Recent Successes of Wave/Turbulence Driven Models of Solar Wind Acceleration

Steven R. Cranmer[1], Joseph V. Hollweg[2], Benjamin D. G. Chandran[2], and Adriaan A. van Ballegooijen[1]

[1] Harvard-Smithsonian CfA, Cambridge, MA; [2] University of New Hampshire, Durham, NH

Abstract

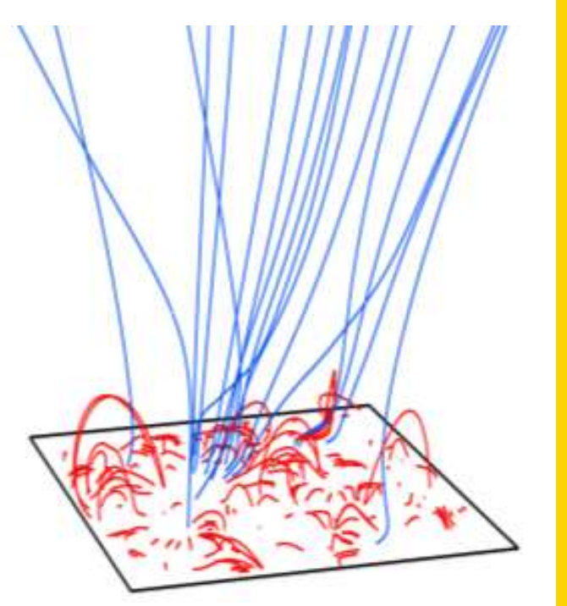
A key obstacle in the way of producing realistic simulations of the Sun-heliosphere system is the lack of a first-principles understanding of coronal heating. Also, it is still unknown whether the solar wind is "fed" through flux tubes that remain open (and are energized by footpoint-driven wavelike fluctuations) or if mass and energy are input intermittently from closed loops into the open-field regions. In this presentation, we discuss self-consistent models that assume the energy comes from solar Alfvén waves that are partially reflected, and then dissipated, by magnetohydrodynamic (MHD) turbulence. These models have been found to reproduce many of the observed features of the fast and slow solar wind without the need for artificial "coronal heating functions" used by earlier models. For example, the models predict a variation with wind speed in commonly measured ratios of charge states and elemental abundances that agrees with observed trends.

This presentation also reviews two recent comparisons between the models and empirical measurements: **(1)** The models successfully predict the amplitude and radial dependence of **Faraday rotation fluctuations** (FRFs) measured by the *Helios* probes for heliocentric distances between 2 and 15 solar radii. The FRFs are a particularly sensitive test of turbulence models because they depend not only on the plasma density and Alfvén wave properties in the corona, but also on the turbulent correlation length. **(2)** The models predict the correct sense and magnitude of changes seen in the polar high-speed solar wind by *Ulysses* from the previous solar minimum (1996–1997) to the more **recent peculiar minimum** (2008–2009). By changing only the magnetic field along the polar magnetic flux tube, consistent with solar and heliospheric observations at the two epochs, the model correctly predicts that the wind speed remains relatively unchanged, but the *in situ* density and temperature decrease by approximately 20% and 10%, respectively.

Motivations

Two distinct classes of theoretical explanation have been proposed for the combined problem of coronal heating and solar wind acceleration:

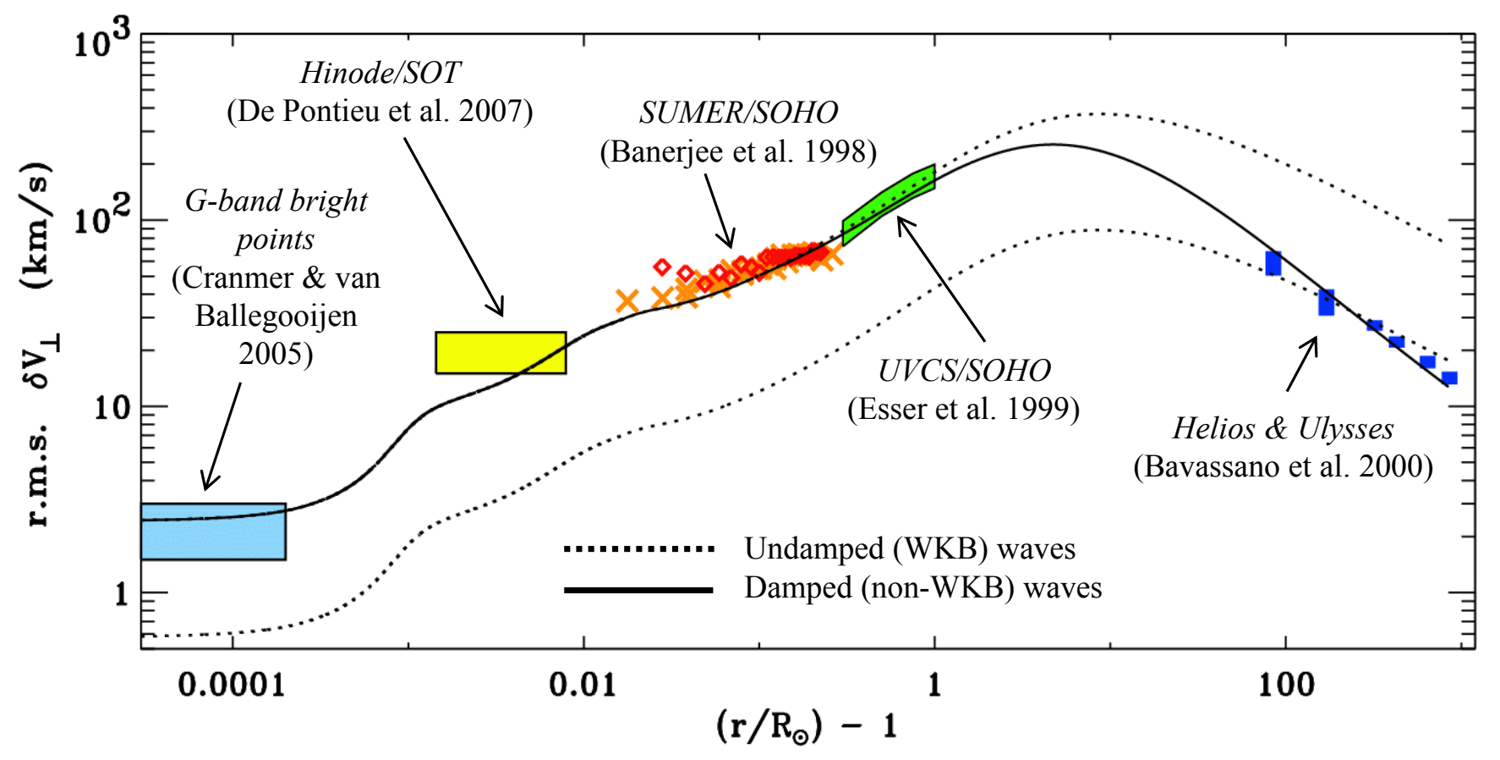
- In **wave/turbulence-driven (WTD)** models, convection jostles open flux tubes, producing Alfvén waves that propagate up, partially reflect, cascade to small scales, and dissipate.
- In **reconnection/loop-opening (RLO)** models, closed loops are the dominant source of mass and energy into open-field regions, via "interchange" reconnection in the Sun's magnetic carpet.



