Connections Between the Magnetic Carpet and the Unbalanced Corona:

New Monte Carlo Models and Energy Estimates

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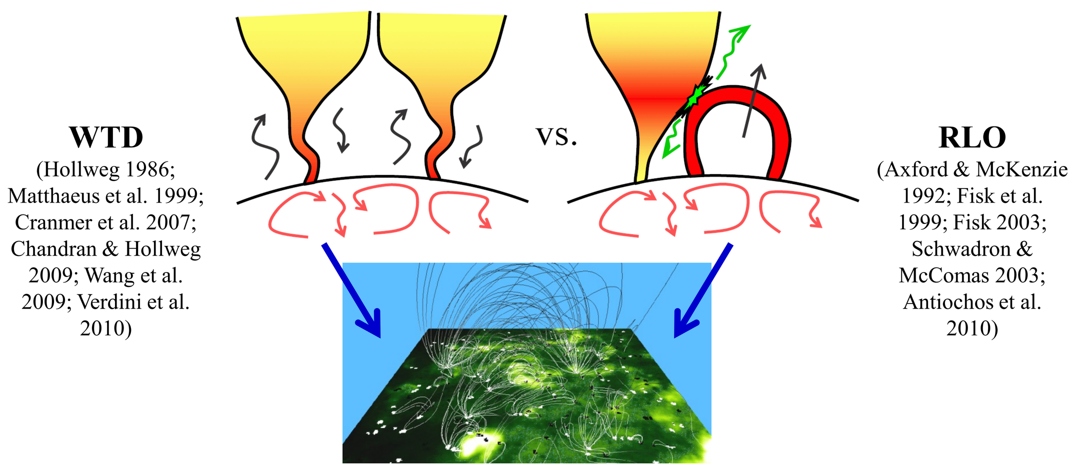
Abstract

It is clear from observations of the solar magnetic carpet that much of the heating in closed-field regions is driven by the interplay between emergence, separation, merging, and cancellation of many small flux elements. However, we do not yet know to what extent the open flux tubes are energized by these processes. In order to begin investigating this, we developed Monte Carlo simulations of the photospheric magnetic carpet and extrapolated the time-varying magnetic field up into the corona. These models were constructed for a range of different magnetic flux imbalance ratios (i.e., for both quiet regions and coronal holes), and they appear to be the first simulations to utilize newly observed flux emergence rates that are at least an order of magnitude larger than those used in earlier models.

The results agree with a wide range of observations, including surface flux densities and number distributions of magnetic elements. Despite having no imposed supergranular motions in the models, a realistic network of magnetic funnels appeared spontaneously. We also computed the rate at which closed field lines open up (i.e., the recycling times for open flux), and we estimated the energy flux released in reconnection events involving the opening up of closed flux tubes. For quiet regions and mixed-polarity coronal holes, these energy fluxes were found to be much lower than required to accelerate the solar wind. For the most imbalanced coronal holes, the energy fluxes may be large enough to power the solar wind, but the recycling times are far longer than the time it takes the solar wind to accelerate into the low corona. Thus, reconnection and loop-opening processes in the magnetic carpet may be responsible for intermittent events in coronal holes (e.g., polar jets), but probably not for the majority of bulk solar wind acceleration.

Motivations

- Recently, two distinct classes of theoretical explanation have been proposed for the combined problem of coronal heating & solar wind acceleration:
- In **wave/turbulence-driven (WTD)** models, convection jostles open flux tubes, producing Alfvén waves that propagate up, partially reflect, cascade, and damp.
- In **reconnection/loop-opening (RLO)** models, closed loops are the dominant source of mass and energy into open-field regions, via "interchange" reconnection.



- Both ideas are "rooted" in the complex, continually evolving magnetic carpet.
- Both ideas need to be subjected to much more development, testing, & refinement.
- This work aims to see how much of this testing can be done *without* full 3D MHD !

