A comparison of mean density and microscale density fluctuations in a CME at 10 \( R_\odot \)

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1. Observations

[2] Intensity scintillation at 8 GHz is “weak” at 10 \( R_\odot \), so it provides a linear measure of the density fluctuations with spatial scales of the order of 50 km. With the LASCO C3 instrument [Brueckner et al., 1995] it is possible to make a direct comparison between these “microscale” fluctuations and the mean density. Both observations involve line of sight integrals which cannot be directly inverted, but a useful comparison can be made by fitting a simple CME model to the two data sets simultaneously. The comparison can be made with respect to the pre-CME slow wind without requiring absolute calibration of the IPS or the coronagraph.

[3] The structure of the CME is shown clearly in Figure 1. This is a grey-scale version of the summary images available on the SOHO web site (http://sohowww.nascom.nasa.gov/). A description of the image processing is available on the LASCO web site (http://lasco-www.nrl.navy.mil/idl_pros/help_synoptic.html).

[4] Eight C3 images taken during the passage of the CME are shown with the same processing in Figure 2. A 3-hour average of the pre-event corona is used as the slow wind background reference. These images were used to estimate the CME velocity using the running difference technique described by Sheeley et al. [1997]. Height-time plots at the position angle of the radio source show that the velocity of the leading edge was 546 \( \pm \) 26 km/s and the velocity in the center of the CME was 444 \( \pm \) 21 km/s. As the CME is relatively fast, one might expect to see some compression at the leading edge.

[5] To obtain an estimate of the integrated mean electron density from the C3 images, we must separate the \( K \) (electron) component from the \( F \) (dust) component. This is done using polarization measurements because the polarization of the \( K \) and \( F \) components are very different. We assume that the \( K \) component is independent of the CME and calculate it from the pre-CME reference. We know \( P_F/B_F = 0.002 \) at 10 \( R_\odot \) [Mann, 1992]. We calculated \( P_K/B_K \) using well-known expressions [van de Hulst, 1950; Billings, 1966; Hayes et al., 2001]. At 10 \( R_\odot \) the familiar coronal density models are not valid, so we used two spherically symmetric solar wind density models: a polar coronal hole model [Guhathakurta et al., 1999]; and an equatorial streamer model [Muhlenberg and Anderson, 1981]. The two models yielded values of \( P_K/B_K = 0.507 \) and 0.5164, confirming that the polarization is not very sensitive to the density. We measured \( P_T = P_F + P_K \) and \( B_T = B_F + B_K \) at the pre-CME reference location by averaging 17 pixels around the IPS location on the polarized images from August 1 and 2. We obtained \( P_T/B_T = 0.0553 \pm 0.0043 \). Thus \( B_{KREF} = 0.105 B_T \) and \( B_{FREE} = 0.895 B_F \). We then obtain the K corona brightness \( B_K(t) \) during the passage of the CME from the observed total brightness \( B_T(t) \) at the IPS location, using \( B_K(t) = B_T(t) - B_{FREE} \). The normalized brightness \( B_K(t)/B_{KREF} \) is plotted in the top panel of Figure 3.

[6] The IPS measurements were made using three antennas of the VLBA at Kitt Peak, Pictou, and Los Alamos. The data were sampled at 100 Hz and spectra were analyzed in 10 minute blocks. The low frequency drift was removed with a 0.2 Hz highpass filter and the receiver noise was estimated and subtracted. The intensity variance \( \delta I^2 \) was computed by integrating under the autospectra. The variance was normalized by the pre-CME value and plotted in the bottom panel of Figure 3. The CME is very well defined on this plot. Just after the peak of the CME a large but short-lived increase occurred. The data were reanalyzed in 2 minute blocks to provide better resolution of this burst.
The burst cannot be due to radio interference because it was observed at two antennas which are 200 km apart (the Kitt Peak antenna was temporarily stowed due to high wind).

2. Modeling

We write the line of sight integrals in terms of \( \theta \), the angle subtended at the sun, which is a more convenient form for numerical integration through an inhomogeneous medium. The IPS variance depends on many factors which are distance dependent. These are discussed, for example, by Coles et al. [1995]. However the elongation \( x \) of the radio source was essentially constant during the CME passage, so we can simplify the line of sight integral (over \( z = r \sin(\theta) \)) for the intensity variance to

\[
\delta I^2(x) = K \int_{-1}^{z} \delta N_e^2(r) \sqrt{1 + zdz} \\
= K \int_{-\pi/2}^{\pi/2} \delta N_e^2(\theta) \frac{\sqrt{1 + x \tan(\theta)}}{\cos^2(\theta)} d\theta. \tag{1}
\]

Here \( x = r \cos(\theta) \) is the distance of closest approach and \( K \) is a constant which will be normalized out. The variance depends on the square root of the distance from the Earth, \( \sqrt{1 + z} \).

