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Is the Asymmetric Cone Model for Halo Coronal Mass Ejections Correct?

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Abstract A set of 106 limb CMEs which are wide and could be possible halo events, when directed towards Earth, are used to check the accuracy of the asymmetric cone model. For this purpose characteristics of CMEs (widths and radial speeds) measured for the possible halo CMEs are compared with these obtained for halo CMEs using the asymmetric cone model (Michalek, *Solar Phys.* **237**, 101, 2006). It was shown that the width and speed distributions for both datasets are very similar and with a probability of $p > 0.93$ (using the Kolmogorov – Smirnov test) were drawn from the same distribution of events. We also determined the accurate relationship between radial (V_{rad}) and expansion (V_{exp}) speeds of halo CMEs. This relation for the halo CMEs is simply $V_{\mathrm{rad}} = V_{\mathrm{exp}}$ and could be very useful for space weather application.

Keywords Sun: solar activity · Sun: coronal mass ejections

1. Introduction

Space weather is significantly controlled by halo coronal mass ejections (HCMEs) originating close to the central meridian and directed toward Earth. Since their first identification by Howard *et al.* (1982) a large number of CMEs have been observed. Now they are routinely recorded using space-borne coronagraphs. For space weather forecasting it is very important to determine the kinetic and geometric parameters describing HCMEs. Unfortunately coronagraphic observations are subjected to projection effects. Viewing in the plane of the sky does not allow to determine the true radial velocity (V_{rad}), width and source location of CMEs. 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).

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V_{rad} can be obtained from V_{LE} by correcting for projection effects using CME cone models (*e.g.*, Michalek, Gopalswamy, and Yashiro, 2003; 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). Assuming that the shape of HCMEs is an asymmetric cone and they propagate with constant angular widths and speeds, Michalek (2006) developed a technique which can determine the following parameters: the source location, the angular width and the radial velocity of a given HCME. This method was applied to determine these parameters of HCMEs recorded by SOHO/LASCO coronagraph in the period of time 2001 – 2002 (Michalek, Gopalswamy, and Yashiro, 2007). Generally, HCMEs are wider and faster than the whole population of CMEs (Michalek *et al.*, 2004). This difference is not due to special properties of HCMEs but to selection effects. Halo CMEs originating close to the disk center must be fast and wide to appear above the entire occulting disk. In the present paper we test the cone model accuracy. For this purpose we compare properties of HCMEs considered by Michalek, Gopalswamy, and Yashiro (2007) with limb CMEs which are wide and potentially could be halo events when directed toward Earth. In other words, some part of the main body of these limb CMEs appears above the opposite edges of occulting disk in sky – plane projection.

This paper 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

In this paper we consider similarities between two samples of CMEs. The HCMEs considered by Michalek, Gopalswamy, and Yashiro (2007) and the halo-type events originating from the solar limb. In the present section, we describe a procedure to compile lists of events used for this study.

2.1. Limb CMEs

In the present study we use limb CMEs because they are nearly free from projection effects. For these events we can measure, from LASCO images, the true angular width, radial and expansion speeds. A set of 379 CMEs originating within 30° from the solar limb (the same set of events as in paper of Gopalswamy *et al.*, 2009a, Figure 1) was selected for our considerations. Fast CMEs compress surrounding coronal plasma which appears as bright structures in LASCO observations. These disturbances influence the width determination. This effect is responsible for the observation of halo CMEs but originating from the solar limb. For the SOHO/LASCO catalog measurements compressed material is also included (Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2009b). In order to get more accurate linear and angular dimensions of the limb CMEs, we determined the angular and lateral widths only from the main body (the flux rope portion of the CMEs) of CMEs and only from images recorded in LASCO C3 field of view. It is important because real HCMEs are mostly observed in C3 images. We consider only CMEs for which at least two successive angular and lateral widths measurements were possible. This allows us to determine the average angular widths and expansion speeds for 256 CMEs from our sample. Details of these measurements are described in the paper of Michalek, Gopalswamy, and Yashiro (2009).

