Identification of Earth-Directed Partial Halo Coronal Mass Ejections

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Abstract

In searching for solar sources of interplanetary disturbances or geomagnetic storms and in investigating of the storm effectiveness of coronal mass ejections (CMEs), frontside partial halo CMEs are often implicitly assumed to be Earth-directed, i.e., the interplanetary counterpart of the CMEs will hit the Earth tens of hours after the onset of the CMEs. We show the observational evidence showing that this assumption is not acceptable for most of frontside partial halo CMEs. By using the observation-based cone model [Zhao et al., 2002; Xie et al., 2004] we put forward a method to distingush the frontside partial halo CMEs with constant angular width from that with varying angular width. This method along with the observed CME span may be used to determine whether or not a frontside partial halo CME is Earth-directed. The results may be used to improve the space weather forecasting.

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1. Introduction

The Earthward direction of a CME is a necessary condition for the CME to be storm-effective, though it is not a sufficient condition. Identification of Earth-directed CMEs is an important task in space weather forecasting. By "Earth-directed" here we mean that there is a component of the CME that is able to hit the Earth, though the central axis of the CME may not be aligned with the line-of-sight.

The Full halo CME has a span of 360° and is described as "... a halo of excess brightness completely surrounding the occulting disk and propagating radially outward in all directions from the Sun". Since full halo CMEs are interpreted as a broad shell or bubble of dense plasma ejected toward or away from the Earth [Howard et al., 1982], frontside full halo (FFH) CMEs, i.e. halo CMEs having associated near surface activities located near the Sun's disk center, are thus believed to be Earth-directed [Zhao and Webb, 2003].

The span of partial halo CMEs ranges from a lower limit to 359 degrees. The lower limit is defined somewhat arbitrary from 100° [Lyons et al., 1998] to 140° [Webb et al., 2000]. Partial halo CMEs may be interpreted as a broad shell or bubble of dense plasma ejected radially away from the Sun and originated in sources located somewhat far away from Sun's disk center. Thus how to identify Earth-directed partial halo CMEs from frontside partial halo (FPH) CMEs is a question to be answered.

2. Are all frontside partial halo (FPH) CMEs Earth-directed?

In studying of the storm-effectiveness of halo-type CMEs [Wang et al., 2002; Yermolaev and Yermolaev, 2003], and in searching for the solar source of interplanetary disturbances [Cane et al., 2000] and geomagnetic storms [Zhang et al., 2003] it is often implicitly assumed that all FPH CMEs are Earth-directed. Based on this assumption the obtained storm-effectiveness of frontside halo-type CMEs, both FFH and FPH (i.e., the ratio of the number of frontside halo-type CMEs that are associated with geomagnetic storms to the total number of frontside halo-type CMEs between 1996 and 2000), is less generally than 0.5 (See Table 1).

We have examined the storm-effectiveness of FFH CMEs alone between 1996 and 2000, especially those full halo CMEs with their associated surface activities located within 45 degrees of the disk center, the "centered FFH" CMEs. FFH CMEs are rather certain to be Earth-directed, their storm-effectiveness depends mainly on whether or not the component of the CMEs that hit the Earth contains and/or generates storm-effective solar wind

Table 1: Storm-effectiveness of frontside halo-type CMEs

Number of CMEs	Number of Storms	Storm-effectiveness	Reference	Remarks
132	59	0.45	Wang et al., 2002	FFH & FPH, Kp > 5
132	26	0.20	Wang et al., 2002	FFH & FPH, Kp > 7
125	44	0.35	Yermolaev .. 2003a	FFH & FPH, Dst < -60
125	50	0.40	Yermolaev .. 2003b	FFH & FPH, Dst < -50
70	45	0.64	Zhao & webb 2003	FFH Dst < -50
49	35	0.71	Zhao & webb 2003	Centered FFH Dst < -50

