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KINETIC PROPERTIES OF CMEs CORRECTED FOR THE PROJECTION EFFECT

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Abstract. Observations of coronal mass ejections (CMEs) with coronagraphs are subject to a projection effect, which results in statistical errors in many properties of CMEs, such as the eruption speed and the angular width. In this paper, we develop a method to obtain the velocity and angular width distributions of CMEs corrected for the projection effect, and then re-examine the relationship between CMEs and the associated flares. We find that (1) the mean eruption speed is 792 km s^{-1} and the mean angular width is 59°, compared to the values of 549 km s^{-1} and 77°, respectively before the correction; (2) after the correction, the weak correlation between CME speeds and the GOES X-ray peak flux of the flares gets unexpectedly poorer; and (3) before correction, there is a weak correlation between the angular width and the speed of CMEs, whereas the correlation is absent after the correction.

1. Introduction

Coronal mass ejections (CMEs) are large-scale solar eruptions that are observed carrying billions of tons of plasma out of the Sun. This plasma and the frozen-in magnetic field can severely disturb the magnetosphere and trigger geomagnetic storms or substorms. After the launch of the SOHO spacecraft in December 1995, CMEs have been continually observed. Their apparent properties are measured and recorded in the CME catalog maintained by the Center for Solar Physics and Space Weather (CSPSW).[1] The catalog contains a list of all identified CMEs with the following information for each event: the date and time of the first appearance in the field of view of the C2 coronagraph, central position angle, angular width, speed, acceleration obtained from the quadratic fitting, etc. These parameters are very important for the understanding of the CMEs as well as for space weather forecasts, and therefore have been widely used. For example, St. Cyr *et al.* (2000) investigated the angular width distribution of the CMEs observed from 1996 to 1998, and found that the average angular width is 72°; Moon *et al.* (2002) studied the relationship between the X-ray fluxes of limb flares and the projected speeds of the associated CMEs observed from 1996 to 2000, and found a correlation coefficient of 0.47 between them. However, those parameters are subject to the projection effect, especially for the events propagating far from the plane of sky. Therefore, attempts have been made to correct the projection effect.

[1] *http://cdaw.gsfc.nasa.gov/*

Based on the fact that many CMEs propagate with a constant angular width (Webb *et al.*, 1997), Zhao, Plunkett, and Liu (2002) proposed an empirical model for halo CMEs, in which a CME is assumed to be a cone with its geometrical and kinematic parameters derived from the observations. The model was later developed by Xie, Ofman, and Lawrence (2004) in order to quantitatively and consistently determine the actual CME speed, width, and source location by using coronagraph data, hence to optimize space weather forecasts. Michalek, Gopalswamy, and Yashiro (2003) presented another technique to derive the corrected parameters of halo CMEs, and statistically study the characteristics of a sample of halo CMEs. It was found that after correction these halo CMEs have an average speed of 1080 km s^{-1}, 20% larger than the velocities measured in the plane of the sky, and their corrected average width is approximately equal to 120°, which is also significantly larger than the value before the correction. For non-halo CMEs, Hundhausen, Burlepile, and St. Cyr (1994) and Leblanc *et al.* (2001) developed a method to correct the projection effect, and obtained the real CME speeds with a formula in which the angular width is an unknown parameter. For simplicity, they adopted the average value of the angular width of CMEs, i.e., 72°, in the formula. This may result in extra errors since the angular widths of CMEs vary over a large range as revealed by St. Cyr *et al.* (2000). In this paper, we improve the method of Leblanc *et al.* (2001) with the consideration of real angular width for each CME. As applications, we re-examine the correlation between the CME speeds and the peak flux of the associated GOES soft X-ray flares, and that between the CME angular widths and the speeds.

