonic solar wind in interplanetary space (Snyder and Neugebauer 1964; see also Neugebauer 1997). Also, Velli (2001) showed that the subsonic breeze solutions are formally unstable, and that the truly stable solution for the solar wind case is the one that goes through the sonic point.

In the years since Mariner 2, many other deep-space missions have added to our understanding of the solar wind. The turbulent inner heliosphere was probed by the two Helios spacecraft, which measured particle and field properties between 0.29 and 1 AU (Marsch 1991). In the 1990s, Ulysses became the first probe to venture far from the ecliptic plane and soar over the solar poles to measure the solar wind in three dimensions (Marsden 2001). The Voyager probes are still sending back data on the outer reaches of the solar wind, and one of them may have passed through the termination shock separating the heliosphere from the interstellar medium (e.g., Krimigis et al. 2003).

It has not been possible to send space probes closer to the Sun than about the orbit of Mercury, so our understanding of the corona is limited to remote-sensing observations. Ultraviolet and X-ray studies of the “lower” corona (i.e., within about 0.1 to 0.3 R$_\odot$ from the surface) began in the 1960s and kept improving in spatial resolution from Skylab in the 1970s (Vaiana 1976) to Yohkoh in the 1990s (Martens and Cauffman 2002). Until the 20th century, total solar eclipses were the only means of seeing any hint of the dim “extended” corona (heights above 0.3 R$_\odot$) where most of the solar wind’s acceleration occurs. However, with the invention of the disk-occulting coronagraph by Lyot in 1930 and the development of rocket-borne ultraviolet coronagraph spectrometers in the 1970s (Kohl et al. 1978; Withbroe et al. 1982), a continuous detailed exploration of coronal plasma physics became possible.

3. The SOHO Mission

The Solar and Heliospheric Observatory (SOHO) is the most extensive space mission ever dedicated to the study of the Sun and its surrounding environment. SOHO resulted from international collaborations between ESA and NASA dating back to the early 1980s (see, e.g., Huber et al. 1996) and became a cornerstone mission in the International Solar-Terrestrial Physics (ISTP) program. The SOHO spacecraft was launched on December 2, 1995 and entered a halo orbit around the Earth-Sun L1 point two months later. This orbit allows an uninterrupted view of the Sun, essential for helioseismology, but the distance (about 4 Earth-Moon distances) also puts limits on the amount of data telemetry that can be received. SOHO hosts 12 instruments that study the solar interior, solar atmosphere, particles and fields in the solar wind, and the distant heliosphere. Early results from the first year of operations were presented by Fleck and Švestka (1997), and a more up-to-date summary of the mission—along with details about how to access data and analysis software—is given by Domingo (2002).

This paper presents results mainly from the 5 instruments designed to observe the hot, outer atmosphere of the Sun (excluding the photosphere) where the solar wind is accelerated. These instruments are listed below in alphabetic order.

1. CDS (Coronal Diagnostic Spectrometer) is a pair of extreme ultraviolet spectrometers that view the solar disk and low off-limb corona in the wavelength range 150–785 Å with spectral resolution = 700–4500, and with 2–3 $^\circ$ spatial resolution (Harrison et al. 1995).

2. EIT (Extreme-ultraviolet Imaging Telescope) is a full-disk imager with 5 $^\circ$ spatial resolution that obtains narrow-bandpass images of the Sun at 384, 171, 195, and 284 Å (Delaboudinière et al. 1995). EIT images and movies are probably the most reproduced data products from SOHO (see, e.g., the covers of many popular magazines).

3. LASCO (Large Angle Spectroscopic Coronagraph) is a package of 3 visible-light coronagraphs with overlapping annular fields of view (Brueckner et al. 1995). The C1 coronagraph observes from 1.1 to 3 R$_\odot$ with 5 Fabry-Perot filter bandpasses. The C2 and C3 coronagraphs observe the radii 2–6 R$_\odot$ and 4–30 R$_\odot$, respectively, in either linearly polarized or unpolarized light. C1 was fully operational from launch until the 3-month SOHO interruption in June 1998.

