

Halo coronal mass ejections and geomagnetic storms

Nat Gopalswamy

NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

(Received June 21, 2008; Revised xxxx xx, 2008; Accepted October 27, 2008; Online published xxxx xx, 2009)

In this letter, I show that the discrepancies in the geoeffectiveness of halo coronal mass ejections (CMEs) reported in the literature arise due to the varied definitions of halo CMEs used by different authors. In particular, I show that the low geoeffectiveness rate is a direct consequence of including partial halo CMEs. The geoeffectiveness of partial halo CMEs is lower because they are of low speed and likely to make a glancing impact on Earth.

Key words: Coronal mass ejections, geomagnetic storms, geoeffectiveness, halo CMEs.

1. Introduction

Coronal mass ejections (CMEs) that appear to surround the occulting disk of the observing coronagraphs in sky-plane projection are known as halo CMEs (Howard *et al.*, 1982). Halo CMEs are fast and wide on the average and are associated with flares of greater X-ray importance because only energetic CMEs expand rapidly to appear above the occulting disk early in the event (Gopalswamy *et al.*, 2007). Extensive observations from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraphs (LASCO) have shown that full halos constitute $\sim 3.6\%$ of all CMEs, while CMEs with width $\geq 120^\circ$ account for $\sim 11\%$ (Gopalswamy, 2004). Full halos have an apparent width (W) of 360° , while partial halos have $120^\circ \leq W < 360^\circ$. Halo CMEs are said to be frontside if the site of eruption (also known as the solar source) can be identified on the visible disk usually identified as the location of H-alpha flares or filament eruptions. Details on how to identify the solar sources can be found in Gopalswamy *et al.* (2007). Halos with their sources within $\pm 45^\circ$ of the central meridian are known as disk halos, while those with a central meridian distance (CMD) beyond $\pm 45^\circ$ but not beyond $\pm 90^\circ$ are known as limb halos. Disk halos are likely to arrive at Earth and cause geomagnetic storms, while limb halos only impact Earth with their flanks and hence are less geoeffective (see Gopalswamy *et al.*, 2007).

Since CMEs propagate approximately radially from the Sun (except for a small eastward deflection due to solar rotation—see Gosling *et al.*, 1987), disk halos are likely hit Earth. Of course, the interplanetary counterpart of CMEs (ICMEs) must contain southward magnetic field component (B_s) to be geoeffective. It is well known that the intensity of the resulting magnetic storm depends on the magnitude of B_s and the speed V with which the CME impacts Earth's magnetosphere (see e.g., Gonzalez *et al.*, 1994; Tsurutani and Gonzalez, 1997). Halo CMEs are more energetic (av-

erage speed is ~ 1000 km/s compared to ~ 470 km/s for ordinary CMEs), so the V part is expected to be high. When CMEs are aimed directly at Earth, the ICMEs are likely to arrive at Earth as magnetic clouds (MCs), which are a subset of ICMEs that have flux rope structure. Since Earth passes through the nose of the MC, the chance of encountering B_s somewhere within the MC is high (except for unipolar MCs with north-pointing axis—see Yurchyshyn *et al.*, 2001). When the ICME is shock-driving, the sheath portion lying between the shock and the MC may also play a significant role in producing geomagnetic storms (see e.g., Gosling *et al.*, 1990). The sheath may have intervals of north and south-pointing magnetic fields, in addition to the varying field orientation in the MC portion. An Earth-directed halo CME leads to a situation whereby Earth passes through the nose of the shock, where the sheath field is most intense and may cause intense magnetic storm if south-pointing. Thus the ability of a halo CME in producing a geomagnetic storm depends on the structure of its interplanetary counterpart (the ICME event).

Since halos became common place in the SOHO era, there have been several attempts to characterize their geoeffectiveness (see e.g., Zhao and Webb, 2003; Yermolaev and Yermolaev, 2003; Kim *et al.*, 2005; Yermolaev *et al.*, 2005; Gopalswamy *et al.*, 2007). Using CMEs from the rise phase of solar cycle 23, St. Cyr *et al.* (2000) concluded that $\sim 75\%$ of the frontside CMEs are geoeffective. In most of the works discussed here, the geoeffectiveness is defined as the ability of a CME or an interplanetary structure to cause geomagnetic storms with intensity (D_{st}) ≤ -50 nT. While most of the intense storms are caused by CMEs, moderate storms (-100 nT $< D_{st} < -50$ nT) may also be caused by other structures such as corotating interaction regions. Zhao and Webb (2003) found an overall geoeffectiveness rate of $\sim 64\%$ for frontside halos detected up to the solar maximum in 2000. Yermolaev and Yermolaev (2003) used data from the period 1976–2000 and came up with a lower rate of 40–50%. Michalek *et al.* (2006) found that $\sim 56\%$ of frontside halos are geoeffective, but they did not use all the halos because of limitations in the method of obtaining

