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The Solar Wind: Our Current Understanding and How We Got Here

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Abstract. In the original theory for the solar wind, the electron pressure gradient was the principal accelerating force. This was soon recognized to be insufficient to drive the high-speed streams. Subsequently, the discovery of Alfvén waves in the solar wind led to a long series of models in which wave pressure provided additional acceleration, but these wave-driven models ultimately failed to explain the rapid acceleration of the fast wind close to the Sun. An alternate view was that the pressure of hot protons close to the Sun could explain the rapid acceleration, with the proton heating coming from the cyclotron resonance. SOHO has provided remarkable data which have verified some of the predictions of this view, and given impetus to ongoing studies of the ion-cyclotron resonance in the fast wind. After a historical review, we discuss the basic ideas behind current research, emphasizing the importance of particle kinetics. We conclude with some guesses as to how work might proceed in the future.

Key words. Solar wind—coronal holes—solar corona—cyclotron resonance—MHD waves.

1. Introduction

Early spacecraft data in the 1960s revealed solar wind properties which could not be well-explained by models in which the electron pressure gradient was the principal accelerating force. The Alfvén waves discovered around 1970 to be plentiful in the solar wind were thought for a while to provide additional energy and momentum, but they ultimately failed to explain the rapid acceleration of the fast wind close to the Sun. The issue remained clouded until the mid-1990s when the Solar and Heliospheric Observatory (SOHO) began yielding remarkable data concerning the origin of the solar wind, and the heating of the corona from which it originates. (The coronal heating problem is certainly the most famous, but it is often forgotten that the power requirements of the chromosphere per unit of solar surface area are comparable to, and sometimes greater than those of the corona.) SOHO has forced us to discard some long-held ideas, and has also stimulated a number of entirely new ideas. The purpose of this review is to survey our current understanding of the fast solar wind, emphasizing the particle kinetics and the roles of the cyclotron resonance. We also emphasize that there are many remaining problems, especially the source of the ion-cyclotron waves. Since we may be at a watershed, we will also review the historical context.

We will, for the most part, concentrate on the fast solar wind for four reasons: First, we have a pretty good idea where it comes from, especially the large polar coronal holes; see Miralles *et al.* (2002, 2004) for discussions of solar wind flows out of smaller non-polar holes. Second, the fast wind is much steadier than the slow wind, and seems to be less structured. It has always been hoped that this apparently simpler wind would be more amenable to yielding its secrets. But in spite of this, the waves and turbulence in the slow wind seem to have less power than in the fast wind (e.g., Tu & Marsch 1995). Third and most importantly, the fast wind has long been known to be less influenced by Coulomb collisions than the slow wind (e.g., Neugebauer 1981). This means that signatures of other kinetic processes are more readily seen in the data. Indeed, one of our conclusions will be that microscale kinetic processes are an essential ingredient of the physics of the fast wind. Fourth, the physics of the slow wind is widely believed to be very different from that of the fast wind. Thus the slow wind really requires an extensive review of its own; see for example Cranmer (2005); Einaudi *et al.* (1999); Wang *et al.* (2000); Fisk & Schwadron (2001); Lapenta & Knoll (2005); and references therein.

The reader should be aware that we are not attempting a complete literature survey. We do try, however, to refer key papers which themselves provide references to the bulk of the literature. See especially recent reviews by Hollweg & Isenberg (2002, hereafter 'HI'); Cranmer (2002, 2004); Erdös (2003); and Hollweg (2006a, 2006b). We also recommend the review of the physics of wave-particle interactions by Tsurutani & Lakhina (1997).

2. The electron-driven wind

Parker (1958) noted the thermal conductivity of ionized hydrogen scales as $T_e^{5/2}$, where T is temperature and subscript e denotes electrons. If outward thermal conduction dominates the heat equation, then $T_e \propto r^{-2/7}$ in a spherically-symmetric corona, r being heliocentric distance. For a corona in static equilibrium, Parker showed that the slow decline of T_e leads to a plasma pressure at $r \to \infty$ which is many orders-of-magnitude larger than the interstellar pressure. He concluded that with nothing to contain the asymptotic pressure, the corona must expand; the expansion is driven by the electron pressure gradient because T_e remains high.

However, in a later review, Parker (1965) compared theoretical predictions with the by then known properties of the solar wind at 1 AU. He concluded "thus the model for the hypothetical conduction corona leads to a temperature falling too rapidly with radial distance from the Sun, indicating that the actual solar corona is probably actively heated for some considerable distance by the dissipation of waves". We are not yet sure whether waves are responsible, but we now know that he was right about extended coronal heating.

Hartle & Sturrock (1968) presented the first two-fluid model of the solar wind, with separate energy equations for electrons and protons. They obtained a very slow wind: 250 km s^{-1} at 1 AU compared to a typical fast wind speed of 750 km s^{-1} (see Feldman *et al.* (1976) for an early review of the properties of the fast wind). They also found that the model protons were much too cold: 4400 K at 1 AU compared to several times 10^5 K in fast wind. They concluded that "departures of the solar wind characteristics near Earth from those of this model are also to be attributed to heating by a flux of non-thermal energy".

Neither Parker nor Hartle and Sturrock said anything about coronal heating. They began their models at $r = r_S$ with 10^6 K coronal temperatures, and no subsequent heat addition (r_S is the solar radius).

3. The wave-driven wind

The next major advance was the discovery (Belcher & Davis 1971) of the ubiquitous presence of Alfvén waves in the solar wind. Most of the wave power resides at long periods, of the order of hours. The waves predominantly propagate away from the Sun, especially in the fast wind. The outward propagation strongly suggests that the Sun is the source of these waves. One of the outstanding questions is: what on the Sun is responsible for the dominance of the observed timescales of hours?

It was immediately realized that the Alfvén waves might be Parker's "waves", and Hartle and Sturrock's "flux of non-thermal energy". Alazraki & Couturier (1971) and Belcher (1971) inaugurated the concept of the wave-driven wind by noting that the waves exert a 'wave pressure' $-\nabla\langle\delta\mathbf{B}^2\rangle/8\pi$ on the wind (in cgs units, which we shall use throughout); **B** is magnetic field, the prefix δ denotes a fluctuation, and the angle brackets denote a time-average. Hollweg (1973) showed how the wave energy equation could be extended to include dissipation and plasma heating. With heating and wave pressure, the wave-driven models were able to explain the high-speeds and hot protons observed in the fast wind in interplanetary space (e.g., Hollweg 1978).

An early mention of the radiation pressure of Alfvén waves can be found in Bretherton & Garrett (1969). Their work was expanded upon by Dewar (1970) and Jacques (1977).

