Turbulent Heating and Wave Pressure in Solar Wind Acceleration Modeling:

New Insights to Empirical Forecasting of the Solar Wind

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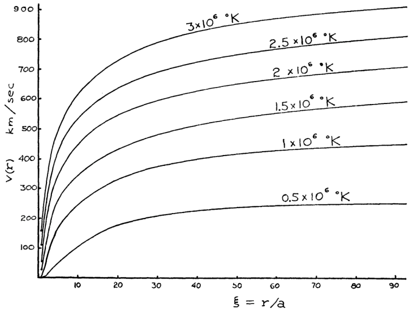
Coronal heating problem



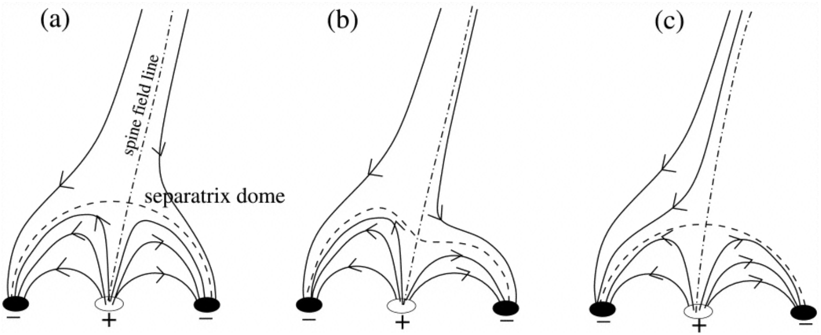
Evidence for the solar wind is intimately tied to the existence of a million degree corona.

Left: Parker 1958, Fig. 1

Proposed mechanisms for coronal heating of two paradigms:

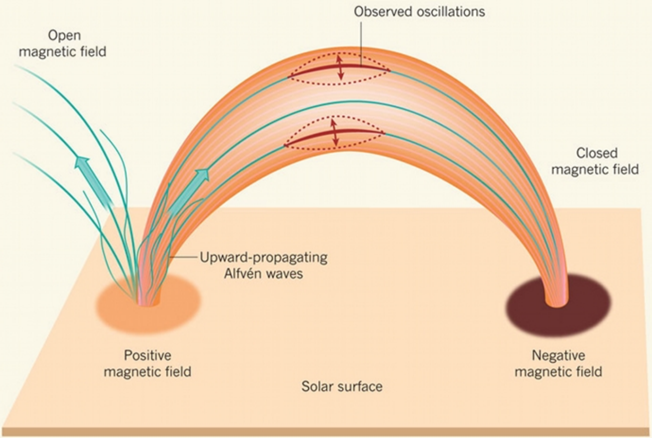
- Reconnection/Loop-Opening (RLO)
- Wave/Turbulence-Driven (WTD)

Reconnection/Loop-Opening (RLO) models



Fletcher, L., Metcalf, T. R., Alexander, D., Brown, D. S., and Ryder, L. A., "Evidence for the Flare Trigger Site and Three-Dimensional Reconnection in Multiwavelength Observations of a Solar Flare", ApJ 554, 451-463, 2001

Wave/Turbulence-Driven (WTD) models



Peter Cargill & Ineke De Moortel (2011) *Nature* **475**

Heating and the turbulent cascade

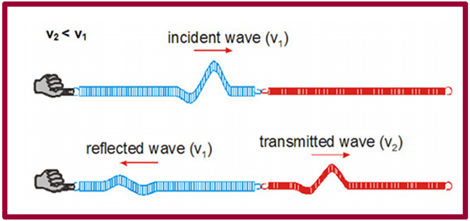
Turbulent heating rate:
$$Q \approx \rho \frac{Z_-^2 Z_+ + Z_+^2 Z_-}{4L_\perp}$$

