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Expansion Speed of Coronal Mass Ejections

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Abstract A large set of limb coronal mass ejections (CMEs) are used to determine the accurate relationship between radial (V_{rad}) and expansion (V_{exp}) speeds of CMEs. It is demonstrated that this relation is exceptionally well described by the function $f(w) = 1/2(1 + \cot w)$, representing a full cone model for the CME with a half-width, w. We also demonstrate that for extremely fast CMEs ($V_{\mathrm{exp}} > 3000\ \mathrm{km\,s^{-1}}$), it is better to use the approximation $V_{\mathrm{rad}} \approx V_{\mathrm{LE}}$. This implies that such CMEs expand spherically above the solar surface.

Keywords Sun: solar activity · Sun: coronal mass ejections

1. Introduction

Space weather is significantly controlled by coronal mass ejections (CMEs), which effect Earth in different ways. CMEs originating close to the central meridian, directed toward Earth, excite immediate scientific concern. In coronagraphic observations they appear as an enhancement surrounding the entire occulting disk and hence are called "halo CMEs." Since their first identification by Howard *et al.* (1982) a large number of them have been observed; now they are routinely imaged by spaceborne coronagraphs such as on the *Solar and Heliospheric Observatory* (SOHO). Models predicting the arrival of CMEs in the vicinity of Earth (*e.g.*, Gopalswamy *et al.*, 2001; Michalek *et al.*, 2004) critically depend on the radial speed of CMEs.

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Measuring sky-plane speeds, it is possible to estimate V_{rad}. Two kinds of sky-plane speeds can be measured from coronagraph images: *i*) the leading-edge speed (V_{LE}) is obtained from the fastest-moving structure of the CME front (Yashiro *et al.*, 2004), and *ii*) the expansion speed (V_{exp}), which is the rate of change of the lateral dimension of a CME at its widest part (Dal Lago, Schwenn, and Gonzales, 2003; Schwenn *et al.*, 2005). V_{rad} can be obtained from V_{LE} by correcting for projection effects using CME cone models (*e.g.*, Xie, Ofman, and Lawrence, 2004; Michalek, 2006) or from V_{exp} using an empirical relationship between V_{exp} and V_{rad} (Dal Lago, Schwenn, and Gonzales, 2003; Schwenn *et al.*, 2005). The empirical relation ($V_{rad} = 0.88V_{exp}$) obtained by Dal Lago, Schwenn, and Gonzales (2003) is too simple because it does not include the CME width dependence. Recently, Gopalswamy *et al.* (2009a) examined the V_{rad}/V_{exp} relationship for different CME cone models (a flat cone, a shallow ice-cream cone, and a full ice-cream cone). They demonstrated from theoretical considerations that the relationship was $V_{rad} = f(w)V_{exp}$, where $f(w)$ described the CME width dependence. The function $f(w)$ is different for the three cone models (Gopalswamy *et al.*, 2009a, Figure 6). The purpose of the present article is to obtain an accurate V_{rad}/V_{exp} relationship from CME measurements and compare it with the theoretical relationships obtained by Gopalswamy *et al.* (2009a).

This article is organized as follows. In Section 2, data considered for the study and measurements method are described. In Section 3, we present results of our considerations. Finally, conclusions and discussion are presented in Section 4.

2. Data and Measurements

CMEs occurring close to the solar limb are free from projection effects and are used for the present purposes. For our study we select a set of 379 limb CMEs originating within 30° from the limb (the same set of events as in Gopalswamy *et al.*, 2009a, Figure 1). The number is much larger than the one used by Dal Lago, Schwenn, and Gonzales (2003). During the expansion, especially for the very fast events, coronal plasma around the CME is compressed. These disturbances appear as bright structures in LASCO observations influencing the width determination. In cataloging CMEs, the width measurements typically include these compressions (Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2009b). In order to get more accurate linear and angular dimensions of the limb CMEs, we determine the width only from the main body of CMEs and only from images recorded in LASCO C3 field-of-view. By "main body" we mean the flux rope portion of the CMEs. By doing this, we treat both shock-driving and nonshock CMEs with the same standard.

Figure 1 shows an example of width determination for the CME on 24 November 1998. In this CME, we can see both the main body and the shock-like disturbances around it. The double-headed arrows indicate the lateral extent of the main body. For this event, we are able to measure six successive lateral and angular widths that allow us to calculate five values for the expansion speed. The average of these five values is taken as the expansion speed of the CME. Formally, V_{exp} for a given CME could be written as:

$$V_{exp} = \frac{\sum_{i=2}^{n} \frac{L_i - L_{i-1}}{T_i - T_{i-1}}}{n}, \qquad (1)$$

where n is the number of measurements for a given CME, i is the frame number in which CMEs are visible, T_i is the time, and L_i is the widest lateral dimension of CME in the ith frame. The angular width of the CME is taken as the average value of the six width