There is natural appeal to the RLO idea, since only a small fraction of the Sun's magnetic flux is open at any one time. The magnetic carpet is continuously evolving & reconnecting (making, e.g., **polar jets**).

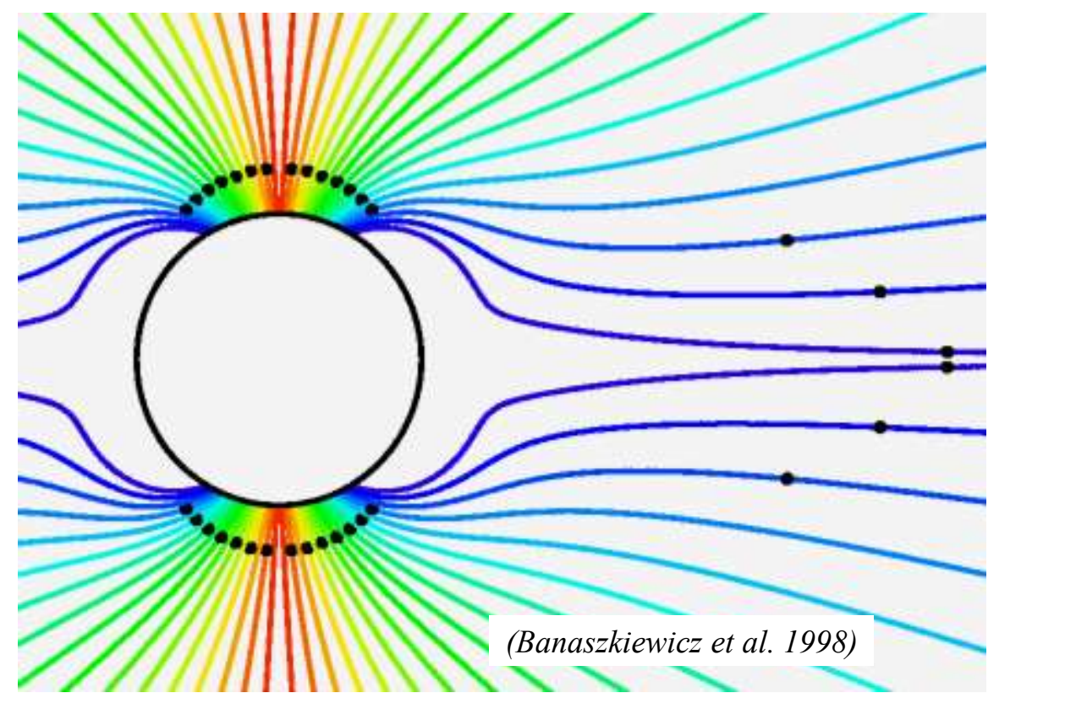
However, Cranmer & van Ballegooijen (2010) estimated that the energy lost in loop-opening RLO events is *far smaller* than that needed to heat the corona or accelerate the solar wind!

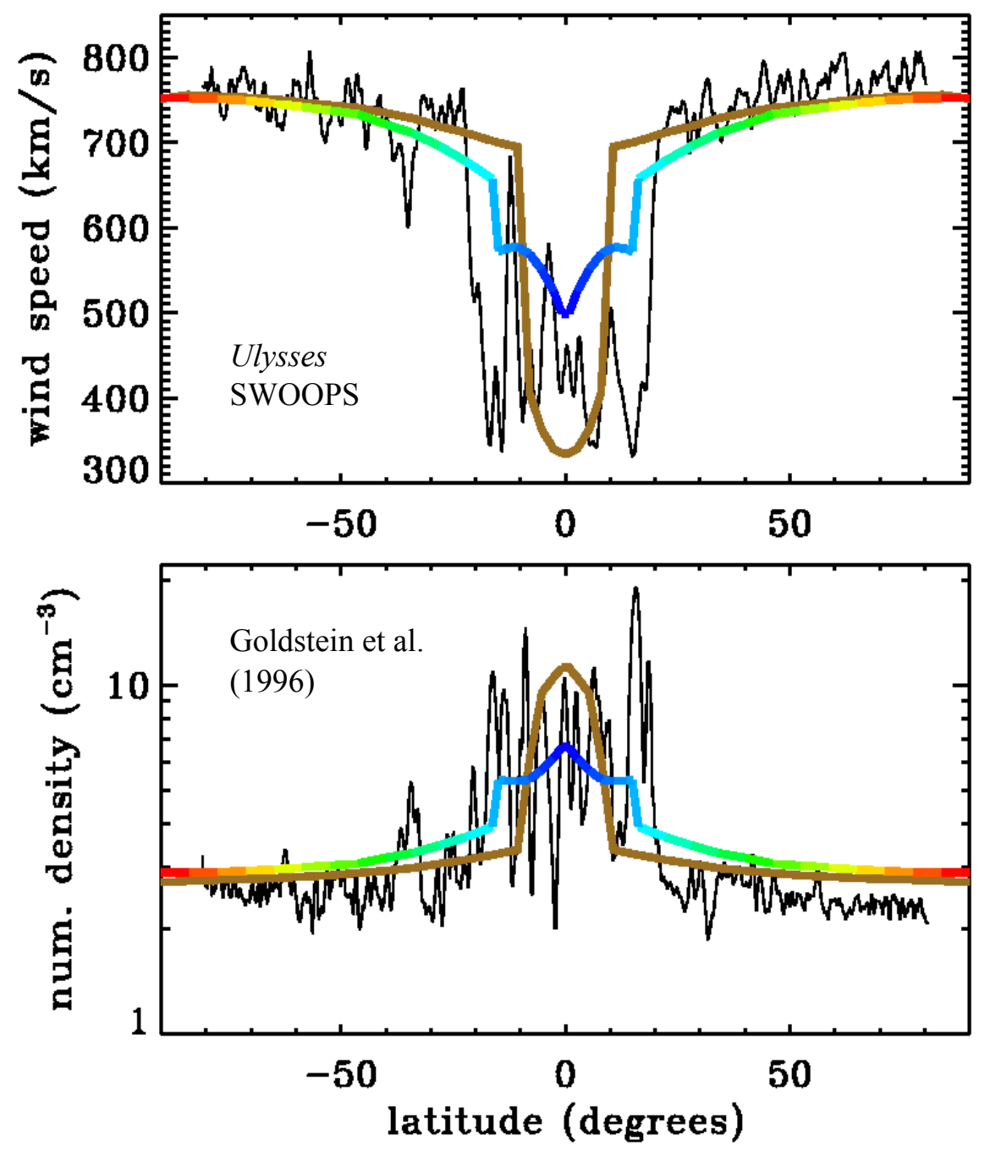
We know that MHD waves and turbulent fluctuations are present everywhere from the photosphere to the heliosphere, so it is worth while to investigate what impact *they* have on heating/acceleration.



