On Competing Models of Coronal Heating and Solar Wind Acceleration:  
The Debate in ’08  

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ABSTRACT  

In preparation for lively debate at the May 2008 SPD/AGU Meeting in Fort Lauderdale, this document attempts to briefly lay out my own view of the evolving controversy over how the solar wind is accelerated. It is still unknown to what extent the solar wind is fed by flux tubes that remain open (and are energized by footpoint-driven wavelike fluctuations), and to what extent much of the mass and energy is input more intermittently from closed loops into the open-field regions. It may turn out that a combination of the two ideas is needed to explain the full range of observed solar wind phenomena.  

1. Introduction  

The solar corona is the hot, ionized outer atmosphere of the Sun that expands into interplanetary space as a supersonic solar wind (Parker 1958, 1965, 1991, 2001). This tenuous and unbounded medium is a unique laboratory for the study of magnetohydrodynamics (MHD) and plasma physics with ranges of parameters (e.g., densities and temperatures) that are inaccessible on Earth. Despite more than a half-century of study, though, the basic physical processes responsible for heating the million-degree corona and accelerating the solar wind are still not known. Identification of these processes is important not only for understanding the origins and impacts of space weather (e.g., Feynman & Gabriel 2000; Cole 2003), but also for establishing a baseline of knowledge about a well-resolved star that is directly relevant to other astrophysical systems.  

Different physical mechanisms for heating the corona probably govern active regions, closed loops in the quiet corona, and the open field lines that give rise to the solar wind (see reviews by Marsch 1999; Hollweg & Isenberg 2002; Longcope 2004; Gudiksen 2005; Aschwanden 2006; Klimchuk 2006). The ultimate source of the energy is the solar convection zone (e.g., Abramenko et al. 2006; McIntosh et al. 2007). A key aspect of solving the “coronal heating problem” is thus to determine how a small fraction of that mechanical energy is transformed into magnetic and thermal energy above the photosphere. It seems increasingly clear that loops in the low corona are
heated by small-scale, intermittent magnetic reconnection that is driven by the continual stressing of their magnetic footpoints. However, the extent to which this kind of impulsive energy addition influences the acceleration of the solar wind is not yet known. Figure 1 illustrates a range of ideas concerning how the magnetic topology varies between the coronal base and open flux tubes.

Intertwined with the coronal heating problem is the heliophysical goal of being able to make accurate predictions of how both fast and slow solar wind streams are accelerated. Empirical correlation techniques have become more sophisticated and predictively powerful (e.g., Wang & Sheeley 1990, 2006; Arge & Pizzo 2000; Leamon & McIntosh 2007; Cohen et al. 2007; Vršnak et al. 2007) but they are limited because they do not identify or utilize the physical processes actually responsible for solar wind acceleration. There seem to be two broad classes of physics-based models that attempt to self-consistently answer the question: “How are fast and slow wind streams heated and accelerated?”

1. In **Wave/Turbulence-Driven (WTD) models**, it is generally assumed that the convection-driven jostling of magnetic flux tubes in the photosphere drives wave-like fluctuations that propagate up into the extended corona. These waves (usually Alfvén waves) are often proposed to partially reflect back down toward the Sun, develop into strong MHD turbulence, and/or dissipate over a range of heights. These models also tend to explain the differences between fast and slow
solar wind not by any major differences in the lower boundary conditions, but instead as an outcome of different rates of lateral flux-tube expansion over several solar radii \( (R_\odot) \) as the wind accelerates (see, e.g., Hollweg 1986; Wang & Sheeley 1991; Matthaeus et al. 1999; Cranmer 2005; Suzuki 2006; Suzuki & Inutsuka 2006; Verdini & Velli 2007; Cranmer et al. 2007).