These wave-driven models generally succeeded in explaining solar wind data far from the Sun, but they failed close to the Sun. In the early 1990s, spacecraft gave us new coronal hole density data, which verified previous evidence that the density declines very rapidly with increasing r (Guhathakurta & Holzer 1994; Fisher & Guhathakurta 1995; Guhathakurta & Fisher 1998). That requires the flow speed to increase very rapidly with r. The wave-driven models could not achieve such rapid accelerations. The reason is simply that, close to the Sun, the wave pressure is small compared to other terms in the momentum balance.

There were other difficulties as well, particularly concerning heavy ions, the best observed being He^{++} because of its relatively high abundance. Ions flow faster than the protons, roughly by the Alfvén speed V_A, and they are hotter than the protons, roughly in proportion to their masses; see Neugebauer (1992) for a review. These properties are most noticeable in the fast wind, because Coulomb collisions are weaker there. Efforts (mainly in the early 1980s) to explain these observations generally invoked the ion-cyclotron resonance to heat and accelerate the ions; see reviews by Isenberg (1983); Cranmer (2002, 2004), and HI. These models were only partially successful. One difficulty was that these early studies considered resonant effects only far from the Sun, well beyond the acceleration region. In contrast, the SOHO data show extensive heavy ion heating in the acceleration region.

There were other indications that the ion-cyclotron resonance was at work. As reviewed by Marsch (1991), *in situ* measurements of proton distribution functions often show that the protons in the vicinity of the peak of the distribution are anisotropic, with more thermal energy perpendicular to the local magnetic field than along the field; this is most noticeable in high-speed wind. Moreover, the average magnetic moment, $T_{p\perp}/B$, increases with distance from the Sun ($T_{p\perp}$ is the proton temperature perpendicular to $\mathbf{B}$). Both of these observations suggest that perpendicular heating is occurring in interplanetary space, and that in turn suggests the cyclotron resonance.

4. The proton-driven wind

Hollweg (1986) and Hollweg & Johnson (1988, hereafter 'HJ') applied these ideas to the solar wind close to the Sun. They assumed that the Sun launches low-frequency Alfvén waves which undergo a turbulent cascade to high frequencies, where they are dissipated into heat via the cyclotron resonance; HJ assumed that the resonant dissipation would heat only the protons, and that this was the only source of coronal heating. The heating rate was dictated by the rate at which energy cascades to high frequencies; HJ took the Kolmogorov rate, $Q = \rho\langle\delta\mathbf{V}^2\rangle^{3/2}/L_{\mathrm{corr},\perp}$ (Q is the volumetric heating rate, ρ is plasma density, $\langle\delta\mathbf{V}^2\rangle$ is the velocity variance associated with the waves, and $L_{\mathrm{corr},\perp}$ is the correlation length perpendicular to the magnetic field). These models also included acceleration by the wave pressure. The waves were taken to be outward-propagating in the short-wavelength WKB limit. (We shall later see that this is formally inconsistent with turbulence.) These models succeeded in reproducing the observed high-speed wind far from the Sun, as well as the rapid acceleration close to the Sun. HJ found that the protons close to the Sun in $r > 3r_{\mathrm{S}}$ were considerably hotter than the electrons. The pressure of the hot protons was mainly responsible for the rapid flow acceleration. The available data at the time indicated that the protons were not hot close to the Sun, and so these models were discarded. Isenberg (1990) extended HJ by including He^{++}. This model too had hot protons close to the Sun, and was discarded.

As it happened, HJ and Isenberg (1990) actually predicted the results which SOHO would soon obtain for coronal holes: hot coronal protons, and heavy ions which flow faster and are more than mass-proportionally hotter than the protons close to the Sun. Moreover, the SOHO results, especially from the Ultraviolet Coronagraph Spectrometer (UVCS), indicate that positive particles in coronal holes close to the Sun are heated mainly perpendicular to the magnetic field; this result is firm for O^{+5} (Dodero *et al.* 1998; Kohl *et al.* 1998; Antonucci *et al.* 2000), but less certain for protons. Thus the SOHO/UVCS results suggest:

1. Consistent with the perpendicular heating of O^{+5}, the cyclotron resonance is at work.
2. With protons hotter than electrons, the solar wind flow is mainly proton-driven, via the divergence of the (presumably anisotropic) proton pressure tensor.
3. At least in the fast wind, coronal heating is proton and ion-dominated. It is not Joule dissipation.
4. The peculiar properties of heavy ions originate close to the Sun in the wind's acceleration region.
5. Coronal heating extends through the acceleration region into the supersonic wind. Most remarkable is O^{+5}, which has a temperature 3×10^8 K at $r = 3.5r_{\mathrm{S}}$; the temperature is still an increasing function of r, in spite of strong adiabatic cooling (Kohl *et al.* 1998). Coronal heating and solar wind acceleration must be treated together. Parker (1965) was right about extended heating.
6. Other instruments on SOHO, especially SUMER (Solar Ultraviolet Measurements of Emitted Radiation), also show indications of ion heating low in the corona (e.g., Tu *et al.* 1998; Moran 2003; Peter & Vocks 2003).

There is, however, one note of caution. The proton and oxygen temperatures are derived from spectral linewidths, assuming that non-thermal broadening due to waves or turbulence is negligible. This is almost certainly true for O^{+5}, which shows considerably higher linewidths than the protons (Esser *et al.* 1999; Cranmer 2004). (Recall that $\mathbf{E} \times \mathbf{B}$ drifts would be the same for all particles if their flow speeds differ by much less than V_A; $\mathbf{E}$ is the electric field.) Moreover, models (e.g., HI) suggest that waves or turbulence do not contribute substantially to any of the observed linewidths.

Finally, we note that other authors investigated the effects of hot coronal protons (Esser & Habbal 1995, 1996; Hansteen & Leer 1995; Axford & McKenzie 1996; Esser *et al.* 1997; McKenzie *et al.* 1995, 1997; Lie-Svendsen *et al.* 2001), but only *ad hoc* heating functions were used. Li (1999, 2002); Li & Habbal (1999); and Li *et al.* (1999, 2004) have extended the original models of HJ and Isenberg (1990) to include thermal anisotropy, wave dispersion, and other effects.

5. The ion-cyclotron resonance

The cyclotron resonance occurs when the wave frequency seen by a particle matches the particle's cyclotron frequency. Formally the resonance condition is $\omega - k_\parallel V_\parallel = \pm\Omega$, where ω is the wave angular frequency, $k_\parallel$ is the wavenumber along $\mathbf{B}$, $V_\parallel$ is the particle's drift speed along $\mathbf{B}$, and Ω is the gyro-frequency. For ions resonating with left-hand polarized waves the $+$ sign is appropriate, while the $-$ sign is used for right-hand waves. When the resonance condition is satisfied, the particle's energy changes secularly. The secular energy change can be a gain or a loss, depending on the phase of the particle's gyro-motion relative to the wave. In a random field, that phase will be random, the particle will gain or lose energy randomly, and consequently the particle will undergo a random walk in velocity space, which in turn leads to velocity space diffusion, frequently referred to as pitch-angle diffusion; heating and acceleration of a particle distribution is formally analyzed using diffusion equations in velocity space.

