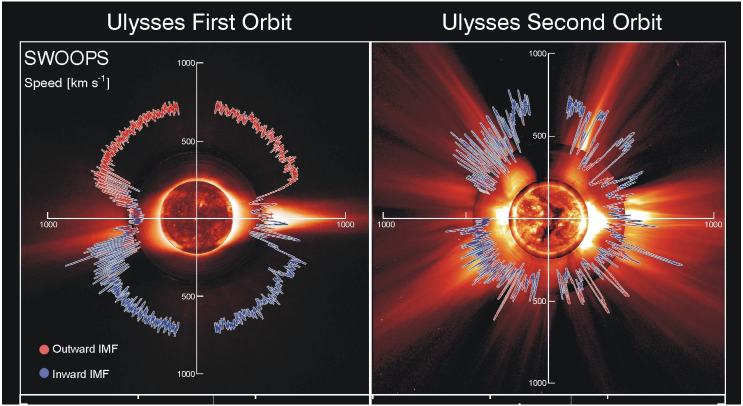
Solar wind up to the lower boundary of ENLIL

Rui Pinto, Alexis Rouillard

The solar wind and the solar cycle



McComas et al. (2003)

Solar minimum

Fast wind / slow wind separation
Dipolar large-scale magnetic field, **few AR**

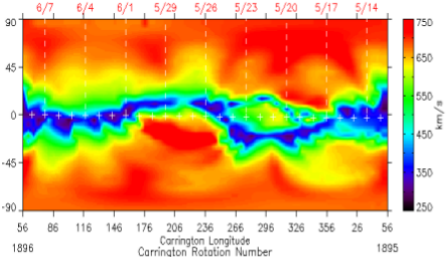
Solar maximum

Fast wind / slow wind mixed together
Multipolar large-scale magnetic field, **many AR**

Goals

- **Predict wind parameters**
  from surface data
- Data: **in-situ data** $\leftrightarrow$ **remote sensing**

WSA semi-empirical scaling law



$$V_{wind} = 265 + \frac{1.5}{(1+f_{ss})^{1/3}} \times$$
$$\times \left[5.8 - 1.6 \exp\left[1 - \frac{\theta_b{}^3}{7.5^3}\right]\right]^{3.5} \text{ km s}^{-1}$$

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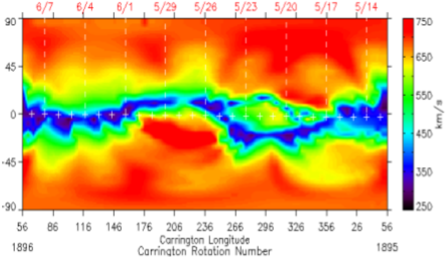

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Going beyond WSA

→ Wind speed at **different heights**

→ **Other plasma parameters** (density, temperature, etc)

→ Add *minimal* amount of complexity

New strategy

Multi-VP

Multiple 1D flux-tube wind solutions sampling the whole corona.

(Mid-way between specialised local models and global 3D MHD models)

Modelling chain

Sun / surface observations
(magnetograms)

↓

Coronal B-field reconstruction
(PFSS SolarSoft)

↓

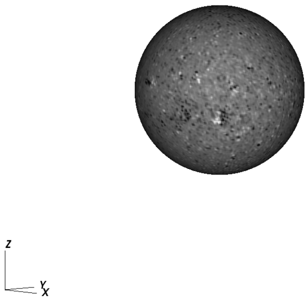
MULTI-VP

↓

Heliospheric propagation models
(ENLIL)

↓

Earth / interplanetary medium
In-situ data, heliospheric imaging



Surface magnetic field B_r (± 30 G)

Modelling chain

Sun / surface observations
(magnetograms)
↓
Coronal B-field reconstruction
(PFSS SolarSoft)
↓
MULTI-VP
↓
Heliospheric propagation models
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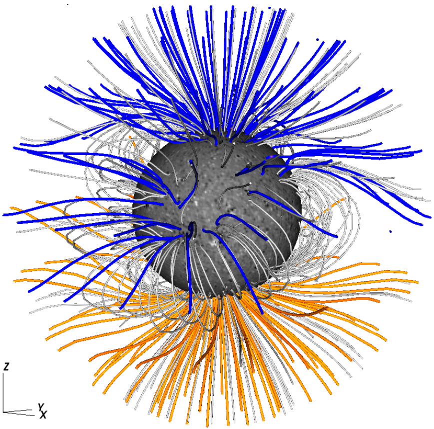

PFSS field lines positive/negative polarity

Modelling chain

Sun / surface observations
(magnetograms)