structures. Thus our result (see Table 1) may be used to understand why the storm-effectiveness of all frontside halo-type CMEs is so low. We found that for the centered FFH CMEs the storm-effectiveness is about 1 near solar minimum and about 0.5 near solar maximum [Zhao and Webb, 2003], suggesting that the capability of the FFH CMEs in producing storm-effective solar wind structure decreases as solar activity increases, and that all FFH CMEs are indeed able to hit the Earth. The average storm-effectiveness of centered FFH CMEs is significantly greater than 0.5. The difference in storm-effectiveness between centered and all FFH CMEs suggests that the capability in producing storm-effective solar wind structure is highest in the centric component of the CMEs (magnetic ropes). Table 1 shows that only 5 of 50 moderate magnetic storms ($<$ -50 nT) during the period of time are caused by FPH CMEs and only 9% of FPH CMEs are responsible for 10% of moderate magnetic storms, suggesting that most of FPH CMEs are not Earth-directed.

In searching for the solar sources of major ($<$ -100 nT) geomagnetic storms between 1996 and 2000, Zhang et al. (2003) found 16 major geomagnetic storms associated with unique frontside halo-type CMEs, 12 with FFH CMEs and 4 with FPH CMEs. In the period of time, there were 141 full halo CMEs and 158 partial halo CMEs. It suggests that only 25% of FPH CMEs with lower limit of 140° are Earth-directed if the difference between FFH and FPH CMEs is only the source location in the solar surface.

3. Identifying Earth-directed partial halo CMEs

Is there a threshold apparent span size for halo-type CMEs above which there is a component that will hit the Earth, and below which the CME will miss the Earth?

Many limb CMEs propagate almost radially beyond the first couple of solar radii, and the angular width of the CMEs remain nearly constant while propagating through the corona. The shell of dense plasma, that scatter the white light along the line of sight and form a halo of excess brightness in the plane of the sky, may be approximately described by a conical shell [Howard et al., 1982] or an "ice cream cone" model [Fisher and Munro, 1984]. If there are no deflections of preexisting features, the halo-type CMEs may be expressed by an ellipse as follows,

$$\frac{(x - D_{dc})^2}{S_{mn}^2} + \frac{y^2}{S_{mj}^2} = 1, \tag{1}$$

where parameters s_{mn} and s_{mj} denote the semi-minor and semi-major axes of the ellipse, and D_{dc}, the distance of the ellipse center from the Sun's disk center. These parameters can be measured from the observed white light coronal images. In addition, the orientation of the ellipse, i.e., the angle between the minor axis and the east-west direction, α, can also be measured (see Figure 1). These parameters depend on the characteristics of the CME, i.e., the angular width, 2ω, the radial distance, r, and the central position of the CME as follows,

$$S_{mj} = r \sin \omega, \tag{2}$$

$$S_{mn} = r \sin \omega \sin \chi, \tag{3}$$

$$D_{dc} = r \cos\omega \cos\chi, \tag{4}$$

where symbol χ denotes the angle between the central axis and the plane of the sky (see Figure 2).

The characteristics of the CME can thus be determined uniquely on the basis of observed white-light images as follows,

$$\chi = \sin^{-1}\left(\frac{S_{mn}}{S_{mj}}\right), \tag{5}$$

$$\omega = \tan^{-1}\left(\frac{S_{mj}}{D_{dc}}\cos\chi\right). \tag{6}$$

For the conical shell model, the obtained ω from images corresponding to different time should be identical. If there is a component of the CME that is able to hit the Earth, it must be $S_{mn} \geq D_{dc}$. Thus the criterion for cone-like frontside halo-type CMEs to be Earth-directed is $\omega \geq \mu = 90 - \chi$. The middle and right columns of Figure 3 indicate that the angular span of Earth-directed partial halo CMEs must be close to or greater than 180° if the CMEs have conical shell structure. Figure 4 shows an example of FPH CMEs that is not Earth-directed.

However, there are storm-effective FPH CMEs with angular span significantly less than 180°. This fact suggests that these CMEs do not linearly expand, i.e., their angular width increases while propagating from the corona to the heliosphere. There are studies to identify such Earth-directed partial halo CMEs. Webb et al [2000] used the span of 140° as a threshold for selecting partial halo CMEs and found that the frontside partial halo CMEs between December 1996 and June 1997 are storm-effective when the source region in the low corona is within ~ 0.5 radii of the Sun's disk center. Another selection criterion for identifying such Earth-directed partial halo CMEs is selecting CMEs whose spans exceed $100°$ and encompasses one or the other of the solar poles [Lyons et al., 1998]. Thompson et al [2000] used a similar criterion but with a lower limit of $120°$. Figure 5 shows the ratio of the number of cross-pole partial halo CMEs to the total number of partial halo CMEs when the lower limit of the span is $120°$. It indicates that using the cross-pole constrain may exclude only $\sim 25\%$ of all partial halo CMEs.

