A statistical study of the relationship between the sunspot number, maximum CME speed and geomagnetic indices

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Abstract. We investigated the relationship between the monthly averaged maximal speeds of coronal mass ejections (CMEs), sunspot number (SSN) and the geomagnetic Dst and Ap indices covering the 1996-2008 time interval. The study was carried out using frequency and correlation analyses. Frequency analysis of the maximum speed of CMEs (or CME speed index) shows a cyclic behavior similar to that found for SSN and the Ap index. Our new findings are as follows. 1) Unlike the SSN, the CME speed index does not exhibit a double peak maximum. 2) The CME speed index has a correlative relationship with SSN and Dst and Ap indices (correlation coefficients are 0.76, -0.53, 0.68 respectively). Various peculiarities in the monthly Dst index are better correlated with the fine structures in the CME speed profile than that in the SSN data. 3) Similar to the Ap index, both CME speed and the Dst indices lag behind the sunspot numbers by several months. We thus conclude that CME speed index may be a good parameter to describe the geo-effectiveness of solar activity.

Keywords; sunspot numbers, maximum CME speed, geomagnetic Ap index, correlation analysis, frequency analysis

Introduction

When coronal mass ejections (CMEs) erupt from the Sun, high speed particles and strong magnetic fields can hurl earthward thus causing a significant impact on the near Earth space environment (geomagnetic storms) such as adverse effects on satellites and communications, electric power, pipelines, etc. Numerous severe storms occur during the maximal phase of the solar cycle, and they are mostly associated with CMEs (Gopalswamy et al., 2007; Zhang et al., 2007). Disturbances of the near Earth environment are measured by various parameters, such as *aa* (Mayaud 1973), Ap (Bartels et al., 1939) and Dst (Sugiuara 1964) indices, to name a few. Variations in solar activity are traced by measuring sunspot numbers (Hoyt & Schatten 1998), solar flare indices (Ozguc et al., 2003), total solar irradiance (Lean et al., 1995). Gopalswamy et al., (2006) introduced CME daily rate as a new solar activity indicator closely correlated to the geo-magnetic activity. All these indices display periodic behavior with periods lasting from days to hundred of years (Kirivova & Solanki 2002; Echer et al., 2004; Braun et al., 2005; Atac et al., 2006; Kilcik et al., 2010), and they also have correlative relationships with one another. Although the relationship between the solar and geomagnetic activity indices has been extensively studied (e.g., Stamper et al., 1999), it still eludes satisfactory explanation (Echer et al., 2004).

In this study, we use the CME plane-of-the-sky speeds to further explore their geomagnetic activity. One obvious reason to use this parameter is that fast CMEs are very often associated with strong geomagnetic storms (Srivastava & Venkatakrishnan 2004; Yurchyshyn et al., 2004, 2005) and the correlation is best when an earthward CME is associated with a magnetic cloud (Gopalswamy 2010). While sunspot numbers are quite suitable for characterizing solar activity, they may not always accurately reflect the overall intensity of solar eruptions, since not all sunspot groups are equally capable of producing powerful energetic events (Abramenko 2005). There is a tendency to have more flares in the declining phase of a sunspot cycle and this tendency was even stronger during the decline of the 23rd cycle (Bai (2006). Shi & Wang (1994) also reported that more than 95% of all X-ray class flares occurred in δ-type active regions. The monthly maximum CME speed therefore is probably modulated by super active regions, which do not usually follow solar activity cycle (Gopalswamy et al., 2006). Moon et al. (2002), however, reported only a weak correlation between time integrated X-ray flux of CME associated flare and CME speeds. Therefore, the CME speed index as a measure of geo-effective solar activity may have advantages over the sunspot numbers in that it is more objective and better reflects the intensity of Earth directed solar eruptions.

