Time Dependent MHD Modeling: Towards a Real-Time Model of the Corona and Solar Wind

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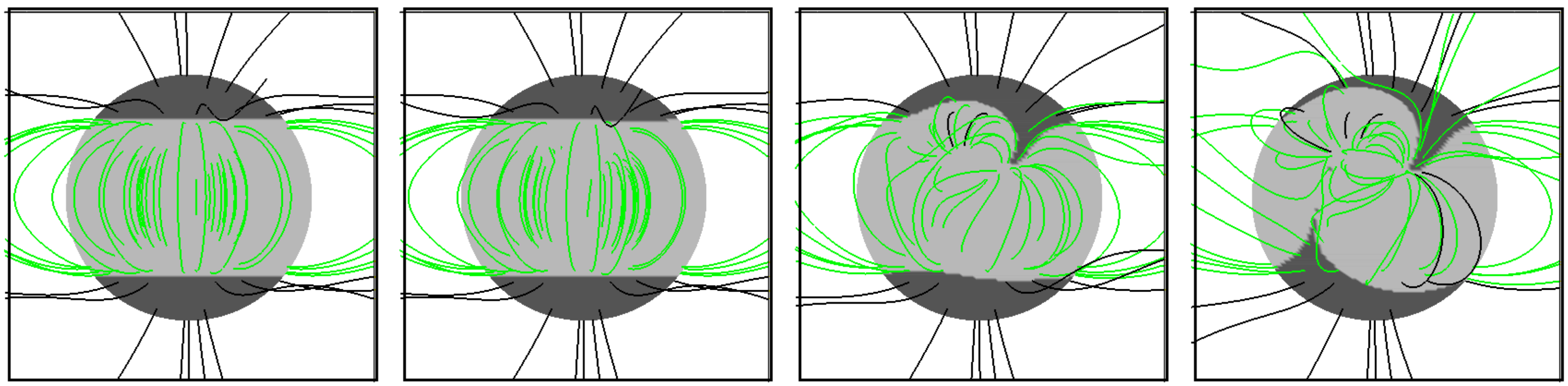

Collaborators:

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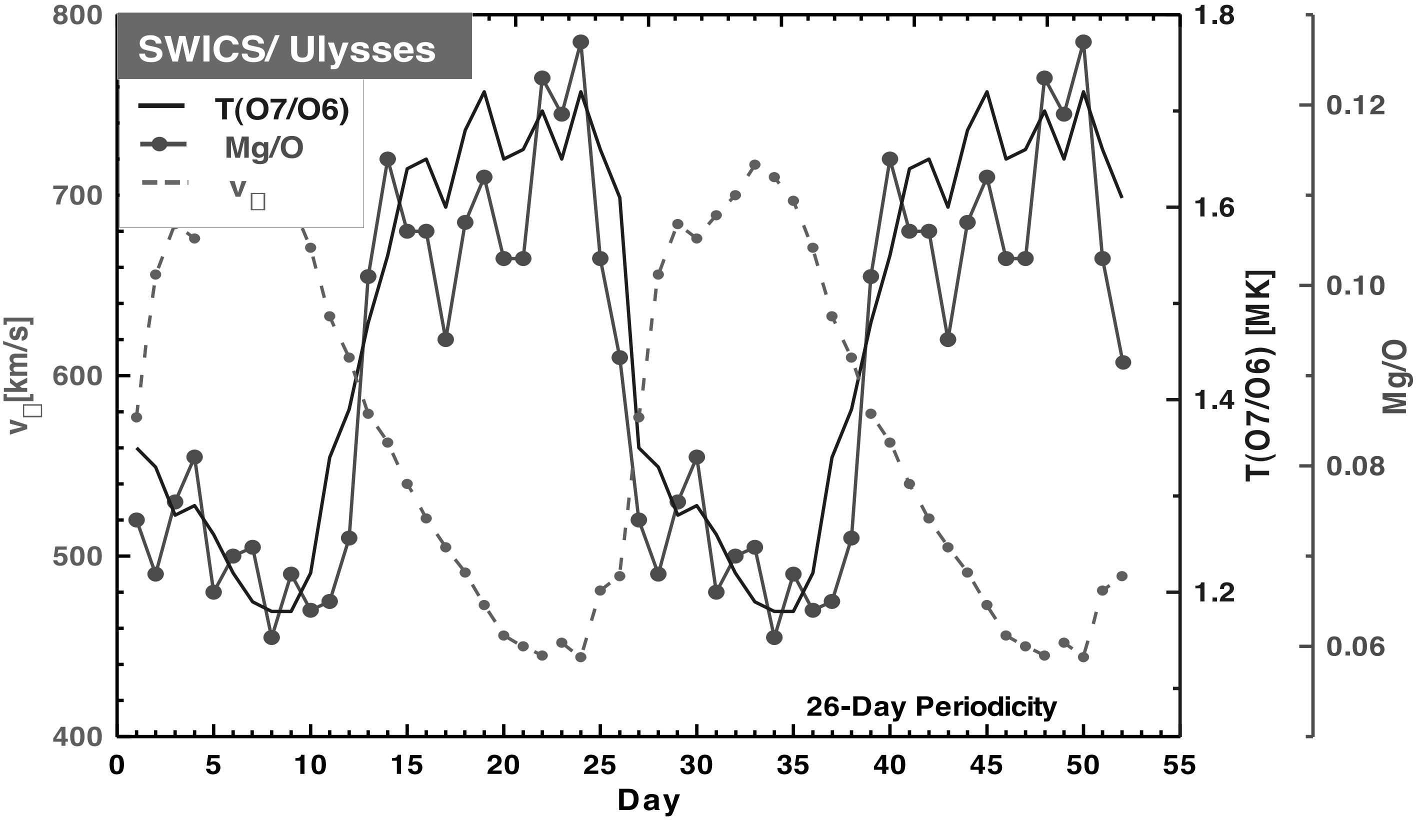
Introduction