Not all particles can resonate. The heavy curve in Fig. 1 shows the dispersion relation for the electromagnetic ion-cyclotron wave propagating along $\mathbf{B}$ in a cold electron–proton plasma: $k^2 V_{Ap}^2 = \Omega_p \omega^2/(\Omega_p - \omega)$, where V_{Ap} is the Alfvén speed based on the proton density (we have taken $m_e = 0$ for these low-frequency waves), and Ω_p is proton gyro-frequency; Fig. 1 is in the frame moving with the bulk proton flow. In Fig. 1, the resonance condition is a straight line with slope $V_\parallel / V_{Ap}$ and an ordinate intercept at Ω/Ω_p. Near the top of the figure we show the resonance conditions for two test protons, one (line 'A') with $V_\parallel > 0$ and moving with the wave, and the other (line 'B') with $V_\parallel < 0$ and moving against the wave. Resonance can only occur if the resonance condition intersects the dispersion relation. For line 'A' there is no resonance. Thus only protons moving against the wave can resonate. Also shown in Fig. 1 are resonance conditions for four O^{+5} test particles, two with $V_\parallel > 0$ (lines 'C' and 'D') and two with $V_\parallel < 0$ (lines 'E' and 'F'). Lines 'D'–'F' show that resonance is possible for oxygen ions moving both with and against the wave. In resonant heating and acceleration, this gives the ions a major advantage over the protons. However, line 'C' also shows that O^{+5} can drop out of resonance if $V_\parallel$ becomes too large; we will return to this point below. (Actually, He^{++} is sufficiently abundant to modify the dispersion relation. As discussed by Hollweg (2000a) and HI, He^{++} suffers a disadvantage similar to that of the protons. UVCS gives no information about He^{++} and we will ignore this issue here.)

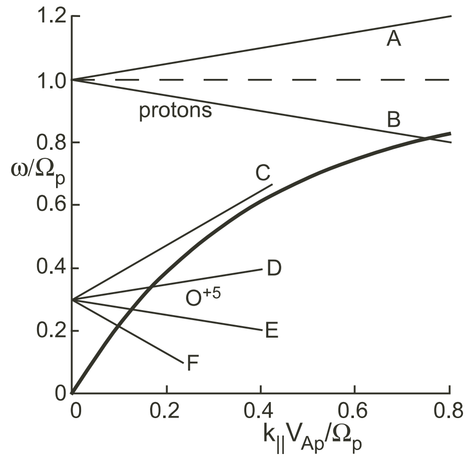

Figure 1. Dispersion relation (heavy curve) for the parallel-propagating ion-cyclotron mode in a cold electron-proton plasma, as viewed in the bulk proton frame. The resonance condition is shown as the thin straight lines, with positive (negative) slopes for test particles moving with (against) the wave. The top two lines are the resonance conditions for protons; only protons moving against the wave can be in resonance. The lower four lines are for O^{+5}; ions moving with and against the wave can be in resonance, but they can drop out of resonance if they move too rapidly with the wave. Lines 'E' and 'F' show that O^{+5} ions moving against the wave never drop out of resonance. In fact, as they move more rapidly against the wave, they become more resonant in the sense of resonating with lower frequency waves which presumably have more power. In the corona, antisunward moving ions may be affected mainly by sunward-propagating waves.

Figure 2 illustrates several effects associated with velocity space diffusion. To keep things simple, we will here ignore dispersion, so that we can define a wave frame. Since there is no wave electric field in that frame, particles will conserve energy and diffuse along circular arcs $V_\|^2 + V_\perp^2 = \text{constant}$ ($V_\perp$ is the velocity perpendicular to **B**). In Fig. 2, the circular arcs are centered on the phase speed in the proton frame. In reality protons will resonate with slower-moving waves than O^{+5}, so we have drawn separate circles for those particles. Marsch & Tu (2001) have actually found evidence that solar wind protons diffuse along circular arcs; they write "direct observational evidence from Helios plasma data is shown for the occurrence of this pitch angle diffusion of solar wind protons, induced by resonance with parallel ion-cyclotron waves propagating away from the Sun . . . parts of the isodensity contours in velocity space are well outlined by a sequence of segments of circles centered at the adapted wave phase speed . . . "

We consider what happens to a group of particles that start out on the abscissa with $V_\perp = 0$. Those particles will diffuse upward along their arcs, thereby acquiring a perpendicular temperature; this is the most important part of the resonant heating since particles with large $V_\perp$ can subsequently be accelerated via the magnetic mirror force. Particles which start with the same $V_\|$ will acquire a spread in $V_\|$, and thus an increased parallel temperature, as they diffuse. (It is also possible for $T_\|$ to decrease (Dusenbery & Hollweg 1981; Li *et al.* 1999). $T_\|$ heating or cooling is not a major effect, and we will not consider it further.) As particles diffuse upward along their arcs, they also move to the right. This represents a bulk resonant acceleration of the particles, but it is generally not as important as the magnetic mirroring. Now note the thick portions

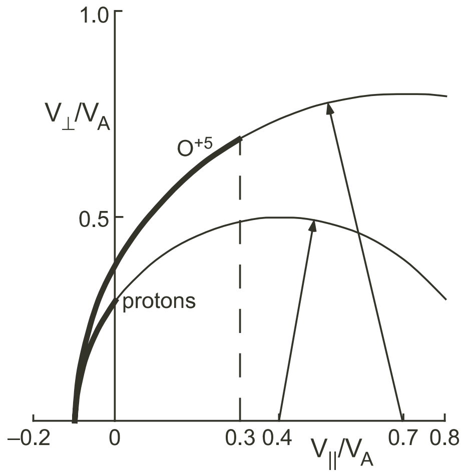

Figure 2. Particle diffusion, as viewed in the bulk proton frame. In the wave frame particle energy is conserved, so particles diffuse along circular arcs centered on the wave phase speed. The arcs for O^{+5} and protons are centered on different values of $V_\parallel$, because O^{+5} tends to resonate with faster-moving waves than do the protons. The thicker portions of the arcs indicate the values of $V_\parallel$ for which the particles can be in resonance. O^{+5} (and other heavier ions as well) can diffuse to higher values of $V_\perp$ than can the protons. Thus if the diffusion is fast enough, ions can become more than mass-proportionally hotter than the protons.

of the arcs in Fig. 2. They indicate the values of $V_\parallel$ for which particles can be in resonance. Only protons with $V_\parallel < 0$ (i.e., moving against the wave) are in resonance, while O^{+5} ions drop out of resonance only when $V_\parallel$ is sufficiently positive (i.e., moving with the wave). Diffusion will tend to fill up the dark arcs, but not beyond. This fact, along with the two circles having different radii, clearly allow O^{+5} to attain larger values of $V_\perp$ than the protons. Recalling that temperature is proportional to mass times (thermal speed)^2, we see that diffusion tends to give $T_{\mathrm{oxygen},\perp}/T_{\mathrm{p}\perp} > m_{\mathrm{oxygen}}/m_{\mathrm{p}}$, in qualitative agreement with the UVCS/SOHO results (m denotes particle mass). Finally, the oxygen advantage is furthered by the fact that O^{+5} resonates with lower frequency waves which are observed to have more power.