space speeds. Kim *et al.* (2005) reported that only about 40% of the frontside halos are geoeffective. Yermolaev *et al.* (2005) compiled published results and noted that the geoeffectiveness rate varied from <40% to >80%. Recently Gopalswamy *et al.* (2007) analyzed 378 halo CMEs covering almost whole of solar cycle 23 and found that $\sim 71\%$ of frontside halos are geoeffective. Zhao and Webb (2003) and Gopalswamy *et al.* (2007) used the same definition of halo CMEs ($W = 360^\circ$) and obtained similar geoeffectiveness rates. On the other hand, Kim *et al.* (2005) and Yermolaev and Yermolaev (2003) defined their halos as CMEs with $W \geq 120^\circ$ and obtained the lower geoeffectiveness rate. The purpose of this letter is to show that the discrepancy in the rate of geoeffectiveness can simply be explained by the different definition of halo CMEs used by these authors. We take Kim *et al.* (2005) and Gopalswamy *et al.* (2007) representing the low and high geoeffectiveness rates, respectively. Both these works have published their list of events and the study periods have maximum overlap. They also use data from the same instrument (SOHO/LASCO), so the comparison is straightforward. Finally, both works use the same definition of geoeffectiveness: the ability of a CME to produce a geomagnetic storm with $D_{st} \leq -50$ nT.

2. Geoeffectiveness of Partial Halo CMEs

Kim *et al.* (2005) investigated 305 CMEs (1997 to 2003) that included full ($W = 360^\circ$) and partial halos ($120^\circ < W < 360^\circ$) and found that 121 of them were geoeffective. On the other hand Gopalswamy *et al.* (2007) studied 378 full halos for the period 1996 to 2005. For making a proper comparison, we first separate the full and partial halos in Kim *et al.* (2005). We then use the geoeffectiveness of a subset of full halos from Gopalswamy *et al.* (2007) corresponding to the Kim *et al.* (2005) study period to estimate the geoeffectiveness of partial halo CMEs.

Among the 378 full halos reported by Gopalswamy *et al.* (2007), 168 occurred during the period 1997 to 2003 (the study period of Kim *et al.*, 2005). Many geomagnetic storms during the study period had multiple CME association, so we eliminate 68 such CMEs in estimating the geoeffectiveness rate. Sixty five of the remaining 100 frontside full halos (65%) were geoeffective. Note that this rate is close to the one obtained by Zhao and Webb (2003). Excluding the full halos from the CMEs in Kim *et al.* (2005), we get 205 partial halos (305 minus 100), out of which 56 (121 minus 65) were geoeffective. Thus we get a geoeffectiveness rate of 27% (56 out of 205) for the partial halos alone. The 40% geoeffectiveness rate obtained by Kim *et al.* (2005) is thus a consequence of combining highly geoeffective (65%) full halos and marginally geoeffective (27%) partial halos.

Note that we used the CME data for the period 1997–2003 in the above calculation. To extend this result to the whole study period (1996–2005) considered by Gopalswamy *et al.* (2007), we need to estimate the fraction of partial halos that are geoeffective. Since Gopalswamy *et al.* (2007) did not include partial halos in their study, we estimate the geoeffectiveness of partial halos by extrapolation. To do this, we make use of the fact that 3.5% of

all CMEs are full halos, while 11% are full + partial halos (Gopalswamy, 2004). Assuming that these fractions apply equally well to the front and backside CMEs and recalling that 229 full halos were front-sided, one can estimate the frontside wide CMEs as $(11\%/3.5\%) \times 229 = 720$. Therefore, $720 - 229 = 491$ is the likely number of partial halos. At the 27% geoeffectiveness rate estimated above, 134 of the 491 partial halos are expected to be geoeffective. Therefore, out of the 720 wide CMEs, 163 full halos and 134 partial halos (total of 297 or 41%) are geoeffective. This is virtually the same as the 40% rate obtained by Kim *et al.* (2005) and confirms that inclusion of partial halos lowers the overall geoeffectiveness rate. Note that the geoeffectiveness of halos varies with the phase of the solar cycle (see Gopalswamy *et al.*, 2007, figure 8; Zhao and Webb, 2003) and the way multiple halos associated with a given storm are treated. We estimate that these effects can account for an additional 10% variation.

