Observing the Unobservable? Modeling coronal cavities to determine cavity density

Jim Fuller

Advisors: Sarah Gibson, Giulianna de Toma
Motivations

- Cavities are known to be correlated with coronal mass ejections.
- Understanding the physics of cavities is essential to understanding and predicting phenomena such as CMEs.
Background

- Cavities are regions with lower density located at the base of coronal helmet streamers.
- Cavities are associated with CMEs.
- Lower cavity density may imply stored magnetic energy within cavity.
- Cavities are often long-term structures.
Goals of project

- Create a cavity model that will allow us to observe cavity material
- Find cavities that fit parameters of model so we can claim we are observing only cavity material
- Invert polarized brightness measurements to determine cavity density
Observing a Cavity

- Each pixel brightness is an integral over the line of sight, integral is proportional to density.
- Cavity wall, other features often get in the way.
- 2D image cannot tell 3D structure so we must observe for several days.
Polarized brightness measurements as a function of latitude at constant height

- Cavity has lower brightness than rim, higher brightness than coronal holes
Our Model

- Cavity is modeled as an axisymmetric torus encircling Sun at constant latitude.
- The model is not intended to apply to all cavities but will work if cavity has the right properties.
- Cavity must maintain constant size and latitude for several days.
- Cavity must be large and at low latitudes.
- These cavities will allow density analysis.
Geometry of Cavity Along Line of Sight

- Material from altitude higher than $R_{\text{pos}}$ projects into line of sight as scattering angle increases.
- Material from altitude below $R_{\text{pos}}$ can never project into line of sight.
Limitations on Observable Cavities

- Bigger cavities are easier to observe because they extend to larger heights.
- Cavities near equator are easier to observe because they curve less.
- Cavity must also be visible a couple days before and after observation in order to prove it has large enough longitudinal extent.
In order to fit our model, a cavity must be a large enough fraction of a donut that it is axisymmetric along our line of sight.

The size of the donut slice can be measured by observing how many days a cavity is visible.

This plot tells us the total number of days a cavity must be visible that the cavity fits our model and is suitable for observation on the middle day.
Assuming cavity is axisymmetric, a bigger cavity is best for observation.

- Scattering angle at edge of cavity is larger for bigger cavities.
- This means that light comes from within the cavity as opposed to outside it.

- Scattering angle at edge of cavity also dependent on $R_{\text{pos}}$.
- Lines of sight at low altitudes yield higher scattering angle.
Our Cavity
What date works best for measurements?

<table>
<thead>
<tr>
<th>Date</th>
<th>Days Required</th>
<th>Days Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/25/06</td>
<td>$2.50_{-1.13}^{+1.11}$</td>
<td>0 before, 5 after</td>
</tr>
<tr>
<td>01/27/06</td>
<td>$2.66_{-1.13}^{+1.12}$</td>
<td>2 before, 3 after</td>
</tr>
<tr>
<td>01/28/06</td>
<td>$2.71_{-1.17}^{+1.14}$</td>
<td>3 before, 2 after</td>
</tr>
<tr>
<td>01/29/06</td>
<td>$2.80_{-1.17}^{+1.14}$</td>
<td>4 before, 1 after</td>
</tr>
<tr>
<td>01/30/06</td>
<td>$2.70_{-1.12}^{+1.10}$</td>
<td>5 before, 0 after</td>
</tr>
</tbody>
</table>

Our cavity is almost axisymmetric on the 27th and 28th.
Cavity Properties

- Cavity is big and fairly close to the equator so $\alpha_{\text{max}}$ is large
- Plot at right (Hundhausen 1993) shows polarized brightness as function of $\alpha$ for $R_{\text{pos}}=1.25$
- Over 88% of light comes from within our cavity if we observe it $R_{\text{pos}}=1.25$