Methods

- We simulated the magnetic carpet in a photospheric "patch" (200 x 200 Mm) with a **Monte Carlo** ensemble of positive and negative monopole sources of magnetic flux.
- These sources are assumed to emerge from below (as bipolar ephemeral regions), move around on the surface, merge or cancel with their neighbors, and spontaneously fragment.
- We used the photospheric flux sources to extrapolate field lines up into the corona by assuming the field is derivable from a **scalar potential** (e.g., Wang 1998).
- Although the actual solar field has significant non-potential components (Parnell & Galsgaard 2004; Edmondson et al. 2009), a potential-field approximation has been found to be useful in identifying regions where reconnection must be taking place (e.g., Close et al. 2005).
- We use Longcope's (1996) **minimum current corona (MCC)** method to estimate how much magnetic energy is liberated by reconnection events that transfer closed magnetic flux into open-field flux.
- To study both quiet sun (QS) regions as well as coronal holes (CH), the models are computed for a range of mean **flux imbalance fractions** ξ between 0 and 1.

$$\xi = \frac{|\Phi_+| - |\Phi_-|}{|\Phi_+| + |\Phi_-|}$$

The "Zoo" of Processes

- What governs the evolution of the individual flux elements?

1. New magnetic fields appear due to **flux emergence** from below the photosphere. We use new emergence rates from Hagenaar et al. (2008, 2010), and sample random fluxes for each new element from a truncated exponential probability distribution.
2. Flux elements undergo stochastic **horizontal motions** on the surface that are often described as being "subdiffusive" (Cadavid et al. 1999). We specify a mean random-walk velocity for weak elements (6 km/s), and assume that for stronger elements the velocity decreases exponentially (see, e.g., Schrijver 2001).
3. When two flux elements encounter one another inside a given "radius of influence," they are assumed to **coalesce** into a single element (for like polarities) or **partially cancel** (for unequal and opposite polarities) or **completely cancel** (for equal and opposite polarities). Radii of influence scale with $\Phi^{1/2}$, and are constrained to be between 1 and 10 Mm.
4. Observations show that flux elements often **spontaneously fragment** into several pieces (Berger & Title 1996). We use a modified version of Schrijver's (2001) fragmentation probability distribution to decide when any given element will break up into two random pieces.

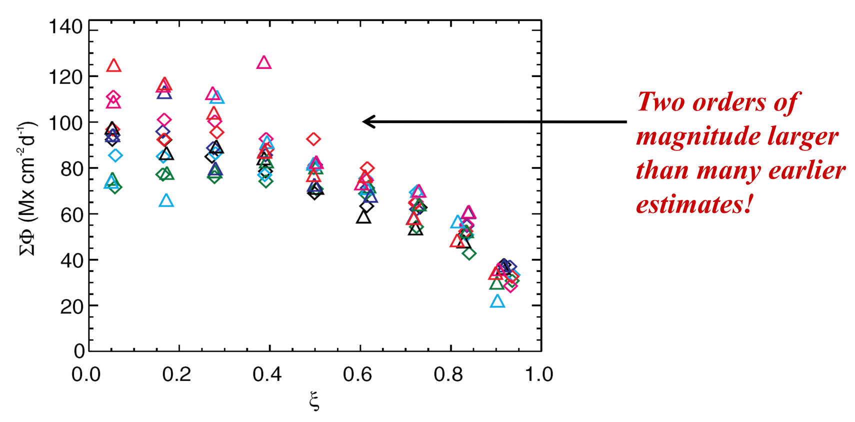
(see also Schrijver et al. 1997; Parnell 2001; Simon et al. 2001; Crouch et al. 2007)

How Much Emergence?

- The rate of emergence of new magnetic flux has been determined in various ways:

E (Mx/cm²/day)	Source
0.2 to 3.5	Schrijver (2001)
~ 0.7	Parnell (2001)
~ 1.1	Simon et al. (2001)
~ 7.8	Krijger & Roudier (2003)