Fast & Slow Solar Wind from Varying Flux-tube Expansion

- For a single choice for the photospheric wave properties, the Cranmer et al. (2007) models produced a realistic range of slow and fast solar wind conditions by varying only the coronal magnetic field.

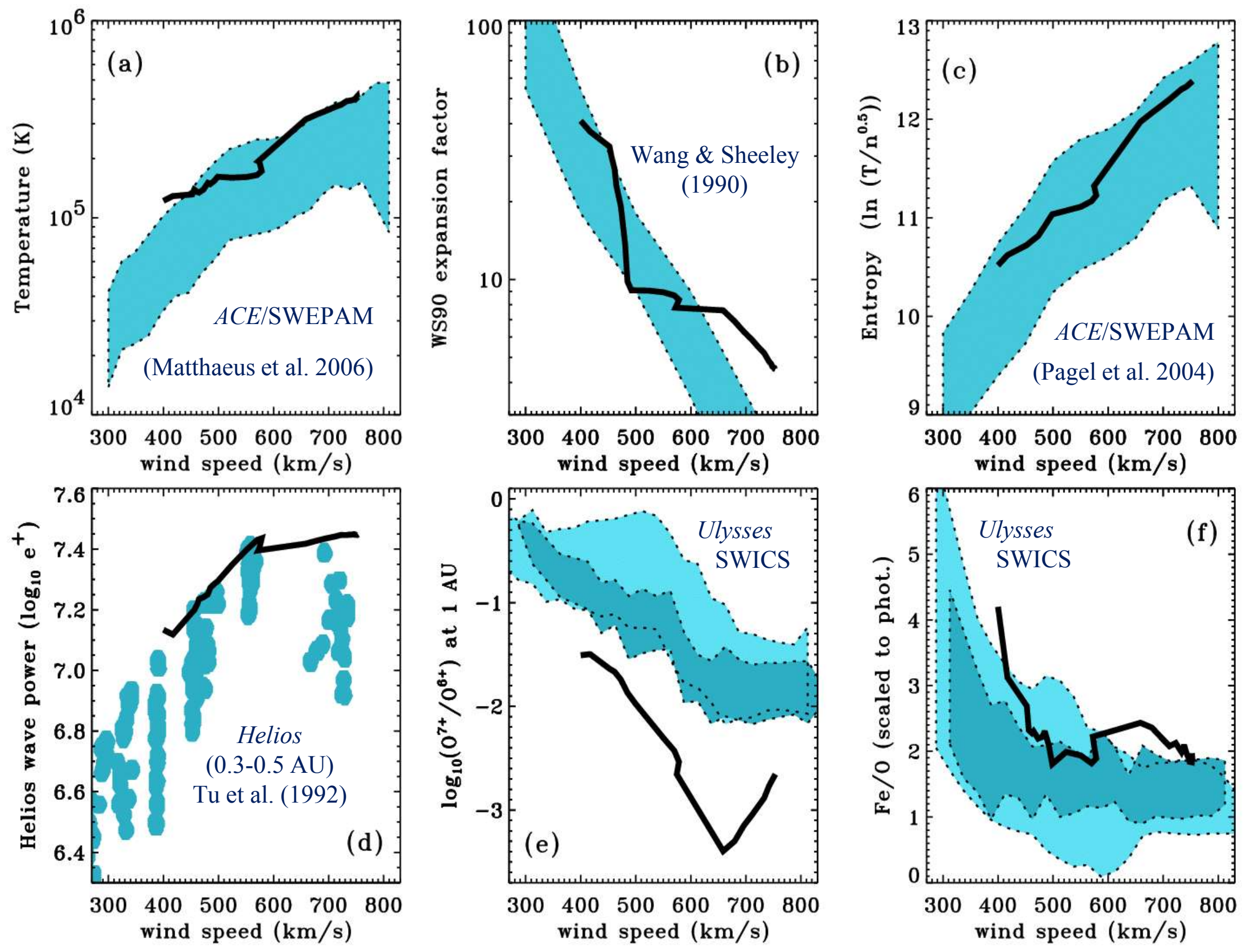




- The flux-tube geometry determines the radius of the Parker (1958) critical point:
  - Low r_{crit}: supersonic heating → fast wind
  - High r_{crit}: subsonic heating → slow wind

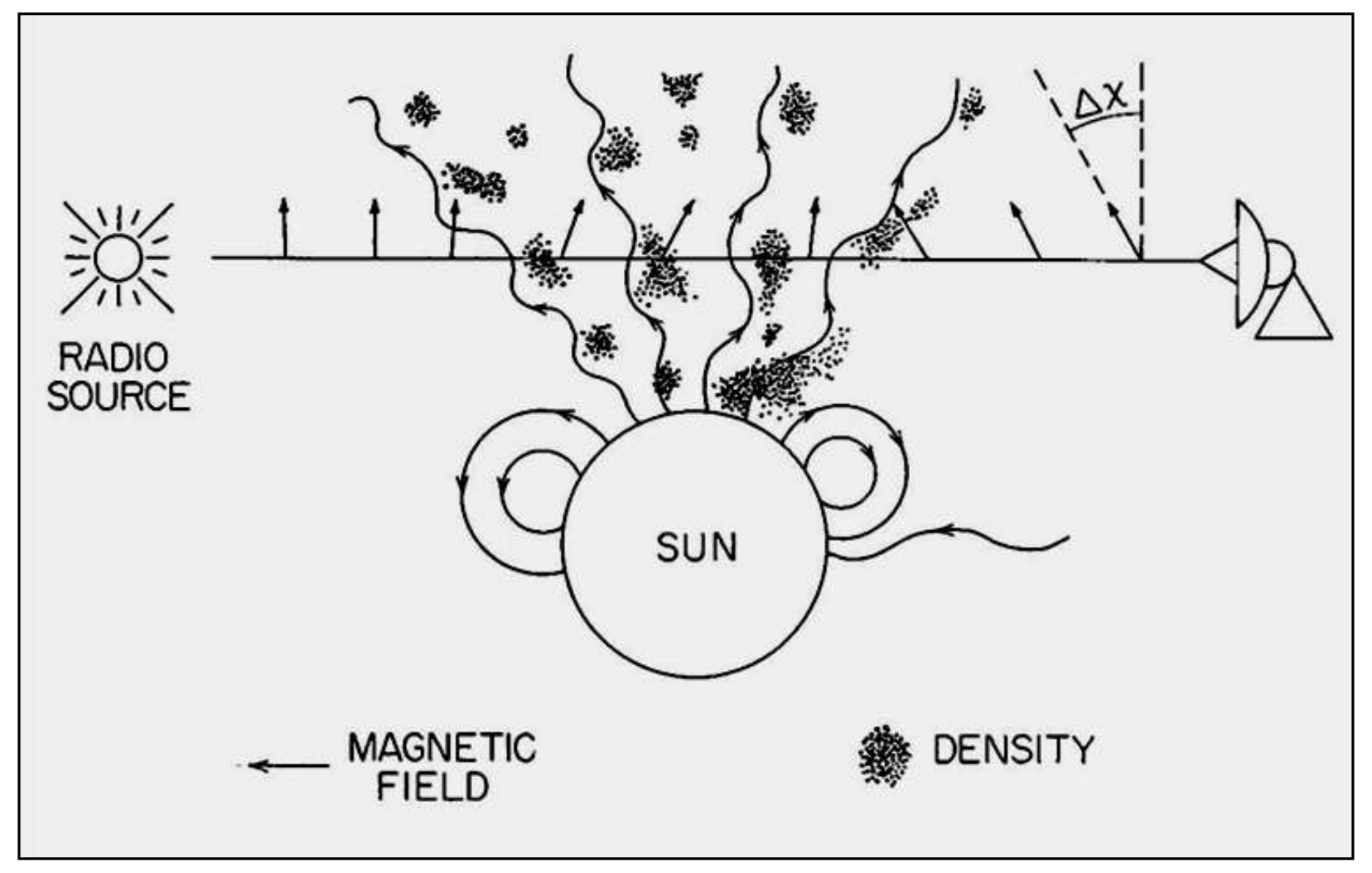
(Leer & Holzer 1980; Pneuman 1980)

