Determining Cavity Density Profiles using Cavity Model

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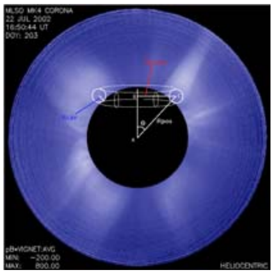
Abstract

Cavities in coronal helmet streamers can easily be seen in white light coronagraph images. However, they are difficult to observe without contamination from the obstructing presence of features along the line of sight such as the helmet streamer surrounding the cavity. Our goal is to find cases where such spurious non-cavity contributions are minimal, and can be incorporated in a density analysis as conservatively estimated uncertainties in the data. To that end, we present a model of coronal cavities in which a cavity exists as an axisymmetric torus that encircles the Sun at constant latitude. We use Mauna Loa Solar Observatory (MLSO) polarized brightness data to show that the cavity that exists from January 25-30 of 2006 fits the parameters of our model. By examining the geometry of the model and the physics of the polarized brightness of scattered white light in the corona, we show that it is possible to observe the cavity without significant contribution from surrounding material. Using a Van de Hulst of inversion of polarized brightness measurements, we calculate a radial density profile for cavity material and for the surrounding helmet streamer. Our results show the cavity density to be roughly 50% lower than a helmet streamer and roughly three times as great as a coronal hole. We also discuss the geometry of cavities imaged using emission line data and provide guidelines for determining whether a given cavity is unobstructed enough so that it can be analyzed for density and temperature profiles of cavity material.

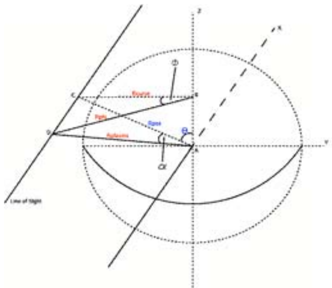
Problem

Cavities under coronal helmet streamers have been observed for many decades and are known to be correlated with CME's. It is believed that large amounts of energy stored in cavities' twisted magnetic fields may help power CME's. Sometimes cavities are short-lived, but they often exist as long-term structures that last for days or weeks at a time. Unfortunately, it is very difficult to observe cavity material because surrounding features project into the line of sight and contaminate measurements. The goal of this project is to find a case in which contributions from surrounding material can be minimized, so that we can determine the density of cavity material.

Model

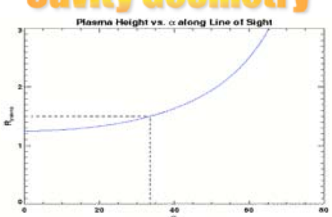


The Sun and cavity as viewed from Earth. The distance from the center of the Sun to the center of the cavity is $1+R_{cav}$. R_{curve} is the radius of curvature of the cavity. R_{pos} is the height in the plane of the sky through which the line of sight passes. The angle θ is the colatitude of the cavity.

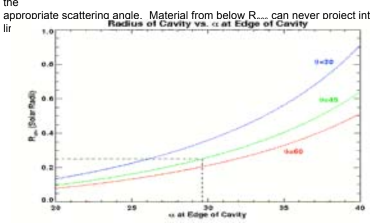


Geometry of the model. The angle α of any point D along the line of sight is the scattering angle at that point. The angle Φ defines the longitude of the point. The distance R_{plasma} is the actual height of the point D from the center of the sun.