<table>
<thead>
<tr>
<th>Date</th>
<th>$R_{\text{cav}}$</th>
<th>$\theta$</th>
<th>$\alpha_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/25/06</td>
<td>0.230 ± 0.030</td>
<td>124.80 ± 0.74</td>
<td>30.32 ± 1.48</td>
</tr>
<tr>
<td>01/27/06</td>
<td>0.260 ± 0.035</td>
<td>128.44 ± 0.63</td>
<td>31.17 ± 1.53</td>
</tr>
<tr>
<td>01/28/06</td>
<td>0.270 ± 0.045</td>
<td>129.64 ± 0.67</td>
<td>31.40 ± 1.85</td>
</tr>
<tr>
<td>01/29/06</td>
<td>0.285 ± 0.045</td>
<td>132.40 ± 0.89</td>
<td>31.54 ± 1.81</td>
</tr>
<tr>
<td>01/30/06</td>
<td>0.260 ± 0.030</td>
<td>131.36 ± 0.54</td>
<td>30.69 ± 1.33</td>
</tr>
</tbody>
</table>
Calculating Cavity Density

Step 1:

- Select regions at which to make radial polarized brightness measurements
- Heights below 1.18 contaminated by substructure
- Heights above 1.4 measure very little cavity
- Beware of active regions!
Problem

- Van de Hulst inversion requires cylindrical symmetry of density fall off, i.e. the radial fall off must be identical at all scattering angles.
- Jump in density from cavity to cavity rim breaks this symmetry.
Uncertainties

- Inversion requires value:

\[ pB_{cav}\Big|_{-q_0}^{q_0} = 2pB_{cav}\Big|_{\alpha_{max}}^{q_0} + 2pB_{cav}\Big|_{0}^{\alpha_{max}} \]

- The measured value is:

\[ pB_{meas} = pB_{cav} + pB_{non} = 2pB_{cav}\Big|_{0}^{\alpha_{max}} + 2pB_{non}\Big|_{\alpha_{max}}^{q_0} \]

- The value given to our program is:

\[ pB_{cav}\Big|_{-q_0}^{q_0} = pB_{meas} + (2pB_{cav}\Big|_{\alpha_{max}}^{q_0} - 2pB_{non}\Big|_{\alpha_{max}}^{q_0}) \]

where the term in parentheses is the uncertainty in measurement
Another Problem

- Cavity is not quite axisymmetric
- Using number of days before and after observation, we calculate values of $\alpha_{\text{max}}$ in front of and behind cavity at which line of sight exits cavity
- Uncertainties utilize smallest values of $\alpha_{\text{max}}$ to ensure account for largest possible error
Fitting a curve to pB measurements

Step 2:

- Create log(pB) vs log(r) plot
- Log-log plot has linear profile
- Our program determines parameters of line of best fit
Calculating Cavity Density

Step 3:

Using calculated fit parameters, perform Van Hulst inversion and calculate density profile.
- Cavity has about 60-100% the density of the cavity rim
- Cavity has about 2-5 times the density of a coronal hole
- Cavity rim has very similar density to a bright helmet streamer
Implications

- Cavity has lower density than rim and slower density fall off
- To ensure pressure continuity, cavity must have higher temperature or higher magnetic pressure
- Our results are consistent with models in which cavity is created by twisted magnetic flux rope
- Twisted magnetic flux rope would create a higher magnetic pressure and flatter density fall off within cavity
Conclusions

- People have said that cavities are unobservable because the helmet streamer gets in the way and because cavities are empty.

- We have demonstrated cases in which contributions from the helmet streamer are negligible and have proven that cavities are far from empty.

- Our results reveal a density profile that is consistent with the magnetic flux rope model for cavities.
Future Work

- Apply this technique to more cavities
- Apply geometry of the model to cavities imaged in emission lines
- Submit article for publishing
- Use emission line data to determine temperature profiles of cavities
References

- Van de Hulst, H.C. 1950, Bulletin of the Astronomical Institutes of the Netherlands, 11, 135