- Global modeling of the corona/solar wind has primarily focused on steady-state solutions.
- Important aspects of the corona and solar wind are inherently time-dependent.
- To what extent can SDO supply data for time-dependent boundary conditions?
- Can we extend the Lockheed-Martin flux-Evolution/potential field model with MHD?
- Focus on HMI data products.

The Non-Steady Nature of the Ambient Solar Wind

- Steady-state models can describe many features of the solar wind
- However, there are important features that cannot be understood from a steady-state approach
- Example: Solar wind composition

Solar Wind Composition contains important clues about dynamical processes in the Solar Corona



Superposed Epoch Analysis of Ulysses Data
Low-FIP, Plasma of Higher Temperature origin dominates in the Slow Solar Wind
(Geiss et al. 1995)

Implies that the plasmas making up the fast and slow wind have a different origin

AN EVOLVING SOLAR WIND MODEL

- We can run a time-dependent coronal model with continuous updates of the photospheric magnetic field driven by observations
- We can use daily or more frequent updates (determined primarily by resources)
- The boundary magnetic field B_{r_0} in the model is updated using an electric field at the boundary
- The coronal solution and solar wind respond to the boundary condition changes
- A "quasi-real-time" model can be developed if a massively parallel computer is used (e.g., a Beowulf cluster with 32 processors) for a medium-resolution run [$\sim O(100^3)$ mesh points]

MHD Equations

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}$$

$$\boxed{\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}}$$

$$\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = \frac{1}{c} \mathbf{J} \times \mathbf{B} - \nabla p - \nabla p_w + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathrm{v}) = (\gamma - 1)(-p \nabla \cdot \mathrm{v} + S)$$

Time-Dependent Boundary Conditions for MHD

- $\boldsymbol{E}_t$ = electric field transverse to the boundary (E_θ, E_ϕ) can be specified, normal field (E_r) is part of solution.
- In idealized calculations (e.g. exploration of CME initiation), $\boldsymbol{E}_t$ may result from specified flows
- Data-driven simulations: We can find an $\boldsymbol{E}_t$ to go between B_{r} maps, but it is not unique.