In the present study we are mainly interested in a subsample of limb CMEs which are wide and could appear as halo events when directed toward Earth. We selected, using a dimensional criterion, a new sample of events which are halo-type CMEs. The limb events which have lateral width, in any LASCO C3 image, larger than occulting disk are assumed to be halo-type events. In other words, the main body of these limb CMEs appear above the opposite edges of occulting disk in sky – plane projection. Using such a criterion we obtained the sample of 106 halo-type limb CMEs. For these events we determined the average angular widths and expansion speeds which were used for further considerations.

The radial speeds (V_{rad}) of the limb halo CMEs were taken from the SOHO/LASCO CMEs catalog (http://cdaw.gsfc.nasa.gov, Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2009b).

2.2. Halo CMEs

Michalek (2006) developed the asymmetric cone model to obtain the radial speed, width and source location of HCMEs. This method was applied to determine the parameters of all front-sided HCMEs observed by SOHO/LASCO experiment during the period of time 2001 – 2002. 69 HCMEs were studied and their cone parameters were determined (Michalek, Gopalswamy, and Yashiro, 2007, Table 1). Theses events are used in the present considerations.

3. Analysis and Results

Having the parameters for the two samples of CMEs (halo and halo-type limb events) it is useful to consider their similarities. The limb events which are free from projection effects are great candidates to examine the cone model accuracy.

3.1. Width Distributions

In Figure 1, the angular width distributions for both samples of CMEs are presented. In the successive panels (a) the catalog width distribution for 256 limb CMEs, (b) the main body width distribution for 256 limb CMEs, (c) the main body width distribution for 106 halo-type limb CMEs and finally (d) the cone model width distribution for 69 CMEs are shown. The width distribution for catalog measurements covers the widest range of angles (0 – 360 degrees). Note that the catalog width measurements correspond to the outermost part of the CME, which might include compressed material around CMEs. It is why we observe a significant difference between the width distributions for the catalog and the main body measurements. The main body widths are distributed in smaller range of angles (0 – 150 degrees for the all 256 CMEs and 40 – 150 degrees for the 106 halo-type limb CMEs). The most interesting for us is comparison of the width distributions obtained for the halo-type limb CMEs (c) and for HCMEs using the cone model (d). There are no significant differences between these width distributions. They have almost the same average widths (83° and 85°, respectively) and ranges of distributions (40 – 160 degrees). To validate these similarities we performed the Kolmogorov – Smirnov test which determine if two datasets differ significantly. We use it to check if two datasets collected in different ways are drawn from the same distribution. In our considerations we used the KSTWO procedure written in IDL software. The result of the Kolmogorov – Smirnov test demonstrated that with probability equal to 0.999 we can say that the widths measured for halo-type limb events (c) and determined from the cone model (d) are drawn from the same distributions.