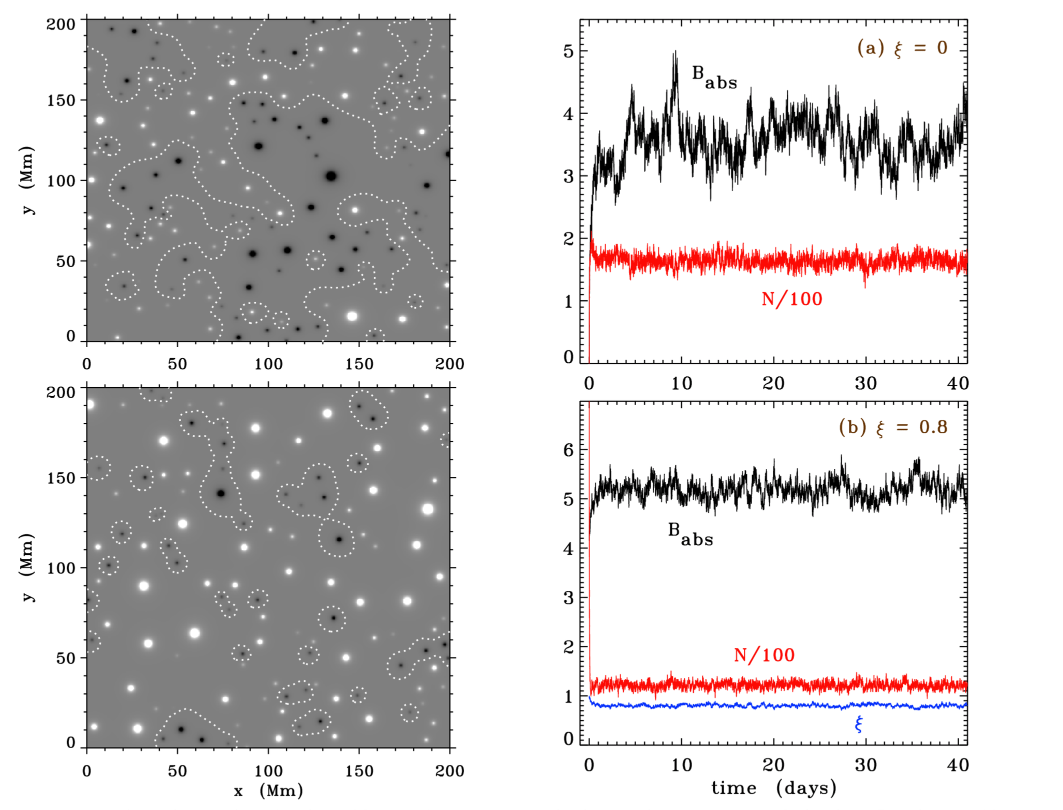
- As sensitivity & cadence improved, empirically derived values of *E* **increased!** Hagenaar et al. (2008, 2010) found much larger rates than any previous study:



- Starting with 2001-era model parameters, if all we did was increase *E*, the time-steady models would contain **far too much magnetic flux.** More emergence requires more cancellation (e.g., faster horiztonal diffusion, more fragmentation).

Results: Photospheric Field

- Monte Carlo models were evolved in time (Δt = 5 min) for total times of 30–100 days. Simulated magnetograms (left) and time-evolving statistical averages (right):

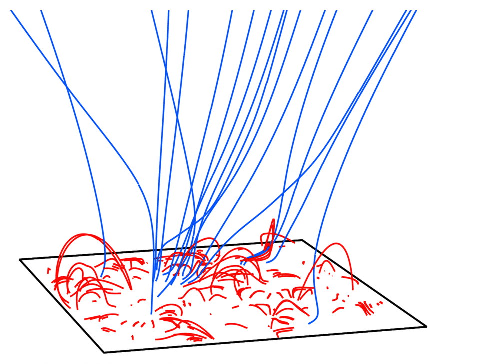


Upper: ξ=0, lower: ξ=0.8, dotted line: |B|=0, black/white saturation: 100 G

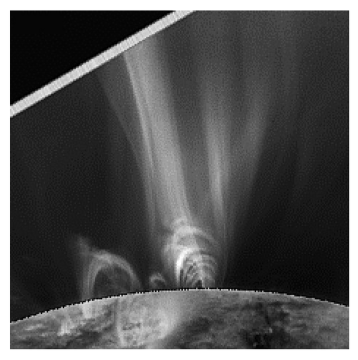
Black: simulation-averaged absolute flux density (G); Red: number of flux elements/100

Results: Coronal Field

- At each time step, the vector field above the (200 Mm)² patch was extrapolated using a potential field approximation.