Incorporation of Evolving Photospheric Magnetic Fields

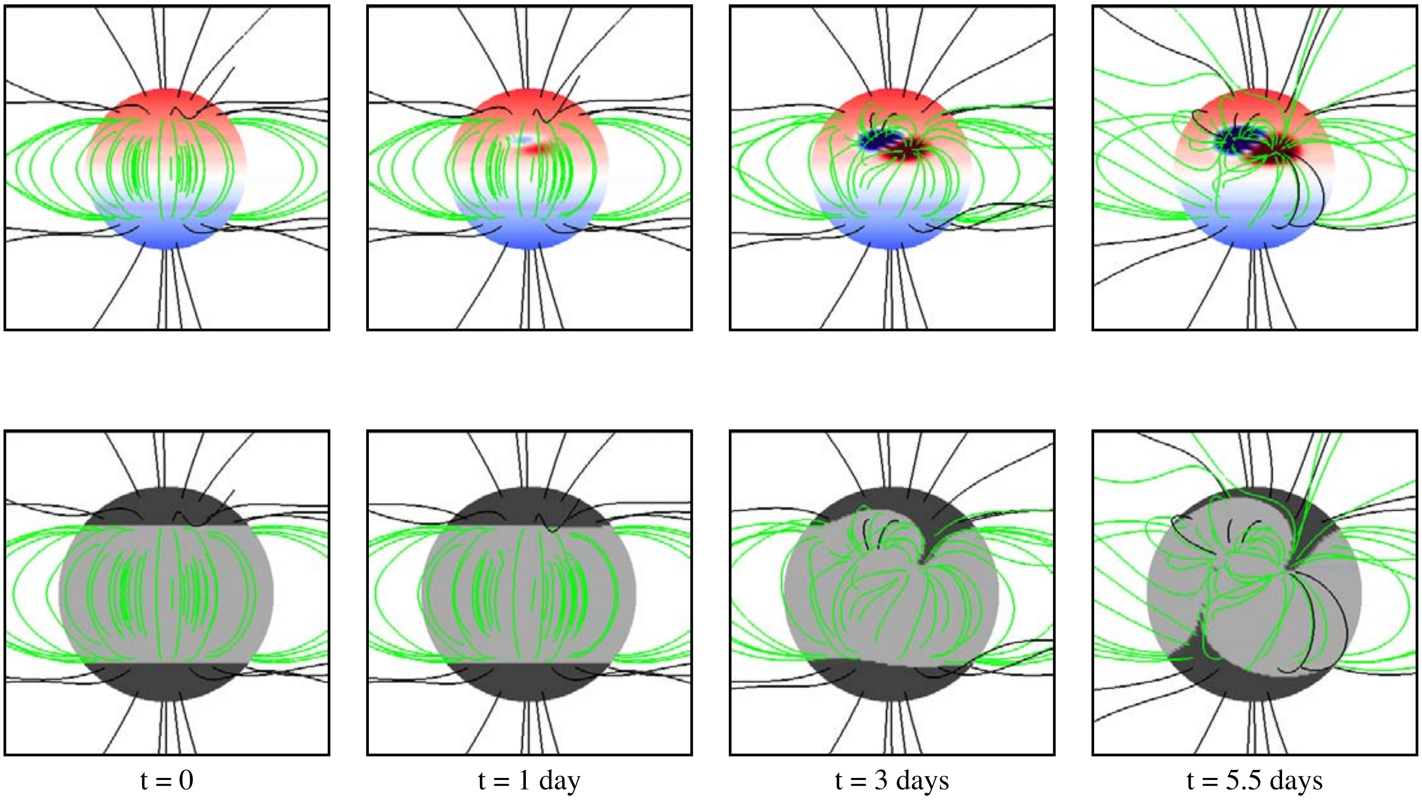
- Steady-state solutions: set $\mathbf{E}_{t\text{o}} = 0$. Then $B_{r\text{o}}$ is fixed in time.

- To make the flux evolve to match observed changes, $\mathbf{E}_{t\text{o}}$ must be chosen to match the required $\partial B_{r\text{o}} / \partial t$.

- In general, $\mathbf{E}_{t\,\text{o}} = \nabla_t \times \boldsymbol{\Psi}\,\hat{\mathbf{r}} + \nabla_t \boldsymbol{\Phi}$, where $\boldsymbol{\Psi}(\theta, \phi), \boldsymbol{\Phi}(\theta, \phi)$ are arbitrary functions.

- For $\boldsymbol{\Phi} = 0$, solve $c\,\nabla_t^{\,2} \boldsymbol{\Psi} = \partial B_{r\text{o}} / \partial t$ for $\boldsymbol{\Psi}$.

- $\boldsymbol{\Phi}$ can be evolved to match a desired vector field (if known).