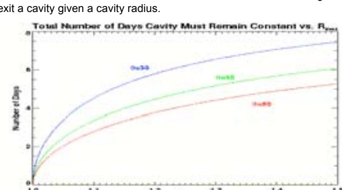
Cavity Geometry



The actual height R_{plasma} along the line of sight as a function of the angle to the line of sight. The height R_{pos} of the line of sight is given by the y-intercept of the curve. Material from higher up projects into this line of sight when it is at the
appropriate scattering angle. Material from below R_{pos} can never project into the lir

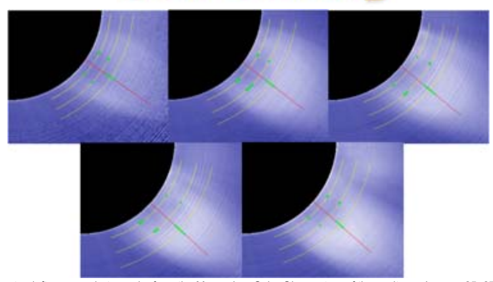


Minimum cavity radius as a function of the scattering angle for which we are still inside the cavity. The plot assumes a line of sight through the center of the cavity. The dotted lines show how the curves can also be used to find the angle at which we exit a cavity given a cavity radius.



The total number of days that the cavity must retain constant size and latitude as a function of R_{max} so that the cavity has a large enough longitudinal extent to fit our model. R_{max} is the effective height of the top of the cavity for white light or the altitude at which emission dies out for EIT data. The plot assumes a value of R_{pos} midway between the photosphere and R_{max}.

Our Cavity



From top left across, photographs from the Mauna Loa Solar Observatory of the cavity on January 25, 27, 28, 29, and 30.

Date	R_{cav}	θ	α_{max}	ϕ_{max}
01/25/06	.250 ± .030	124.80 ± .74	$30.32^{+1.88}_{-1.63}$	$35.46^{+1.63}_{-1.81}$
01/27/06	.260 ± .035	128.44 ± .63	$31.17^{+1.52}_{-1.71}$	$37.68^{+1.62}_{-1.90}$
01/28/06	.270 ± .045	129.64 ± .67	31.40 [illegible]	38.40 [illegible]
01/29/06	.285 ± .045	132.40 ± .89	$31.54^{+1.61}_{-1.07}$	39.73 [illegible]
01/30/06	.260 ± .030	131.36 ± .54	$30.69^{+1.22}_{-1.45}$	$38.34^{+1.48}_{-1.64}$

Cavity properties for each date of observation. The values of α_{max} and Φ_{max} indicate the scattering angle and longitude of the edge of the cavity for $R_{pos}=1+R_{cav}$.

Date	Days Required	Days Observed
01/25/06	2.50 [illegible]	0 before, 5 after
01/27/06	2.66 [illegible]	2 before, 3 after
01/28/06	2.71 [illegible]	3 before, 2 after
01/29/06	2.80 [illegible]	4 before, 1 after
01/30/06	2.70 [illegible]	5 before, 0 after

The number of days a cavity must maintain constant latitude and size before and after an observation for our model to hold true. The table also lists the actual number of days the cavity maintains constant latitude and size.

Cavities in Emission Lines

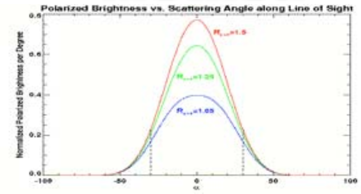
Cavity imaged at 19.6nm on July 3rd, 1997. The cavity was visible for roughly two days on either side of the observation, making it a candidate for measurements in an emission line that dies out by about 1.2 solar radii. By taking measurements along a line at constant altitude, we could get temperature and density information for the cavity rim, cavity, and central prominence.

- Most emission lines die out at altitudes less than the cavity top so the cavity top is not visible.
- We do not need to worry about cavity top projecting into line of sight for this case.
- The scattering angle is unimportant for emission so we must be very careful about the cavity rim projecting into the line of sight.
- Depending on the altitude R_{max} at which the emission line dies out, the cavity must exist for a few days on either side of an observation (see chart at bottom left).
- Emission is dependent on both temperature and density so we must be careful in making temperature or density measurements.