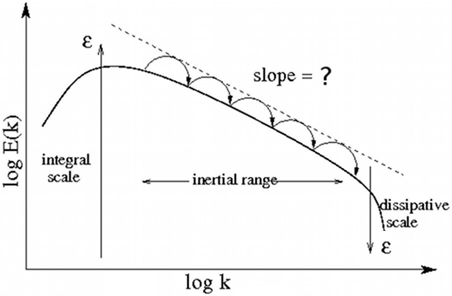
$L_\perp$ is effective turbulence correlation length, assume: $L_\perp \propto B^{-1/2}$

For Alfvén waves at low heights: $Z_\pm \propto \rho^{-1/4}$

In thin flux tube limit: $B \propto \rho^{1/2}$

Therefore, in thin flux tube limit we can show $\boxed{Q \propto B}$





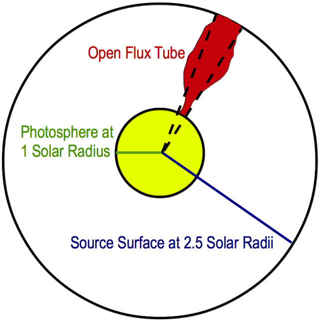
Forecasting from empirical relations

From Wang & Sheeley (1990):

$$f_s = (R_\odot / R_{ss})^2 [B(R_\odot)/B(R_{ss})]$$

Ranges of expansion factor and characteristic wind speed

f_s	v_w (km s^{-1})
<3.5	700
3.5 - 9	600
9 - 18	500
18 - 54	400
>54	330



Forecasting from empirical relations

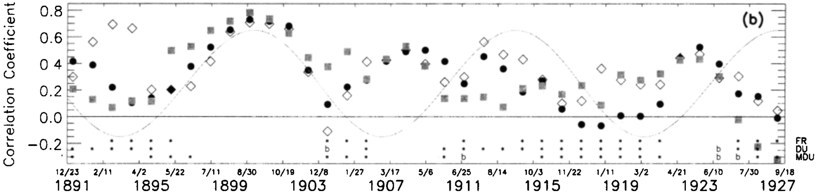
From Arge & Pizzo (2000), “applies strictly near the solar equator”:

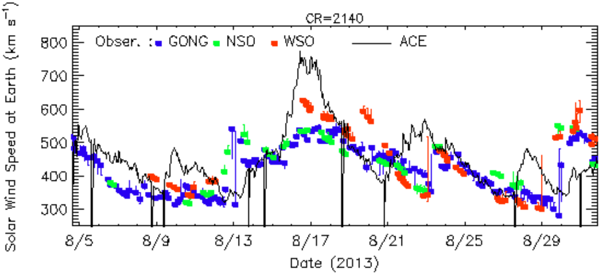
$$V(f_s) = 267.5 + \left(\frac{410}{f_s^{2/5}}\right) \text{ km s}^{-1}$$

From Arge et al. (2004), now with two coronal parameters:

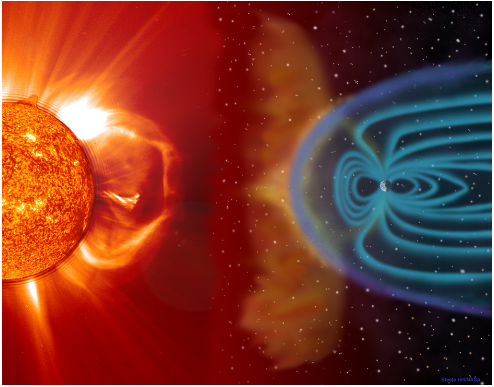
$$V(f_s, \theta_b) = 265 + \frac{1.5}{(1+f_s)^{1/3}} \left(5.9 - 1.5\exp[1 - (\theta_b/7^\circ)^{5/2}]\right)^{7/2} \text{ km s}^{-1}$$