These considerations are qualitatively in accord with the UVCS/SOHO data, but there are quantitative difficulties. Kohl *et al.* (1998) show that the O^{+5} temperature is an increasing function of r in $2 < r/r_S < 3.5$ (the outer limit of the data). But models (Hollweg 2000a; HI) involving resonances with outward-propagating waves have been unable to reproduce this result. The resonant heating is effective in producing very hot O^{+5} rather close to the Sun. But the large values of $V_\perp$ then lead to a rapid acceleration via the mirror force, causing the oxygen to drop out of resonance, and to experience strong adiabatic cooling.

Resonances with sunward-propagating waves can save the day. (Sunward-propagating waves can arise from reflections or instabilities.) An outward-moving ion resonating with a sunward-propagating wave will have a resonance condition with negative slope in Fig. 1, e.g., line ‘E’ in the figure. As the particle accelerates outward while still interacting with inward waves, the slope of the straight line will become even more negative, e.g., line ‘F’. Not only will the particle never drop out of resonance, but it will resonate at ever smaller wavenumbers, where there is more power.

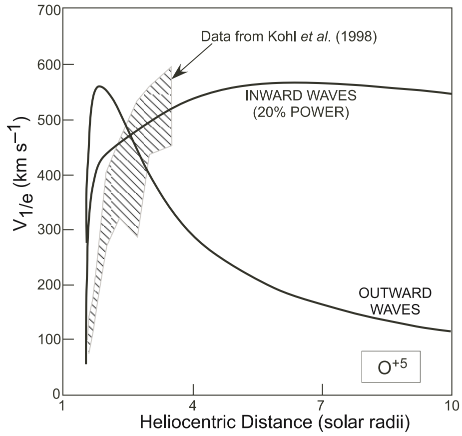

Figure 3. The thermal speed $V_{1/e}$ of O^{+5} in a simple model which demonstrates that the effects of inward- and outward-propagating waves are qualitatively different, for the reasons discussed in the text. The cross-hatched area represents the coronal hole data from Kohl *et al.* (1998). These data are remarkable in that they show that the O^{+5} temperature increases with increasing r out to $3.5r_S$ (the outer limit of the data), in spite of strong adiabatic cooling. Outward-propagating waves fail to explain this, even qualitatively, because the particles drop out of resonance. Inward-propagating waves do not suffer this defect, and generally succeed in matching the data.

The efficacy of this idea has been illustrated in a simple "proof of principle" model of the acceleration of O^{+5} in a coronal hole (Hollweg 2006c). In Fig. 3, we show the perpendicular heating of O^{+5} (as represented by the perpendicular thermal velocity) for two cases: pure outward-propagating waves, and pure inward-propagating waves with one-fifth the power of the outgoing waves. The two cases produce very different behaviors, even qualitatively. Particles resonating with outgoing waves are heated very rapidly close to the Sun, thereby acquiring large $V_\perp$ which results in a strong outward mirror acceleration, which in turn causes the particles to drop out of resonance (line 'C' in Fig. 2) and cool adiabatically at greater distances from the Sun. In contrast, particles resonating with ingoing waves never drop out of resonance, and have $V_\perp$ increasing with r in regions where particles resonating with outgoing waves have $V_\perp$ decreasing with increasing r. The grey shading in Fig. 3 indicates the UVCS data from Kohl *et al.* (1998); values of $V_\perp$ for particles resonating with outgoing waves do not resemble the data at all, while particles resonating with inward waves show a better match. Hollweg (2006c) also finds that the observed behavior of the bulk flow speed of O^{+5} is better explained by interactions with ingoing waves. Detailed modeling of the ion resonances will have to carefully consider the mix of sunward-propagating and antisunward-propagating waves. Unfortunately, this represents a significant lacuna in our understanding, since we are not sure where the ion-cyclotron waves come from in the first place.

Another effect associated with sunward-propagating waves has been discussed by Isenberg (2001a), who pointed out that O^{+5} can simultaneously resonate with sunward and antisunward waves, while the protons cannot. (To see this, imagine the dark arcs in Fig. 2 flipped about the vertical axis. Those flipped arcs will represent pitch-angle diffusion caused by waves propagating to the left in the figure. Now imagine the flipped arcs superimposed on the arcs that are already in the figure. The two sets of arcs will represent the pitch-angle scattering which occurs when waves propagating both to the left and to the right are present. The two sets of arcs for protons will not overlap; this means that a proton can resonate either with a left-propagating wave or with a right-propagating wave, but not with both waves simultaneously. In contrast, the two sets of arcs for O^{+5} will overlap to some extent; this means that a given O^{+5} ion can resonate with left- and right-propagating waves simultaneously.) In terms of diffusion, protons diffuse only along the arcs, while O^{+5} can diffuse across the arcs. This cross-arc transport is more commonly called second-order Fermi acceleration (e.g., Terasawa 1989). Since it is available to O^{+5} but not to the protons, it represents an energization mechanism which is inherently preferential to heavy ions. (He^{++} would tend to behave like protons in this scenario.) Quantitative evaluation of the simultaneous effects of sunward- and antisunward-propagating waves remains to be carried through. (See Isenberg & Vasquez (2006) for some early fully kinetic computations of how distribution functions evolve when resonances with both ingoing and outgoing waves are operative, but it should be kept in mind that, that paper does not include the tendency of the mirror force to accelerate the ions to the point where they drop out of resonance with outgoing waves. The author strongly suspects that once the ions are accelerated outward by the mirror force, they will interact mainly with the sunward-propagating waves.)

Another puzzle concerns Mg^{+9}, which has also been studied by SOHO/UVCS. Whereas O^{+5} is heated more than mass-proportionally relative to the protons, Mg^{+9} attains temperatures which are roughly mass-proportional. Why is there such different behavior for ions with similar values of q/m? The answer is not known; see discussions in HI and Cranmer (2002).

6. Whence the ion-cyclotron waves?

The UVCS/SOHO data seem to be plangent evidence for the cyclotron resonance. But there is no agreement on where the ion-cyclotron waves come from.