↓

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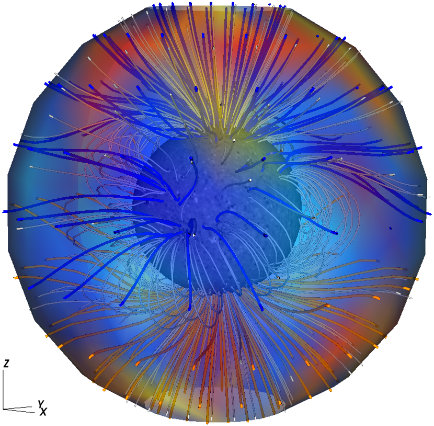

Wind speed: red = 650 km/s; blue = 350 km/s

Modelling chain

Sun / surface observations
(magnetograms)
↓

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↓

MULTI-VP

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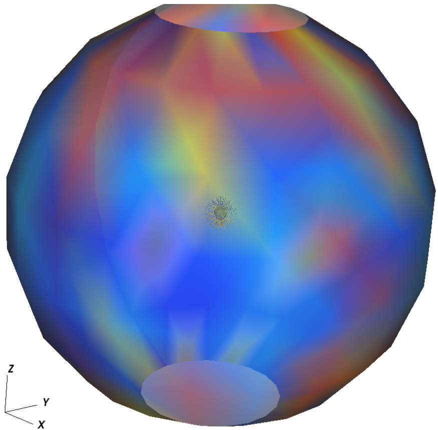
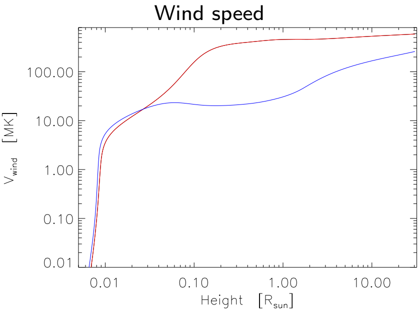
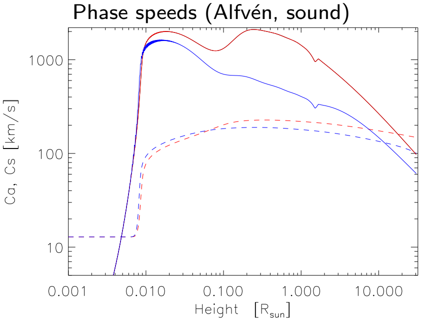
Earth / interplanetary medium
In-situ data, heliospheric imaging



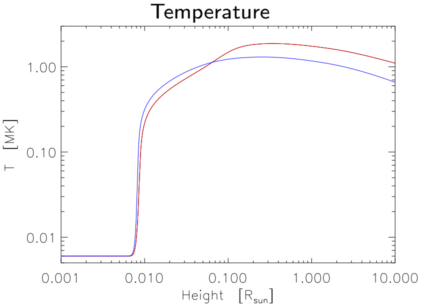
Wind speed: red = 650 km/s; blue = 350 km/s

Wind flows surface to heliosphere





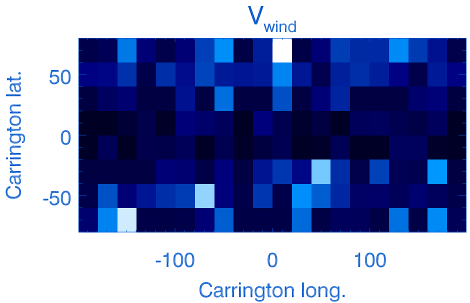
Red lines: fast wind profile
Blue lines: slow wind profile



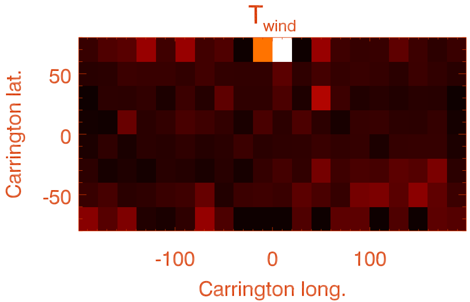
Prototype wind maps

Carrington maps 2008/06/01

Wind speed at $r = 32 \ R_\odot$



Temperature at $r = 32 \ R_\odot$



Model physics

$$\partial_t \rho + \nabla \cdot (\rho \mathrm{u}) = 0$$

$$\partial_t \mathrm{u} + (\mathrm{u} \cdot \nabla)\, \mathrm{u} = -\frac{\nabla\,(P + P_w)}{\rho} - \frac{GM}{r^2}\hat{\mathrm{r}} + \nu \nabla^2 u$$

$$\partial_t T + \mathrm{u} \cdot \nabla T + (\gamma - 1)\, T \nabla \cdot \mathrm{u} = -\frac{\gamma - 1}{\rho}\left[\nabla \cdot F_h + \nabla \cdot F_c + \rho^2 \Lambda\,(T)\right]$$

(F_h: external heat flux;
F_c: SH conductive flux, transition to ballistic flux)
Ideal e-o-s with $\gamma = 5/3$

Magnetic field inclination:
$\Rightarrow$ $-g_0 \cos\alpha$, $\nabla P \cos\alpha$, heat fluxes $//\mathbf{B}$