Predictions with WSA: Arge & Pizzo (2000) and SWPC





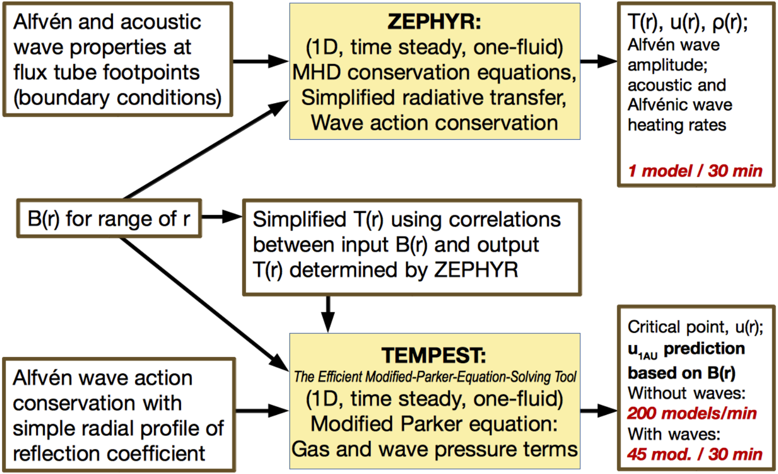
Improvements to space weather forecasting



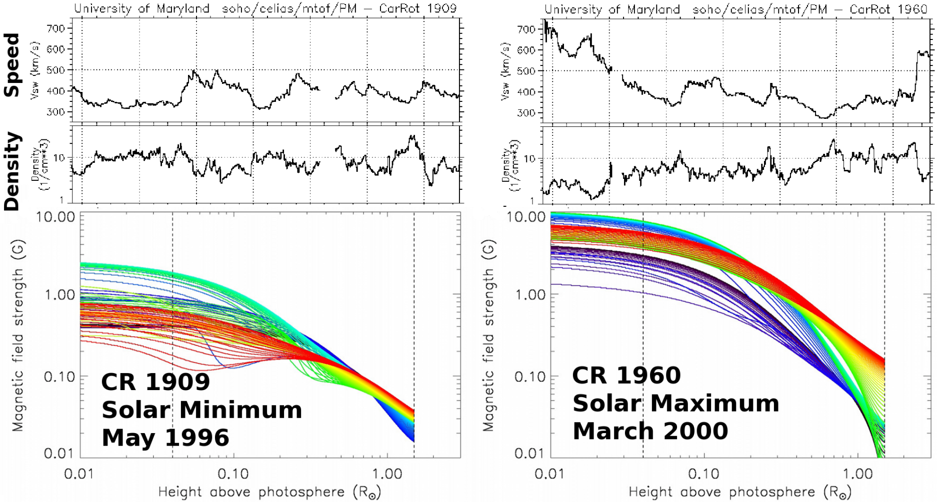
Reliance on WSA-ENLIL modeling is problematic.
Need to accurately predict effects on:

- GPS navigation
- Power grids
- Satellite communications
- Astronaut safety

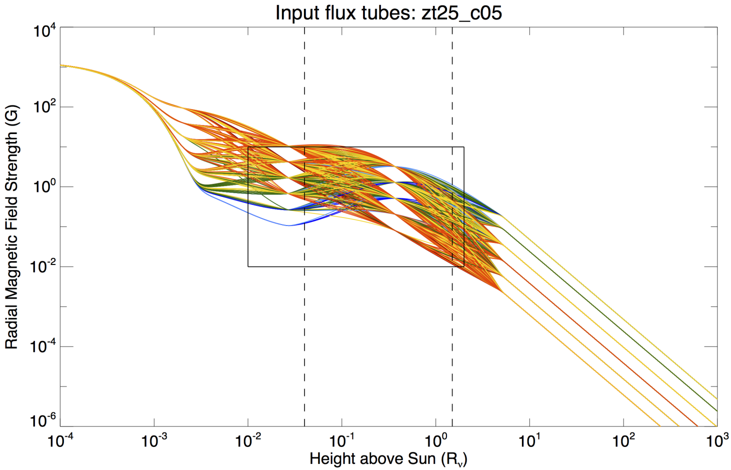
We take a step beyond the empirical expansion factor relation.