If the 3-D shell of a CME may be described by a spherical shell of dense plasma, as suggested by Howard et al. [1982], Equations (1) – (6) are also valid and can be used to determine the angular width of the CME using each image at a specific time. If the angular width obtained from the last image of the FPH CME is significantly greater than the previous one, then the FPH CME may be a candidate of the Earth-directed CME, though the span of the FPH may be significant less than $180°$. This provides a new way to identify Earth-directed partial halo CMEs from FPH CMEs. Figure 6 shows an example of CMEs whose angular width increases.

In addition to this scattering mechnism/geometry, halo CMEs may also be formed by deflections of preexisting rays and streamers due to CME shocks [St. Cyr and Hundhausen, 1998; Sheeley et al., 2000]. Figure 7 displays a series of images showing the effect of CME shocks on the deflection of preexisting features. As pointed out by Sheeley et al [2000], such formed halo CMEs should have ragged spatial structure distinguishing such super-Alfvenic CMEs from other halo-type CMEs.

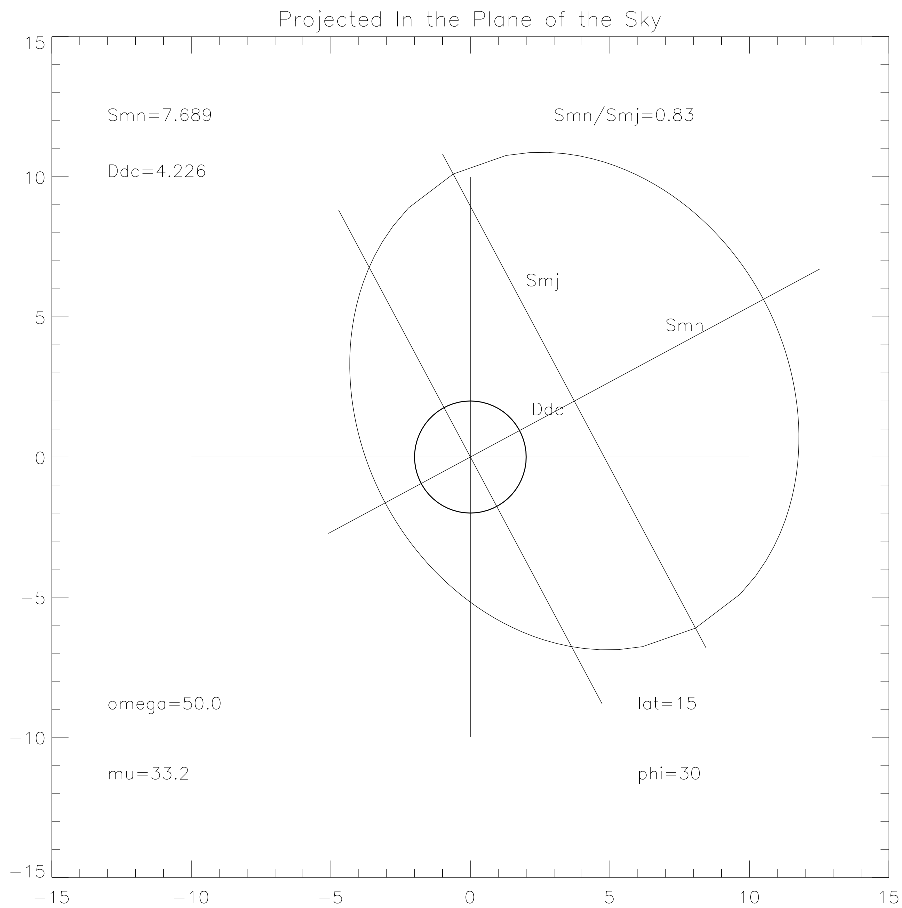

Fig. 1.— The four parameters characterizing halo-type CMEs

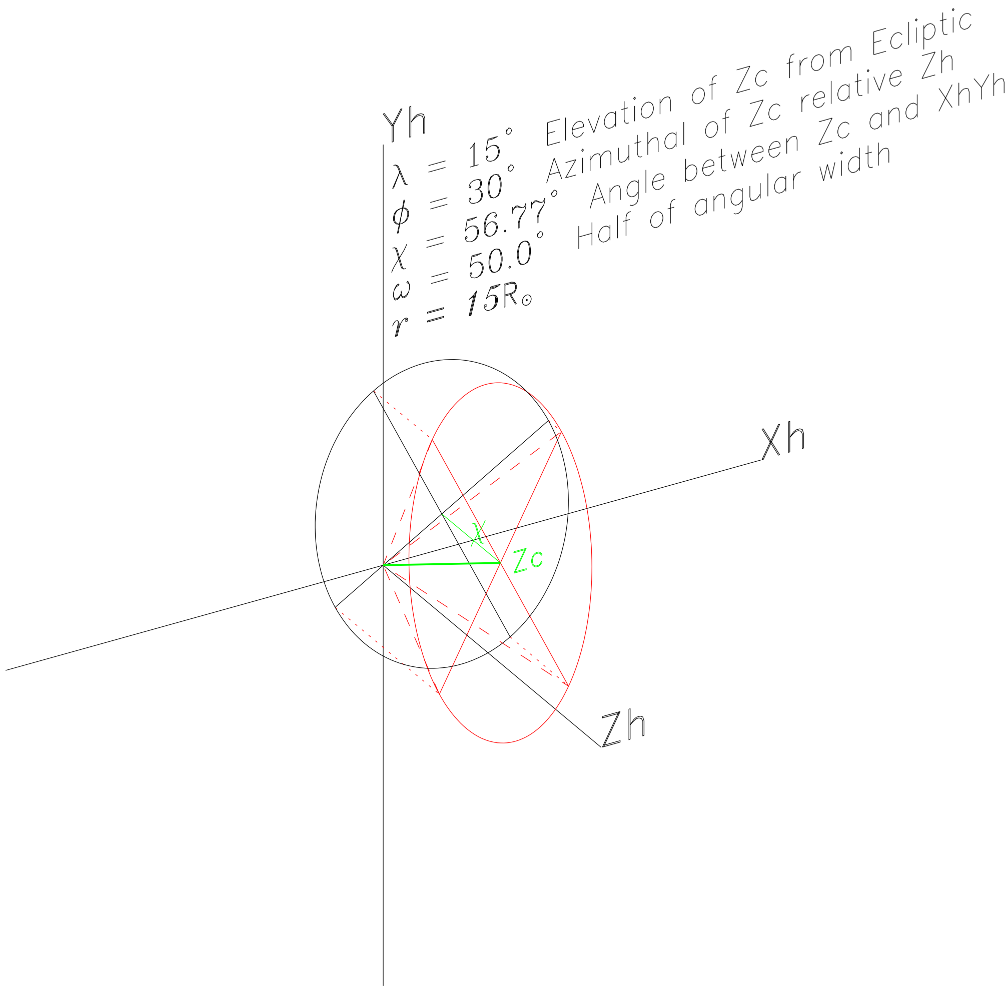

Fig. 2.— The geometrical properties of conical or spherical shell CMEs which determine the characteristics of halo-type CMEs.