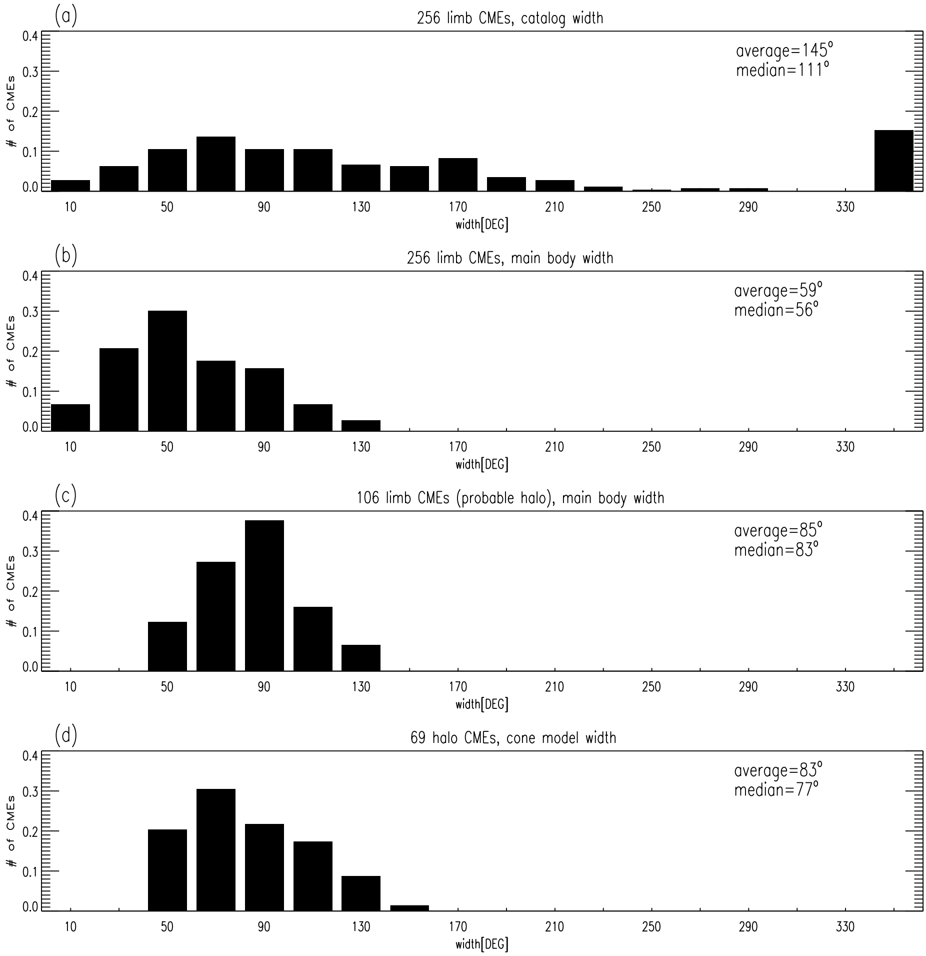

Figure 1 The width distribution for different samples of CMEs. In the successive panels (a) the catalog width distribution for 256 limb CMEs, (b) the main body width distribution for 256 limb CMEs, (c) the main body width distribution for 106 halo-type limb CMEs and finally (d) the cone model width distribution for 69 CMEs are shown.

3.2. Speed distributions

The second important parameter describing CMEs which we can compare is the radial speed. Figure 2 demonstrates the radial speed distributions for the samples of events. In the successive panels (a) the catalog radial speed distribution for 256 limb CMEs, (b) the catalog radial speed distribution for 106 halo-type limb CMEs, (c) the catalog projected speed distribution for 69 halo CMEs and (d) the cone model radial speed distribution for 69 halo CMEs are displayed. As it could be expected, the limb CMEs (panel (a)) which are free from projection effects have almost two times larger catalog speeds (average radial speed = 945 $\mathrm{km\,s^{-1}}$) than the whole population of CMEs from the SOHO/LASCO catalog (average speed is equal 485 $\mathrm{km\,s^{-1}}$, Yashiro *et al.*, 2004). For these CMEs we observe a clear peak in the speed distribution at about 700 $\mathrm{km\,s^{-1}}$. The halo-type limb CMEs (b) are on