- The superradial flux tube expansion gives rise to multiple "potential wells" in the Parker (1958) equation of motion. The time-steady critical point occurs at the global minimum, which can shift abruptly in radius even for gradually evolving flux-tube expansion (see also Vásquez et al. 2003).
- Note that the models produce variations in: **(e)** frozen-in **charge states** and **(f)** **FIP-sensitive abundance ratios** that vary similarly as the *in situ* composition measurements. The FIP fractionation was computed using Laming's (2004) wave acceleration theory.
- This seems to contradict the commonly held assertion that slow-wind FIP and charge-state properties can only be explained by the injection of plasma from closed-field regions on the Sun (see also Pucci et al. 2010).



Faraday Rotation Fluctuations as a Probe of Turbulent Scales

- Polarized radio signals passing through the corona are sensitive to a wide range of plasma fluctuations.
- Transmissions from the *Helios* probes (1975-1977) were used to measure fluctuations in **Faraday rotation,** which helps constrain the properties of coronal turbulence (Hollweg et al. 1982, 2010).



(Image courtesy of S. R. Spangler)

- The Faraday rotation depends on the line-of-sight (LOS) integral of the product of electron density and the LOS-component of the magnetic field:

$$\Delta\phi = \frac{e^3\lambda^2}{2\pi m_e c^4}\int n_e\,\mathbf{B}\cdot d\mathbf{s}$$

- Faraday rotation fluctuations (FRFs) depend on variations in the density and magnetic field (see Hollweg et al. 2010):

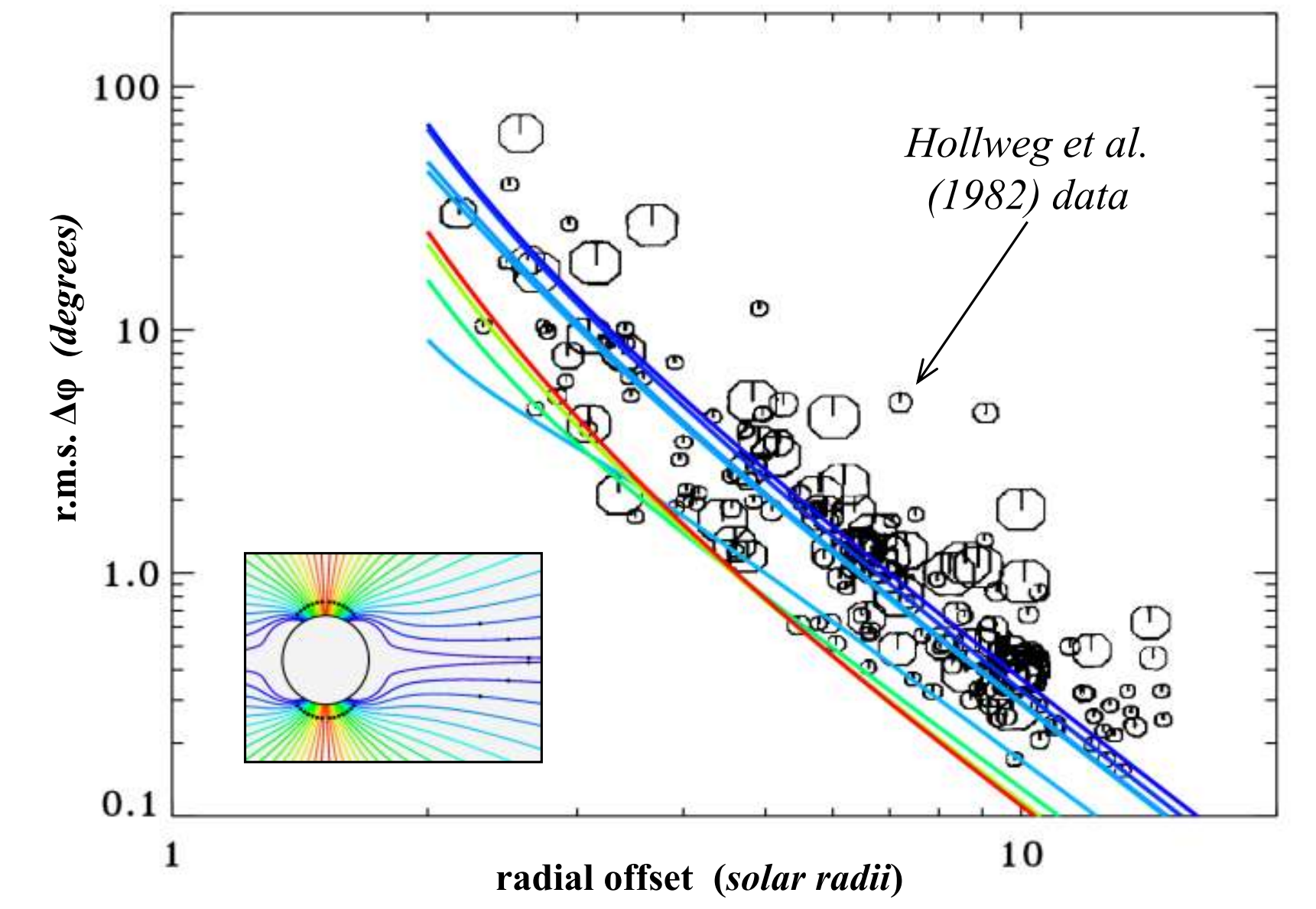
$$\langle\Delta\phi^2\rangle \approx \frac{e^3\lambda^2}{\pi m_e c^4}\int ds\,\Big[\cancel{B_0^2\,\langle\delta n_e^2\rangle\,L_n} + n_{e_0}^2\,\langle\delta B^2\rangle\,L_B\Big]_s$$

δ*n* term is neglibigle

depends on turbulent correlation length of magnetic fluctuations

- The Cranmer et al. (2007) models used Hollweg's (1986) assumption that the correlation length scales with the width of the flux tube (i.e., $L \sim B_0^{-1/2}$), and that it is normalized by the photospheric motions of **G-band bright points** (i.e., $L \sim 100$ km in the photosphere).