4. SUMER (Solar Ultraviolet Measurements of Emitted Radiation) is an ultraviolet spectrometer that observes the solar disk and low corona in the wavelength range 330–1610 Å with a spectral resolution of about 12000, and with 1.5 $^\circ$ spatial resolution (Wilhelm et al. 1995). SUMER observa-
5. **UVCS** (Ultraviolet Coronagraph Spectrometer) is a combination of an ultraviolet spectrometer and a linearly occulted coronagraph that observes a 2.5 $R_{\odot}$ long swath of the extended corona, oriented tangentially to the solar radius, at heliocentric heights ranging between 1.3 and 12 $R_{\odot}$ (Kohl et al. 1995). The spectrometer slit can be rotated around the Sun. UVCS observes the wavelength range 470–1360 $\AA$ with $10^4$ spectral resolution and $7^\circ$ spatial resolution.

### 4. SOHO Solar Wind Results

The bulk of this paper describes results from the above SOHO instruments (and associated theoretical work) concerning the physics of solar wind acceleration and heating. Figure 2 is an illustrative summary of the topics covered by the following subsections.

#### 4.1. Wind Origins in Open Magnetic Regions

Most of the plasma that eventually becomes the time-steady solar wind seems to originate in thin magnetic flux tubes (with observed sizes of order 100–200 km) observed mainly in the dark lanes between granular cells and concentrated most densely in the supergranular network. These strong-field (1–2 kG) flux tubes have been known as G-band bright points, network bright points, or in groups as “solar filigree” (e.g., Dunn and Zirker 1973; Spruit 1984; Berger and Title 2001). Somewhere in the low chromosphere, the thin flux tubes expand laterally to the point where they merge with one another into a more-or-less homogeneous network field distribution of order 100 G. At a larger height in the chromosphere, these network flux bundles are thought to merge again into a large-scale “canopy” (Gabriel 1976; Dowdy et al. 1986). This second stage of merging is accompanied by further lateral expansion into “funnels” that may be the lowest sites of observable solar wind acceleration.

SUMER has added substantially to earlier observations of Doppler shifts and nonthermal line broadening in the chromosphere, transition region, and low corona (see H. Peter, these proceedings). Observations of blueshifts in supergranular network lanes and vertices, especially in coronal holes that host the fastest solar wind, may be evidence for either the solar wind itself or upward-going waves that are linked to wind acceleration processes (e.g., Hassler et al. 1999; Peter and Judge 1999; Aiouaz et al. 2004). These interpretations are still not definitive, though, because there are other observational diagnostics that imply more of a blueshift in the supergranular cell-centers between funnels (e.g., He I 10830 Å in coronal holes; Dupree et al. 1996; Malanushenko and Jones 2004).

Off-limb measurements with SUMER and CDS have also provided constraints on plasma temperatures at very low heights in the corona. In coronal holes, ion temperatures exceed electron temperatures even for $r < 1 \, d \, R_{\odot}$, where densities were presumed to be so high as to ensure rapid collisional coupling and thus equal temperatures for all species (Tu et al. 1998; Moran 2003). Spectroscopic evidence is also mounting for the presence of transverse Alfvén waves propagating into the corona (e.g., Banerjee et al. 1998). Electron temperatures derived from line ratios (David et al. 1998; Doschek et al. 2001) exhibit surprisingly small values in the low off-limb corona (300,000 to 800,000 K) that are not in agreement with higher temperatures derived from “frozen-in” in situ charge states. The only way to reconcile these observations seems to be some combination of non-Maxwellian electron velocity distributions or differential flow between different ion species even very near the Sun (see Esser and Edgar 2002).

**SOHO** has made new inroads into our understanding of the basic coronal heating problem, but a full review of these results is is outside the scope of this paper. The nature of coronal heating must be closely related to the evolution of the Sun’s magnetic field, which changes on rapid time scales and becomes organized into progressively smaller stochastic structures (see, e.g., Priest and Schrijver 1999; Aschwanden et al. 2001; C. Schrijver, these proceedings). As computer power increases, the direct ab initio simulation of time-dependent coronal heating is becoming possible (Gudiksen and Nordlund 2004).
4.2. THE FAST SOLAR WIND

It has been known for more than three decades that dark coronal holes coincide with regions of open magnetic field and the highest-speed solar wind streams (Wilcox 1968; Krieger et al. 1973). At the minimum of the Sun’s 11-year magnetic cycle the coronal magnetic field is remarkably axisymmetric (e.g., Banaszkiewicz et al. 1998), with large coronal holes at the north and south poles giving rise to fast wind ($v_\perp > 600$ km/s) that fills most of the heliosphere. It was fortunate that the first observations of SOHO were during this comparatively simple phase, thus minimizing issues of interpretation for lines of sight passing through the optically thin outer corona.