Variations correlated with solar activity cycle were reported earlier for CME occurrence rate and speeds (Hildner et al., 1976; Webb & Howard 1994; Gopalswamy et al., 2003), latitude distribution (Gopalswamy et al., 2003), angular widths (Kahler et al., 1989; St. Cyr & Webb 1991), and speeds (Ivanov & Obridko, 2001; Gopalswamy et al., 2003; 2008). On the other hand, a number of papers analyzed the physical relationship between various CME parameters (speed, angular extent, orientation, rate, etc.) and geomagnetic storms (Richardson et al., 2001; Yurchyshyn et al., 2004), Kp index (Zhang et al., 2003; Miyoshi & Kataoka 2005), Ap index (Leamon et al., 2003; Forbes et al., 2005) and *aa* index (Luhmann 1997; Richardson et al., 2002). Many of these papers were either case studies or studies on small statistics not aimed at exploring the solar cycle variation and long-term relationships. Gopalswamy et al., (2003) reported that the CME occurrence rate peaks two years after the solar cycle maximum. Ramesh (2010) further found that this lag is minimized when the sunspot area is used to describe the solar activity. Also, CMEs with higher speeds appear to follow the sunspot cycle much better then the entire population of CMEs.

Here we propose and explore a new solar activity index based on the maximum speed of CMEs (Section 2). In Section 3, we compare the CME speed index with the sunspot numbers and the geomagnetic Ap and Dst indices. The discussion and conclusions are given in Section 4.

Data and Methods

To derive the CME index, we used data from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO, Brueckner et al., 1995) as compiled in the CME catalog[1] (Yashiro et al., 2004, Gopalswamy et al., 2009). The catalog covers the period from 1996 until the present. For each day, we only chose the eruption with the maximum linear fit speed, and the CME speed index was calculated as a monthly averaged maximum CME speed (Figure 1, solid line). A total of 3925 daily maximum speed measurements were selected out of a 4740 day interval and used for the correlation analysis. There were two large gaps in the CME data covering July-September 1998 and January 1999. Thus for the frequency analysis, where uninterrupted data are required, we used daily indices for the period from February 1999 to December 2008 (total 3618 daily data points). We also calculated the CME number by counting all events reported for a given Carrington rotation Gopalswamy et al., 2003). The CME rate is somewhat subjective, due to the difficulty in (CR) and dividing the sum by the LASCO operational time over that CR (identifying the narrow and weak CMEs during solar maximum (Yashiro et al., 2008). For this reason Gopalswamy et al. (2010) considered CMEs with width exceeding 30 degree, which showed a good correspondence with sunspot number (see Fig. 2, 3 in Gopalswamy et al., 2010). In this paper the CME number is calculated based on all events in the CME catalog.

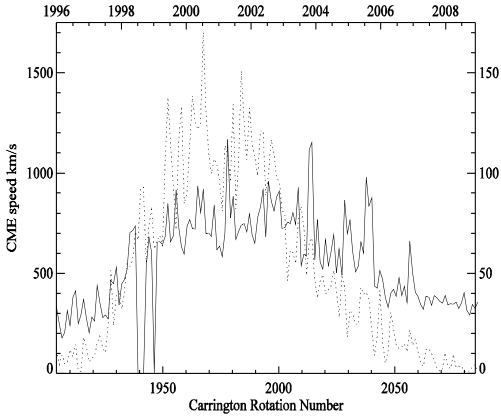

Figure 1. Comparison of monthly data sets. For display purposes, ISSN (dotted line) values were scaled.

The international sunspot number (ISSN) and the geomagnetic Ap index data were taken from the National Geophysical Data Center[2]. The Dst index data were provided by the World Data Center for Geomagnetism at Kyoto University[3].

The planetary Ap index measures the solar particle effect on Earth's magnetic field, and characterizes the general level of geomagnetic activity over the globe for a given day. It is derived from *a* and Kp indices (Bartels et al., 1939), measured at a number of mid-latitude stations world-wide, characterizing variations of the geomagnetic field due to currents flowing in Earth's ionosphere and, to a lesser extent, in Earth's magnetosphere.