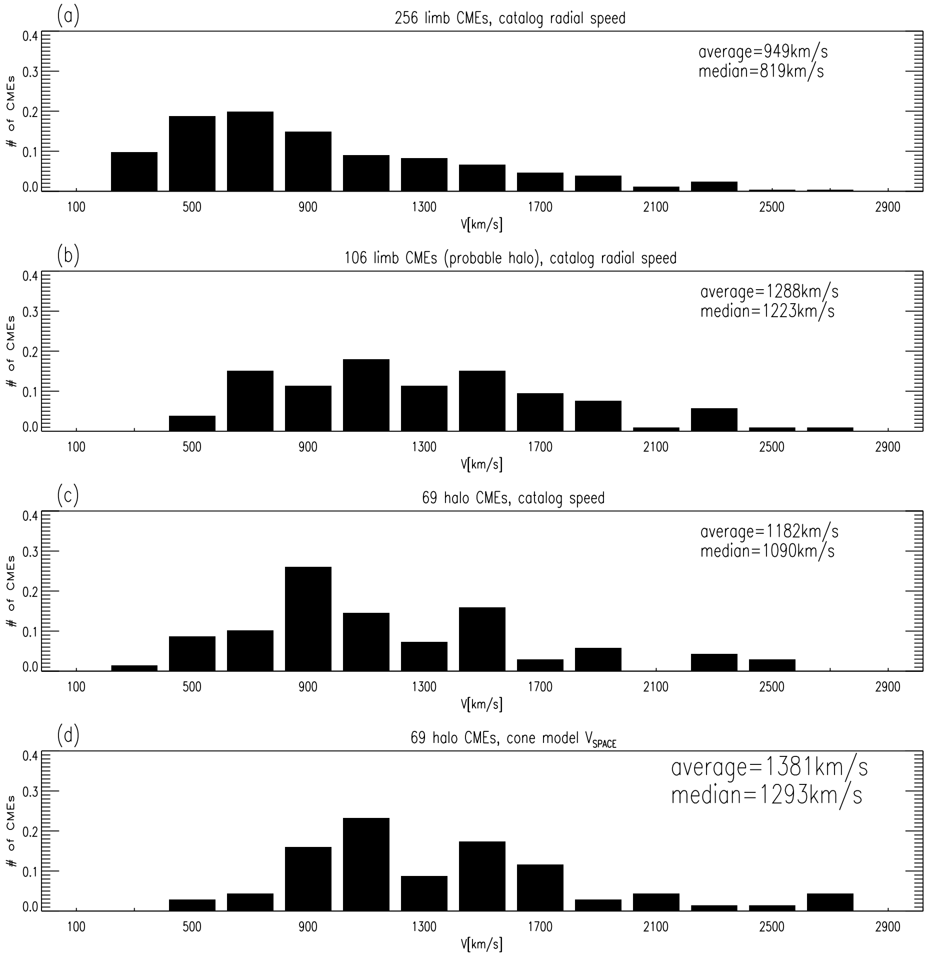

Figure 2 The radial speed distribution for different samples of CMEs. In the successive panels (a) the catalog radial speed distribution for 256 limb CMEs, (b) the catalog radial speed distribution for 106 halo-type limb CMEs, (c) the catalog projected speed distribution for 69 halo CMEs, (d) the cone model radial speed distribution for 69 halo CMEs.

average much faster (average speed = 1288 $\mathrm{km\,s^{-1}}$) and their width distribution is rather flat without any clear peak. The last two panels ((c) and (d)) displayed the sky – plane and space speed (obtained using the cone model) distributions for HCMEs. The distributions are similar but the cone model radial speeds are on average larger than the sky – plane speeds (the average radial speeds = 1381 $\mathrm{km\,s^{-1}}$ and the average sky – plane speeds = 1182 $\mathrm{km\,s^{-1}}$). The distributions are generally irregular. In the case of the sky – plane speeds there is a clear peak in the distribution at around 900 $\mathrm{km\,s^{-1}}$. For the cone model speeds we recognize rather two peaks around 1100 $\mathrm{km\,s^{-1}}$ and 1500 $\mathrm{km\,s^{-1}}$. Again, the most interesting is the comparison of the cone model velocity distribution (d) and the halo-type speed distribution (b). The distributions seem to be similar (similar ranges of velocity distributions and average values). To validate these similarities we performed also the Kolmogorov – Smirnov