Alfvén and acoustic wave properties at flux tube footpoints (boundary conditions)
ZEPHYR:
(1D, time steady, one-fluid) MHD conservation equations, Simplified radiative transfer, Wave action conservation
T(r), u(r), ρ(r); Alfvén wave amplitude; acoustic and Alfvénic wave heating rates
1 model / 30 min
B(r) for range of r
Simplified T(r) using correlations between input B(r) and output T(r) determined by ZEPHYR
Alfvén wave action conservation with simple radial profile of reflection coefficient
TEMPEST:
The Efficient Modified-Parker-Equation-Solving Tool
(1D, time steady, one-fluid) Modified Parker equation: Gas and wave pressure terms
Critical point, u(r); u_{1AU} prediction based on B(r)
Without waves:
200 models/min
With waves:
45 mod. / 30 min

Input Magnetic Fields



The main grid of models used for the current analysis



Plot: L. Woolsey

Introducing ZEPHYR

Cranmer, van Ballegooijen, and Edgar (2007)

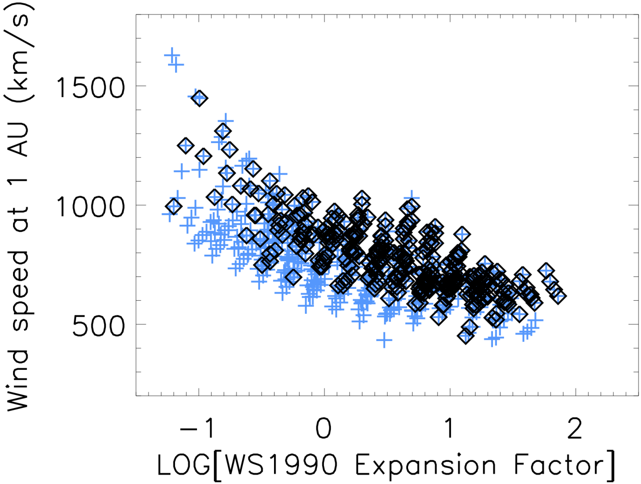
Written in Fortran 77

Physics includes:

- hydrodynamic conservation equations
- radiative heating and cooling
- heat conduction
- Alfvén and acoustic waves

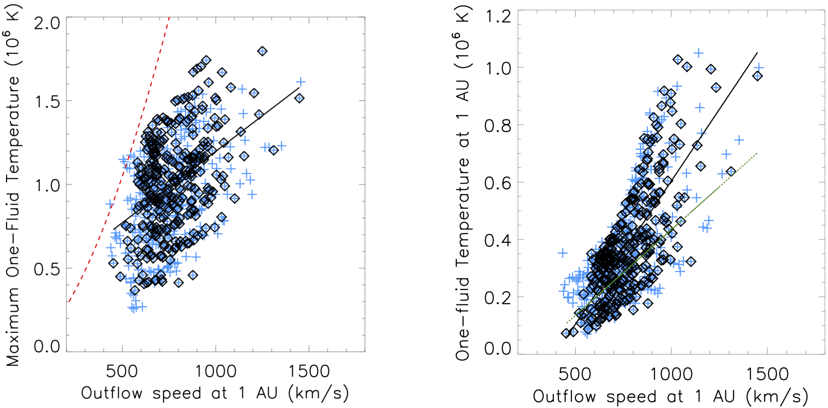
Solves for self-consistent, 1D, steady-state solution for bulk properties of the solar wind ($T(r), \rho(r), u(r)$) from an open flux tube with footpoint in the solar photosphere

Does the Wang & Sheeley (1990) anti-correlation hold?



