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Prediction of Space Weather Using an Asymmetric Cone Model for Halo CMEs

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Abstract Halo coronal mass ejections (HCMEs) are responsible of the most severe geomagnetic storms. A prediction of their geoeffectiveness and travel time to Earth's vicinity is crucial to forecast space weather. Unfortunately, coronagraphic observations are subjected to projection effects and do not provide true characteristics of CMEs. Recently, Michalek (*Solar Phys.* **237**, 101, 2006) developed an asymmetric cone model to obtain the space speed, width, and source location of HCMEs. We applied this technique to obtain the parameters of all front-sided HCMEs observed by the SOHO/LASCO experiment during a period from the beginning of 2001 until the end of 2002 (solar cycle 23). These parameters were applied for space weather forecasting. Our study finds that the space speeds are strongly correlated with the travel times of HCMEs to Earth's vicinity and with the magnitudes related to geomagnetic disturbances.

Keywords Sun: solar activity · Sun: coronal mass ejections · Sun: space weather

1. Introduction

Halo coronal mass ejections (HCMEs) originating from regions close to the central meridian of the Sun and directed toward Earth cause the most severe geomagnetic storms (Gopalswamy, Yashiro, and Akiyama, 2007, and references therein). Therefore, it is very important to determine the kinetic and geometric parameters describing HCMEs. One of the most important parameter is the space speed of CMEs used as input to CME and shock arrival models. Unfortunately, coronagraphic observations from the Sun – Earth line are subjected

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to projection effects (*e.g.*, Kahler, 1992; Webb *et al.*, 2000; St. Cyr *et al.*, 2000; Gopalswamy, Lara, and Yashiro, 2003; Gopalswamy *et al.*, 2001; Gopalswamy, 2004; Gopalswamy, Yashiro, and Akiyama, 2007; Yashiro *et al.*, 2004). There have been several attempts to obtain space speeds and other parameters of CMEs [Zhao, Plunkett, and Liu (ZPL), 2002; Michalek, Gopalswamy, and Yashiro (MGY), 2003; Xie, Ofman and Lawrence (XOL), 2004]. These techniques need special measurements in the Large Angle Spectroscopic Coronagraph (LASCO; Brueckner *et al.*, 1995) field of view. These models assume that CMEs have cone shapes and propagate with constant speeds. Recently, Michalek (2006) determined the space parameters of HCMEs with an asymmetric cone model using the projected speeds obtained at different position angles around the occulting disk. In the present study we use this technique to get the space characteristics of all front-sided HCMEs observed by LASCO in a period of time form 2001 until the end of 2002. Next, we use these parameters to obtain the travel times (TTs) of CMEs to Earth's vicinity and the magnitudes of the geomagnetic disturbances (Dst index). The paper is organized as follows: Section 2 describes the method used to determine the space parameters presented here. In Section 3, we use the improved parameters for space weather forecasting. Finally, conclusions are presented in Section 4.

2. Determination of the Space Parameters of HCMEs

Michalek (2006) implemented a cone model to obtain the space parameters free from projection effects. The model assumes that the shape of HCMEs is an asymmetric cone and that they propagate with constant angular widths and speeds, at least in their early phase of propagation. We can determine the following HCME parameters: the longitude of the cone axis (φ), the latitude of the cone axis (λ), the angular width α (cone angle $= 0.5\alpha$), and the space velocity V_{space}. CMEs often have a flux-rope geometry (*e.g.*, Chen *et al.*, 1997, 2000; Dere *et al.*, 1999; Plunkett *et al.*, 2000; Forbes, 2000; Krall *et al.*, 2001; Chen and Krall, 2003), which encouraged us to introduce the asymmetric cone model in which the shape of CMEs is a cone but the cone cross section is an ellipse. The eccentricity and orientation of the ellipse are two additional parameters of the model. They are not important for space weather applications so we neglect them in the present study. The following procedure was carried out to obtain the parameters characterizing HCMEs. First, using the height – time plots the projected speeds at different position angles (every 15°) were determined. This allowed us to obtain 24 projected velocities for a given HCME, which are required for the fitting procedure. Second, using numerical simulation to minimize the root mean square error, we obtained the cone model parameters. Details of the numerical simulation and the equation used can be found in Michalek (2006). To save time, the simulation procedure was performed with constraints on the cone model parameters. We assumed that the space speed is not smaller than the maximal measured projected velocity for a given event. Second, using the Extreme ultraviolet Image Telescope (EIT) (Delaboudiniére *et al.*, 1995) and Solar Geophysical Data we determine the associated eruptive phenomena (coronal dimmings, erupting filaments, and Hα flares) that are coincident with the LASCO CME onset time. This allows us to estimate source regions of HCMEs on the solar disk and recognize front-sided events. The second assumption on the cone model parameters is that the cone model axis is localized in a quadrant of the Sun where the associated phenomena appear. To check these assumptions, for some events we performed the simulation for a wider range of the cone model parameters. Always, the best-fit cone model parameters fulfilled these constraints. Our numerical procedure allows us to place the apex of the cone at the center of the Sun or on the solar surface. In the previous paper (Michalek, 2006), we found that the better fits were obtained when the apex of a cone is placed at the center of the Sun, which is the position we use in this paper.