2. In **Reconnection/Loop-Opening (RLO) models**, the flux tubes feeding the solar wind are assumed to be influenced by impulsive bursts of mass, momentum, and energy addition in the lower atmosphere. This energy is usually assumed to come from magnetic reconnection between closed, loop-like magnetic flux systems (that are in the process of emerging, fragmenting, and being otherwise jostled by convection) and the open flux tubes that connect to the solar wind. These models tend to explain the differences between fast and slow solar wind as a result of qualitatively different rates of flux emergence, reconnection, and coronal heating at the basal footpoints of different regions on the Sun (see, e.g., Axford & McKenzie 1992, 2002; Fisk et al. 1999; Ryutova et al. 2001; Markovskii & Hollweg 2002, 2004; Fisk 2003; Schwadron & McComas 2003; Woo et al. 2004; Fisk & Zurbuchen 2006).

It is notable that both the WTD and RLO models have recently passed some basic “tests” of comparison with observations. Both kinds of model have been shown to be able to produce fast \( (v \gtrsim 700 \text{ km/s}) \), low-density wind from coronal holes and slow \( (v \lesssim 400 \text{ km/s}) \), high-density wind from streamers rooted in quiet regions. Both kinds of model also seem able to reproduce the observed in situ trends of how frozen-in charge states and the FIP effect vary between fast and slow wind streams.

The fact that both sets of ideas described above seem to mutually succeed at explaining the fast/slow solar wind could imply that a combination of both ideas would work best. However, it may also imply that the existing models do not yet contain the full range of physical processes—and that once these are included, one or the other may perform noticeably better than the other. It also may imply that the comparisons with observations have not yet been comprehensive enough to allow the true differences between the WTD and RLO ideas to be revealed.

Several recent observations have pointed to the importance of understanding the relationships and distinctions between the WTD and RLO models. *Hinode* has shown that open-field regions are filled with numerous coronal jets that may contribute a sizable fraction of the solar wind mass flux (Culhane et al. 2007; Cirtain et al. 2007; Shimojo et al. 2007). Also, new observations of Alfvén waves above the solar limb indicate the highly intermittent nature of how kinetic energy is distributed in spicules, loops, and the open-field corona (Tomczyk et al. 2007; De Pontieu et al. 2007). Spectroscopic observations of blueshifts in the chromospheric network have long been interpreted as the launching points of solar wind streams, but it remains unclear how nanoflare-like events or loop-openings contribute to these diagnostics (He et al. 2007; Aschwanden et al. 2007; McIntosh et al. 2007). Even out in the in situ solar wind—far above the roiling “furnace” of
flux emergence at the Sun—there remains evidence for ongoing reconnection (Gosling et al. 2005; Gosling 2007) as well as turbulence timescales that may come from flux cancellation in the low corona (Hollweg 1990, 2006).

Determining whether the WTD or RLO paradigm—or some combination of the two—is the dominant cause of global solar wind variability is a key prerequisite to building physically realistic predictive models of the heliosphere (Zurbuchen 2006, 2007). Many of the widely-applied global modeling codes (e.g., Riley et al. 2001; Roussev et al. 2003; Tóth et al. 2005; Usmanov & Goldstein 2006; Feng et al. 2007) continue to utilize relatively simple empirical prescriptions for coronal heating in the energy conservation equation. Improving the identification and characterization of the key physical processes will provide a clear pathway for inserting more physically realistic coronal heating “modules” into 3D MHD codes.

This paper does not go into detail about the specific avenues of future work, both theoretical and observational, that need to be pursued in order to better determine the relative contributions of the WTD and RLO processes. Thus, the following two sections just give some additional information about the WTD and RLO paradigms as they stand in 2008.

2. The Wave/Turbulence-Driven (WTD) Solar Wind Idea

There has been substantial work over the past few decades put into exploring the idea that coronal heating and solar wind acceleration along open flux tubes may be explained as a result of wave dissipation and turbulent cascade. No matter the relative importance of reconnections and loop-openings in the low corona, we do know that waves and turbulent motions are present everywhere from the photosphere to the heliosphere, and it is important to determine how they affect the mean state of the plasma. Although this section mainly describes recent work by the author, these results would not have been possible without the earlier work on wave/turbulent heating by, e.g., Coleman (1968), Hollweg (1986), Isenberg (1990), Li et al. (1999), Matthaeus et al. (1999), Dmitruk et al. (2001, 2002) and many others.