Result: Synthesized FRFs for **equatorial streamer** flux tubes agree well with the *Helios* measurements; **coronal hole** flux tubes do not.

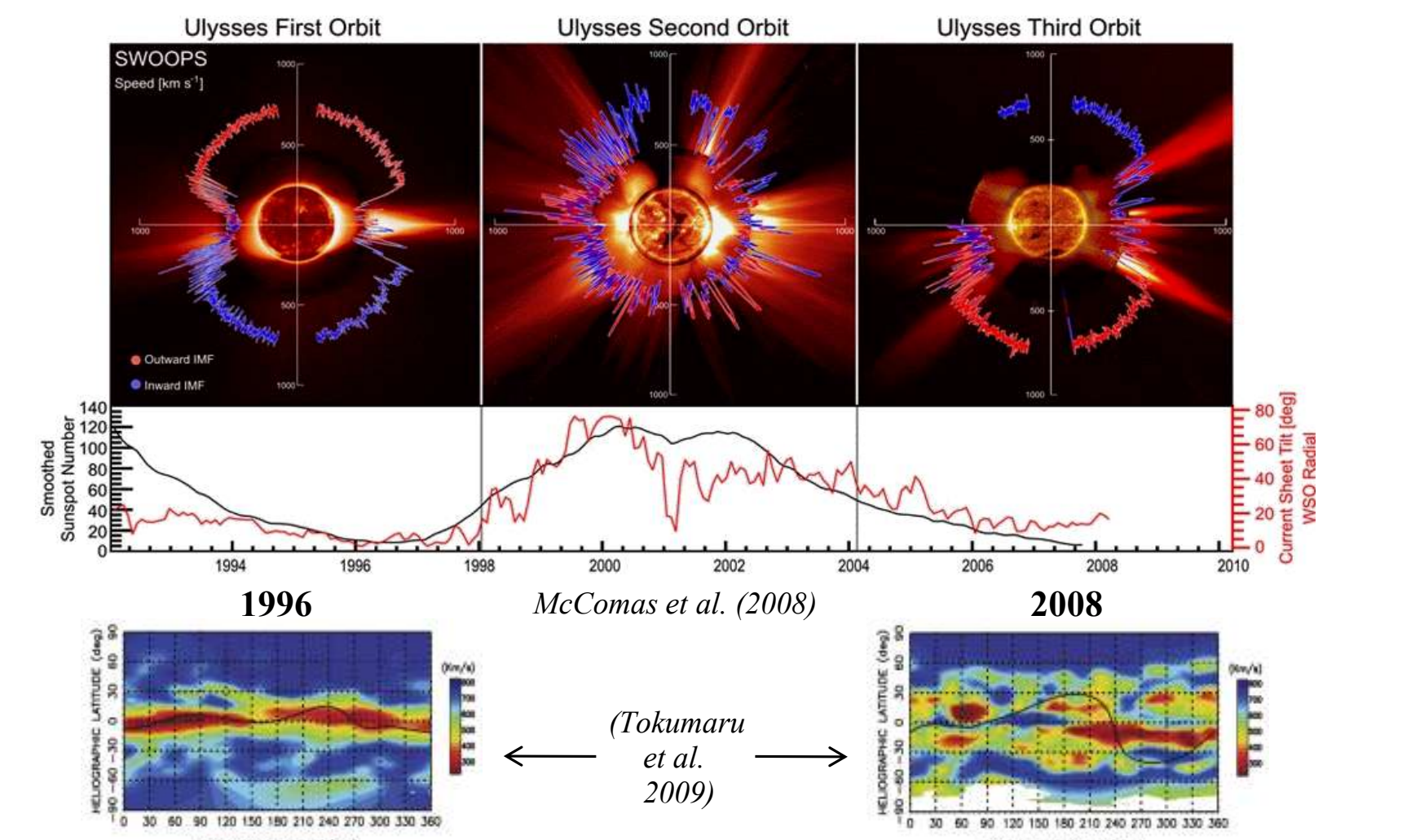


- Disagreement for coronal hole flux tubes is unsurprising, since the *Helios* lines of sight were all very close to the ecliptic plane.
- Other models of turbulent coronal heating that use **different L_B normalizations** (e.g., Verdini et al. 2009, 2010) should be tested by comparing with measured FRFs as well.

The Peculiar 2008–2009 Solar Activity Minimum

When comparing 2008-2009 to the previous (1996-1997) minimum,

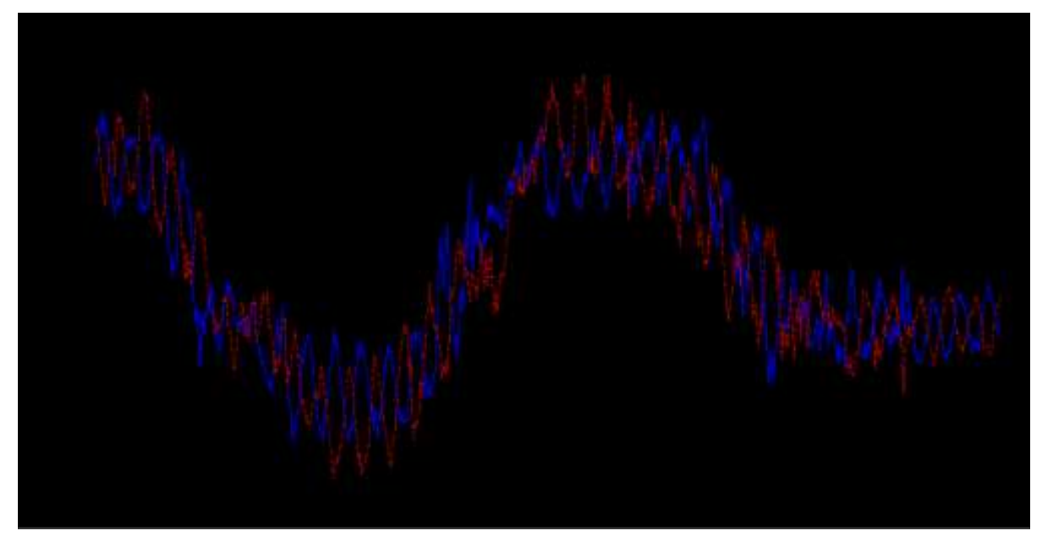
- Polar **coronal holes** are smaller, with lower field strengths, and there are more equatorial coronal holes.
- The latitude spread of the **streamer belt** is larger.
- The *in situ* **fast wind** has a lower magnetic flux, lower density, and lower temperature, but comparable outflow speed.