Based on seminal work by Coleman (1968) and Barnes (1979), one school of thought follows Hollweg (1986) and HJ: the Sun launches low-frequency waves which undergo a turbulent cascade that produces the high-frequency resonant waves. This viewpoint is well-motivated observationally. *In situ* observations of magnetic field and velocity fluctuations show most power at low frequencies, but with power law power spectra extending to high frequencies (e.g., Marsch & Tu 1990). The power law indices have a preference for the $-5/3$ value expected for a Kolmogorov turbulent cascade. *In situ* data for the corona are not available. Radio studies do give some information about density fluctuations, though their connection with ion-cyclotron waves is unclear. The data are suggestive nonetheless. Most power resides at low frequencies (corresponding to periods of hours), and the power spectra have the Kolmogorov index at higher frequencies, with some flattening just below the turbulence dissipation range (Coles & Harmon 1989). In both radio and *in situ* data, the power spectra steepen at the spatial scales expected if the ion-cyclotron resonance is coming into play (e.g., Leamon *et al.* 1998a, 1998b, 1999, 2000; Yamauchi *et al.* 1998; Bale *et al.* 2005; Harmon & Coles 2005); the spectral steepening is identified with the dissipation range.

It is often suggested that the turbulence scenario has a serious flaw: MHD turbulence tends to produce large cross-field wavenumbers, $k_\perp$, rather than the large values of

$k_\parallel$ needed for cyclotron resonance (e.g., Shebalin *et al.* 1983; Ng & Bhattacharjee 1996; Milano *et al.* 2001; Oughton *et al.* 2004). But the observational fact is that there is substantial power at large $k_\parallel$'s. This is especially true in the high-speed wind at low frequencies (Dasso *et al.* 2005), but also near the dissipation range (Leamon *et al.* 1998a, 1998b, 1999, 2000). From radio studies close to the Sun, Harmon & Coles (2005) have concluded "radio scattering indicates there must be a substantial parallel component to the wave power which, in the turbulence picture, suggests a substantial non-perpendicular cascade". Vasquez *et al.* (2004) have proposed that large $k_\parallel$'s can be produced by turbulence if the background is spatially structured; the waves advect the structures, which in turn refract the waves, and so on, quickly leading to large $k_\parallel$'s. Perhaps non-MHD processes are at work, particularly near the dissipation range where kinetic effects can come into play. We believe that a particularly important point has been made by Chandran (2005) who writes "incompressible and weakly compressible MHD neglect the fast wave ... when fast waves are accounted for, MHD turbulence in low-β plasmas transfers energy to high-frequency fast waves and, to a lesser extent, high-frequency Alfvén waves". In other words, the common wisdom that MHD turbulence only produces high $k_\perp$ may be wrong. (See also Cranmer & van Ballegooijen (2003) for a discussion of the $k_\parallel$ problem.)

If the turbulence scenario is correct, the Sun must launch sufficient power at long periods to drive the fast wind; an energy flux density of 5×10^5 erg cm^{-2} s^{-1} at the coronal base is a representative number. This issue has been addressed by looking at Faraday rotation fluctuations impressed on a radio signal as it traverses the corona. Hollweg *et al.* (1982) used the linearly polarized signal from the Helios spacecraft. They found that the polarization direction varied with timescales of the order of hours, suggesting a connection with the long-period Alfvén waves observed *in situ*. They showed that the observed Faraday rotation fluctuations in $2r_S < r < 15r_S$ closely matched what would be expected if there were indeed long-period Alfvén waves in the corona with enough power to drive the fast solar wind. Similar results were obtained by Andreev *et al.* (1997). However, Mancuso & Spangler (1999) and Spangler (2002) looked at Faraday rotation fluctuations from natural radio sources and concluded that there was not enough long-period wave power to drive the fast wind. But it should be pointed out that there are two basic problems with the Faraday rotation studies. The first is that the observed rms fluctuations depend on the line-of-sight correlation length for the turbulence, which has to be guessed. The second difficulty is that the studies so far have extrapolated the data back to the coronal base without allowing for dissipation; if these waves ultimately heat the corona and drive the fast wind, there has to be significant dissipation. (For example, HI found that the wave action falls off approximately as r^{-1} in a simple model with turbulent dissipation.) Allowing for dissipation would lead to a larger value of the energy flux density at the coronal base.

Harmon & Coles (2005) have used other radio data, sensitive to the density fluctuations, to investigate the energetics of the turbulence cascade close to the Sun. Their conclusion is "the cascade energy dissipated in proton-cyclotron damping and electron Landau damping is large enough to be an important factor in solar wind heating and dynamics".

Like the *in situ* data, the Faraday rotation and density fluctuations in the corona usually have timescales of the order of hours (not the 5-minute or 3-minute periods we are most accustomed to hearing about, though we will mention an exception in the following paragraph). What on the Sun is responsible for these timescales? We know of only one solar phenomenon which occurs on timescales of hours: the flux cancellation events (Livi *et al.* 1985; Martin *et al.* 1985; Ryutova *et al.* 2003). It is not unreasonable to suppose that the drastic alteration of magnetic field in a flux cancellation event could launch long-period Alfvén waves with substantial energy fluxes (Hollweg 1990). This conclusion is probably closely related to recent studies by Close *et al.* (2004, 2005). They found that "the timescale for magnetic flux to be remapped in the quiet-Sun corona is, surprisingly, only 1.4 hr ... implying that the quiet-Sun corona is far more dynamic than previously thought." In view of the long-known presence of hour periods in the low corona and solar wind, they shouldn't have been surprised. (Twisting or shaking of intense magnetic flux tubes by the convective motions should also launch Alfvén waves. The trouble is that the timescales aren't right. The solar granulation has timescales of minutes while the supergranulation has timescales of tens of hours. The photosphere also contains weaker fields, called inter-network or intra-network fields (e.g., Lites & Socas-Navarro 2004; Cerdeña *et al.* 2006); the possible role of these fields in launching waves has, to our knowledge, not been explored.)

A variation of the turbulence scenario is suggested by results of Ulrich (1996). He looked at line-of-sight velocity and magnetic field fluctuations in the chromosphere, and found that they were correlated consistent with outgoing Alfvén waves. The time-averaged upward Poynting flux was about the amount required to power the chromosphere and corona in strong field active regions, where the data were taken. The study has not been done, but it is not unreasonable to suppose that the Alfvénic energy flux in regions of weaker fields, e.g., in coronal holes, might be sufficient to drive the high-speed solar wind. However, unlike the *in situ* data and much of the radio data, Ulrich's fluctuations were mainly in the 5-minute band. In this context, it is interesting to note that Chashei *et al.* (1999) have provided observations of Faraday rotation fluctuations (due to magnetic field fluctuations which are believed to be associated with Alfvén waves) of radio signals propagating through the corona in the acceleration region of the solar wind; there is evidence of a peak at periods around 5 minutes, in an otherwise broad power spectrum. Might the putative turbulent cascade originate from waves with periods of the order of 5 minutes, rather than hours? (See also Cranmer & van Ballegooijen (2005) for a discussion of Alfvén wave generation by random walks, induced by the solar "5-minute oscillations", of photospheric magnetic flux tubes.)