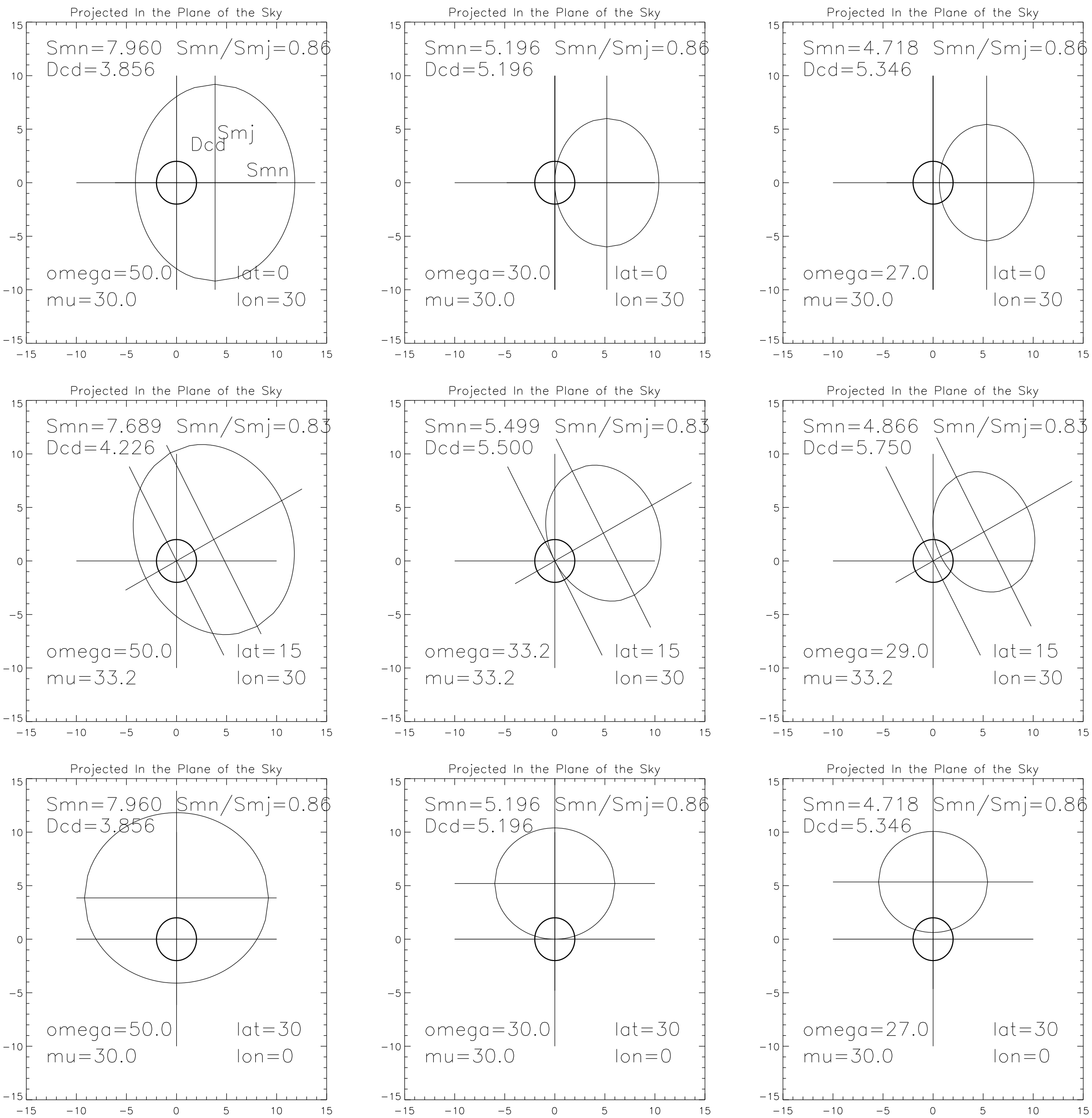

Fig. 3.— The criterion of Earth-directed CMEs when conical shell model is valid – The span of partial halo CMEs close to or greater than 180°.