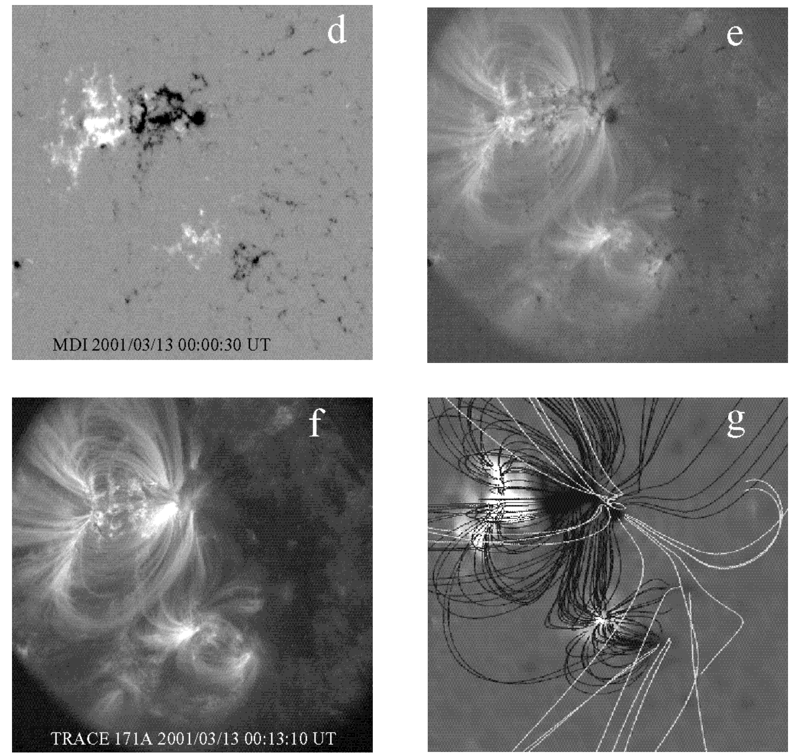
Simulaton of the Emergence of a Bipolar Active Region

Play Movie

Play Movie

Photospheric Flux Evolution Model

- Flux evolution model can be used to physically connect different states.
- Can constrain $\boldsymbol{E}_t$ by supplying surface flows.



Schrijver &DeRosa (2003)

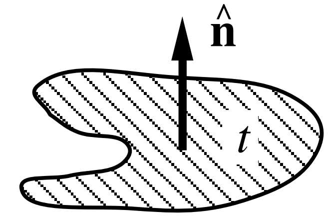
Data Inputs to the Model

- Line-of-sight or vector magnetic field, as a full Sun map
- For vector field, require well-processed data, ambiguity resolution.
- Can use highest resolution data (e.g. have already used 2 arc sec MDI) but only in selected regions
- We will need to work with HMI team to develop a processing protocol for magnetic maps destined for the MHD calculation
- Cadence? A few good magnetograms are better than a lot of bad ones

Desired HMI Data Products

- Best Flux estimate: Use LOS and vector ***B*** to get best possible estimate of radial field
- Improvements to polar field estimates over present
  - Combine flux evolution and seasonally-weighted observations?
- "Synoptic" maps with new observations pasted in (several a day).
- Far-side image data included with polarity estimate
- Ambiguity resolved vector ***B*** in active regions

USING A SEQUENCE OF VECTOR MAGNETOGRAMS



- Boundary tangential electric field (definition):

$$\mathbf{E}_t = \nabla_t \times (\Psi \hat{\mathbf{n}}) - \nabla_t \Phi$$

- Evolution of the normal boundary magnetic field, B_n:

$$\frac{1}{c}\frac{\partial B_n}{\partial t} = -\hat{\mathbf{n}}\cdot\nabla_t \times \mathbf{E}_t = \nabla_t^2 \Psi$$

$\Rightarrow$ A sequence of magnetograms can be used to determine Ψ

- Evolution of the normal boundary current density, J_n:

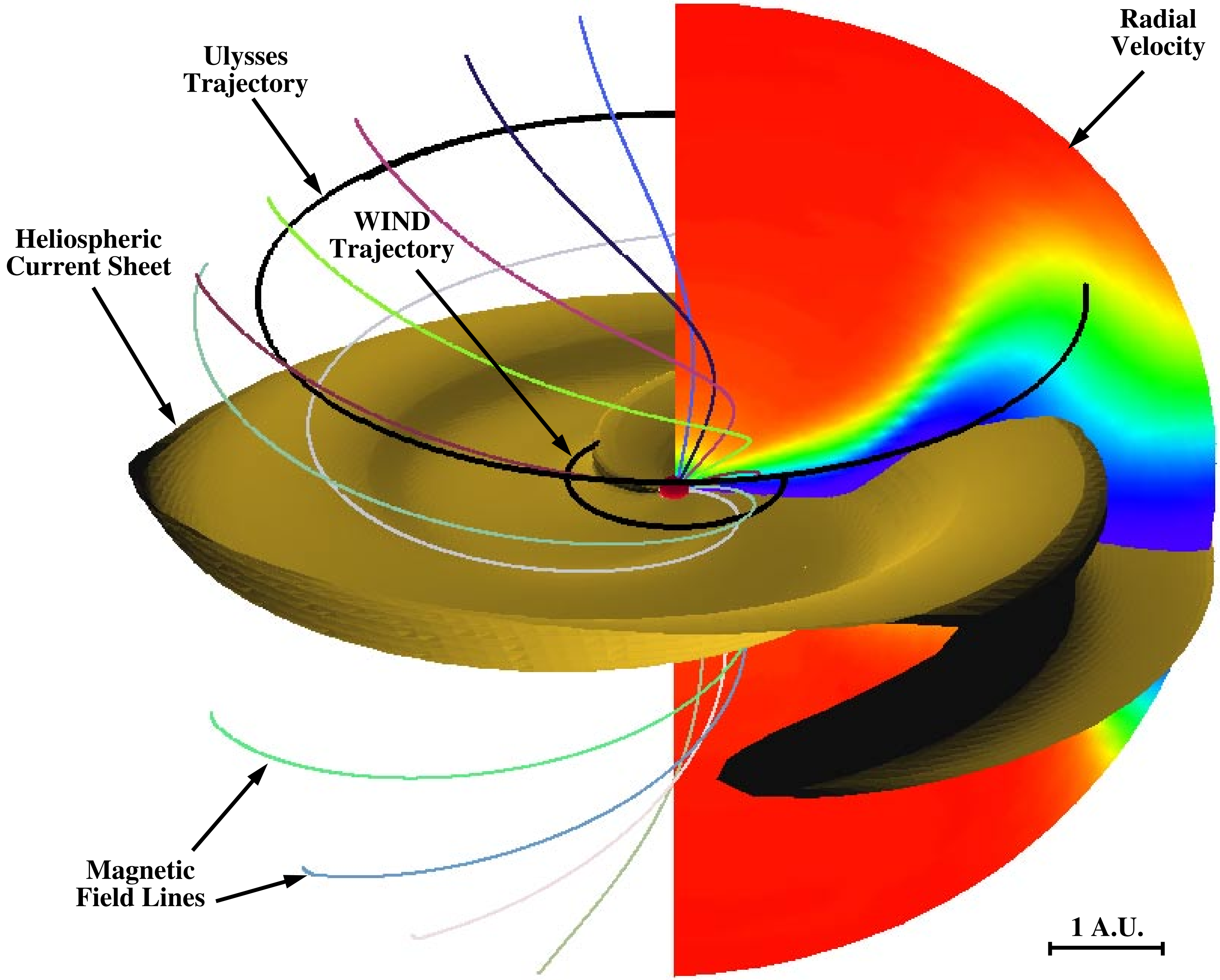
$$\frac{\partial \Phi}{\partial t} = \frac{\eta\, l}{\tau_{RC}}(J_n^{\mathrm{o}} - J_n)$$