An alternate proposal for the origin of the ion-cyclotron waves is that magnetic reconnection events in the photosphere or chromosphere launch waves with the kilohertz frequencies that are resonant with protons and ions in the corona (e.g., Schwartz *et al.* 1981; Axford & McKenzie 1992, 1996; McKenzie *et al.* 1995, 1997; Czechowski *et al.* 1998; Ruzmaikin & Berger 1998). To generate kilohertz frequencies, the reconnecting elements would have to be extremely small. The waves originate well below the local ion-cyclotron frequencies in the photosphere and chromosphere, but they become resonant in the corona where the magnetic field is much weaker. Tu & Marsch (1997) and Marsch & Tu (1997) presented detailed solar wind models based on this scenario. They assumed that the waves propagate along **B** with a prescribed power spectrum. Hollweg (2000b) suggested that oblique propagation is far more likely, in which case the waves would be weakly compressive. Using a power spectrum specified by Tu and Marsch, he calculated the expected power spectrum of density fluctuations, if the waves propagate obliquely. At high wavenumbers, the predicted density spectrum at $r = 5r_S$ is 2–3 orders of magnitude larger than the observations reported by Coles & Harmon (1989). Unless the waves really are nearly parallel-propagating, which is difficult to imagine in a structured corona, we conclude that the direct-launching scenario is not viable. (See HI for a discussion of other objections to direct launching.)

A third proposal for the origin of the ion-cyclotron waves has emerged in recent years, viz., the waves are locally generated by plasma microinstabilities in the corona or transition region (e.g., Viñas *et al.* 2000; Markovskii 2001; Markovskii & Hollweg 2002a; Voitenko & Goossens 2002a, 2003, 2005; Chen & Zhou 2003). The unstable waves usually propagate highly oblique to the background magnetic field. In some studies the instabilities are driven by the currents or gradients associated with low-frequency waves which contain most of the power. But the unstable waves are cyclotron resonant with protons and ions. The net result is a direct transfer of wave energy from low to high frequencies, without a 'cascade' through intermediate frequencies.

In other studies the instabilities are driven by electron or proton beams. An example of this type of study (one which we believe to be particularly promising) is the work of Markovskii & Hollweg (2002b, 2004a, 2004b). They assume that microflares near the coronal base intermittently launch bursts of large electron heat flux outward into the corona. Via a Landau resonance with the distorted thermal electron distribution function, the heat flux drives electrostatic or electromagnetic ion-cyclotron waves unstable. These waves are highly oblique to the magnetic field, but with sunward $\omega/k_{\|}$ (in the local plasma frame); as discussed above in connection with Fig. 3, these sunward-propagating waves could be crucial to the behavior of O^{+5}. The cyclotron waves give perpendicular proton and ion heating. (Since the generated waves are highly dispersive, the particles diffuse approximately along hyperbolae in velocity space, not the circles used in our previous examples.)

Markovskii *et al.* (2006) have proposed a completely different idea, one which does not involve the generation of waves with high $k_{\|}$. They note that a turbulent cascade involves velocity-shears which in turn drive up instabilities with high $k_{\perp}$. These unstable waves have resonances at harmonics of the proton–cyclotron frequency. This model agrees with several observational features of the turbulent spectrum:

1. The theoretical spectrum tends naturally toward k^{-3} in the dissipation range, as is frequently (but not always) observed.
2. As predicted by the model, the observed values of the wavenumber at which the spectrum transitions from the inertial range into the dissipation range correspond to the same dimensionless "velocity shear parameter" under a wide range of conditions.

7. A few promising recent ideas

In section 4, we mentioned that some models were internally inconsistent in that they assumed purely outward-propagating Alfvén waves in the WKB limit. In that case the nonlinear terms which lead to turbulence sum to zero. For turbulence to develop, there must be a mix of inward- and outward-propagating waves, or the waves must be non-WKB. Dmitruk *et al.* (2002) proposed a simple model based on equations which describe the non-WKB propagation of linear Alfvén waves, but with an additional nonlinear term giving a dissipation rate dimensionally similar to the Kolmogorov rate, but with the important difference that there is no dissipation unless both inward- and outward-propagating waves are present. Dmitruk *et al.* (2002) offer some numerical calculations of the volumetric heating rates in the corona; the derived heating rates are comparable to what is required to drive the fast wind. We believe that this approach contains a significant amount of the physics needed for describing how the Alfvén wave amplitudes evolve as they propagate away from the Sun, and for describing the overall heating in the corona and interplanetary space; at the same time, this approach offers the virtue of simplicity. (See also Matthaeus *et al.* (1999); Dmitruk *et al.* (2001); and Dmitruk & Matthaeus (2003).) Cranmer & van Ballegooijen (2005) have shown that the approach of Dmitruk *et al.* (2002) accounts well for what is known about the evolution of wave amplitudes throughout the corona and interplanetary space. However, there is a note of caution: The Dmitruk *et al.* model presupposes a cascade to high $k_\perp$ rather than high $k_\parallel$; is there some way to modify it along the lines of Chandran (2005)?

The reader might also wish to consult Isenberg *et al.* (2003); Matthaeus *et al.* (2004); and Breech *et al.* (2005) for examples of calculations of the evolution of turbulent fluctuations in the solar wind far from the Sun, where V_A can be neglected compared to the solar wind flow speed. Unlike Dmitruk *et al.* (2002), these models include the effects of velocity shear and pick-up ions. Velocity shear may be an important aspect of the evolution, perhaps accounting for some of the differences between the evolution of waves/turbulence in fast and slow solar wind flows (Breech *et al.* 2005).