We model the body of the CME as an oblate spheroid ball of uniform density to match the image shown in Figure 1. The measured angular width is 84.4 ± 3.0 deg at 10 \( R_e \), and the time for the CME to pass 10 \( R_e \) was 234 ± 22 min. Using a velocity of 500 km/s we estimate the apparent axial ratio is 1.46 ± 0.15. If it were exactly an oblate spheroid the true axial ratio would be 1.57, but the difference is within the statistical error and we don’t know the shape well enough to justify further refinement. The normalized mean and rms density \( \langle N_e \rangle \) and \( \delta N_e \), and the duration at the IPS location are the only free parameters. The data weights were adjusted so both data sets contribute equally to the mean squared error. The model best-fit to the data, excluding the IPS data between 23:30 and 23:40 UT, gives: \( N_e = 2.18 \), \( \delta N_e = 1.76 \), duration = 170 min. This model is plotted over the observations on Figure 3. The model matches the leading edge of the CME in both observations reasonably well. However at the trailing edge we see that the IPS falls more quickly than the C3 brightness. This suggests that the trailing edge of the CME is less turbulent, but the effect is marginally significant. The ratio \( \delta N_e / N_e \), which we define to be unity in the pre-CME slow wind, is slightly lower in the CME, \( \delta N_e / N_e = 0.81 \pm 0.10 \), which is also marginally significant.

The transient IPS enhancement between 23:30 and 23:40 UT is not visible in the C3 images but we can make some inferences about its structure. We tried to fit it with a simple model of a spherical plasmoid with the same velocity as the CME itself. The duration of the IPS response implies a diameter of 253,000 ± 32,000 km and the magnitude of the IPS increase implies a density of 12.8 ± 2.5 times the background. Although this model fits the IPS data very well, it would increase the C3 brightness by 13.5% over a region 7 pixels in diameter. This is a 1 σ increase in...
brightness over the plasmoid and would normally have been visible in the C3 image. We simulated this enhancement and found that it was detectable in a single image 75% of the time. Since it would have been visible in at least two images, and we know exactly where it would be, it is unlikely that such a compact plasmoid can be present. An alternative model is that the enhancement is caused by a thin radially-extended structure which is pushed laterally across the line of sight as the CME passes. It could be either a thin shell or a thin flux tube. We have tested both models using a transverse velocity calculated from the images in Figure 2.

At the time of the IPS enhancement the radio source was near the edge of the CME in a region with a steep transverse density gradient. We measured the position of a constant brightness contour in successive images at 23:18 and 23:42 UT. To reduce the estimation error we chose a contour with a steep gradient, and we smoothed the images over 9 pixels. The apparent velocity of this contour line, $80.5 \pm 15.7$ km/s, provides an estimate of the transverse velocity of the plasma if the mean CME density at 10 $R_{\odot}$ is constant.

We model the flux tube as a simple addition to the bulk CME. For the shell we use the radius of curvature of the bulk CME and fill the inside with the pre-CME density level. If the inside of the shell is filled with the bulk CME density the model cannot be fit at all. The best-fit flux tube, plasmoid, and shell models are plotted over the observations on Figure 3 as thick solid, thin solid, and dotted lines respectively. The flux tube and plasmoid models fit the IPS equally well and are indistinguishable on this plot. However the flux tube provides a smaller enhancement in the C3 brightness, $0.5 \sigma$. The IPS response of the shell is more extended than either the plasmoid or flux tube models, therefore the best fit shell is thinner than either. The shell model predicts an enhancement of $2 \sigma$ in the C3 brightness, and it does not fit either data set as well as the plasmoid or flux tube models. The minimum $\chi^2(34)$ values for the flux tube and shell models are 62.2 and 94.9 respectively. A flux tube or a shell would appear in a C3 image as a radial line, one pixel wide and many pixels long. Simulations showed that a one pixel wide linear feature becomes distinguishable from the background noise with a brightness enhancement of between 1 and 1.5 $\sigma$. Thus the shell would have been easily detectable in the C3 image, whereas the flux tube would be lost in the background noise.

The flux tube diameter is 40,800 ± 7,900 km and its density is $31.5 \pm 6.2$ times the reference background. The most straightforward interpretation of this model is that the flux tube was pre-existing and was pushed aside by the CME. In this case one has to explain a rather thin dense structure at 10 $R_{\odot}$.

The objective of the IPS measurements had been to estimate the flow velocity of the quasi-static wind. The auto- and cross-correlations between the antennas were calculated so time delays could be measured and the velocity distribution estimated [Grall et al., 1996].

3. CME Complexity in IPS

The IPS auto-spectra estimated at 10-minute intervals during the passage of the CME. The time (UT) is indicated to the right of each. The error bars indicate the data, the solid lines are a pre-CME slow wind model drawn over each spectrum for comparison.
correlations can be used to estimate the axial ratio, the spectral exponent, and the velocity distribution of the microstructure. However this requires the spatial structure and velocity be quasi-static and that is clearly not valid during this CME. One suspects that it is never valid during a CME, although the problem is less severe outside of 20 \( R_\odot \) where the microstructure is more isotropic. In this case we can fit all the cross-correlation functions individually but we must use a different angle between the magnetic field and the flow for each correlation.

4. Conclusion

[16] A fast CME is easily seen in IPS at 10 \( R_\odot \), and can be modeled in conjunction with simultaneous coronagraph images. These indicate that \( \delta N_e/N_e \) in the CME slightly lower than in the background slow wind. In general IPS is more sensitive to small, but dense, structures than is a coronagraph because it responds to \( N_e^2 \) rather than \( N_e \). In this CME the IPS shows a structure 30 times denser than the background which is so thin that it is not visible in the C3 coronagraph. Finally we see that the spatial structure of this CME was far too complex to unravel with IPS alone.

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