Plot: L. Woolsey

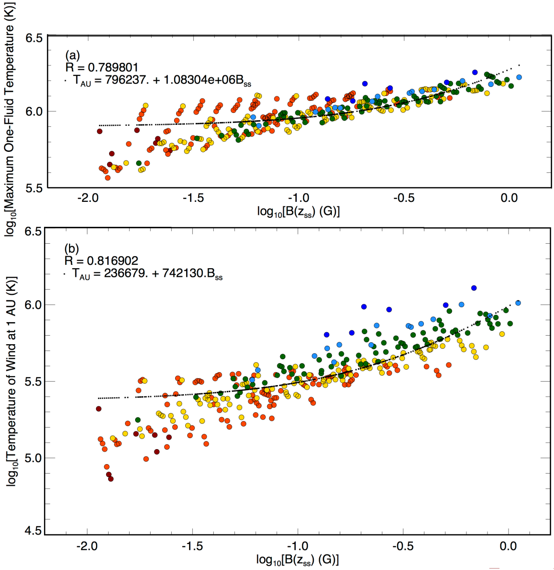
Temperature correlations, part 1: wind speed



Left: Red line is prediction from Parker isothermal corona model
Right: Green line is empirical relation for T_p (Elliott et al. 2012)

Plots by L. Woolsey

Temperature correlations, part 2: magnetic field



Introducing TEMPEST

Woolsey and Cranmer (in prep)

Written in Python

Physics includes:

- momentum conservation equation (modified Parker equation)
- Alfvén wave action conservation
- temperature profiles based on ZEPHYR turbulent heating results

Solves for self-consistent, 1D, steady-state solution for outflow speed of the solar wind from an open flux tube with footpoint in the solar photosphere

The Efficient Modified Parker Equation Solving Tool

The modified Parker equation we use has the form:

$$\left(u - \frac{u_c^2}{u}\right)\frac{du}{dr} = -\frac{GM_\odot}{r^2} - u_c^2\frac{d\ln B}{dr} - a^2\frac{d\ln T}{dr}$$

where the full form of the critical speed is given by:

$$u_c = \sqrt{a^2 + \frac{U_A}{4\rho}\left(\frac{1+3M_A}{1+M_A}\right)}$$

and the Alfvén wave energy density is defined as:

$$U_A(r) \equiv \rho v_\perp^2 = \frac{S(r)B(r)V_A(r)}{(u(r)+V_A(r))^2}$$

See Jacques (1977), Isenberg & Hollweg (1982), Cranmer et al. (2007)

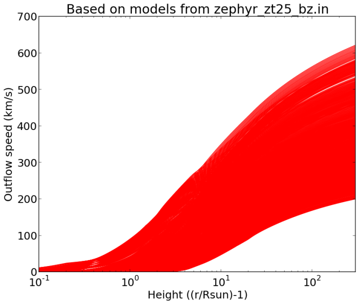
Solution Algorithm

$$\left(u - \frac{u_c^2}{u}\right)\frac{du}{dr} = -\frac{GM_\odot}{r^2} - u_c^2\frac{d\ln B}{dr} - a^2\frac{d\ln T}{dr}$$

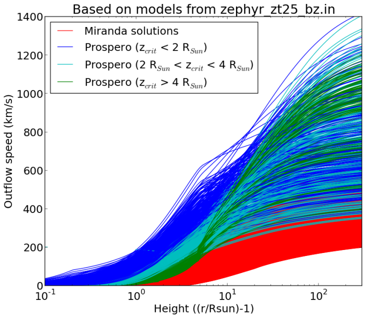
1. Initally, set $u_c = a = \sqrt{kT/m}$
2. Find roots of RHS of modifed Parker equation
3. Use root corresponding to **true** critical point
4. Use L'Hôpital's rule to find slope at critical point
5. Integrate outwards using Runge-Kutta method to get outflow
6. With initial solution, add waves i.e. full expression for u_c
7. Follow steps 2-5, converging toward the stable solution