The hourly Dst index (Sugiura 1964) is obtained from several magnetometer stations near the equator. Dst index is a direct measure of the hourly averaged perturbation of the horizontal (H) component of the geomagnetic field caused by the

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[1] http://cdaw.gsfc.nasa.gov/CME_list/index.html

[2] http://www.ngdc.noaa.gov/

[3] http://wdc.kugi.kyoto-u.ac.jp/dstdir/

varying magnetospheric ring current. Large negative Dst values indicate an increase in the intensity of the ring current (geomagnetic storm). Fares Saba et al., (2005) showed that the Ap and Dst indices are highly correlated during the geomagnetic storms mainly because in both cases the ring current is a dominant contributor. Figure 2 plots monthly averaged values of the Ap and Dst indices. Although their absolute values differ, at times significantly, there is general agreement (correlation coefficient is -0.81) and synchronous cyclic variations are apparent.

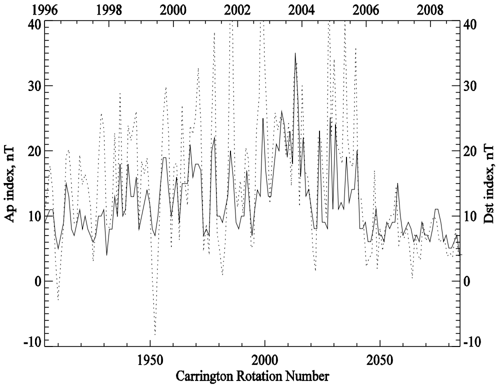

Figure 2. Comparison of monthly geomagnetic Ap and Dst (dotted) indices. For display purposes the sign of the Dst index was reversed.

Two statistical analysis methods were applied. First, we used the Pearson correlation method, which determines a correlation coefficient, *r*, between the CME speed index, ISSN and the Ap index. To compare the spectral characteristics of the CME speed index, we also utilized multi-taper method (MTM) developed by Thomson (1982) for reducing variance of spectral estimates by means of tapers. This method has been successfully used for the analysis of different climate (Ghil & Vautard 1991; Yiou et al., 1996; Anandan et al., 2004; Vaquero et al., 2010) and solar (Kilcik et al., 2008, 2010) time series. Details of this method can be found elsewhere (e.g., Ghil et al., 2002). Here we used three sinusoidal tapers and the frequency range was taken from 0.0005 to 0.041/day (i.e., 25 - 2000 days). The selection of this time interval is based on two main criteria: (i) the smallest detectable periodicity must include at least one CR and (ii) the largest periodicity must not exceed half of the studied interval. The significance test was carried out with respect to red noise approximation. All harmonic signals were obtained using confidence level of 95 %.

Results

The Pearson correlation test and MTM frequency analysis were used to a) obtain the degree of relationship between the three data sets and b) investigate the periodic behavior of the maximal speed of CMEs. Figure 1 plots CME speed index and ISSN. The CME speed index shows the presence of the 11 year solar activity cycle. In general, the monthly mean speeds exceed 700 km/s during the maximum phase, while they remain at a ~400 km/s level during the rising and declining phase of the solar cycle. We emphasize that the monthly averaged maximum CME speeds do not exactly follow the ISSN. During the rising phase of the cycle both indices show a similar behavior, however, the maximal and declining phases reveal differences between them. The double maximum in the ISSN is not at all prominent in the speed index. Instead, the CME speed index gradually rises until it peaks at CR 1995 (October 2002). While the sunspot number rapidly drops in the declining phase, the monthly averaged speed remains relatively high, even when there are only a few sunspots. As it follows from the figure, the maximum of the CME speed index appears to be delayed relative to the solar cycle maximum (October 2000) by nearly two years. It must be pointed out that the solar-cycle variation of the mean CME speed (Gopalswamy et al., 2003; 2009) differs from the CME index in the present work. The mean speed includes the speeds of all CMEs averaged over Carrington Rotation periods. The maximal speed includes only the highest daily CME speed averaged over each month. The mean speed clearly shows a double hump with a dip during the solar maximum (year 2001) when plotted as annual averages (see Fig. 1 in Gopalswamy et al., 2008b). In the present work, we select only the maximum speeds, so the super active regions get a higher weightage because they produce high speed CMEs in great numbers (Gopalswamy et al., 2006). The spikes seen in Fig. 1 are also seen in the plot of the mean speed reported in Gopalswamy et al. (2010). Finally, the CME index closely matches the number of fast and wide CMEs reported in Gopalswamy et al. (2008b). Since the geo-effective population of