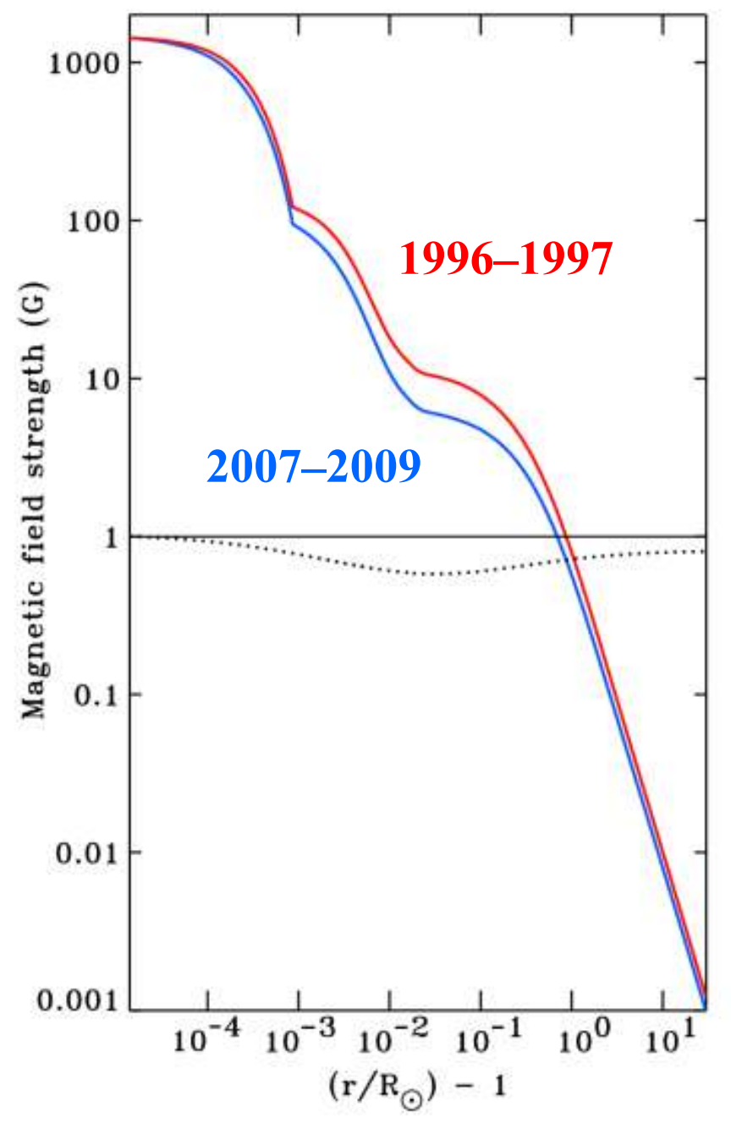
McComas et al. (2008)

(Tokumaru et al. 2009)

- Cranmer et al. (2009a) produced a new model of the fast wind from a polar coronal hole, similar in all ways to that of Cranmer et al. (2007) except that the magnetic field strength was weaker, as seen during the 2008-2009 minimum:
- We postulated the photospheric field strength in individual (100 km width, 1.5 kG) flux tubes to be unchanged.
- In the upper chromosphere/low corona, WSO found a low-resolution polar field strength ~40% lower than in 1996-1997:



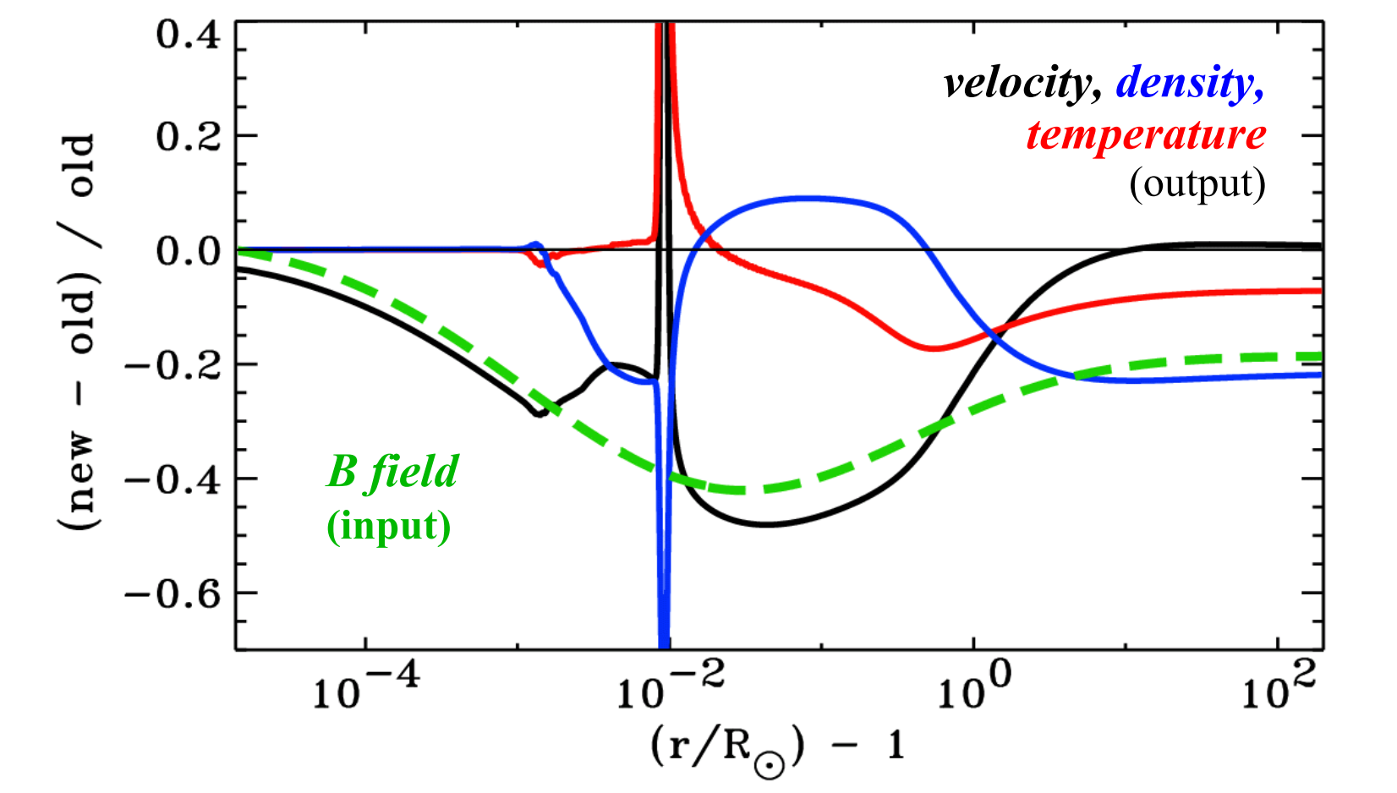
- At distances > 1 AU, *Ulysses* measured the polar field strength to be ~18% lower than during previous min. (Smith & Balogh 2008).