Results with current version of TEMPEST

Miranda: no wave pressure



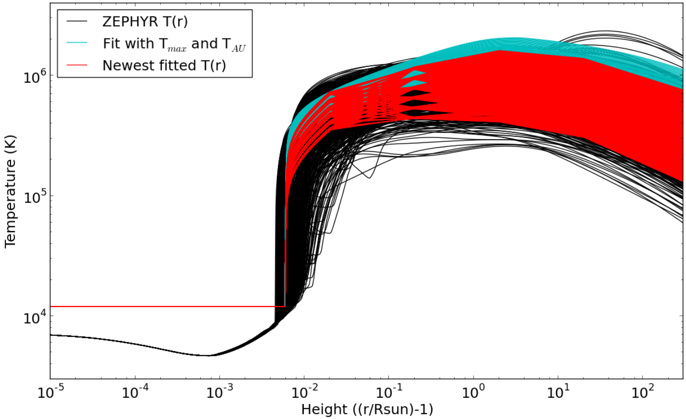
Prospero: waves with damping



Different ranges along y-axes! Miranda does not have wave pressure term: consistently underpredicts wind speed; Prospero has waves that in some cases are underdamped: can overpredict wind speed.

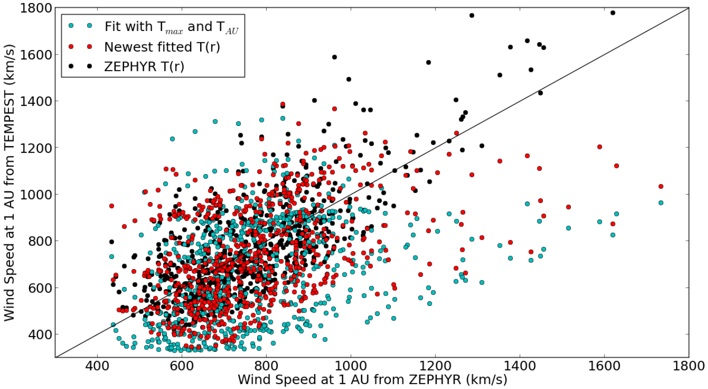
Plots by L. Woolsey

Wind speed comparison - temperature profiles



Plot: L. Woolsey

Wind speed comparison - temperature profiles



Plot: L. Woolsey

Most important results in this project

From ZEPHYR:

- Recovery of Wang-Sheeley 1990 expansion factor relation
- Temperature-Magnetic Field relations with $\mathcal{R} > 0.8$

From TEMPEST:

- A less computationally-intensive outflow prediction code
- Incredibly fast education tool using Miranda only
- Wind speed predictions requiring only $B(r)$ from user

The next steps

1. Investigate which assumptions introduce the most “error”
   - Reflection coefficient throughout solar atmosphere*
   - Shape of temperature profile (T_{TR}, z_{TR}, T_{max}, z_{max})
   - One-fluid treatment (in both codes)

2. Test using magnetogram data and *in situ* measurements

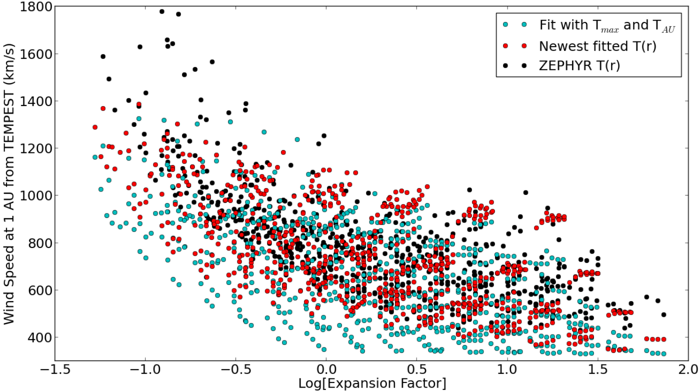
*no longer a constant

Conclusions

TEMPEST will become a flexible, publicly available solar wind tool for forecasting the dangerous high-speed wind streams that can cause geomagnetic storms.