2. The Method

With the assumption that each CME is like a cone with the front described by an arc of a circle, Hundhausen *et al.* (1994, see also Leblanc *et al.* (2001)) derived a formula to relate the real radial speed of the CME, $V_{\rm rad}$, to its apparent velocity measured on the plane of the sky, $V_{\rm sky}$, which reads as

$$V_{\rm rad} = V_{\rm sky}\frac{1+\sin\alpha}{\sin\phi+\sin\alpha}. \tag{1}$$

In the equation, α is the actual half angular width of the CME, and ϕ is the heliocentric angle of the central axis of the CME, which is given by $\cos\phi = \cos\lambda\,\cos\psi$, where λ and ψ are the corresponding latitude and longitude of the source region center, respectively. Figure 1 shows an example of the speed correction using the above formula. It is clear that the formula has a singular point at $\alpha = \phi = 0$, near which the resulting $V_{\rm rad}$ is extremely large. Therefore, those events with small α and ϕ that result in $V_{\rm rad}$ larger than 3000 km s^{-1} are excluded in our sample. It is noted that in the above formula only $V_{\rm sky}$ is a quantity which can be measured directly, while both ϕ and α should be deduced from certain procedures.

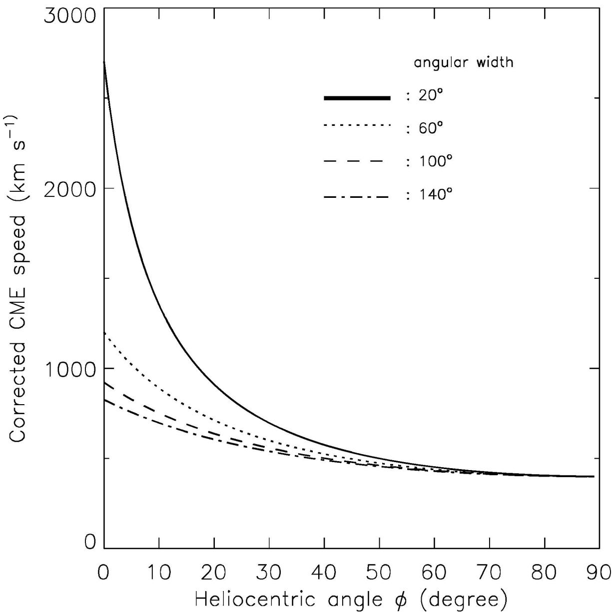

Figure 1. The radial velocity V_{rad} corrected for the projection effect using Leblanc's formula. The value of V_{rad} becomes unrealistically large when ϕ and α are both small.

2.1. Determination of ϕ

Since solar flares are often offset from the central axes of the associated CMEs, their sites are not suitable to be considered as the source region centers of the CMEs. For case studies, it is better to analyze the running difference images of the EIT data to determine the source region centers of the CMEs. However, it is not appropriate to do so for statistical researches, which require a simple procedure to roughly determine the center of the CME source region. Therefore, Leblanc *et al.* (2001) proposed a practical method, which assumes that (1) the origin of a CME is near an active region from which the CME propagates radially outward at a certain position angle (PA); (2) the CME originates in conjunction with a flare in the active region; (3) the best estimation of the location of the origin of the CME is taken to be the point in the PA line that is the shortest to the flare site in the projected plane, i.e., the projection of the flare site on its PA line.

In this study, we modify the third assumption with the following consideration. The radial directions of all points in a quarter of a large circle, i.e., curve L in Figure 2, have the same projected position angle (PA) as the CME. The center of the CME source region is determined to be the point that has the shortest spherical distance to the flare site. Note that the flare site is determined with the following steps: (1) the trajectory of each CME is backward extrapolated to the half solar radius measured from the solar disk center with a uniform acceleration assumption