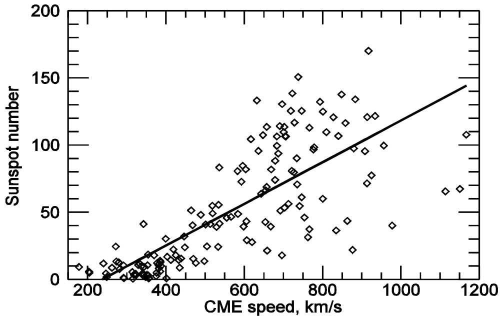

Figure 3. Relationship between monthly ISSN and CME speed index.

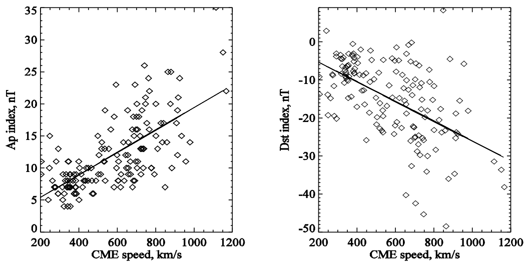

Figure 4. Relationship between the monthly CME speed index and the geomagnetic Ap index (left) and the Dst index (right).

CMEs is generally fast and wide, we think the CME index is a good indicator of the geo-effectiveness as will be shown below.

To quantify the relationship among various indices, we applied the Pearson correlation test and found high correlation between the CME speed index and ISSN (r=0.76, Figure 3), Ap index (r=0.68) and the Dst index (r=-0.53). Figure 4 shows that both the Ap and Dst indices depend on the speed of coronal ejecta, with the interval of values in the Dst index being twice of that in the Ap index. In spite of the fact that the Dst index is expected to reflect geomagnetic activity associated with CMEs, the correlation between the CME speed and Dst indices is much lower than that for the CME speeds and the Ap indices. The reason for that may be in very irregular time profile of the Dst index (as compared to the Ap index). The irregularity may come from two sources: 1) some strong eruptions missed the Earth and thus did not cause any response in the Dst index and 2) some events that encountered the Earth might have contained an unorganized magnetic structure and/or unfavorable direction of orientation, so that no significant and long lasting southward Bz component was present in the interplanetary ejecta and no associated disturbance was registered in the Dst index. This can be seen from a very strong correlation between the Dst index and the speeds of CMEs, associated with magnetic cloud structures (Burlaga et al., 1981) reported by Gopalswamy et al. (2008a). However, this correlation is substantially weaker when only non-magnetic cloud ejecta are considered (Gopalswamy 2010).

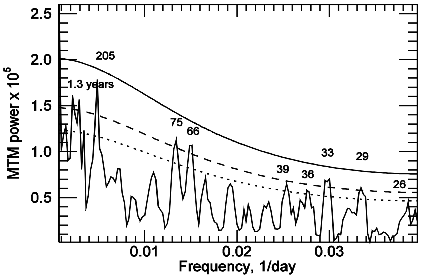

Figure 5. The MTM power spectrum of the daily maximum speed of CMEs. The smooth curves indicate various confidence levels (90, 95 and 99 respectively).

To further explore the CME speed index, we utilized the MTM frequency analysis and compared the results (Figure 5) with the frequency analysis results obtained in earlier studies for other solar time series (Kirivova & Solanki 2002; Lara et al., 2008; Chowdhuri et al., 2009; Kilcik et al., 2010 and reference therein). The MTM spectra shows nearly all meaningful periods of 1.3 year (455 days), 205, 75, 66, 39, 36, 33, 29, and 26 days, which seem to be related to solar activity. The 1.3 year periodicity was found by Kirivova & Solanki (2002) in their analysis of sunspot areas and the sunspot number data. The 205 day periodicity was reported by Lara et al. (2008) based on CMEs numbers and maximum entropy method. Other short periods were also reported for ISSN (Joshi et al., 2006), sunspot area (Joshi et al., 2006; Chowdhuri et al., 2009) and X-ray flares (Lou et al., 2003). Recently Kilcik et al. (2010) analyzed solar flare index from 1976 to 2008 using MTM and wavelet analysis. They reported 73, 62, 41, and 37 day periods with at least 90% confidence levels. The most important periodicity may be a Carrington rotation periodicity (33, 29 and 26 days) obtained here from the daily CME speed index data, seen in the aforementioned studies. Therefore, based on a comparison with solar and geomagnetic indices as well as frequency analysis, we conclude that the newly introduced CME speed index seems to adequately describe the solar activity cycle, although many details are not examined yet.