Conclusions

- Cavity ranges from roughly half the density to the same density as the cavity rim and bright coronal streamer.
- Cavity is roughly 2 to 5 times as dense as a coronal hole and has higher density by about 2×10^{7} gcm^{-3}
- If temperature is constant between cavity and cavity rim, lower cavity density and shallower fall off imply increased magnetic field strength and slower magnetic fall off within cavity.
- This analysis should be applied to more cavities to determine if all cavities have these characteristics.
- Analysis should be applied using EIT data to estimate cavity temperature profile

Method



Polarized brightness as a function of scattering angle for various altitudes of the line of sight. Limb darkening is taken into account with μ=.585. The curves have been normalized to demonstrate how brightness drops off faster with alpha at higher altitudes. Without the normalization, lower values of R_{pos} would have higher peak brightnesses. The curves assume a spherically symmetric density that falls off as r^7. The curves show that over 88% of scattered light comes from within α=±30 for R_{pos}=1.25. Therefore, most light comes from the cavity and not the cavity rim when observing the center of our cavity.

To determine cavity density from polarized brightness measurements we use a Van de Hulst inversion. The inversion assumes the cylindrical symmetry of objects along the line of sight. Due to the density change from cavity to cavity rim, this cylindrical symmetry does not exist. The inversion requires the value of

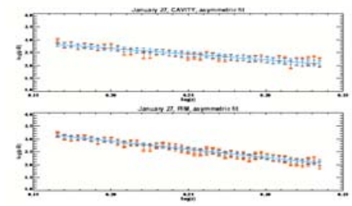
$$pB_{cav}\Big|_{-90}^{90} = 2pB_{cav}\Big|_{\alpha_{max}}^{90} + 2pB_{cav}\Big|_{0}^{\alpha_{max}}$$

but the measured value is

$$pB_{meas} = pB_{cav} + pB_{non} = 2pB_{cav}\Big|_{0}^{\alpha_{max}} + 2pB_{non}\Big|_{\alpha_{max}}^{90}$$

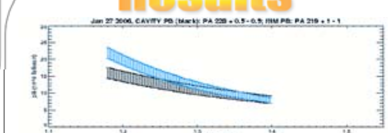
Combining these above two equations yields the value that we input into the inversion, shown below. The terms inside the parentheses are the uncertainties added to the measurements, which is negative if the non-cavity material is a helmet streamer and positive if the non-cavity material is a coronal hole.

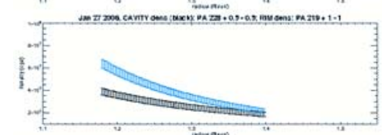
$$pB_{cav}\Big|_{-90}^{90} = pB_{meas} + \left(2pB_{cav}\Big|_{\alpha_{max}}^{90} - 2pB_{non}\Big|_{\alpha_{max}}^{90}\right)$$



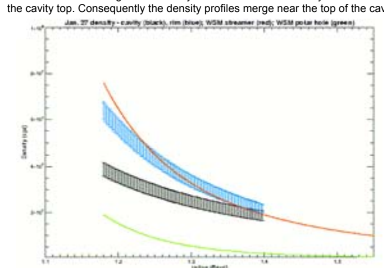
Linear fit to the radial log(pB) measurements for both the cavity (top) and the rim (bottom) on January 27. The red error bars are centered on the measurement points and indicate the uncertainties added to the measurements by the method described above. The blue error bars are centered on the line of best fit and indicate the uncertainty in the fit. This uncertainty is passed through to the density calculation. The curves follow a linear falloff with log(pB)=a-b*log(r), where a and b are the fitted parameters. This linear falloff corresponds to a power law falloff of the form pB=a*r-b.

Results





Radial polarized brightness (top) and density (bottom) profiles for the cavity (black) and cavity rim (blue) on January 27. The polarized brightness measurements converge as the cavity becomes contaminated by material from the cavity top. Consequently the density profiles merge near the top of the cavity.



Density profile of the cavity (black) and cavity rim (blue) on January 27 as compared to the density profile for a bright coronal streamer (red) and a coronal hole (green).

References

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