Cranmer et al. (2007) described a set of models that solve for the time-steady plasma properties along a 1D magnetic flux tube that is rooted in the solar photosphere and expands into interplanetary space. The numerical code developed in this work, called ZEPHYR, solves the one-fluid equations of mass, momentum, and energy conservation simultaneously with transport equations for Alfvénic and acoustic wave energy. ZEPHYR is the first code capable of producing self-consistent solutions for the photosphere, chromosphere, corona, and solar wind that combine: (1) shock heating driven by an empirically guided acoustic wave spectrum, (2) extended heating from Alfvén waves that have been partially reflected, then damped by anisotropic turbulent cas-
cade, and (3) wind acceleration from gradients of gas pressure, acoustic wave pressure, and Alfvén wave pressure.

The only input “free parameters” to ZEPHYR are the photospheric lower boundary conditions for the waves and the radial dependence of the background magnetic field along the flux tube. The majority of heating in these models comes from the turbulent dissipation of partially reflected Alfvén waves (see also Mattheaues et al. 1999; Dmitruk et al. 2002; Verdi et al. 2007). Measurements of G-band bright points in the photosphere were used to constrain the Alfvén wave power spectrum at the lower boundary, and non-WKB wave transport equations were solved to determine the degree of linear reflection. The resulting values of the Elsasser amplitudes \( Z_{\pm} \), which denote the energy contained in upward (\( Z_- \)) and downward (\( Z_+ \)) propagating waves, were then used to constrain the energy flux in the cascade. Cranmer et al. (2007) used a phenomenological form for the damping rate that has evolved from studies of Reduced MHD and comparisons with numerical simulations. The resulting heating rate (\( \text{erg s}^{-1} \text{ cm}^{-3} \)) is given by

\[
Q = \rho \left( \frac{1}{1 + \left( t_{\text{eddy}}/t_{\text{ref}} \right)^n} \right) \frac{Z_+^2 Z_- + Z_-^2 Z_+}{4L_\perp}
\]

(e.g., Hussain et al. 1995; Zhou & Mattheaues 1990). The transverse length scale \( L_\perp \) is an effective perpendicular correlation length of the turbulence, and Cranmer et al. (2007) used a standard assumption that \( L_\perp \) scales with the cross-sectional width of the flux tube (Hollweg 1986). The term in parentheses above is an efficiency factor that accounts for situations in which the cascade does not have time to develop before the waves or the wind carry away the energy (Dmitruk & Mattheaues 2003). The cascade is “quenched” when the nonlinear eddy time scale \( t_{\text{eddy}} \) becomes much longer than the macroscopic wave reflection time scale \( t_{\text{ref}} \). In most of the models, Cranmer et al. (2007) used \( n = 1 \) based on analytic and numerical models (Dobrowolny et al. 1980; Oughton et al. 2006), but they also tried \( n = 2 \) to explore a stronger form of this quenching.

Figure 2 summarizes the results of varying the magnetic field properties while keeping the lower boundary conditions fixed. For a single choice for the photospheric wave properties, the models produce a realistic range of slow and fast solar wind conditions. Specifically, a 2D model of coronal holes and streamers at solar minimum reproduces the latitudinal bifurcation of slow and fast streams seen by Ulysses. The radial gradient of the Alfvén speed affects where the waves are reflected and damped, and thus whether energy is deposited below or above the Parker critical point. As predicted by earlier studies, a larger coronal “expansion factor” gives rise to a slower and denser wind, higher temperature at the coronal base, and less intense Alfvén waves at 1 AU.