One of the most surprising early results from the UVCS instrument concerned the widths of emission line profiles of the O VI 1032, 1037 Å doublet in coronal holes. These lines were an order of magnitude broader than expected, indicating kinetic temperatures exceeding 100 million K at $r > 2 R_\odot$ (Kohl et al. 1997). Because the observational line of sight passes perpendicularly through the nearly-radial magnetic field in large coronal holes, this kinetic temperature is a good proxy for the local ion $T_\perp$. Further analysis of the O$^{5+}$ velocity distribution was made possible by use of the “Doppler dimming/pumping” effect; i.e., by exploiting the sensitivity to the radial velocity distribution when the coronal scattering profile is substantially Doppler shifted away from the stationary profile(s) of solar-disk photons. This technique allowed the ion temperature anisotropy ratio $T_\perp/T_k$ to be constrained to values of at least 10, and possibly as large as 100. Temperatures for both O$^{5+}$ and Mg$^{9+}$ were found to be significantly greater than mass-proportional when compared to protons (the latter measured by proxy with neutral hydrogen via H I Ly $\alpha$ 1216 Å), and outflow speeds for O$^{5+}$ may exceed those of hydrogen by as much as a factor of two (see also Kohl et al. 1998, 1999; Li et al. 1998; Cranmer et al. 1999b).

Figure 3 shows a summary of the solar-minimum coronal hole temperatures. Note that when $T_{ion}=T_p$, it is not possible to interpret the measurements as a combination of thermal equilibrium and a species-independent “nonthermal speed.” The UVCS and SUMER data (as well as Helios particle data at 0.3 AU) have thus been widely interpreted as a truly “preferential” heating of heavy ions in the fast solar wind. Because of the low particle densities in coronal holes, the observed collection of ion properties has often been associated with collisionless wave damping. The most natural wave mode that may be excited and damped is the ion cyclotron resonant wave; i.e., an Alfvén wave with a frequency approaching the Larmor frequency of the ions $\omega_\perp$. The SOHO observations discussed above have given rise to a resurgence of interest in ion cyclotron waves as a potentially important mechanism in the acceleration region of the fast wind (e.g., McKenzie et al. 1995; Tu and Marsch 1995, 1997, 2001; Hollweg 1999, 2000; Axford et al. 1999; Cranmer et al. 1999a; Li et al. 1999; Cranmer et al. 2000, 2001, 2002; Galinsky and Shevchenko 2000; Hollweg and Isenberg 2002; Vocks and Marsch 2002; Gary et al. 2003; Markovskii and Hollweg 2004).

Figure 3. Coronal hole kinetic temperatures in the acceleration region of the fast wind. Perpendicular temperatures for protons and O$^{5+}$ above 1.5 $R_\odot$ are from an empirical model that reproduced UVCS data (Kohl et al., 1998; Cranmer et al., 1999b). The upper limit on O$^{5+}$ parallel temperature (dotted line) is from the same empirical model. The two O$^{5+}$ boxes at lower heights are representative of ion temperatures derived from SUMER line widths (Hassler et al., 1997), and the electron temperature (dot-dashed line) is from an empirically constrained multi-fluid model (e.g., Hansteen et al. 1997).

There remains some controversy over whether ion cyclotron waves generated solely at the coronal base can heat the extended corona, or if a more gradual and extended generation of these waves is needed. If the latter case occurs, there is also uncertainty concerning the origin of such extended wave generation. MHD turbulence has long been proposed as a likely means of transforming fluctuation energy from low frequencies (e.g., periods of a few minutes; believed to be emitted copiously by the Sun) to the high frequencies required by cyclotron resonance theories (e.g., $10^2$ to $10^4$ Hz). However, both numerical simulations and analytic descriptions of turbulence indicate that the cascade from large to small scales occurs most efficiently for modes that do not increase in frequency. In the corona, the expected type of turbulent cascade would tend to most rapidly increase electron $T_e$, not the ion $T_\perp$ as observed. Cranmer and van Ballegooijen (2003) discussed this issue at length and surveyed possible solutions.