2.1 Why are partial halos less geoeffective?

In studying the geoeffectiveness of CMEs as a function of source latitude, Gopalswamy *et al.* (2007) found that the strongly geoeffective ($D_{st} \leq -100$ nT) and moderately geoeffective ($-50 \geq D_{st} > -100$ nT) CMEs have average longitudes of W10 and E03, respectively. The non-geoeffective CMEs have an average longitude similar to the moderately geoeffective CMEs (E02). Furthermore, the fraction of limb halos steadily increases from 17% for strongly-geoeffective, to 31% for moderately geoeffective, and 37% for non-geoeffective CMEs. The average speeds also decrease in the same order (see figure 9 of Gopalswamy *et al.*, 2007). From these observations, Gopalswamy *et al.* (2007) concluded that non-geoeffective CMEs are relatively slower, originate predominantly from the eastern hemisphere, and have a greater central meridian distance. Partial halos generally have properties similar to the moderately geoeffective and non-geoeffective halos. Thus partial halos are less energetic and do not expand enough to fully surround the occulting disk within the LASCO field of view.

Gopalswamy *et al.* (2007) also reported that the geoeffectiveness rates of limb and disk halos as 60% and 75%, respectively. The geoeffectiveness of partial halos originating closer to the limb is expected to be even lower because they are slower and less likely to impact Earth. Thus, inclusion of partial halos reduces the overall geoeffectiveness rate of halo CMEs and hence correctly explains the lower geoeffectiveness rates reported in the literature.

3. Discussion and Conclusions

One of the important aspects of CME geoeffectiveness studies is to identify the solar source of CMEs. One might argue that the geoeffectiveness may be overestimated when front-sided CMEs are mistakenly classified as back-sided CMEs. This can happen only when front-sided halos have no disk signature. There may also be cases in which a fortuitous disk activity coincides with a backside CME and hence a backside CME gets classified as a frontside CME. Sometimes, one observes a full halo, which may be a combination of multiple CMEs occurring at different position angles. Such occurrences are generally rare and cannot ac-

count for the large discrepancies in the reported geoeffectiveness rate.

To clarify the identification of solar sources of halo CMEs, let us consider the association between CMEs and soft X-ray flares, one of the obvious indicators of disk activity. Whenever the eruption occurs on the frontside (CMD in the range 0 to 90°), we observe a soft X-ray flare. The halo CME appears asymmetric when the solar source has a larger CMD, typically beyond 45°. When the eruption is behind the limb, but not too far behind, we usually observe some EUV dimming above the concerned limb, but no soft X-ray flare is observed because the flare gets occulted by the solar limb. When a flare is partially occulted by a limb, the soft X-ray light curve tends to be very gradual and we observe the CME above the occulting limb. The extreme case is a backside CME whose associated flare is completely occulted, and we see no disk activity. In some of these cases one can see EUV dimming around most part of the solar disk, indicating a backside eruption. This kind of relationship between the soft X-ray flare and CMEs can be easily seen by tracking a large active region (AR) during its disk passage and eventual disappearance behind the west limb (e.g., AR 10486 reported in Gopalswamy *et al.*, 2005).

When one starts from geomagnetic storms and relate them to CMEs near the Sun, occasionally it becomes difficult to identify the CME. Zhang *et al.* (2007) were not able to identify wide CMEs or their solar sources for ~10% of large geomagnetic storms. Zhang *et al.* (2007) started with large geomagnetic storms and searched for CMEs and their solar sources. The solar and geomagnetic events were separated by more than a day to a few days. On the other hand, Gopalswamy *et al.* (2007) started with halo CMEs and identified their solar sources. Observations of the halo CME and the associated disk signature are nearly simultaneous. Halo CMEs are more energetic (see figure 4 of Gopalswamy *et al.*, 2007), so there is usually a prompt (and strong) disk signature if the halo is frontside. Thus, the solar source identification for geomagnetic storms and that for halo CMEs do not have the same level of difficulty. Furthermore, geomagnetic storms can also be caused by non-halo CMEs. If a CME originates close to the disk center and arrives at Earth with a southward magnetic field component, it will cause a geomagnetic storm. It is known that some magnetic clouds, which are interplanetary CMEs (ICMEs) with flux rope structure, are associated with non-halo CMEs. A recent statistical study (Gopalswamy *et al.*, 2008) finds that only ~63% of magnetic clouds are associated with full halos. The fraction increases to ~86% when full and partial halos are combined. The remaining 14% of magnetic clouds are associated with non-halo CMEs originating from close to the disk center. Since magnetic clouds constitute the most geoeffective subset of ICMEs, one expects that some magnetic clouds associated with non-halo CMEs are also geoeffective.

In conclusion, we confirm that the lower rate of geoeffectiveness obtained by some authors is due to the inclusion of partial halos. The reported variation in geoeffectiveness

rates can be readily explained by the different definition of halo CMEs used by different authors. Partial halos are less energetic and generally originate far from the disk center, so most of them behave similar to the nongeoeffective CMEs.