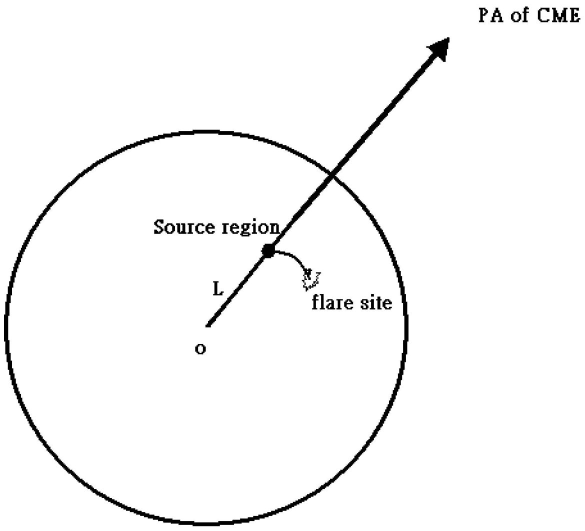

Figure 2. Determination of the CME source region, which should satisfy: (1) its projection site in the PA line (the projected position angle) and (2) the shortest distance to the flare site.

to obtain the onset time of each CME; (2) all solar flares within ±1 h time window are selected from the SGD database, while only those flares that are located within the angular span of the CMEs are chosen for the candidate flares associated with the CMEs; (3) if more than one candidate flare exists after the above steps, the one with the peak time closest to the CME onset time is uniquely determined as the flare associated with this CME.

2.2. Determination of the actual angular width α

The actual half angular width α is another key parameter which is strongly subject to the projection effect. As indicated by limb events, α varies from case to case. In the research of Leblanc *et al.* (2001), α is taken to be half the averaged apparent angular width, i.e., $\alpha = 36^\circ$, in Equation (1) for simplicity. This approximation may result in an extra error in the correction of the CME speeds. To get more accurate results, we derive a formula to relate the apparent angular width to the actual angular width on the basis of the cone model, which reads as

$$\alpha = \arctan(\tan\alpha_0 \, \sin\phi), \tag{2}$$

where α_0 is the apparent half angular width, and ϕ is the heliocentric angle of the CME source region center determined in Section 2.1. Note that the above equality requires that α_0 should be smaller than 90°, i.e., the apparent angular width should be smaller than 180°.

2.3. Selection of the Sample

There are in total about 7880 CMEs from 1996 through 2003 as listed in the aforementioned CME catalog. The sample for our statistical study are chosen from these CMEs with the following steps. First, we select the CMEs that are associated with flares in both timing and spatiality, as described in detail in Section 2.1. Although a significant percentage of CMEs are associated with X-ray flares (e.g., Zhang *et al.*, 2001; Zhou, Wang, and Cao, 2003), only 619 CME-flare events are selected after this step since our selection procedure requires the location records of the optical counterparts of the X-ray flares in the SGD database, which are often not available. Second, we exclude all the halo CMEs since our correction method cannot apply to them. This step reduces the sample to 569 CMEs. Finally, we exclude the events with corrected velocities larger than 3000 km s^{-1}, which are mostly located near the disk center. Therefore, the final sample consists of 557 CMEs.

3. Results

Since the apparent angular width of a cone in the projected plane tends to be larger than the actual one as indicated by Equation (2), it is expected that after the correction, the CME angular width would get smaller. Figure 3 shows the distribution of the CME angular width before the correction (left panel) and after the correction (right panel). It is seen that after the correction the number of the CME events with wide angular spans decreases, whereas the number of those with narrow angular spans increases significantly. The average angular width of the CME