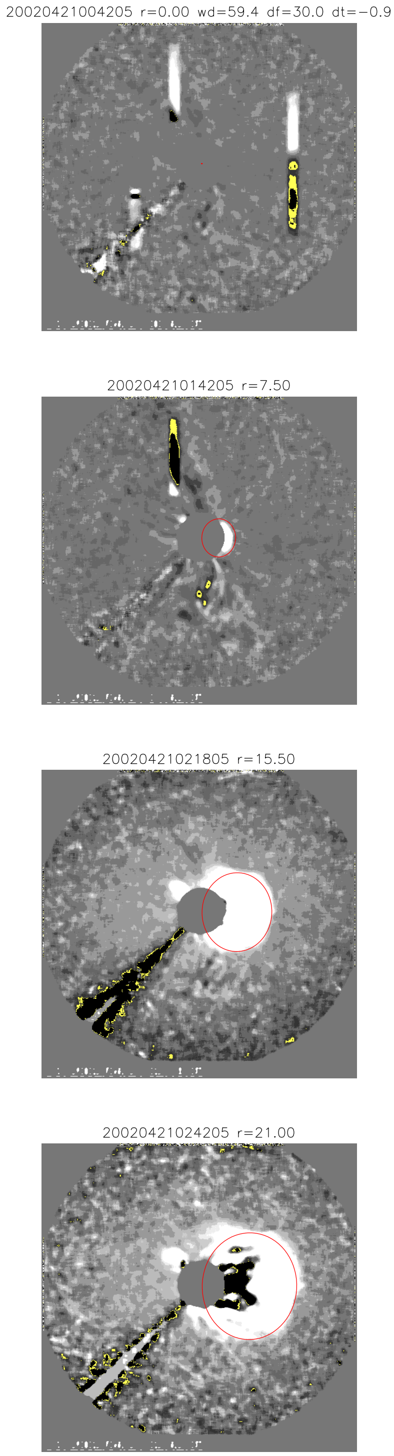

Fig. 4.— Example of constant angular width CMEs.