At times other than solar minimum, coronal holes appear at all solar latitudes and exhibit a variety of properties. UVCS has been used to measure the heating and acceleration of the fast solar wind in a variety of large coronal holes from 1996 to 2004 (Miralles et al. 2001, 2002; Poletto et al. 2002). A pattern is beginning to emerge, in that coronal holes with lower densities at a given heliocentric height tend to exhibit faster ion
outflow and higher ion temperatures (Kohl et al. 2001). However, all of the coronal holes observed by both UVCS and in situ instruments were found to have roughly similar outflow speeds and mass fluxes in interplanetary space. Thus, the densities and ion temperatures measured in the extended corona seem to be indicators of the range of heights where the solar wind acceleration takes place.

### 4.3. The Slow Solar Wind

The slow, high-density component of the solar wind is a turbulent, chaotic plasma that flows at about 300–500 km/s in interplanetary space. Before the late 1970s, the slow wind was believed to be the “ambient” background state of the solar wind, occasionally punctuated by transient high-speed streams. This idea came from the limited perspective of spacecraft that remained in or near the ecliptic plane, and it gradually became apparent that the fast wind is indeed the more quiet and basic state (e.g., Feldman et al. 1976; Axford 1977).

In the corona, the slow wind is believed to originate mainly from the bright streamers seen in coronagraph images. However, since these structures are thought to be mainly closed magnetic loops or arcades, it is uncertain how the wind “escapes” into a roughly time-steady flow. Does the slow wind flow mainly along the open-field edges of these closed regions, or do the closed fields occasionally open up and release plasma into the heliosphere? SOHO has provided evidence that both processes occur, but an exact census or mass budget of slow-wind source regions has not yet been constructed.

Figure 4 summarizes several UVCS results concerning streamers and the slow solar wind. A comparison of the raster images built up from multiple scans with the UVCS slit at many heights shows that streamers appear differently in H I Ly
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Figure 4. Equatorial streamer observed off the west solar limb with UVCS in April 1997. Wavelength-integrated intensities are plotted in reverse (brightest regions plotted as dark) for (a) O VI 1032 Å and (b) H I Ly. White dotted lines show the plane of the ecliptic. Arrows show the computed wind speed, with length proportional to speed, and circles indicate zero speed (see Strachan et al. 2002).

Higher-latitude edges and above the probable location of the magnetic “cusp” between about 3.6 and 4.1 R. Frazin et al. (2003) used UVCS to determine that O5+ ions in the legs of a similar streamer have significantly higher kinetic temperatures than hydrogen and exhibit anisotropic velocity distributions with Tν > Tνx, much like coronal holes. However, the oxygen ions in the core exhibit neither this preferential heating nor the temperature anisotropy. The analysis of UVCS data has thus led to evidence that the fast and slow wind share the same physical processes.

Evidence for another kind of slow wind in streamers came from visible-light coronagraph movies. The increased photon sensitivity of LASCO over earlier instruments revealed an almost continual release of low-contrast density inhomogeneities, or “blobs,” from the cusps of streamers (Sheeley et al. 1997). These features are seen to accelerate to speeds of order 300–400 km/s by the time they reach 30 R, the outer limit of LASCO’s field of view. Wang et al. (2000) reviewed three proposed scenarios for the production of these blobs: (1) “streamer evaporation” as the loop-tops are heated to the point where magnetic tension is overcome by high gas pressure; (2) plasmoid formation as the distended streamer cusp pinches off the gas above an X-type neutral point; and (3) reconnection between one leg of the streamer and an adjacent open field line, transferring some of the trapped plasma from the former to the latter and allowing it to escape. Wang et al. (2000) concluded that all three mechanisms might be acting simultaneously, but
the third one seems to be dominant. Because of their low contrast, though (i.e., only about 10% brighter than the rest of the streamer), the blobs cannot comprise a large fraction of the mass flux of the slow solar wind. This is in general agreement with the above abundance results from UVCS.

Despite these new observational clues, the overall energy budget in coronal streamers is still not well understood, nor is their temporal MHD stability. Recent models run the gamut from simple, but insightful, analytic studies (Suess and Nerney 2002) to time-dependent multidimensional simulations (e.g., Wiegelmann et al. 2000; Lionello et al. 2001; Ofman 2004). Notably, a two-fluid study by Endeve et al. (2004) showed that the stability of streamers may be closely related to the kinetic partitioning of heat to protons versus electrons. When the bulk of the heating goes to the protons, the modeled streamers become unstable to the ejection of massive plasmoids; when the electrons are heated more strongly, the streamers are stable. It is possible that the observed (small) mass fraction of LASCO blobs can give us an observational “calibration” of the relative amounts of heat deposited in the proton and electron populations.