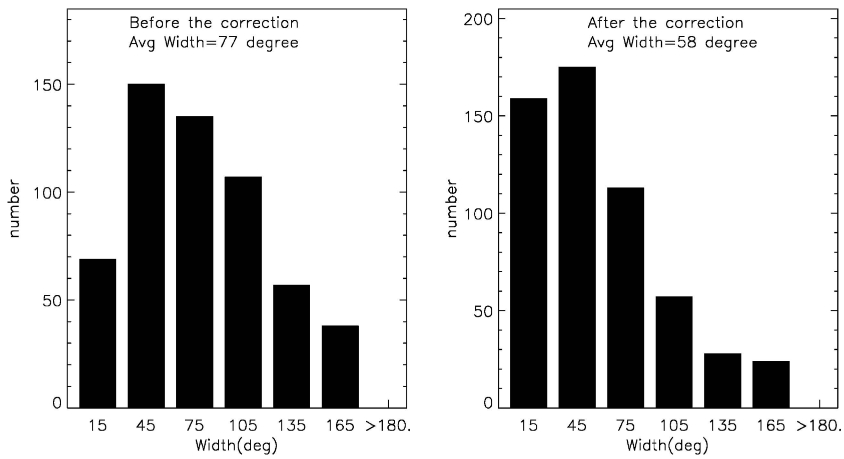

Figure 3. The width distribution of CMEs before the correction (*left panel*) and after the correction (*right panel*).

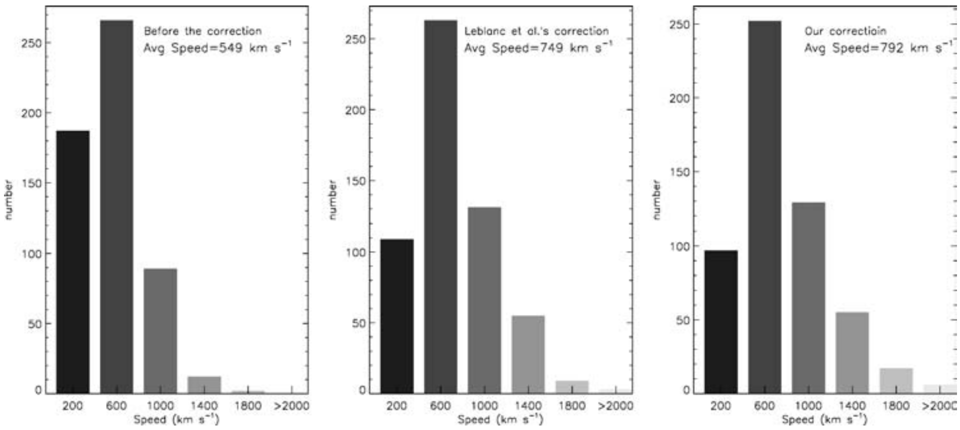

Figure 4. The velocity distribution before correction (*left panel*) and after correction using Leblanc *et al.*'s (2001) method (*middle panel*) and using our method (*right panel*).

in the sample is $\sim 59°$ after the correction, substantially smaller than the uncorrected one, $\sim 77°$.

Figure 4 displays the distribution of CME velocity before the correction (left panel), after the correction with Leblanc's method (2001; middle panel), and with the correction method proposed in this paper (right panel). As expected from Equation (1), the real radial speeds are obviously larger than the projected speeds. It is seen from the figure that after the correction, the high-speed tail of the distribution is significantly enhanced, whereas the low-speed tail is weakened. Note that the average CME speed is 549 km s^{-1} before the correction; however, Leblanc's method gives an average speed of 749 km s^{-1}, and our method presents an average speed of 792 km s^{-1}.

4. Re-examination of Correlation Investigations

4.1. CME SPEEDS VERSUS FLARE FLUX

The relation between CMEs and solar flares is a topic of long controversy (e.g., Andrews, 2003). Hundhausen (1997) studied the relationship between the peak fluxes of flares and the kinetic energies of related CMEs using SMM data and obtained a weak correlation between the two quantities, with the correlation coefficient being 0.53. Yashiro *et al.* (2002) got a similar result with the SOHO/LASCO observations from 1996 through 2001. However, the CME speeds used in these studies are only the apparent speeds projected on the plane of sky. After the correction of the projection effect in this paper, it is worthwhile to re-check their relation. On the basis of the projection correction presented in this paper, we re-examine