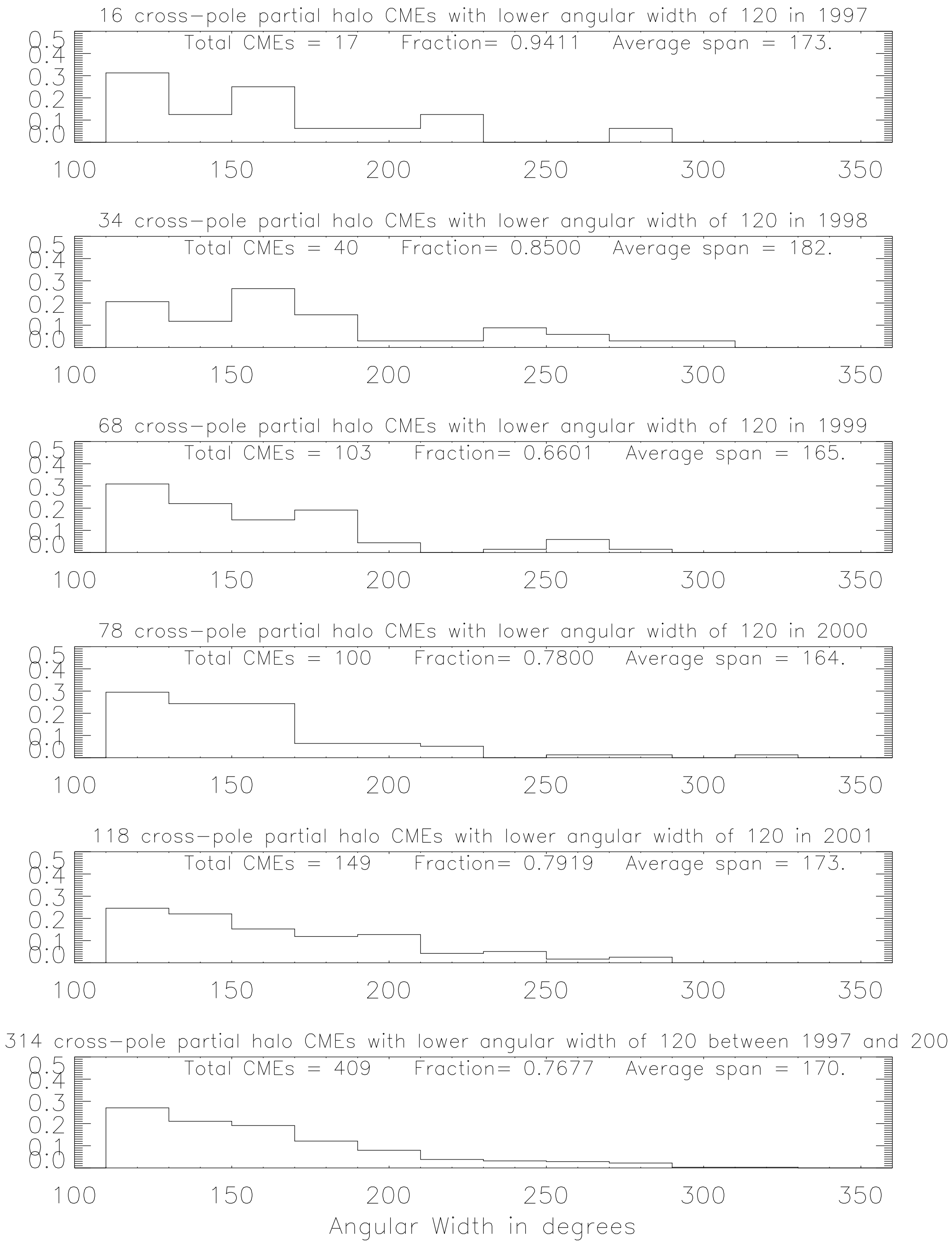

Fig. 5.— The fraction of cross-pole partial halo CMEs between 1997 and 2001.