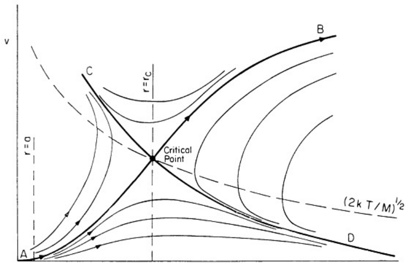
ZEPHYR continues to provide accurate predictions as well as the necessary information to properly calibrate TEMPEST without requiring a slew of free parameters as inputs to either code.

TEMPEST and Wang-Sheeley anti-correlation



Plot: L. Woolsey

Parker Equation (Parker 1958)

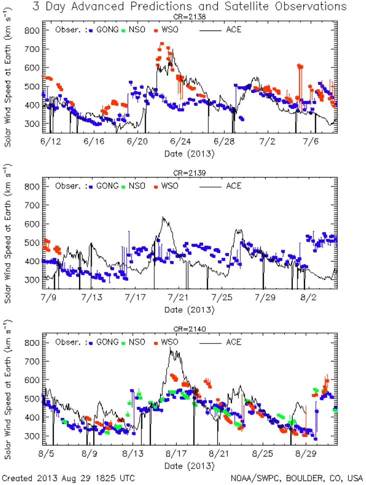


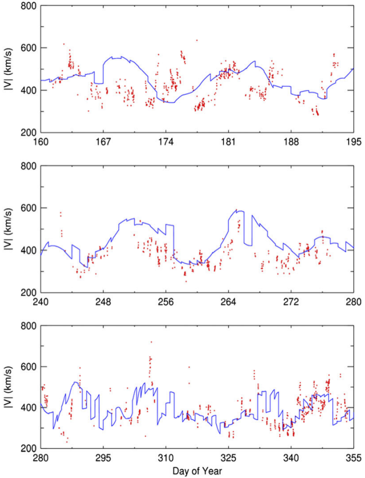
$$Nu\frac{du}{dr} = -\frac{d}{dr}(2NkT/m) - \frac{GNM_\odot}{r^2}$$

$$\frac{d}{dr}\left(r^2 Nu\right) = 0$$

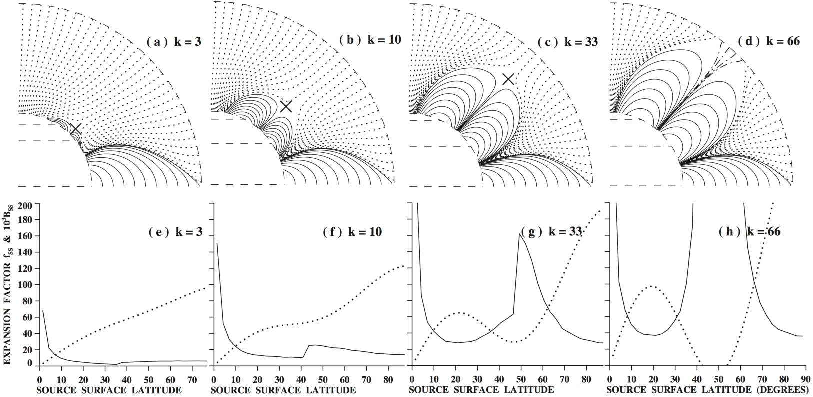
$$\left(u - \frac{u_c^2}{u}\right)\frac{du}{dr} = -\frac{GM_\odot}{r^2} - u_c^2\frac{d\ln B}{dr} - a^2\frac{d\ln T}{dr}$$