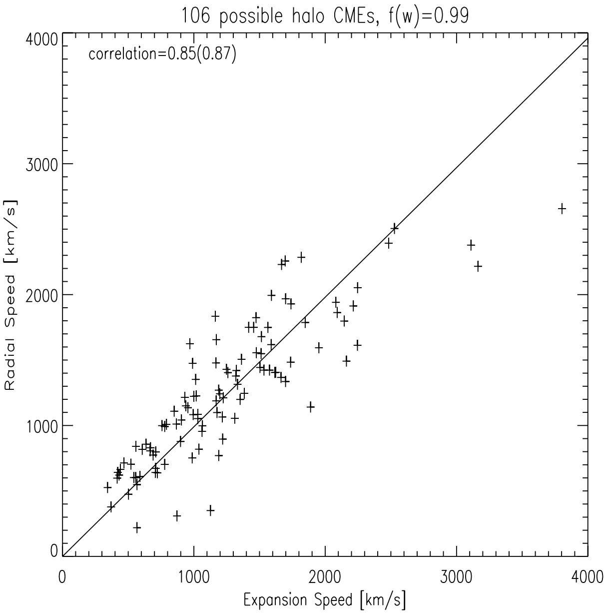

Figure 3 Scatter plot of the expansion speed versus the radial speed for halo-type limb CMEs. Continuous line represent linear fit to the data points.

statistical test. The results show that with a probability equal to 0.93 we can say that both sample of events were drawn from the same distribution.

3.3. Expansion speed

It is also possible to obtain the radial speeds of HCMEs by using expansion speeds. The expansion speed 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_{exp} using an empirical relationship between V_{exp} and V_{rad} (Dal Lago, Schwenn, and Gonzales, 2003; Schwenn *et al.*, 2005). Recently, Gopalswamy *et al.* (2009a) and Michalek, Gopalswamy, and Yashiro (2009) have demonstrated that this relation is exceptionally well described by the function representing a full cone model for the CME. It could be very useful to obtain this relation for halo events. Symmetric halo CMEs originating close to the solar center have expansion speed approximately two times larger than the sky – plane speed (V_{LE}-catalog speed). Having relation between expansion and radial speed for these events we are able to obtain the radial speed from measurements of sky – plane speed. It is very useful because the cone models are the least accurate for symmetric events. In Figure 3, the scatter plot of the V_{exp} versus the V_{rad} of possible halo CMEs is presented. Correlation coefficient between the velocities is significant, almost 0.9. When we excluded the outliers, the correlation coefficient slightly increased (see Figure 3). As we can see, the relation between these velocities for halo events is very simple, $V_{\mathrm{rad}} = 0.99V_{\mathrm{exp}}$ and it can be used for correction of projection effects in HCMEs.

4. Summary and Discussion

CMEs erupting close to the disk center are observed as symmetric full halo CMEs. They could be very geo-effective and cause our special concern. Unfortunately, such events in coronagraphic observations are subject to the largest projection effects. Parameters of CMEs measured in the sky – plane are not very useful for space weather predictions. There are a few cone models used to obtain the true widths and speeds of HCMEs. The observations from the STEREO twin spacecraft could be very useful for testing the cone models. Unfortunately, the STEREO coronagraphs have not recorded a large sample of clear and large events. In the present paper an alternative testing method is presented. For this task a set of 106 possible halo CMEs originating from the solar limb were selected. For these events it is required that the lateral dimension body, in projection on the sky, is larger than the dimension of the occulting disk. To test the cone model, we compare the width and radial speed distributions measured for the 106 halo-type limb CMEs (free from projection effects) with those obtained for HCMEs by using the cone model (Michalek, 2006; Michalek, Gopalswamy, and Yashiro, 2007). The Kolmogorov – Smirnov test demonstrated that with a probability of $p > 0.93$ we can say that both samples of CME were drawn from the same distributions of events.

For the width distributions, which are very similar to each other (Figure 1, panels (c) and (d)) the probability was extremely high ($p = 0.999$). The only difference between these samples of events appears when we compare the peaks of the width distributions.