Finally, SOHO has given us a much better means of answering the larger question: “Why is the fast wind fast, and why is the slow wind slow?” A simple, but probably wrong, answer would be that coronal holes could be heated more strongly than streamers, so it would be natural for a pressure-driven wind to be accelerated faster in regions of greater heating. Even though UVCS has shown that heavy ions in coronal holes are hotter than in streamers, the proton temperatures between the two regions may not be that different, and the electrons are definitely cooler in coronal holes.

Traditionally, the higher speeds in coronal holes have been attributed to Alfvén wave pressure acceleration; i.e., the net work done on the plasma by repeated pummeling from outward-propagating waves in the inhomogeneous plasma (e.g., Leer et al. 1982). This is likely to be a major contributor, but it does not address the question of why the wave pressure terms would be stronger in coronal holes compared to streamers. A key empirical clue came from Wang and Sheeley (1990), who noticed that the eventual wind speed at 1 AU is inversely correlated with the amount of transverse flux-tube expansion between the solar surface and the mid-corona. In other words, the field lines in the central regions of coronal holes undergo a relatively low degree of “superradial” expansion, but the more distorted field lines at the hole/streamer boundaries undergo more expansion. Wang and Sheeley (1991) also proposed that the observed anticorrelation is a natural by-product of equal amounts of Alfvén wave flux emitted at the bases of all flux tubes (see also earlier work by Kovalenko 1978, 1981).

The Wang/Sheeley/Kovalenko hypothesis can be summarized as follows. (Any misconceptions are mine!) In the low corona, the Alfvén wave flux $F_\lambda$ is proportional to $V_{\lambda} h \mathbf{v} \cdot \mathbf{l}$. The density dependence in the product of Alfvén speed $V_{\lambda}$ and the squared wave amplitude $h \mathbf{v} \cdot \mathbf{l}$ cancels almost exactly with the linear factor of $\mathbf{v}$ in the wave flux, thus leaving $F_\lambda$ proportional only to the radial magnetic field strength $\mathbf{B}$. The ratio of $F_\lambda$ at the solar wind sonic point (in the mid-corona) to its value at the photosphere thus scales as the ratio of $B$ at the sonic point to its value at the photosphere. The latter ratio of field strengths is proportional to $1/\varepsilon$, where $\varepsilon$ is the superradial expansion factor as defined by Wang and Sheeley. For equal wave fluxes at the photosphere for all regions, coronal holes (with low $\varepsilon$) will thus have a larger flux of Alfvén waves at and above the sonic point compared to streamers (that have high $\varepsilon$). In other words, for streamers, more of the energy flux will have been deposited below the sonic point. It is worthwhile to recall that the response of the solar wind plasma to extended acceleration and heating depends on whether the energy is deposited in the subsonic or supersonic wind (Leer and Holzer 1980; Pneuman 1980). Adding energy in the subsonic, i.e., nearly hydrostatic, corona raises the density scale height and decreases the asymptotic outflow speed. Adding energy above the sonic point results mainly in a larger outflow speed because the “supply” of material through the sonic point has already been set. This dichotomy seems to agree with the observed differences between coronal holes and streamers.

For other simulations showing how the wind speed depends on the flux tube divergence, see Chen and Hu 2002; Vásquez et al. 2003. For a recent summary of low-frequency Alfvén wave propagation, reflection, and damping from the photosphere to the interplanetary medium, see Cranmer and van Ballegooijen 2004.)

### 4.4. Space Weather and CMEs

In addition to the relatively time-steady solar wind, the Sun exhibits periodic eruptions of plasma and magnetic energy in the forms of flares, eruptive prominences, and coronal mass ejections (CMEs). These “space weather” events have the potential to interrupt satellite communications, disrupt ground-based power grids, and threaten the safety of orbiting astronauts (see, e.g., Feynman and Gabriel 2000; Song et al. 2001).