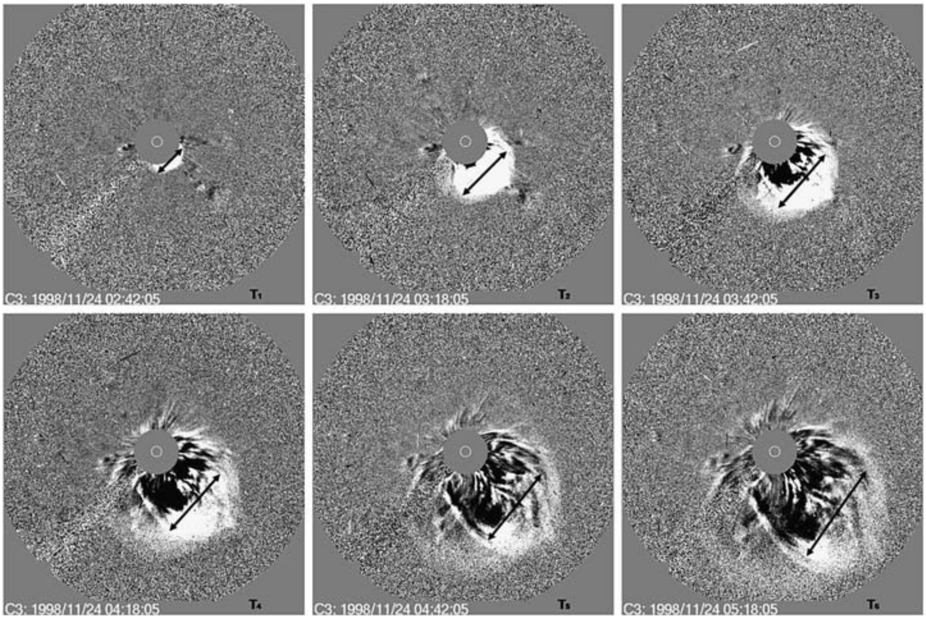


Figure 1 In the successive panels an example of measurements of lateral dimension at the widest part of a main body of CMEs are presented.

measurements. For the 24 November 1998 CME, we get $V_{\mathrm{exp}} = 2144\ \mathrm{km\,s^{-1}}$ and the angular width as 106°. The sky-plane speed of the CME in the catalog is $1798\ \mathrm{km\,s^{-1}}$ and the apparent angular width is 360° (halo CME). We require that at least two successive speed measurements are needed in order to get V_{exp}. With this criterion, we are able to determine V_{exp} of 256 CMEs in our sample; these events are used for further analysis.

The radial speeds (V_{rad}) of the CMEs are taken from the SOHO/LASCO CMEs catalog (http://cdaw.gsfc.nasa.gov, Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2009b). These measurements are made at the fastest-moving segment of the CME leading edge. We also make use of the width measurement available in the catalog for comparison. It must be noted that the catalog width measurement corresponds to the outermost part of the CME, which might include disturbances around the CME.

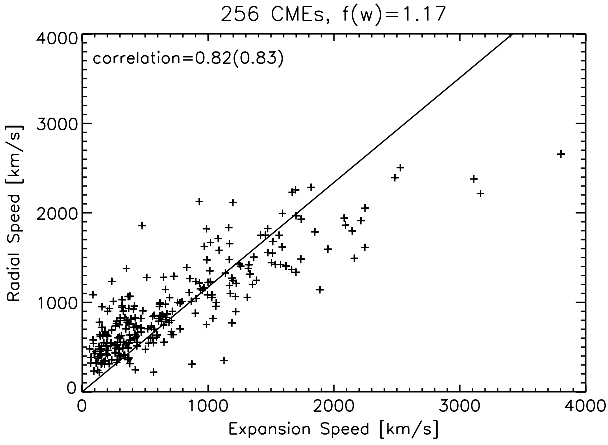
3. Analysis and Results

The CME widths measured here range from 9° to 137°. As we mentioned, the width was determined only from the main body of the CME. Thus there are some differences between the catalog designations and the classification used in this article.

In Figure 2, the scatter plots between V_{exp} and V_{rad} of CMEs for all CMEs are shown. Correlation coefficients between the velocities are significant, larger than 0.8 for the considered limb CMEs. When we exclude the outliers, the correlation coefficients slightly increase (see Figure 2). As we can see, the relation $V_{\mathrm{rad}} = 1.17 V_{\mathrm{exp}}$ in Figure 2 is different from that of Dal Lago, Schwenn, and Gonzales (2003). According to the analytical expression relating V_{rad} and V_{exp} obtained by Gopalswamy *et al.* (2009a),

$$V_{\mathrm{rad}} = f(w) V_{\mathrm{exp}}, \tag{2}$$

Figure 2 Scatter plots of the expansion speeds versus the radial speed for all considered limb CMEs. Continuous line represents linear fit to the data points. Function $f(w)$ describes the slope of the linear fit to data point.



where $f(w) = 1/2(1 + \cot w)$, with w being the half-width of the full ice-cream cone that represents the CME. The slope of the line in Figure 2 is the value of $f(w)$ for the set of CMEs considered in this article. The expression $f(w) = 1.17$ corresponds to a CME cone angle of $w = 36.7°$. This means that the average width of the 256 CMEs is 73.4°. Interestingly, the average width obtained directly from measurements is 60°. Figure 2 thus confirms the importance of the CME width in deciding the relation between V_{rad} and V_{exp}, as pointed out by Gopalswamy *et al.* (2009a).