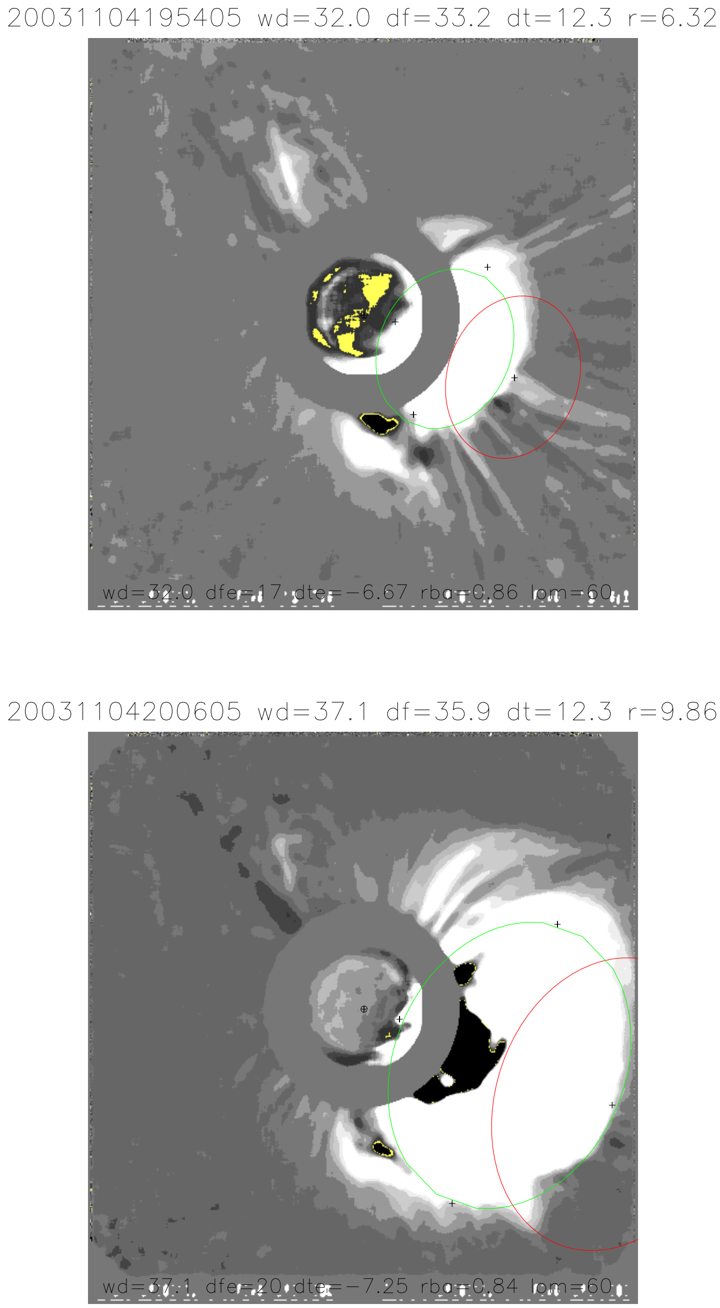

Fig. 6.— Example of varying angular width CMEs

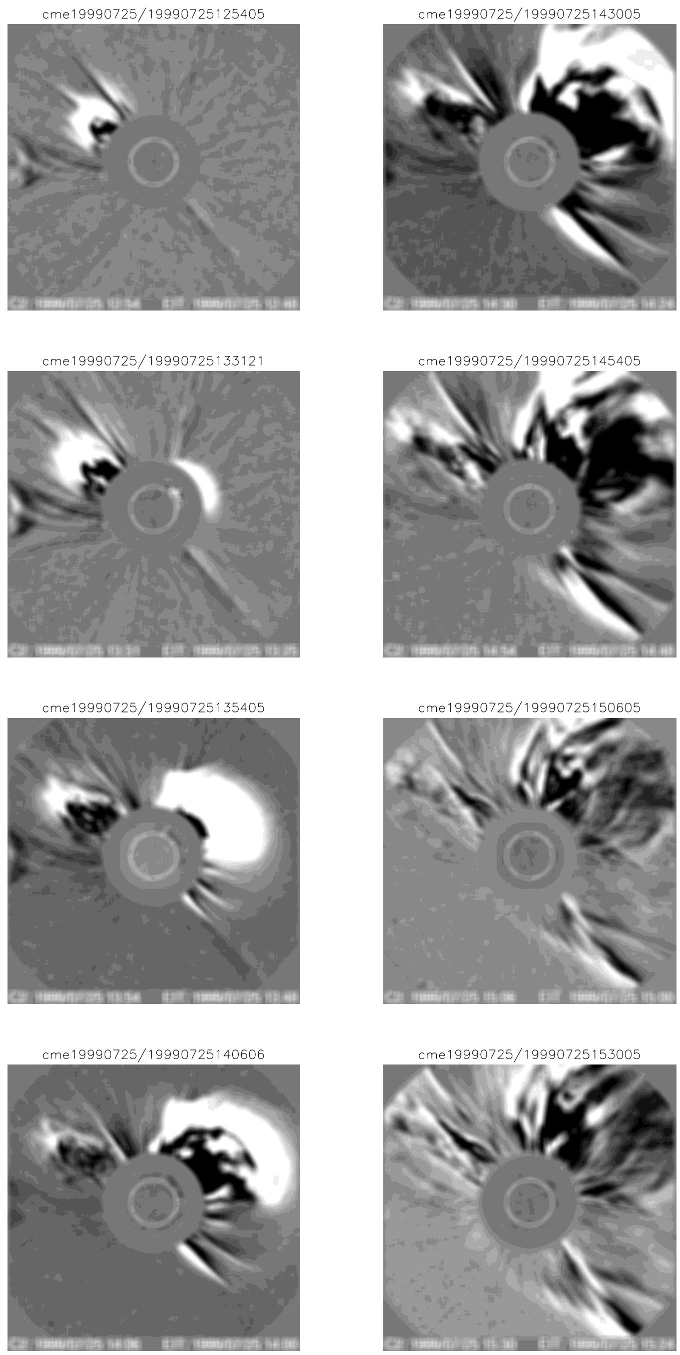

Fig. 7.— The effect of deflections of preexisting features on the formation of halo-type CMEs. This ragged halo CME actually is a limb CME and certainly not Earth-directed.

4. Summary

• Observational evidence shows that most of frontside partial halo CMEs selected using a lower limit of span, say, 140° are not Earth-directed. Only a small fraction of frontside partial halo CMEs are able to hit the Earth.

• Based on the assumption that most of CMEs may be modeled by a conical shell or spherical shell of dense plasma, we present a method to identify Earth-directed partial halo CMEs from frontside partial halo CMEs:

(1) examine the white-light images to see if the partial halo CME has ragged spatial structure and if its associated surface activity located near the limb. If so, the partial halo CME should not be selected to be a candidate of Earth-directed CME.

(2) determine the angular width using the last few halo images to see if the angular width keep the same or varies. If it is a constant then it is Earth-directed only if the span of the CME is greater than 180°. If the obtained angular width increases, the frontside partial halo CME should be a candidate of Earth-directed CME, though its span may be less than 180°.