SOHO observations of CMEs have demonstrated this mission’s capability to combine high resolution imaging with sensitive spectral measurements to obtain the morphology, evolution, and plasma parameters of the ejected material. As the rate of CME events increased from solar minimum to solar maximum, many unprecedented observations were obtained. Specifically, EIT, SUMER, and CDS observations contained information about CME initiation; LASCO constructed a huge catalog of sizes, morphologies, and expansion speeds of CMEs; and UVCS provided plasma densities, temperatures, ionization states, and Doppler shift velocities of dozens of CMEs in the extended corona (see reviews by Forbes 2000; Raymond 2002; Webb 2002; Lin et al. 2003). UVCS spectra have provided the first real diagnostics of the physical conditions in CME plasma in the corona, and they have helped elucidate the roles of shock fronts (Mancuso and Raymond 2004), thin current sheets driven by reconnection (Lin et al. 2004), and helicity conservation (Ciaravella et al. 2000).
SOHO has made significant progress toward identifying and characterizing the processes that heat the corona and accelerate the solar wind. Most of the SOHO instruments are expected to continue performing at full scientific capability for many more years, hopefully surviving to have some overlap with upcoming solar missions such as SDO, STEREO, and Solar-B. Unfortunately, none of these missions continue the UVCS-type coronagraph spectroscopy of the extended corona; a next-generation instrument of this type would provide much tighter constraints on, e.g., specific departures from Maxwellian and bi-Maxwellian velocity distributions that would nail down the physics conclusively. NASA’s Solar Probe, if ever funded fully, would also make uniquely valuable in situ measurements of the solar wind acceleration region. Observations have guided theorists to a certain extent, but ab initio models are still required before we can claim a full understanding of the physics. To make further progress, the lines of communication must be kept open between theorists and observers, and also between the solar and stellar physics communities.

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Discussion

Bob Barber: The Sun is a G5 star. For what other types or classes of star do you think that your models hold?

Cranmer: Late-type stars with hot coronae and solar-type winds probably extend up the main sequence at least into the mid-F spectral type and down to M. Evolved stars between the main sequence and the various “dividing lines” in the upper-right H-R diagram also exhibit coronal signatures and probably have solar-like mass loss rates (see B. Wood, these proceedings). Even the outer atmospheres of the “hybrid chromosphere” stars seem to show some similarities to the solar case.

Andrea Dupree: Any time you have strong magnetic fields in a reasonably high-gravity atmosphere, solar-type coronae and winds seem to be a natural by-product. Even a low-gravity supergiant such as Betelgeuse may have a surface field strength of order 500 G (see B. Dorch, these proceedings) and thus magnetic activity and heating in its outer atmosphere.

Jürgen Schmitt: You pointed out that the slow wind originates from individual helmet streamers. Why is it, then, that the slow wind at the Earth shows such uniform properties?

Cranmer: Well, the slow wind is intrinsically more variable than the fast wind, but taking this variability into account, it is true that the slow wind from one streamer looks very much like the slow wind from another streamer. This uniformity may be related to the overall uniformity in the solar wind mass loss rate, which varies only by about 50% for all types of solar wind (e.g., Galvin 1998; Wang 1998). Older solar wind models could not account for this near-constancy of \( \dot{M} \); indeed they predicted that tiny changes in the coronal temperature would result in exponentially amplified changes in \( \dot{M} \). Hammer (1982) and Hansteen and Leer (1995) explained this by modeling the complex negative feedback that is set up between thermal conduction, radiative cooling, and mechanical heating. This explained the similarity between slow-wind and fast-wind mass loss rates, so I would assume that it even better explains the eventual similarity between different source regions of the slow wind.

Manfred Cuntz: Can you comment on the significance of “polar plumes” regarding the acceleration of the solar wind?

Cranmer: Plumes are bright ray-like features in coronal holes that seem to trace out the superradial expansion of these open-field regions. Plumes are denser and cooler than the ambient “interplume” plasma, but there is still some controversy about whether the solar wind inside them is slower (Giordano et al. 2000; Teriaca et al. 2003) or faster (Gabriel et al. 2003) than the flow between plumes. Wang (1994) presented a model of polar plumes as the extensions of concentrated bursts of added coronal heating at the base—presumably via microflare-like reconnection events in X-ray bright points. This idea still seems to hold up well in the post-SOHO era. EIT and UVCS made observations of compressive MHD waves channelled along polar plumes (DeForest and Gurman 1998; Ofman et al. 1999), and if the oscillations are slow-mode magnetosonic waves they should steepen into shocks at relatively low coronal heights (Cuntz and Suss 2001). Somewhere between about 30 and 100 R_s , plumes seem to blend in with the interplume plasma, but it is not yet clear whether this is a gradual approach to transverse pressure balance or the result of something like a Kelvin-Helmholtz mixing instability.

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