SWPC predictions with WSA | WSA-ENLIL and Messenger



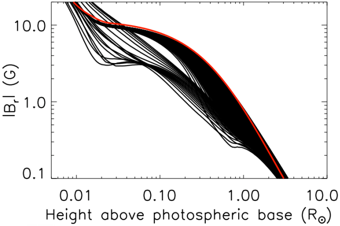


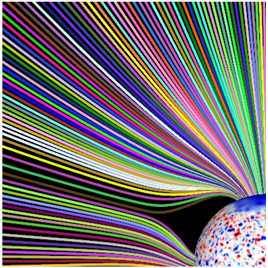
The curious case of pseudostreamers

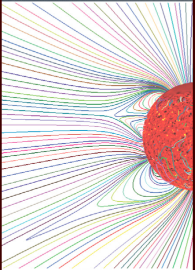


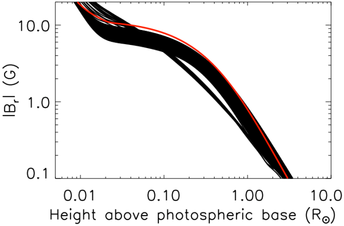
Bottom set of figures: solid line is expansion factor variation, dotted line is source surface field strength

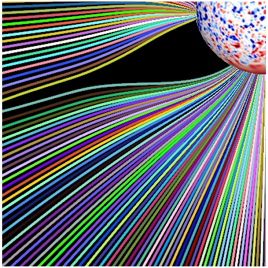
Pseudostreamers vs helmet streamers in current modeling



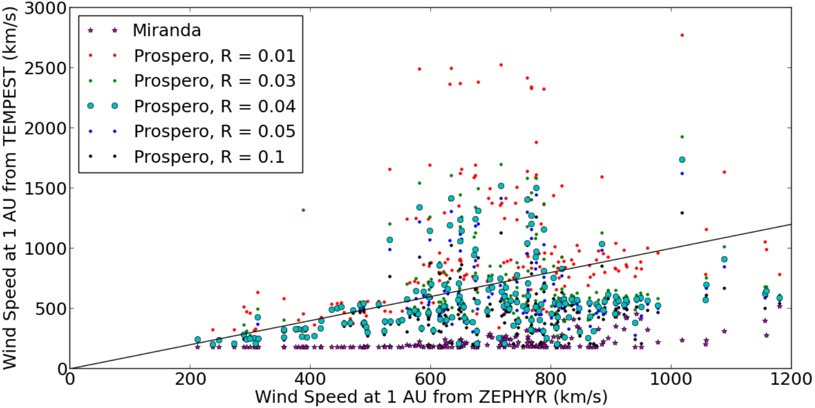






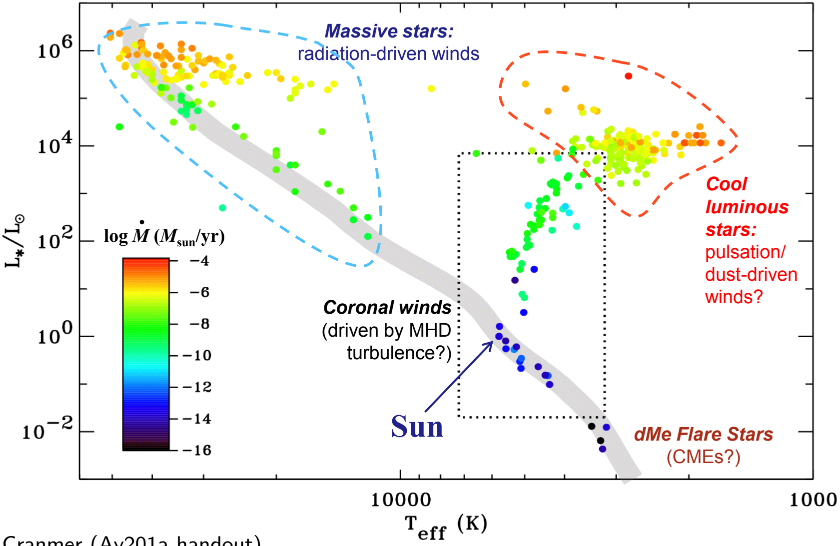


Wind speed comparison - reflection coefficients



(back to results)

Plot: L. Woolsey



S. Cranmer (Ay201a handout)