(Traced field lines for an example time step in a Monte Carlo model with ξ = 0.5)

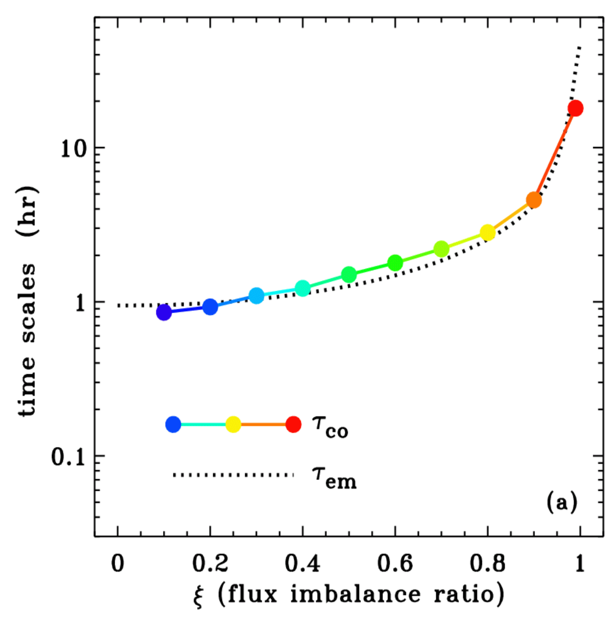


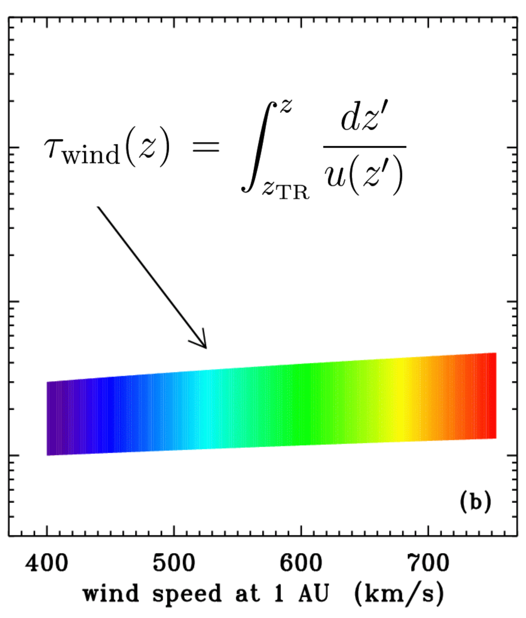
(For comparison, an off-limb close-up of a highly processed SDO/AIA 171 Å image)

- The distribution of **loop heights** vs. ξ matched the observational trend confirmed by Wiegelmann & Solanki (2004): QS = tall loops, CH = short loops.
- To quantify the changes in the field from one time step to the next, we traced field lines from the *N* flux elements and kept track of how much flux stays closed (**cc**), stays open (**oo**), goes from closed to open (**co**), and goes from open to closed (**co**).
- The time scale for flux emergence (τ_{em}) was found to be roughly equal to the time scale for the opening up of closed flux tubes (τ_{co}).

$$\tau_{em} = \frac{\langle B_{abs}\rangle}{E} \qquad \tau_{co} = \frac{\langle B_{open}\rangle}{\langle (dB/dt)_{co}\rangle} = \frac{\langle f_{open}\rangle\, \Delta t}{\langle f_{co}\rangle}$$

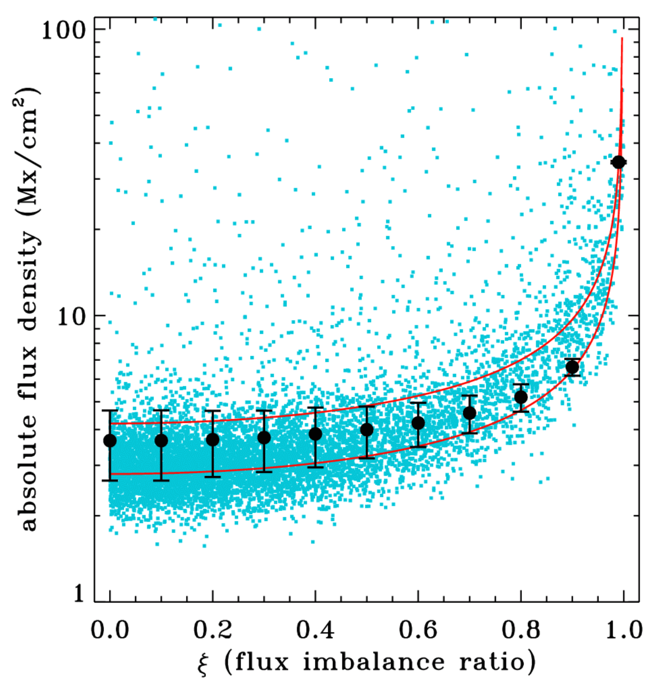
- In the future, full 3D MHD simulations may show that $\tau_{co} >> \tau_{em}$, since reconnection may not be as "instantaneous" as we assumed by using a succession of potential-field states.
- We also computed the **time scale for solar wind acceleration** (using Cranmer et al. 2007 models) from the coronal base up to a height 2–3 times the maximum loop heights **(i.e., where the wind is clearly out of the influence of all RLO processes).**
- In general, lots of wind can be accelerated in the time it takes for the open flux to recycle itself via reconnection in the magnetic carpet.