A wave-turbulence phenomenology such as we have just discussed can describe many aspects of the wave evolution and plasma heating in the fast wind. But there are other aspects of the wave evolution which turbulence phenomenology does not capture. It should first be noted that if waves supply the energy for the wind, then they must be very linear ($|\delta\mathbf{B}|/B \ll 1$) in the vicinity of the acceleration region; otherwise there would be more energy supplied than can be accounted for. However, even allowing for turbulent dissipation, the tendency to conserve wave action implies that the waves become nonlinear ($|\delta\mathbf{B}|/B \approx 1$) in interplanetary space, as is observed. But even though the magnetic field direction fluctuates strongly, the magnetic field strength is observed to be nearly constant ($\delta|\mathbf{B}|/B \ll 1$); in other words, the tip of the magnetic field vector moves nearly on a sphere. How this comes about has been explained via a nonlinear wave analysis combined with hybrid simulations (Vasquez & Hollweg 1996a, 1996b). Nonlinear wave theory (Vasquez & Hollweg 1998, 1999a) has also succeeded in explaining why there are many apparently stable rotational discontinuities (essentially sharp-crested Alfvén waves) imbedded within the waves in interplanetary space (Tsurutani *et al.* 1994), even though an isolated rotational discontinuity would be unstable and very short-lived. Moreover, even in high-speed wind, where the Alfvén waves are most 'pure', there is a weak admixture of fast waves propagating across the background magnetic field and pressure-balanced structures (or perhaps transversely-propagating slow modes) (Tu & Marsch 1994); this result has also been explained as a natural outcome of the nonlinear evolution of Alfvén waves (Vasquez & Hollweg 1999b). Another result best explained using wave theory concerns the behavior of He^{++}. We have already said that the He^{++} in interplanetary space flows faster than the protons, by about V_A. But V_A is a decreasing function of r in interplanetary space, implying that the He^{++} must slow down. This, too, has best been explained in terms of He^{++} interacting with nonlinear waves (Kaghashvili *et al.* 2003).

Thus far, turbulence theory has not addressed what happens in the dissipation range, where non-MHD kinetic processes are critical. Similarly, nonlinear wave studies have not simultaneously reproduced a turbulence cascade and the details of the dissipation range. The goal would be to calculate how the proton and ion distribution functions

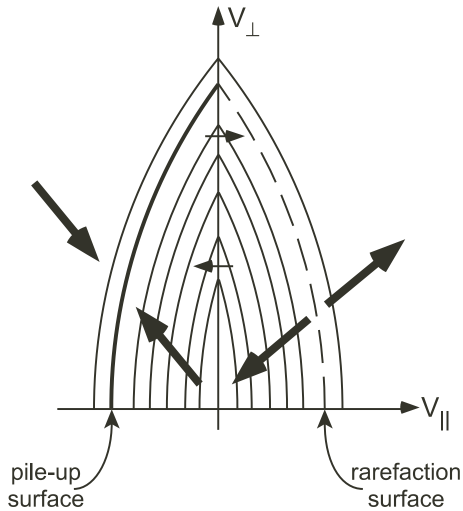

Figure 4. Velocity space diagram illustrating the evolution of the proton distribution in the kinetic shell model, as the plasma moves away from the Sun. Protons interacting with outward (inward) propagating waves diffuse along the arcs in the left (right) half of the diagram. The thick arrows indicate the shell motion, converging on the sunward ($V_\parallel < 0$) side and diverging on the antisunward side ($V_\parallel > 0$). The thin arrows indicate the particle transport across the $V_\parallel = 0$ boundary, determined by the nonresonant forces. The pile-up and rarefaction surfaces are shown as the thick and dashed curves, respectively.

evolve subject to resonant diffusion in velocity space, along with global forces such as gravity, magnetic mirroring, etc. Isenberg *et al.* (2001) and Isenberg (2001b, 2004a, 2004b) have suggested an approximate procedure, which is mostly analytical. They call their approach "the kinetic shell model", the shells being the 3-dimensional versions of the diffusion arcs in Fig. 2. (See also Galinsky & Shevchenko 2000 for independent work which is closely related to the kinetic shell model.) The essence of this model is shown in Fig. 4, which is similar to Fig. 2. Velocity space ($V_\parallel$, $V_\perp$) is displayed with several diffusion arcs for protons. The kinetic shell model's key assumption is that the velocity space diffusion is faster than any other timescale, so that the distribution function is always very nearly uniform along each arc. However, the number of particles can differ from shell to shell. Individual shells can be thought of as moving in response to the global forces: gravity, mirroring, and the charge-separation electric field.

Consider first sunward-moving protons, which we take to have $V_\parallel < 0$. Recall that these protons resonate with outward-propagating waves. The leftmost shells, which reach to large values of $V_\perp$, experience a net mirror force which overwhelms gravity and the electric field, so those shells are pushed to larger values of $V_\parallel$, as indicated by the leftmost arrow. Other shells having $V_\parallel < 0$, but reaching to smaller values of $V_\perp$, are dominated by the sunward combination of gravity and electric field; those shells are driven to more negative values of $V_\parallel$, as indicated by the second arrow from the left. The result is that the sunward-moving protons tend to accumulate near a 'pile-up surface' where all forces balance.

At $V_\parallel = 0$ the protons are resonant with waves having infinite wavenumber, and zero power. Thus, those protons are unaffected by the waves, and in the kinetic shell model they move across the $V_\parallel = 0$ 'boundary' in response to the global forces. If $V_\perp$ is large enough, the particles will be pushed toward $V_\parallel > 0$, as indicated by the right-pointing arrow; conversely for particles with lower $V_\perp$. (Effects such as resonance broadening can also transport protons across $V_\parallel = 0$ (e.g., Gary & Saito 2003), but they are not included in the kinetic shell model.)

Particles with $V_\parallel > 0$ resonate with sunward-propagating waves, and follow the diffusion arcs sketched in the figure. The two rightmost arrows indicate the shell motions in response to the global forces; shells which reach to large $V_\perp$ are pushed to larger values of $V_\parallel$, and so on. In this case the opposite of a pile-up surface develops: there will be a 'rarefaction surface' on which particles are depleted. Even if there are no sunward-propagating waves initially, in this model they will be generated by those protons at large $V_\perp$ which are pushed into the $V_\parallel > 0$ region by the mirror force. The resulting distribution is highly unstable to the generation of sunward-propagating waves; the protons appearing at $V_\parallel > 0$ will diffuse down and to the right in the figure, losing energy which is made available to the sunward waves.

With dispersion ignored (Isenberg 2001b), rapidly accelerating fast winds were obtained. But when wave dispersion was included (Isenberg 2004a, 2004b), only slow winds were produced. The reason has to do with the tops of the arcs in Fig. 4, which tend to flatten out when the waves are dispersive. Thus the arcs extend to smaller values of $V_\perp$, and the net mirror force is reduced. Nonetheless, in the author's opinion the kinetic shell model has many virtues. Perhaps further developments including the warm plasma dispersion relation and obliquely-propagating waves will save the day.

8. Summary and inferences

We have shown how our thinking about the solar wind has progressed from Parker's electron-driven wind, through a wave-driven wind, to our current proton-driven wind, driven mainly the magnetic mirror force if the protons have $T_\perp \gg T_\parallel$. (See Vásquez *et al.* (2003) for a discussion of the importance of thermal anisotropy.) Our current picture also allows for a significant contribution from wave pressure, but this will give a more gradual acceleration acting mainly beyond the sonic point. We have emphasized that the wind is undergoing significant heating in the region where it is rapidly accelerating to supersonic speeds; coronal heating and solar wind acceleration need to be treated together.