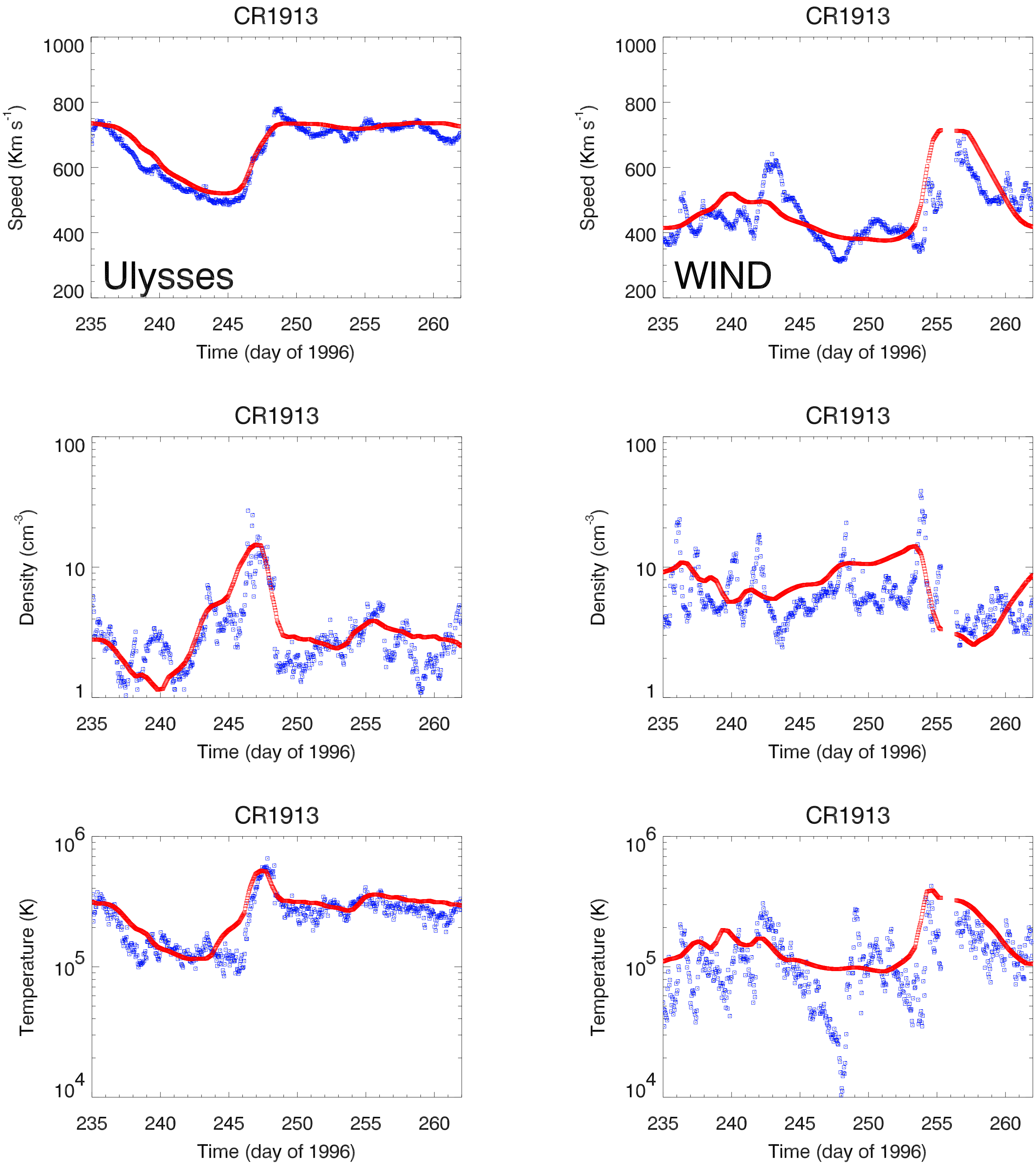
where: l is the scale length of the active region (input)

τ_{RC} is the R–C time for the capacitor controlling the current source J_n^{o} (input)

$J_n^{\mathrm{o}} = \frac{c}{4\pi}\hat{\mathbf{n}}\cdot\nabla_t \times \mathbf{B}_t$ is deduced from a sequence of vector magnetograms

The Heliosphere During Whole Sun Month
August September 1996




CR1913
Speed (Km s^{-1})
1000
800
600
400
200
Ulysses
235
240
245
250
255
260
Time (day of 1996)
CR1913
Speed (Km s^{-1})
WIND
Time (day of 1996)
CR1913
Density (cm^{-3})
100
10
1
Time (day of 1996)
CR1913
Density (cm^{-3})
Time (day of 1996)
CR1913
Temperature (K)
10^6
10^5
10^4
Time (day of 1996)
CR1913
Temperature (K)
Time (day of 1996)

Using Vector Magnetograms: Theory

- Force-free approximation: assume that the coronal plasma pressure is small ($\nabla p = 0$). The coronal plasma is thus force-free:

$$\frac{c}{4\pi} \nabla \times \mathbf{B} = \alpha \mathbf{B}$$

- Topological constraint: $\mathbf{B} \cdot \nabla \alpha = 0$
- Force-free fields (FFF): some theory exists (but it is a nonlinear problem)
- A stable technique requires a boundary-value formulation with boundary conditions on B_n and J_n (Schmidt 1968; Bineau 1972)
- Constant α theory has been used (limited usefulness)
- Nonlinear FFF (α non-constant):
  - Iterative techniques based on Grad–Rubin (1958): Sakurai (1981), Amari *et al*. 1996
  - Minimization technique: Roumeliotis (1994)
  - Extrapolation in height: Wu *et al*. (1990): limited height—unstable
  - Evolutionary technique: FFF is the asymptotic state of a resistive time-dependent problem (Mikić, McClymont, *et al*. 1994)