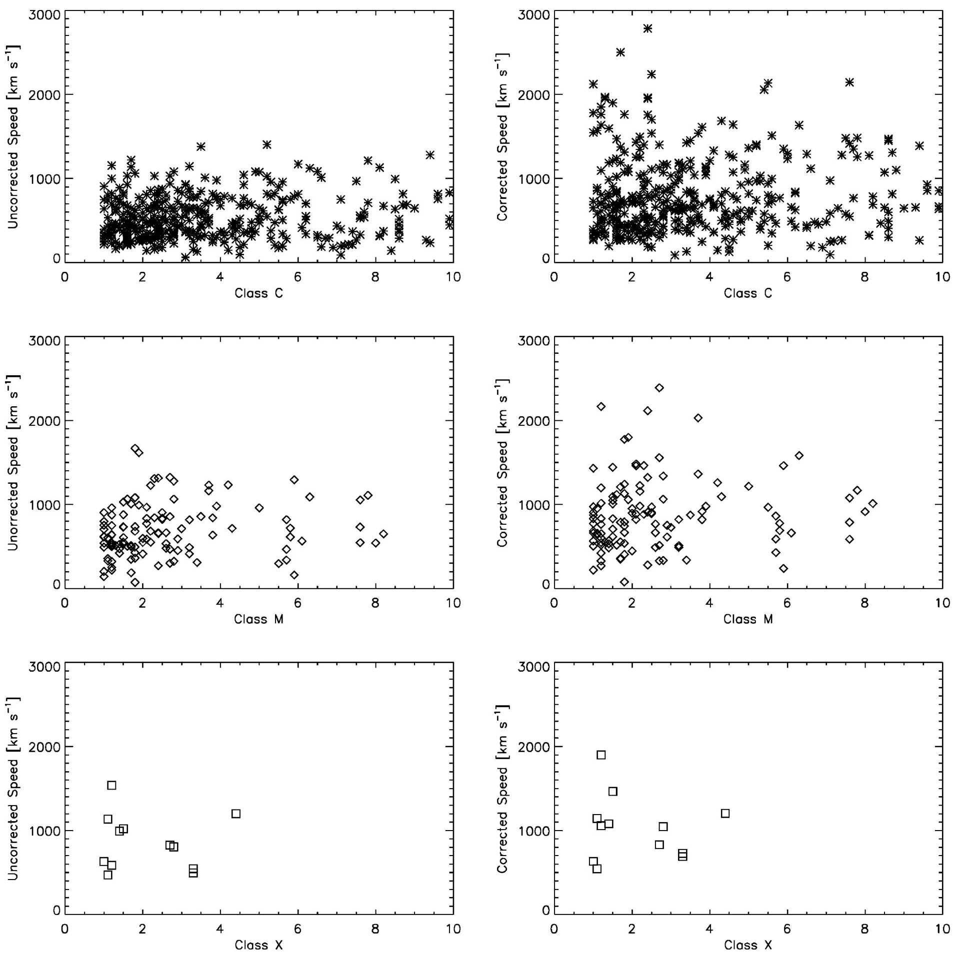

Figure 5. CME speed vs. log X-ray flux of the associated flares. The horizontal axis represents the class of the CME-associated flare. The vertical axis is the speed of CMEs, either uncorrected (*left panels*) or corrected (*right panels*) using our method.

such a relation, and the results are plotted in Figure 5, which compares the relationship between the flare peak flux and the CME speed before and after the projection correction. As expected, before the correction of the projection effect, there exists a weak correlation between the X-ray flux and the projected speed of the associated CME, The correlation coefficients are 0.09, 0.16, and 0.44 for C, M, and X class flares, respectively. After the correction of the projection effect, we find that the correlation between the X-ray flux and the projected speed of associated CME still remains but becomes even weaker; the correlation coefficients are 0.03, 0.11, and 0.32 for C, M, and X class flares, respectively.