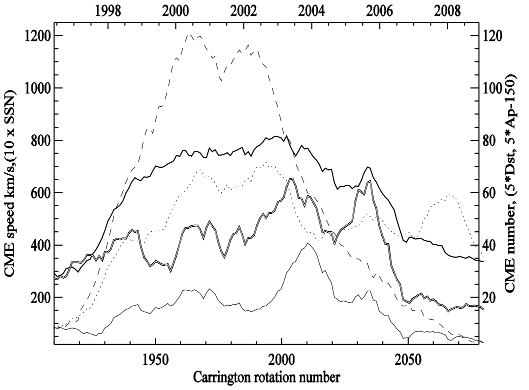

Figure 6. Time profiles of monthly data sets. All data points were smoothed with 12 point running average. In this plot the dashed line shows sunspot numbers, bold solid line - the CME index, the dotted line is the CME number, the double line represents the Dst index and the thin solid line is the Ap index.

Next we will explore whether this index may help us better understand the details of solar-terrestrial interactions. Figure 6 plots 12 step running averages of the ISSN, CME speed and numbers as well as the Ap and Dst indices. There are several moments that we would like to point out. First, the plot shows that the peak of the averaged maximum CME speed (CR 1995, October 2002) and the local peak the CME number (CR 1993, August 2002) are delayed relative to the second sunspot maximum (CR 1985, January 2002). Earlier, Gopalswamy et al., (2009); and Ramesh (2010) reported that the CME occurrence rate is similarly lags behind the sunspot maximum. Second, there is a general trend for CME speeds, CME numbers and sunspot numbers to behave quite differently in the declining phase of the 23rd solar cycle. After October 2002, the average maximum speed began to sharply decline and the trend of this decline is similar to that displayed by the Dst index and is consistent with the sunspot numbers. This may be an artifact of the subjective CME counting. The numbers of faint narrow CMEs were easily detected during the declining phase than during the maximum phase (see Yashiro et al., 2008). This disparate behavior can also be explained by the fact that a significant fraction of CMEs at this time could be low speed events related to quiescent and high latitude polar crown filaments, which are not related to sunspots (Gopalswamy et al., 2010; Ramesh 2010).

The third point is related to the cause of the burst of geomagnetic activity in 2003. The plots clearly show that the Dst and Ap indices are mainly defined by different drivers, although some CME activity is clearly imprinted, at times, onto the Ap profile (e.g., compare the CME number and Ap profiles between CR1955 and CR1975). The Dst index peaks nearly simultaneously with the CME speeds, while the Ap index reached its maximum at the time when the number of coronal holes (CHs) observed on the solar disk peaked (Abramenko et al., 2010). We thus speculate that both CME and CH activity "leaked" into each of the geomagnetic indices, although in different degrees, which may explain the lag between the Dst and Ap indices.