Perhaps more surprisingly, varying the coronal expansion factor also produces correlative trends that are in good agreement with in situ measurements of commonly measured ion charge state ratios (e.g., \( \text{O}^{7+}/\text{O}^{6+} \)) and FIP-sensitive abundance ratios (e.g., Fe/O). Cranmer et al. (2007) showed that the slowest solar wind streams—associated with active-region fields at the base—can
Fig. 2.— Summary of recent WTD models. (a) The adopted solar-minimum field geometry (Banaszkiewicz et al. 1998) with radii of wave-modified critical points marked by symbols. (b) Latitudinal dependence of wind speed at ∼2 AU for models with $n = 1$ (thick black curve) and $n = 2$ (dashed curve), compared with data from the first Ulysses polar pass in 1994–1995 (thin gray curve; Goldstein et al. 1996). (c) $T(r)$ for coronal hole (solid curve), streamer-edge (dashed curve), and strong-field active region (dotted curve) models. Further details can be found in Cranmer et al. (2007).

produce a factor of ∼30 larger frozen-in ionization-state ratio of $O^{7+}/O^{6+}$ than high-speed streams from polar coronal holes, despite the fact that the temperature at 1 AU is lower in slow streams than in fast streams. Also, when elemental fractionation is modeled using Laming’s (2004) theory of preferential wave-pressure acceleration, the slow wind streams exhibit a substantial relative buildup of elements with low First Ionization Potential (FIP) with respect to the high-speed streams. Although the WTD models utilize identical photospheric lower boundary conditions for all of the flux tubes, the self-consistent solutions for the upper chromosphere, transition region, and low corona are qualitatively different. Feedback from larger heights (i.e., from variations in the flux tube expansion rate and the resulting heating rate) extends downward to create these differences.
3. The Reconnection/Loop-Opening (RLO) Solar Wind Idea

It is clear from observations of the Sun’s “magnetic carpet” (Schrijver et al. 1997; Title & Schrijver 1998; Hagenaar et al. 1999) that much of coronal heating is driven by the continuous interplay between the emergence, separation, merging, and cancellation of small-scale magnetic elements. Reconnection seems to be the most likely channel for the injected magnetic energy to be converted to heat (e.g., Priest & Forbes 2000). Only a small fraction of the photospheric magnetic flux is in the form of open flux tubes connected to the heliosphere (Close et al. 2003). Thus, the idea has arisen that the dominant source of energy for open flux tubes is a series of stochastic reconnection events between the open and closed fields (e.g., Fisk et al. 1999; Ryutova et al. 2001; Fisk 2003; Schwadron & McComas 2003; Schwadron et al. 2006).

The natural appeal of the RLO idea is evident from the fact that open flux tubes are always rooted in the vicinity of closed loops (e.g., Dowdy et al. 1986) and that all layers of the solar atmosphere seem to be in continual motion with a wide range of timescales. Indeed, observed correlations between the lengths of closed loops in various regions, the electron temperature in the low corona, and the wind speed at 1 AU (Feldman et al. 1999; Gloeckler et al. 2003) are highly suggestive of a net transfer of Poynting flux from the loops to the open-field regions that may be key to understanding the macroscopic structure of the solar wind. The proposed RLO reconnection events may also be useful in generating energetic particles and cross-field diffusive transport throughout the heliosphere (e.g., Fisk & Schwadron 2001).

Testing the RLO idea using theoretical models seems to be more difficult than testing the WTD idea because of the complex multi-scale nature of magnetic reconnection. It can be argued that one needs to create fully 3D models of the coronal magnetic field (arising from multiple magnetic elements on the surface) to truly assess the full range of closed/open flux interactions. The idea of modeling the coronal field via a collection of discrete magnetic sources (referred to in various contexts as “magnetohydrodynamics,” “tectonics,” or “magnetic charge topology”) has been used extensively to study the evolution of the closed-field corona (e.g., Longcope 1996; Schrijver et al. 1997; Longcope & Kankelborg 1999; Sturrock et al. 1999; Priest et al. 2002; Beveridge et al. 2003; Barnes et al. 2005; Parnell 2007) but applications to open fields and the solar wind have been rarer (see, however, Fisk 2005; Tu et al. 2005).

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