Modeling of Coronal Holes

MHD Simulations

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Summary

Why do coronal holes rotate quasi-rigidly while the underlying photosphere rotates differentially?

Modellers have invoked magnetic reconnection to reconcile these phenomena.

Wang & Sheeley used a source surface model: coronal holes are generated by non-axisymmetric flux and corotate with the active region they are associated with.

Fisk introduced a model of the heliospheric magnetic field. Rigid rotation of coronal holes is assumed and important consequences for the evolution of the magnetic field are drawn.
Summary (Cont.)

We have used our 3D MHD algorithm to model self-consistently the quasi-rigid rotation of coronal holes in response to photospheric differential rotation.

Here we summarize the characteristics of each model and their ability to model observations of coronal holes.
The Wang & Sheeley Model

- Model is base on a source surface (current-free) rendition of the coronal field.
- The magnetic flux distribution is idealized as a dipole plus a bipolar magnetic region across the equator.
- At the solar surface the following flow is applied:

\[ \omega(L) = 13.39 - 2.77 \sin^2 L \text{ degrees day}^{-1}, \]  

(1)

where \( L \) is the latitude.

- They calculated source surface extrapolations at different instants in time.
- The extension of the Northern coronal hole rotates (quasi)-rigidly, but considerable distortion is observed in the Southern extension.
The Wang & Sheeley Model II

Yellow: rigidly rotating CH
Northern extension

Blue: differentially rotating CH
Southern extension

Coronal holes are associated with nonaxisymmetric magnetic flux.

If the nonaxisymmetric flux is near the equator, the CH rotates rigidly, otherwise quasi-rigidly.

Interchange reconnection occurs at the boundary of coronal holes in such a way to oppose the shearing.

The slow wind is released during this reconnection process.
The Fisk Model

The heliospheric magnetic field is in *pressure equilibrium* but is attached to a *differentially rotating* photosphere;

The high-speed solar wind expands nonradially from the polar CHs;

The expansion in the CH is about the North (South) Pole field line, which is rigidly rotating and *offset* from the Sun’s rotation axis.

Open magnetic flux is constant. By means of a *diffusive process* of continual magnetic reconnection with coronal loops, open field lines are moved through coronal holes, and “hop” over the closed field region until they progress back to the opposite coronal hole boundary.
**Fisk: Field Line Transport**

Fisk vs. Wang & Sheeley

Fisk:

- The total open flux may be considered constant.
- Open flux is *mainly* found in coronal holes, but is present also in the quiet Sun.
- Reconnection between open and closed flux occurs everywhere (diffusion process).

Wang & Sheeley:

- The emergence of an active region changes the total open flux and coronal holes.
- Open flux is only present in coronal holes.
- Reconnection between open and closed flux occurs at the boundaries of coronal holes.
Our MHD Simulations

- We prescribe a magnetic flux distribution on the solar surface that is either:
  - Dipole field with 1G intensity at the poles plus a bipolar “active region”, similar to that of Wang & Sheeley.
  - Dipole field with 1G maximum intensity. The magnetic axis is inclined from the rotation axis as in the Fisk model (30° for our case).

- We calculate the initial potential magnetic field corresponding to the aforesaid distributions.

- A Parker’s solar wind solution is used to determine the initial velocity, density, and temperature in the corona.
Our MHD Simulations (Cont.)

- We advance the MHD equations until a steady state with a solar wind and a heliospheric current sheet is reached.

- Differential rotation is then applied to the system. The total shear applied amounts to that of 5 rotations on the Sun.

- We assume uniform density and temperature at the base of the corona.

- Radial velocity on the solar surface is calculated solving the characteristics equation.

- The flow at the outer boundary is super-sonic and super-Alfvénic.
The Polytropic MHD Model

\[ \nabla \times \mathbf{A} = \mathbf{B}, \]

\[ \frac{\partial \mathbf{A}}{\partial t} = \mathbf{v} \times \mathbf{B} - \frac{c^2 \eta}{4\pi} \nabla \times \mathbf{B}, \]

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

\[ \frac{1}{\gamma - 1} \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = -T \nabla \cdot \mathbf{v}, \]

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \frac{\nabla \times \mathbf{B} \times \mathbf{B}}{4\pi} - \nabla p + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v}), \]

\[ \gamma = 1.05. \]
Dipole plus Bipole Configuration

Magnetic flux evolution

Coronal hole evolution

Open field lines
Reconnection event

Closed down field lines
Reconnection event

Reopened field lines
Reconnection event

Closed again field lines

Closed field lines
Reconnection event

Opened up field lines

Magnetic field line evolution
Reconnection Events

$t=t_1$  

$t=t_2$

Opening up

Closing down

Interchange

Interchange reconnection
Tilted Dipole: $B_r$ Evolution

Evolution of surface magnetic flux through differential rotation. Changes at the poles are more noticeable because the differential flow is larger at high latitudes.
Evolution of coronal holes. Black areas represent open field regions. Gray areas are closed field regions. The rotation of coronal holes is almost rigid, with little distortion after 5 rotations. After 11 rotations distortion is more evident.
Differential Rotation Rates

![Graph showing differential rotation rates across different latitudes, illustrating various models and data points from different studies.]

- MHD Model
- Newton and Nunn (1951)
- Timothy et al. (1975)
- Antonucci and Dodero (1977)
- Insley et al. (1995)
- Fisk (1996)
A Look at 15 \( R_{\odot} \)

The foot points of the field lines are advected by the photospheric differential flow. Rings are colored according to the latitude of the connecting field line at 1 \( R_{\odot} \). The latitude of open magnetic field lines appears to change in time.
Latitudinal excursion measured at the $r = 15 \, R_{\odot}$ surface for field lines starting at $75^\circ$ at $r = R_{\odot}$ (left) and for field lines having initially a latitude of $35^\circ$ at $r = 15 \, R_{\odot}$ (right). The heliospheric latitude of the field lines changes over time, as predicted by the Fisk model.
Conclusions

- Our results are in good agreement with the Wang & Sheeley model:
  - The evolution of coronal holes is dependent on that of the flux of the magnetic regions from which they originate.
  - Regions of magnetic reconnection are found at the boundaries of coronal holes.

- Our results confirm the basic idea of the Fisk model, that differential rotation leads to changes in the heliographic latitude of magnetic field lines.

- Fisk’s assumption that coronal holes rotate strictly rigidly is not satisfied in our simulations.
Conclusions (cont.)

- Differential rotation smears the photospheric flux into bands, reducing the “dipole” tilt over time and, consequently, the maximum latitudinal excursion of the coronal field progressively decreases. This is not a realistic effect.

- Our model includes only the large scale magnetic field and not the small-scale “salt and pepper” magnetic structures that allow the magnetic diffusion process in the Fisk model.

- High resolution simulations will be performed to study this scenario in more details.
Bibliography