Discussion and Conclusions

We would like to note that Feynman (1982) decomposed the annual average *aa* index into two periodic functions and found that they are nearly 180 degrees out of phase. The first component, synchronized with the sunspot cycle, was proposed to be due to solar flares, CMEs and transient coronal holes. The other component lags behind the sunspot cycle and peaks during the declining phase. The authors proposed that this component of geomagnetic activity is due to long lived solar wind sources such as polar coronal holes. Echer et al. (2004) analyzed the lag between solar activity, as measured by sunspot numbers, and the *aa* geomagnetic index. The data set covered period between 1868 and 2000. These authors concluded that the lag varies from one cycle to another, reaching 2 year for cycle 22. The explanation for the lag is in the dual peak structure in the *aa* index. The first peak is related to sunspots' CME activity and the second peak is thought to be caused by fast solar wind streams, which increase during the declining phase of the solar cycle as more and more mid-latitude coronal holes appear on the solar surface (Legrand & Simon 1985). Indeed, according to Abramenko et al., (2010), the declining phase of the 23th solar cycle displayed an excess of low-latitude coronal holes. While our analysis supports the Echer et al. (2004) report, the newly introduced CME speed index may refine the explanation for the cause of the second peak in the geomagnetic activity. Since the peak of CME speeds is nearly co-temporal with the peak in the Ap index, both CME and mid-latitude coronal holes may be responsible for the burst of geomagnetic activity during a two-year period starting in May 2002.

Another aspect we would like to emphasize is that there is a high correlation between the monthly averaged maximum CME speeds and geomagnetic activity. This conclusion is in line with earlier works by Srivastava & Venkatakrishnan (2004) and Yurchyshyn et al., (2004, 2005). Srivastava & Venkatakrishnan (2004) selected 64 geo-effective CME events and found a remarkable negative correlation (-0.66) between CME speeds and the corresponding Dst index. Yurchyshyn et al., (2004, 2005) concluded that the CME speed is directly related the intensity of the Bz component of the associated magnetic clouds (also see Qiu & Yurchyshyn 2005), which, in turn, affects the magnitude of the Dst index. Gopalswamy (2010) examined the relationship between CME speeds and the Dst index separately for different types of ejecta. The finding are that the CME exhibiting signatures of magnetic clouds are show the best correlative relationship because the associated CMEs leave from the disc center and hence head directly to Earth.

It is interesting to note that all periods detected in this study were found as well in different solar and geomagnetic indices. The 1.3 year periodicity was reported for the geomagnetic Kp and Ap index by Rangarajan & Iyemori (1997) and Mursula & Zieger (2000). The nearly semi-annual periodicity (205 days) was detected by Gonzalez et al. (1993) and Nayar (2006) in the Ap index. Gonzalez et al. (1993) also reported 75, 39, 36 and CR rotation periods by applying power spectrum analysis to the Ap index data for the interval 1932 through 1982. Our analysis showed that all analyzed data sets have remarkable relationships with each other and all of them show similar cyclic behavior. This study based on the comparison of CME speed index, sunspot numbers and the geomagnetic Ap index confirms that the CME speed index may be a useful index that simultaneously measures solar and geomagnetic activity. Further studies are needed to explore the details of the relationship between this new index and geomagnetic effects.

We summarize the main findings of this study as follows:

1) Unlike the sunspot numbers, the CME speed index does not exhibit a double peak maximum, however, the lowest point in the distribution occurred in year 2001. Instead, the CME speed profile peaks during the declining phase of solar cycle.

2) CME number shows a double peak similar to that seen in the sunspot numbers. The CME occurrence rate remained very high even near the minimum of the solar cycle, when both sunspot number and the CME average maximum speed were reaching their minimum values.

3) There is a well-pronounced relationship between monthly averaged maximum CME speeds and sunspot numbers, Dst and Ap indices (correlation coefficients are 0.76, -0.53, 0.68 respectively). This high correlation between CME speed and geomagnetic activity further emphasizes important role of the speed of Earth directed ejecta as a geo-effective parameter.

4) A well defined peak of the Ap index between May 2002 and August 2004 was co-temporal with the excess of the mid-latitude coronal holes.

5) CME speed index displays significant cyclic behavior, which is in parallel with both solar and geomagnetic activity.

We acknowledge usage of ISSN and Ap index from National Geophysical Data Center. The Dst index data was provided by the World Data Center for Geomagnetism at Kyoto University. The CME catalog is generated, and maintained by the Center for Solar Physics and Space Weather, the Catholic University of America in cooperation with the Naval Research Laboratory and NASA. SOHO is a project of international cooperation between ESA and NASA. We thank W. Cao for help during the manuscript preparation. This research was supported by NASA grants GI NNX08AJ20G and LWS NNX08AQ89G as well as NSF ATM0716512 grant.

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