Result: The new model gave rise to relative changes at 1 AU that agree well with *Ulysses* measurements (McComas et al. 2008):

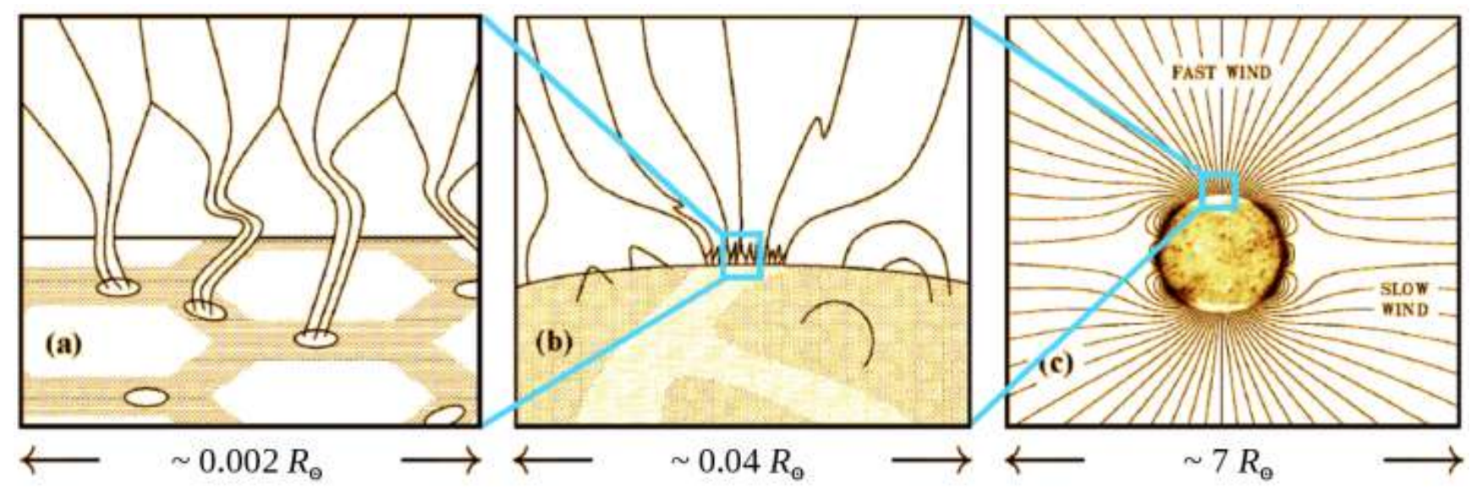
Table 1. Relative changes in fast solar wind from 1996–1997 to 2007–2009

	Ulysses polar data	WTD model output
speed	–03%	+01%
density	–17%	–22%
temperature	–14%	–08%
gas pressure	–28%	–21%
dynamic pressure	–22%	–27%

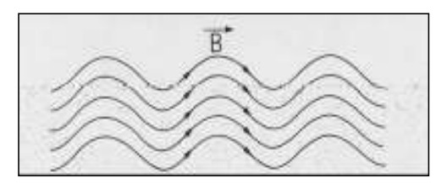


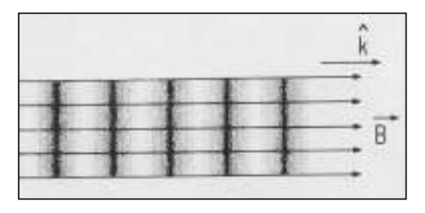
Model Inputs

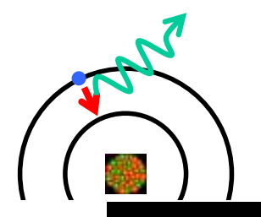
- Cranmer et al. (2007) computed self-consistent solutions for turbulent fluctuations & the background plasma along flux tubes going from the photosphere to the heliosphere:



- The **only free parameters** were the radial magnetic field (i.e., the flux tube expansion rate) and the photospheric boundary conditions on the wave power spectrum.
- No *ad hoc* "coronal heating functions" were used; just the following physically motivated ingredients . . .