The UVCS/SOHO fast solar wind data have shown that coronal heating works mainly on the transverse components $\delta V_\perp$ of protons and ions. It is not Joule heating, as is very commonly presumed to be the case in other parts of the corona. Coronal heating also does not seem to be dominated by viscosity or by heat conduction. Do proton and ion heating dominate other parts of the corona, such as the active region loops, as well?

Heating transverse to the magnetic field strongly implicates the ion-cyclotron resonance. But we still do not know the source of the high-frequency resonant waves. We have given some arguments against the proposal that the Sun directly launches these waves. The Sun could well launch the required energy fluxes at long periods, with the high-frequencies generated by a turbulent cascade. The tendency of MHD turbulence to produce mainly high $k_\perp$ is a difficulty, but we do not believe it is insurmountable. Finally, some workers have begun to explore the promising idea that the high-frequency waves may originate locally in the corona from plasma microinstabilities; this scenario seems worth pursuing.

In the foregoing we have made several references to radio studies of the corona. They provide evidence for a turbulent cascade to high $k_\parallel$ close to the Sun, and we shall see that they provide evidence for electron heating via Landau damping of long-period fluctuations. They are the only means we have of measuring the all-important magnetic fluctuations in the corona, and they are therefore the only means we have of determining whether long-period MHD waves can provide, via a turbulent cascade, sufficient energy to heat the protons and ions and drive the high-speed wind. (If radio studies were to show that there is insufficient power at long periods, then the turbulence scenario would be dead.) We believe that the solar physics community should pay more attention to radio studies than has generally been the case. The author suggests that spacecraft which will be close to superior conjunction with the Sun should be fitted with linearly polarized transmitters to facilitate observations of the coronal magnetic field via Faraday rotation; we cannot emphasize too strongly that, short of a "Solar Probe", this is our only hope of measuring coronal magnetic fluctuations. We would even encourage the placement of a simple spacecraft with little more than a linearly polarized transmitter in an orbit which places it in near constant superior conjunction (Ruzmaikin *et al.* 1997).

We also encourage development of an advanced version of the UVCS, especially one which will allow us to get a handle on the behavior of helium in the acceleration region of the solar wind. A complementary instrument with great promise is the ultraviolet imager discussed by Kohl (this volume). And the author hopes to live long enough to see a "Solar Probe".

We hope that our presentation has made it clear that a complete description of coronal heating and fast wind acceleration will require detailed considerations of particle kinetics; MHD does not tell the whole story. The non-Maxwellian particle distribution functions observed by spacecraft (e.g., Marsch 1991) are trying to tell us something about the physics of heating and acceleration closer to the Sun.

Future studies will need to place more emphasis on wave propagation oblique to the magnetic field. The Sun almost certainly launches highly oblique waves which are subsequently refracted. The microinstabilities considered so far tend to produce highly oblique waves. Oblique waves in a multi-ion plasma show interesting polarization effects, for example at the "crossover frequencies" (e.g., HI; Smith & Brice 1964). There is some evidence (Leamon *et al.* 1998a, 1998b, 1999, 2000; Bale *et al.* 2005) that the dissipation range of the turbulence contains kinetic Alfvén waves, which are essentially highly oblique Alfvén waves (Hollweg 1999) with cross-field wavenumbers of the order of or greater than the inverse ion inertial length. These waves are compressive and therefore subject to Landau damping, especially on the electrons. Voitenko and Goossens (2002b, 2004) have emphasized the possible importance of kinetic Alfvén waves. The latter paper considers what happens to test ions interacting with a large-amplitude kinetic Alfvén wave packet. Surprisingly, under certain circumstances the ions can gain substantial energy even though there is no cyclotron or Landau resonance. This process might be important far from the Sun where the solar wind wave field has large amplitude, but it will not be important close to the Sun where the waves are almost certainly small amplitude with $|\delta\mathbf{B}|/B \ll 1$. On the other hand, Wu & Yang (2007) have recently studied heavy ion energization in a "solitary nonlinear [kinetic Alfvén] wavelet". They find that significant energization can occur even if the magnetic field variation is weak, as long as the electron density varies strongly within the wavelet.

Future studies will also need to expand consideration of sunward-, as well as outward-propagating waves. The mix of inward and outward waves is essential for the development of turbulence. Moreover, we believe that inward-propagating waves are responsible for the extended heating of O^{+5}.

Finally, we need to say something about electron heating, which has been completely ignored in the foregoing. It is difficult to say much about the electrons because we do not understand how to model their heat conduction under weakly collisional conditions. It is possible that the electrons need no external heating, and that collisional coupling with the protons suffices to maintain their temperatures. It is also possible that the electrons are strongly heated intermittently by reconnection events at the coronal base. And it may be that electrons are heated throughout the corona via kinetic Alfvén waves, which are compressive and have a parallel electric field; since the electron thermal speed is comparable to V_A in the corona, the electrons can be heated via the Landau resonance (e.g., Leamon *et al.* 1999, 2000). From their radio studies close to the Sun, Harmon & Coles (2005) conclude "at least half of the total cascade flux goes into electron heating as cascaded power traverses the broad Landau resonance on the way to the cyclotron resonance". It has also been suggested that electrons may be heated by nonlinear dynamics at very small scales, perhaps in association with reconnections in the dissipation range of a turbulent cascade (Matthaeus *et al*. 2003) or in association with kinetic Alfvén waves (Cranmer & van Ballegooijen 2003).

Fisk (2003) and Gloeckler *et al.* (2003) have emphasized observational evidence that the fastest (slowest) solar wind originates from the coronal regions with the coolest (hottest) electrons, a result completely opposite to the model of Parker (1958). They explain this result in terms of 'interchange reconnections' which convert closed loop-like magnetic field lines into open field lines. Plasma originally on the loops is thereby made available to the solar wind. Space does not permit us to reproduce their arguments, but the net result is that the hotter loops contain more mass than the cooler loops, and with more mass to accelerate, slower flows result. Alternatively, Schwadron and McComas (2003) have suggested that coronal regions with hotter electrons give rise to slower solar wind because those regions conduct more energy down to the transition region where it is lost via radiation, leaving less energy for the kinetic energy of the flow. Cranmer *et al.* (2007) have emphasized the magnitude and shape of the magnetic field expansion, which determines where heat is deposited in the corona. Finally, the electron temperature-speed anticorrelation might be consistent with the idea that it is mainly the protons which are heated (by the mechanisms discussed in this paper) in all regions which give rise to the solar wind. The protons then heat the electrons via collisions. Less dense regions, viz., the coronal holes, have weaker collisional coupling between electrons and protons, and this presumably results in lower electron temperatures coupled with faster flows.

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