Magnetic Fluxes

- The "best" empirical input parameters of the Monte Carlo models were found such that resulting magnetic fields best reproduced observational constraints.
- Number distributions of flux elements (not shown here) also agreed with observed distributions given by Parnell (2002) and Hagenaar et al. (2008).

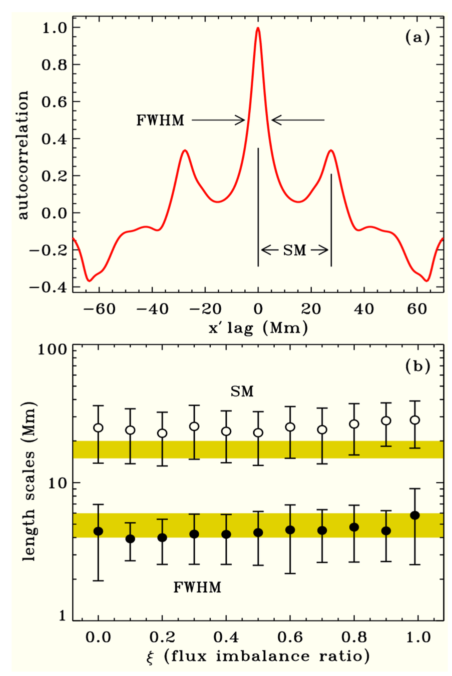


- Observations from VSM on SOLIS (Keller et al. 2003) are shown for example magnetograms taken from 2003 to 2009, using 113″ x 113″ macropixels (**cyan points**).
- Monte Carlo results are shown in **black** (points: means, error bars: 3 standard deviations about means).
- Simple scaling relation (**red curves**) was calculated assuming a constant emergence rate and a cancellation rate that depends on the product of box-averaged B_+B_- (see Cranmer & van Ballegooijen 2010):

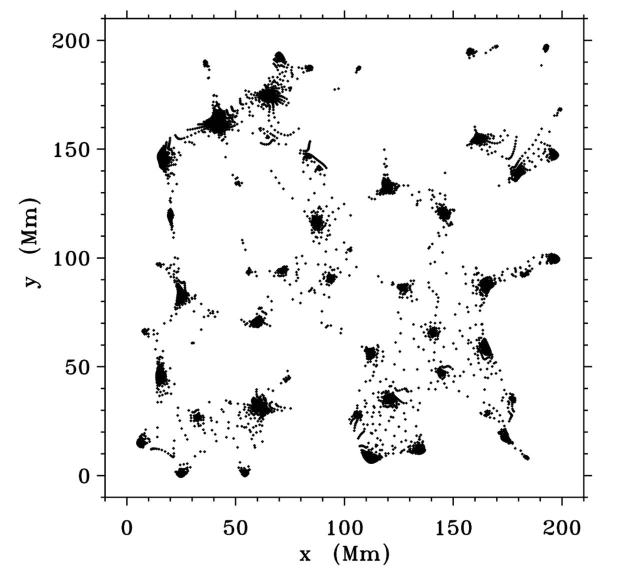
$$B_{abs} = B_+ + |B_-| = \frac{2B_0}{\sqrt{1-\xi^2}}$$

The Supergranular Network

- In order to make quantitative comparisons of the resulting network structure (avoiding arbitrary definitions of "cell diameters"), we computed autocorrelation functions of $B_z(x,y)$ & compared to similarly processed magnetograms (Wang 1988).
- Monte Carlo results (**circles**) matched measured (**yellow bars**) full-widths at half-maximum (FWHM) and the distances to the secondary maximum (SM).