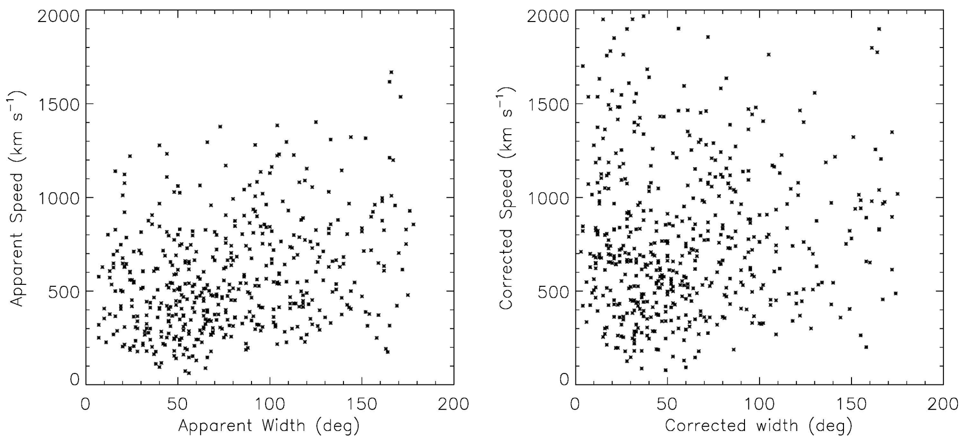

Figure 6. CME speed versus angular width before correction (*left panel*) and after correction using our method (*right panel*).

4.2. CME SPEEDS VERSUS CME ANGULAR WIDTH

The relation between CME speeds and the angular widths was studied recently by Yashiro *et al.* (2004), who revealed that there is a weak correlation between CME speed and width. It is noted here that in this study both of the parameters suffer from the projection effect. With the data sample collected in this paper, the correlation is re-examined after the correction of the projection effect, which is shown in the right panel of Figure 6. For comparison, their correlation before the correction is presented in the left panel. It is seen that a weak correlation exists before correction, with the correlation coefficient being 0.28. However, the correlation completely disappears after the correction for the projection effect.

4.3. DISCUSSIONS

It seems that we obtain an unexpected result, e.g., a poor correlation between the CME speed and the soft X-ray peak intensity after the correction of the projection effects. To confirm the result, we make the following tests. We first split the sample into two subsets randomly. It is found that these two subsets result in the same conclusion. Then, we relax our sampling procedure described in Section 2.1 by extending the time window to be ± 1.5 and ± 2 h and enlarging the angular span by 1.5 and 2 times. Again, the new samples give the same conclusion. However, recently, in order to avoid the projection effect on CME parameters, Burkepile, Hundhausen, and Stanger (2004) investigated the correlation between the CME kinetic energy and the X-ray flare peak intensity for limb events, which were observed by the Solar Maximum Mission (SMM). It is found that the correlation is stronger than previously reported, which is contrary to our results. The discrepancy between their result and ours may be solved by statistically investigating the limb events observed by SOHO/LASCO. Besides, the forthcoming satellite, STEREO, may clarify the problem without ambiguity.

5. Summary

In this paper, we present a method on the basis of the cone model to correct the projection effect for two parameters of CMEs, i.e., the velocity and angular width. A total of 557 CMEs from 1996 to 2003 are selected for this statistical study, which requires that (1) the CME apparent angular width should be less than 180°; (2) there is a flare-association. It is found that both the velocity and the angular width are strongly affected by the projection effect. After the correction, the average angular width of these flare-associated CMEs decreases from 72° to 59°; while the average speed of these CMEs increases from 549 to 749 $\mathrm{km\,s^{-1}}$ for Leblanc's method and 792 $\mathrm{km\,s^{-1}}$ for our method. Though the CME angular width has a rather broad distribution, our result indicates that replacing the angular widths of CMEs by the average value in the correction formula for the real velocity, as done by Leblanc *et al.* (2001), is still a fairly good approximation. As applications of our results, we re-examine some statistical researches on CMEs. It is suggested that the projection effects degrade the correlation between CME speeds and GOES X-ray peak fluxes, and there may be no correlation at all between the speed and width of CMEs in reality.

Acknowledgements

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