The sample size (256) of CMEs used here is much larger so it is possible to perform a more detailed study of the value of the $f(w)$ function. In order to do this, we divided the CMEs according to their width into seven groups. Each group has a width range of 20°. The smallest bin corresponds to 0° – 20°, while the highest bin corresponds to 120° – 140°. For each bin, we determine the ratio $f(w) = V_{\mathrm{rad}}/V_{\mathrm{exp}}$ in two ways: *i*) obtain the ratio as the average of ratios corresponding to individual CMEs in the width bin, and *ii*) plot the V_{exp} and V_{rad} values for all the CMEs in the width bin, fit a straight line to the scatter plot, and take the slope of the straight line. In this way, we are able to obtain $f(w)$ at seven discrete points. The results are presented in Figure 3. The left panel shows the $f(w)$ function when subsets of events are separated using the width of CMEs from our measurements. Also shown for comparison are the three cone models from Gopalswamy *et al.* (2009a). Clearly, our data points fit the function $f(w)$ described by the full cone model extremely well.

A small discrepancy appears only for the very narrow CMEs (the width range between 0° – 20°). These CMEs, which are mostly jets, have different topology than the wider CMEs, and hence, may not be approximated by the cone models. We see that both methods of obtaining $f(w)$ yield very similar results and closely follow the full ice-cream cone model. We also present the function $f(w)$ obtained using the SOHO/LASCO catalog widths. Clearly, the function $f(w)$ agrees with the full ice-cream cone model only for the first three data points (narrower CMEs). For the wider events, the $f(w)$ functions are systematically offset from the model curves. We think this is due to the fact that the shocks and the driving flux ropes expand differently. Note that for narrow CMEs, the catalog and present measurements agree because these CMEs do not drive shocks.

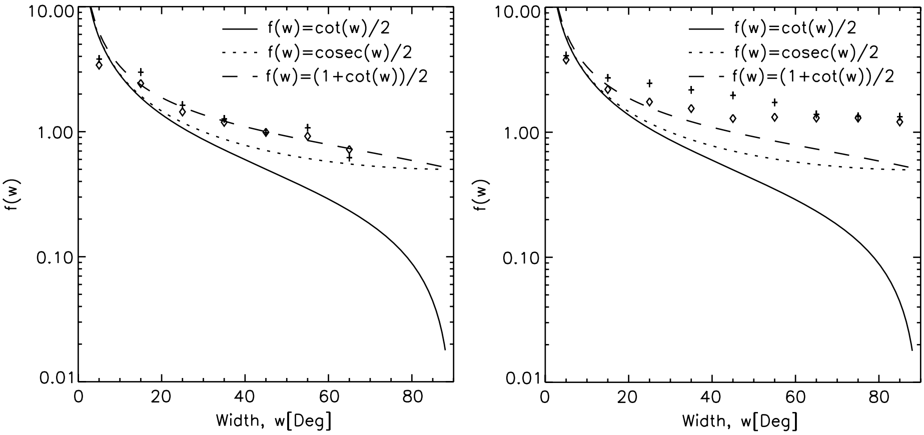


Figure 3 Scatter plots of $f(w)$ for subsets of events separated using our width measurements (left panel) and the SOHO/LASCO catalog width (right panel). Continuous lines illustrate the function $f(w)$ which connects V_{exp} and V_{rad} for the three cone models. Scattered points represent results obtained from our determinations. Crosses show $f(w)$ relation obtained as average value from individual relations between V_{exp} and V_{rad}. Diamonds show the values of $f(w)$ derived from the linear fit to data points for a given subset of events.

4. Summary and Discussion

Using a large set of limb CMEs, we study the relationship between V_{exp} and V_{rad}. It is shown that this relationship is exceptionally well described by the $f(w)$ function obtained from the full cone model (Figure 3, left panel). A small discrepancy appears only for very narrow CMEs, which are mostly jets and might have different topology than wider CMEs. We confirm the previous theoretical result (Gopalswamy *et al.*, 2009a) that the relation of Dal Lago, Schwenn, and Gonzales (2003) is too simple to be used for narrow or wide CMEs. It is important to note that the SOHO/LASCO catalog width, which also includes compressed material, does not give the correct $f(w)$ function (Figure 3, right panel) because flux ropes and shocks have different extents.

Gopalswamy *et al.* (2009a) considered extremely fast CMEs ($V_{\mathrm{exp}} > 3000\ \mathrm{km\,s^{-1}}$). For these CMEs they suggested that $V_{\mathrm{rad}} = (1/2)V_{\mathrm{exp}}$. In our sample of events we find three such super-fast events. As we see from Figure 2, these CMEs are shifted to the right from lines representing linear fits. The average ratio of $V_{\mathrm{rad}}/V_{\mathrm{exp}}$ for these three events is 0.70, much lower than for all the CMEs. For extreme events it is better to use the $V_{\mathrm{rad}} \approx V_{\mathrm{LE}}$ approximation. This implies that such CMEs expand spherically above the solar surface.

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