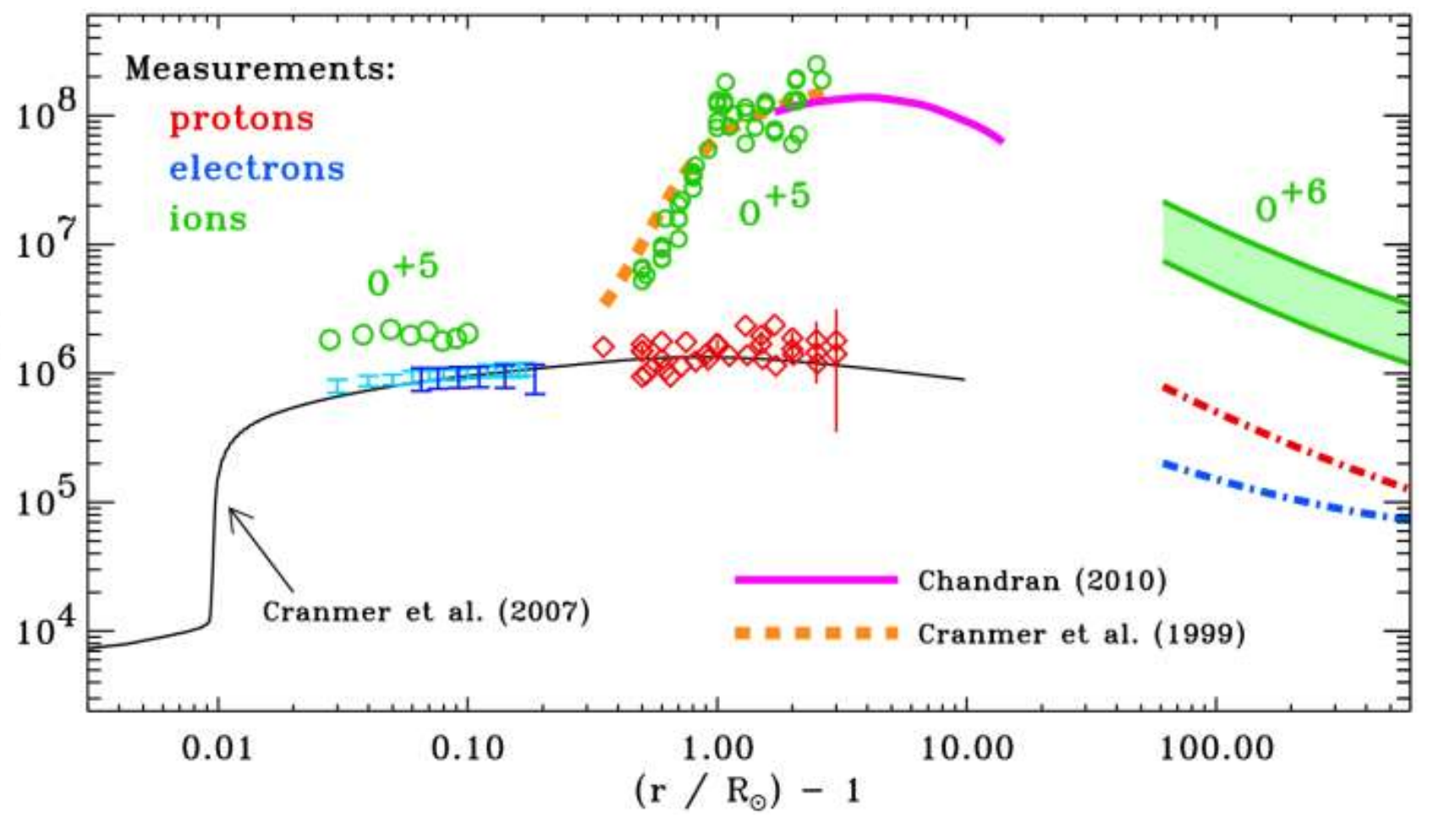


- **Alfvén waves:** Non-WKB reflection with an empirical frequency spectrum, turbulent damping (using phenomenological rates of Hossain et al. 1995; Matthaeus et al. 1999; Dmitruk et al. 2001, 2002), and wave-pressure acceleration.
- **Acoustic waves:** Shock steepening, TΔS and conductive damping, full spectrum above cutoff, & wave-pressure acceleration.
- **Radiative losses:** Transitions from an optically thick (LTE) to optically thin (CHIANTI + PANDORA) cooling rate.
- **Heat conduction:** Transitions from collisional (electron & neutral H) to collisionless "free-streaming" electron conductivity.

- The Sun's **mass loss rate** was determined self-consistently by allowing the height and properties of the Transition Region to "float" until a stable and time-steady solution was found.

Conclusions

- Despite significant progress in building and validating models of wave/turbulence processes, we still do not have conclusive evidence that this mechanism is dominant everywhere in the corona and solar wind. For a contrary view, see Roberts (2010).
- An important next step in testing is to incorporate the proposed heating processes into **3D global simulations** of the Sun–heliosphere system (see Cranmer 2010 for an example of a self contained "coronal heating subroutine" for this purpose).
- Finally, it is important for future models to take account of the **kinetic and multi-fluid** nature of coronal heating and solar wind acceleration (see, e.g., Kohl et al. 2006; Marsch 2006):



- A proper accounting of these kinetic effects will lead to better predictions for measurements to be made by missions such as *Solar Probe Plus,* as well as next-generation spectroscopy that could follow up on the successes of the UVCS instrument on *SOHO*. (See decadal white paper: **http://arXiv.org/abs/1011.2469**)

We would like to thank John Kohl, Dick Edgar, Bill Matthaeus, and Aaron Roberts for valuable discussions. SRC's work is supported by NASA under grants NNX09AB27G and NNX10AC11G to the Smithsonian Astrophysical Observatory. BDGC's work is supported in part by NSF Grants ATM-0851005 and ATM-1003451, DOE Grant DE-FG02-07-ER46372, and NASA Grants NNX07AP65G and NNX08AH52G to the University of New Hampshire.

References

Banaszkiewicz, M., et al. 1998, A&A, 337, 940
Banerjee, D., et al. 1998, A&A, 339, 208
Bavassano, B., et al. 2000, JGR, 105, 15959
Chandran, B. D. G. 2005, Phys. Rev. Lett., 95, 265004
Chandran, B. D. G. 2010, ApJ, 720, 548
Cranmer, S. R. 2002, Space Sci. Rev., 101, 229
Cranmer, S. R. 2004, in SOHO-15, ESA SP-575, 154, astro-ph/0409724
Cranmer, S. R. 2009, Liv. Rev. Solar Phys., 6, 3
Cranmer, S. R. 2010, ApJ, 710, 676
Cranmer, S. R., & van Ballegooijen, A. A.2005, ApJS, 156, 265
Cranmer, S. R., & van Ballegooijen, A. A. 2010, ApJ, 720, 824
Cranmer, S. R., et al. 1999, ApJ, 518, 937
Cranmer, S. R., et al. 2007, ApJS, 171, 520
Cranmer, S. R., et al. 2009a, ASP Conf. Ser. 428, 209
Cranmer, S. R., et al. 2009b, ApJ, 702, 1604
De Pontieu, B., et al. 2007, Science, 318, 1574
Dmitruk, P., et al. 2001, ApJ, 548, 482
Dmitruk, P., et al. 2002, ApJ, 575, 571
Dobrowolny, M., et al. 1980, PRL, 45, 144
Esser, R., et al. 1999, ApJ, 510, L63
Goldstein, B. E., et al. 1996, A&A, 316, 296
Grappin, R., et al. 1993, Phys. Rev. Lett., 70, 2190
Hollweg, J. V. 1986, JGR, 91, 4111
Hollweg, J. V., et al. 1982, JGR, 87, 1
Hollweg, J. V., et al. 2010, ApJ, 722, 1495
Hossain, M., et al. 1995, Phys. Fluids, 7, 2886
Kohl, J. L., et al. 2006, A&A Review, 13, 31
Laming, J. M. 2004, ApJ, 614, 1063
Landi, E., & Cranmer, S. R. 2009, ApJ, 691, 794
Leer, E., & Holzer, T. E. 1980, JGR, 85, 4681
Marsch, E. 2006, Liv. Rev. Solar Phys., 3, 1
Matthaeus, W. H., & Zhou, Y. 1989, Phys. Fluids B, 1, 1929
Matthaeus, W. H., et al. 1999, ApJ, 523, L93
Matthaeus, W. H., et al. 2006, JGR, 111, A10103
McComas, D. J., et al. 2008, GRL, 35, L18103
Oughton, S., et al. 2006, Phys. Plasmas, 13, 042306
Pagel, A. C., et al. 2004, JGR, 109, A01113
Parker, E. N. 1958, ApJ, 128, 664
Pneuman, G. W. 1980, A&A, 81, 161
Pucci, S., et al. 2010, ApJ, 709, 993
Roberts, D. A. 2010, ApJ, 711, 1044
Smith, E. J., & Balogh, A. 2008, GRL, 35, L22103
Spangler, S. R. 2002, ApJ, 576, 997
Tokumaru, M., et al. 2009, GRL, 36, L09101
Tomczyk, S., & McIntosh, S. W. 2009, ApJ, 697, 1384
Tu, C.-Y., Marsch, E., & Rosenbauer, H. 1992, Solar Wind 7, 555
van Ballegooijen, A. A. 1986, ApJ, 311, 1001
van Ballegooijen, A. A., et al. 1998, ApJ, 509, 435
Vásquez, A., et al. 2003, ApJ, 591, 1361
Vasquez, B. J., et al. 2007, JGR, 112, A07101
Velli, M., et al. 1989, Phys. Rev. Lett., 63, 1807
Verdini, A., et al. 2009, ApJ, 700, L39
Verdini, A., et al. 2010, ApJ, 708, L116
Voitenko, Y., & Goossens, M. 2004, ApJ, 605, L149
Wang, Y.-M., & Sheeley, N. R. 1990, ApJ, 355, 726