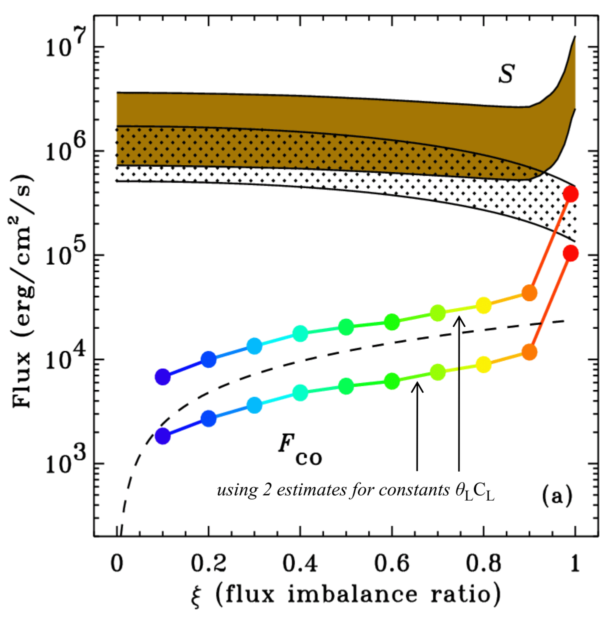
- Footpoints of ***open*** fields (for ξ=0.8) trace the network funnels/lanes/vertices:

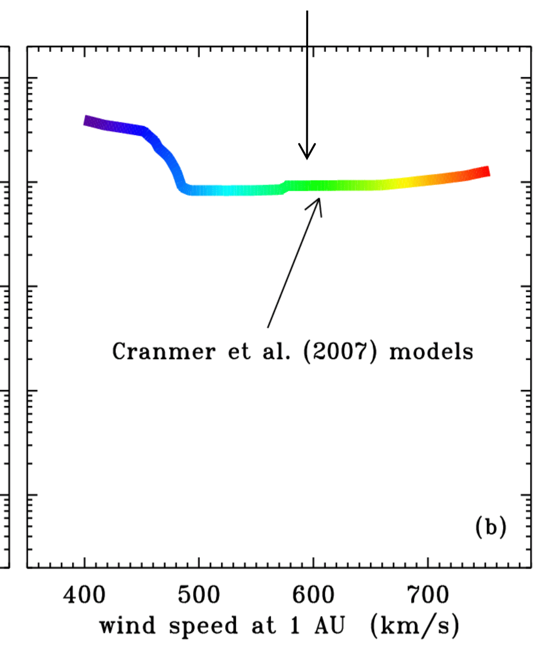


- We estimated the **Poynting flux** *S* corresponding to the magnetic energy injected by emerging bipoles. Two independent methods (see brown & dotted regions) both found *S* ≈ 10⁶ erg/cm²/s.

$$F_{co} = \theta_L C_L \frac{\Phi_1}{\langle d\rangle} \left|\frac{dB}{dt}\right|_{co}$$

- The Longcope (1996) MCC model allowed us to estimate the energy flux F_{co} released by loop-opening events. Generally, $F_{co} << S$.
- F_{co} is also << the energy flux required to heat the corona and accelerate the solar wind!





Conclusions

- Our goal was to begin testing the conjecture that the opening up of closed flux in the magnetic carpet is responsible for driving the solar wind.
- We found that the new flux emergence rates of Hagenaar et al. (2008, 2010) must be balanced by higher rates of diffusion & cancellation to model the "real" Sun.
- For quiet regions (ξ << 1) and most coronal holes (ξ < 0.8), we found that only a tiny fraction of the available Poynting flux (i.e., energy flux in emerging magnetic elements) is released in flux-opening events.
- For the most unipolar coronal holes (ξ ≈ 1), there may be enough energy available, but the time scale for flux opening is much longer than the solar wind travel time to heights far above the tops of loops. Thus, a significant amount of mass accelerates out into the wind in the time it takes for the plasma to be processed by RLO type mechanisms. These processes may be important for **intermittent polar jets** (e.g., Savcheva et al. 2007; Chifor et al. 2008; Pariat et al. 2009).
- Flux-opening events may give rise to Alfvén waves with periods of order the closed-to-open time scale (~1 hr). This may bridge the observational "gap" between photosphere/chromosphere wave measurements (3–10 min. periods) and *in situ* wave measurements (>>1 hr periods); see Cranmer & Chandran poster.
- The results of this work need to be tested and verified with fully 3D MHD models (e.g., Parnell & Galsgaard 2004; Gudiksen & Nordlund 2005; Moreno-Insertis et al. 2008; Edmondson et al. 2009).