(*cf.* Li, et al., 2011, Lionello, et al., 2014)

Divergence operator:

$$\nabla \cdot (*) = \frac{1}{A\,(r)} \frac{\partial}{\partial r}\,(A\,(r)\,*) = B \frac{\partial}{\partial r}\left(\frac{*}{B}\right)$$

(Grappin et al., 2010; Pinto et al., 2009; Verdini et al., 2012)

Standard phenomenological heating flux:

$$F_h = F_{p0}\left(\frac{A_0}{A}\right)^{(-1)} \exp\left[-\frac{r - R_\odot}{H_p}\right]$$

where $\left(\frac{A_0}{A}\right)^{(-1)} = \left(\frac{B}{B_0}\right)$, and $H_p \sim 1\ \ \mathrm{R}_\odot$.

Other forms, Alfvèn wave dissipation:

$$F_h = F_{b0}\left(\frac{A_0}{A}\right)\left(\frac{B}{B_0}\right)^{\mu - 1} = F_{b0}\left(\frac{B}{B_0}\right)^{\mu}$$

where, typically, $\mu - 1 = 1/2$.

$$F_w = F_{w0} * \text{WKB operator}$$

Localised heating (emulating, e.g, transient ohmic dissipation):

$$F_r \propto erf\,(r_0, \delta r) \Rightarrow \nabla \cdot F_r = F_{r0}\, e^{-\frac{(r - r_0)^2}{\delta r^2}}$$

Reference surface flux:
$F_0 = 4 - 8 \times 10^5\ \mathrm{erg} \cdot \mathrm{cm}^{-2}\mathrm{s}^{-1}$

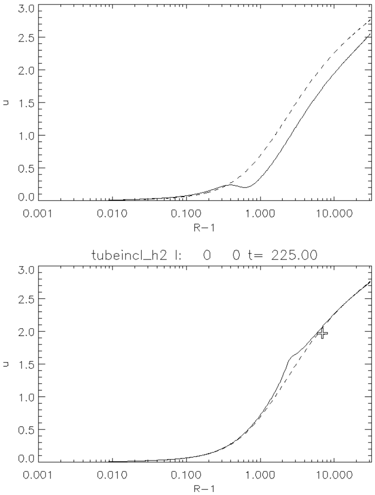
Key parameters

1) Super-radial expansion
Fast to moderately slow winds
(fast/slow wind not sharp enough,
slow wind not slow enough)

2) Field-line inclination
around coronal streamers
(makes the slow wind slower, by $\sim 15\%$)

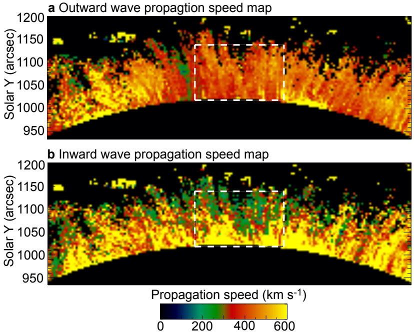
3) Appropriate heating functions
(how much energy, where it's dissipated)

Effect of inclination on wind speed
(Pinto, Rouillard, et al, in prep.)



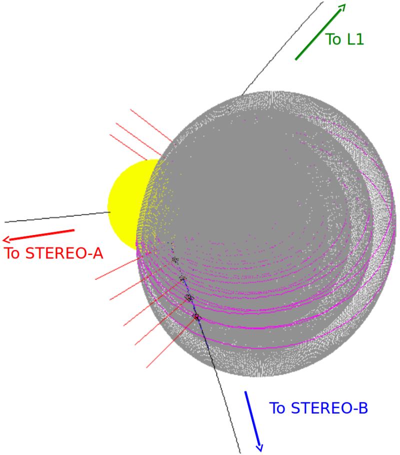
Calibration and case-studies

Aflvén wave power and spectra
in coronal holes



(Morton, Tomczyk, Pinto, submitted)

CME shock propagation



(Rouillard, Pinto, et al, in prep)

Summary and conclusions

New wind model in construction (based on a mature wind code):

Synoptic maps of wind speed and plasma parameters at $30 - 60\ R_{\odot}$ (WP6)

Propagation: **flow and phase speeds (photosphere to heliosphere)**

Strengths

- quick and robust
- good thermodynamics (not polytropic, chromo+TR+corona)
- Slow / fast wind
- Predicts wind speeds and temperature, density, phase speeds

Limitations

- 1D (even if multi-1D)
- Flux-tube geometry only as good as reconstruction method allows
- Steady-state background wind
- Simplified chromosphere (requires calibration of T, ρ at the TR)

Future and on-going work:

- Calibration, case studies (multi-spacecraft data, IPS)
- Performance optimisation
- Detailed synoptic maps of wind speed, density, temperature, phase speeds

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