For the radial speed distributions (Figure 2, panels (b) and (d)), the Kolmogorov – Smirnov test gave a slightly lower probability ($p = 0.93$) that both samples were drawn from the same distributions. The radial speeds for all considered samples of CME are similar and are distributed over wide velocity ranges. Differences appear when we compare the average velocities. The largest average velocity (1381 $\mathrm{km\,s^{-1}}$) was obtained for speeds determined using the cone model. The halo-type limb CMEs are slightly slower (the average speed is 1288 $\mathrm{km\,s^{-1}}$). The smallest average velocities (949 $\mathrm{km\,s^{-1}}$) are for the 256 limb events. Note that these events are free from projection effects and are on average almost two times faster than the whole sample of SOHO/LASCO events (Yashiro *et al.*, 2004). As we mentioned earlier, the differences between speed distributions for CMEs shown in Figure 2 are not significant. HCMEs are wide and the speed correction for projection effects is not very significant. Michalek, Gopalswamy, and Yashiro (2003) demonstrated that on average the space speeds are about 10% larger in comparison with the sky – plane speeds.

Summarizing, we can say that statistically the asymmetric cone model works very well and provides reasonable parameters of HCMEs. We performed an analysis for a sample of events without consideration of any particular CME. So, it could be possible that for a given HCME the cone model correction could provide the space parameter with larger inaccuracy. The accuracy of the cone model strongly depends on sky – plane measurements and on the quality of a given event.

The differences between properties of both samples of CME could be caused by selection methods. Yashiro *et al.* (2004) demonstrated that the properties of CMEs change with solar cycle; for example, the speeds of CMEs increase with solar activity. Although the limb events selected covered the whole Solar Cycle 23, HCMEs were considered only during the solar maximum activity (2001 – 2002). This could explain why the average cone corrected speed for these events is the highest.

Using the new method, we demonstrated that HCMEs are on average very wide and fast. The average width (∼85 degrees) and radial speed (∼1288 $\mathrm{km\,s^{-1}}$) are about two times larger than for the all CMEs recorded by the SOHO/LASCO coronagraphs (Yashiro *et al.*, 2004).

We also determined a simple relation between V_{rad} and V_{exp} for halo CMEs. Figure 3 demonstrates that $V_{\mathrm{rad}} = V_{\mathrm{exp}} \approx 2V_{\mathrm{LE}}$. This simple relation could be very useful for the determination of the radial speed of symmetric halo events which are potentially the most geo-effective (Michalek, Gopalswamy, and Yashiro, 2007).

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References

Dal Lago, A., Schwenn, R., Gonzales, W.D.: 2003, *Adv. Space Res.* **32**, 2637.
Gopalswamy, N., Dal Lago, A., Yashiro, S., Akiyama, S.: 2009a, *Cent. Eur. Astrophys. Bull.* **248**, 113.
Gopalswamy, N., Yashiro, S., Michalek, G., Stenborg, G., Vourlidas, A., *et al.*: 2009b, *Earth Moon Planets*. doi:10.1007/s11038-008-9282-7.
Howard, R.A., Michels, D.J., Sheeley, N.R., Koomen, M.J.: 1982, *Astrophys. J.* **263**, L101.
Michalek, G.: 2006, *Solar Phys.* **237**, 101.
Michalek, G., Gopalswamy, N., Yashiro, S.: 2003, *Astrophys. J.* **584**, 472.
Michalek, G., Gopalswamy, N., Yashiro, S.: 2007, *Solar Phys.* **246**, 399.
Michalek, G., Gopalswamy, N., Yashiro, S.: 2009, *Solar Phys.* doi:10.1007/s11207-009-9464-0.
Michalek, G., Gopalswamy, N., Lara, G., Manoharan, P.K.: 2004, *Astron. Astrophys.* **423**, 729.
Schwenn, R., Dal Lago, A., Huttunen, E., Gonzalez, W.D.: 2005, *Annal. Geophys.* **23**, 1033.
Xie, H., Ofman, L., Lawrence, G.: 2004, *J. Geophys. Res.* **105**, 5081.
Yashiro, S., Gopalswamy, N., Michalek, G., St. Cyr, O.C., Plunkett, S.P., Rich, N.B., Howard, R.A.: 2004, *J. Geophys. Res.* **109**, A07105.