Acknowledgments. Work supported by NASA's LWS and TR&T programs.

References

- Gonzalez, W. D., J. A. Joselyn, Y. Kamide, H. W. Kroehl, G. Rostoker, B. T. Tsurutani, and V. M. Vasyliunas, What is a geomagnetic storm?, *J. Geophys. Res.*, **99**, 5771, 1994.
- Gopalswamy, N., A global picture of CMEs in the inner heliosphere, in *The Sun and the Heliosphere as an Integrated System*, edited by G. Poletto and S. T. Suess, chap. 8, p. 201, Kluwer Acad., Boston, 2004.
- Gopalswamy, N., S. Yashiro, Y. Liu, G. Michalek, A. Vourlidas, M. L. Kaiser, and R. A. Howard, Coronal mass ejections and other extreme characteristics of the 2003 October–November solar eruptions, *J. Geophys. Res.*, **110**, A09S15, doi:10.1029/2004JA010958, 2005.
- Gopalswamy, N., S. Yashiro, and S. Akiyama, Geoeffectiveness of halo coronal mass ejections, *J. Geophys. Res.*, **112**, A06112, doi:10.1029/2006JA012149, 2007.
- Gopalswamy, N., S. Akiyama, S. Yashiro, G. Michalek, and R. P. Lepping, Solar sources and geospace consequences of interplanetary magnetic clouds observed during solar cycle 23, *J. Atm. Sol. Terr. Phys.*, **70**, 245, doi:10.1016/j.jastp.2007.08.070, 2008.
- Gosling, J. T., M. F. Thomsen, S. J. Bame, and R. D. Zwickl, The eastward deflection of fast coronal mass ejecta in interplanetary space, *J. Geophys. Res.*, **92**, 12399, 1987.
- Gosling, J. T., D. J. McComas, J. L. Phillips, and S. J. Bame, Coronal mass ejections and large geomagnetic storms, *Geophys. Res. Lett.*, **17**, 901, 1990.
- Howard, R. A., D. J. Michels, N. R. Sheeley, Jr., and M. J. Koomen, The observation of a coronal transient directed at earth, *Astrophys. J.*, **263**, L101, 1982.
- Kim, R.-S., K.-S. Cho, Y.-J. Moon, Y.-H. Kim, Y. Yi, M. Dryer, S.-C. Bong, and Y.-D. Park, Forecast evaluation of the coronal mass ejection (CME) geoeffectiveness using halo CMEs from 1997 to 2003, *J. Geophys. Res.*, **110**, A11104, doi:10.1029/2005JA011218, 2005.
- Michalek, G., N. Gopalswamy, A. Lara, and S. Yashiro, Properties and geoeffectiveness of halo CMEs, *Space Weather*, **4**, S10003, doi:10.1029/2005SW000218, 2006.
- St. Cyr, O. C. *et al.*, Properties of coronal mass ejections: SOHO LASCO observations from January 1996 to June 1998, *J. Geophys. Res.*, **105**, 18,169, 2000.
- Tsurutani, B. T. and W. D. Gonzalez, The Interplanetary Causes of Magnetic Storms: A Review, in *Magnetic Storms*, edited by B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo, p. 77, AGU Monograph 98, AGU, Washington DC, 1997.
- Yermolaev, Yu. I. and M. Yu. Yermolaev, Statistical Relationships between Solar, Interplanetary, and Geomagnetic Disturbances, 1976–2000: 3, *Cosmic Res.*, **41**, 539, 2003.
- Yermolaev, Yu. I., M. Yu. Yermolaev, G. N. Zastenker, L. M. Zelenyi, A. A. Petrukovich, and J.-A. Sauvaud, Statistical studies of geomagnetic storm dependencies on solar and interplanetary events: a review, *Planet. Space Sci.*, **53**(1–3), 189–196, 2005.
- Yurchyshyn, V. B., H. Wang, P. R. Goode, and Y. Deng, Orientation of the Magnetic Fields in Interplanetary Flux Ropes and Solar Filaments, *Astrophys. J.*, **563**, 381, 2001.
- Zhang, J. *et al.*, Solar and interplanetary sources of major geomagnetic storms (Dst < -100 nT) during 1996–2005, *J. Geophys. Res.*, **112**, A10102, doi:10.1029/2007JA012321, 2007.
- Zhao, X. P. and D. F. Webb, Source regions and storm effectiveness of frontside full halo coronal mass ejections, *J. Geophys. Res.*, **108**(A6), 1234, doi:10.1029/2002JA009606, 2003.