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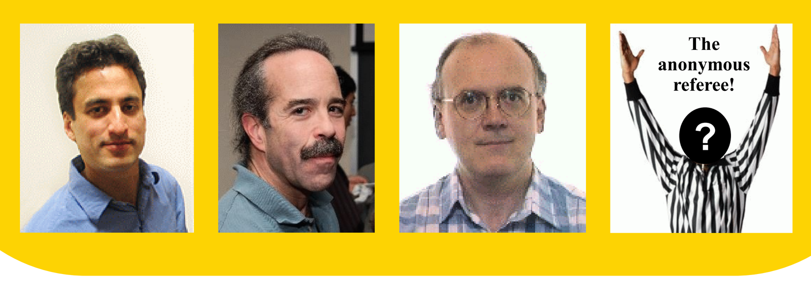

References

Antiochos, S. K., et al. 2010, ApJ, submitted
Axford, W. I., & McKenzie, J. F. 1992, Solar Wind Seven, 1
Berger, T. E., & Title, A. M. 1996, ApJ, 463, 365
Cadavid, A. C., et al. 1999, ApJ, 521, 844
Chandran, B. D. G., & Hollweg, J. V. 2009, ApJ, 707, 1659
Chifor, C., et al. 2008, A&A, 491, 279
Close, R. M., et al. 2005, Solar Phys., 231, 45
Cranmer, S. R., van Ballegooijen, A. A., & Edgar, R. J. 2007, ApJS, 171, 520
Crouch, A. D., Charbonneau, P., & Thibault, K. 2007, ApJ, 662, 715
Edmondson, J. K., et al. 2009, ApJ, 707, 1427
Fisk, L. A. 2003, JGR, 108, 1157
Fisk, L. A., Schwadron, N. A., & Zurbuchen, T. H. 1999, JGR, 104, 19765
Gudiksen, B. V., & Nordlund, Å. 2005, ApJ, 618, 1020
Hagenaar, H. J., De Rosa, M. L., & Schrijver, C. J. 2008, ApJ, 678, 541
Hagenaar, H. J., De Rosa, M. L., & Schrijver, C. J. 2010, ApJ, 715, 696
Hollweg, J. V. 1986, JGR, 91, 4111
Hollweg, J. V. 1990, Comput. Phys. Rep., 12, 205
Keller, C. U., et al. 2003, ASP Conf. Ser. 307, 13
Krijger, J. M., & Roudier, T. 2003, A&A, 403, 715
Longcope, D. W. 1996, Solar Phys., 169, 91
Matthaeus, W. H., et al. 1999, ApJ, 523, L93
Moreno-Insertis, F., et al. 2008, ApJ, 673, L211
Pariat, E., et al. 2009, ApJ, 691, 61
Parker, E. N. 1958, ApJ, 128, 664
Parnell, C. E. 2001, Solar Phys., 200, 23
Parnell, C. E. 2002, MNRAS, 335, 389
Parnell, C. E., & Galsgaard, K. 2004, A&A, 428, 595
Savcheva, A., et al. 2007, PASJ, 59, S771
Schrijver, C. J. 2001, ApJ, 547, 475
Schrijver, C. J., et al. 1997, ApJ, 487, 424
Schwadron, N. A., & McComas, D. J. 2003, ApJ, 599, 1395
Simon, G. W., Title, A. M., & Weiss, N. O. 2001, ApJ, 561, 427
Title, A. M., & Schrijver, C. J. 1998, ASP Conf. Ser. 154, 345
Verdini, A., et al. 2010, ApJ, 708, L116
Wang, H. 1988, Solar Phys. 116, 1
Wang, Y.-M. 1998, ApJ, 501, L145
Wang, Y.-M., et al. 2009, ApJ, 691, 760
Wiegelmann, T., & Solanki, S. K. 2004, Solar Phys., 225, 227