3. Data

The list of HCMEs studied in this paper is displayed in Table 1. We considered only front-sided full HCMEs during the period of time from the beginning of 2001 until the end of 2002. We select this limited period of time to get a representative sample of HCMEs that could be use to test our new cone model. In the SOHO/LASCO catalog 115 HCMEs are listed, 70 of which were front-sided. One of them was too faint to perform the necessary measurements. For the remaining 69 events height – time plots were obtained at different position angles (every 15°). The projected speeds from the height – time plots were then used for the fitting procedure to obtain the space parameters of HCMEs. Using data from the World Data Center (http://swdcdb.kugi.kyoto-u.ac.jp) allowed us to identify geomagnetic disturbances caused by these events. To find a relationship between HCMEs and magnetic disturbances a two-step procedure was performed. First, we found all geomagnetic disturbances, in the considered period of time (2001 – 2002), with Dst index ≤ -30 nT. This very high limit (-30 nT) was chosen following Michalek *et al.* (2006). Such Dst values could also be attributed to other sources such as corotating interaction regions. We assume that the associated magnetic disturbance should start no later than 120 hours after the first appearance of a given event in LASCO field of view and no sooner than the necessary travel time of a given CME to Earth calculated from the measured maximal projected velocity. We related a given disturbance with a HCME if it was within the specified time range. Unfortunately, we were unable to follow CMEs during their entire trip to Earth, so there is some ambiguity in associating the magnetic storms with CMEs. During high solar activity there are frequently more than one CME that could be associated with a given magnetic disturbance. In our list there are some magnetic disturbances associated with two different halo CMEs. If we consider all CMEs included in the SOHO/LASCO catalog (not only HCMEs) a number of multiple magnetic storms could be found. Further study into this association can be found in Gopalswamy, Yashiro, and Akyama (2007).

Twenty events from our list were not geoeffective (Dst > -30 nT). These HCMEs were slow or originated closer to the solar limb. By examining solar wind plasma data (from Solar Wind Experiment on *Wind*; Ogilvie *et al.*, 1995) and interplanetary magnetic field data [from the *Wind* Magnetic Field Investigation (MFI) instrument; Lepping *et al.*, 1995], we identified interplanetary shocks driven by respective interplanetary CMEs (ICMEs). By measuring the time when a HCME first appears in the LASCO field of view and the arrival time of the corresponding shock at Earth the travel time can be determined (*e.g.*, Manoharan *et al.*, 2004). The results of our study are displayed in Table 1. The first two columns are from the SOHO/LASCO catalog and give the date of the first appearance in the LASCO field of view and the projected speeds (V). The width and space speeds (V_{space}) estimated from the cone model are shown in columns 3 and 4, respectively. In column 5 the r.m.s error (in km s^{-1}) for the best fits are given. The parameters γ and source locations are shown in columns 6 and 7, respectively. In column 8 the minimal values of Dst indices for geomagnetic disturbances caused by HCMEs are presented. Finally, in column 9 the travel times to Earth of magnetic clouds are given.

Table 1 List of front-sided halo CMEs (2001 – 2002).

Date	V (km s^{-1})	Width (deg)	V_{space} (km s^{-1})	Error (km s^{-1})	γ (deg)	Source location	Dst (nT)	TT (hours)
2001/01/10	832	59	1290	57	80	S04E09	–	–
2001/01/20a	839	111	893	55	57	N06E32	−61	66
2001/01/20b	1507	115	1513	219	47	N09E42	−61	64
2001/01/28	916	152	1080	95	39	S19W48	−40	68
2001/02/10	956	59	1090	63	75	N14E04	−50	69
2001/02/11	1183	93	1150	106	62	N13W24	−50	50
2001/03/19	389	54	700	33	81	N01E08	−75	81
2001/03/24	906	71	1088	88	70	N15E13	−56	72
2001/03/25	677	81	1070	115	70	N16W12	−87	67
2001/03/28	519	134	540	59	75	S13E07	–	–
2001/03/29	942	53	2731	139	87	N02W02	−387	38
2001/04/01	1475	96	1470	85	58	N04E31	–	–
2001/04/05	1390	115	1360	117	58	N13E29	−59	49
2001/04/06	1370	141	1243	116	75	N07E13	−63	41
2001/04/09	1192	76	1549	54	77	S08W10	−271	46
2001/04/10	2411	81	2680	161	77	S11W06	−271	33
2001/04/11	1103	66	1423	95	72	S12W12	−77	42
2001/04/12	1184	70	1610	98	73	S04W16	−75	35
2001/04/26	1006	62	1396	55	76	N12E09	−47	41
2001/08/14	618	62	1042	70	84	N05W02	−105	67
2001/08/25	1529	141	1529	144	44	S27E38	–	–
2001/09/11	791	105	803	79	56	N03E33	–	–
2001/09/24	2402	68	3010	115	71	S09E16	−102	34
2001/09/28	846	65	1293	33	82	S08E01	−148	59
2001/10/01	1405	111	1415	175	49	S30W29	−166	55
2001/10/09	973	101	1116	51	65	S25E02	−71	54
2001/10/19	558	69	803	47	69	N01W21	–	–
2001/10/19	901	63	1465	26	83	N03W06	−187	48
2001/10/22	1336	51	2180	76	80	S05E08	−57	35
2001/10/25	1090	76	1335	50	75	S14W02	−157	58
2001/11/01	453	57	732	52	72	N06W16	–	–
2001/11/03	457	128	560	41	57	N29W15	–	–
2001/11/04	1810	74	2530	108	82	N01W07	−292	33
2001/11/17	1379	130	1460	112	54	N25E26	−48	54
2001/11/21	518	92	615	32	70	S15W13	–	–
2001/11/22a	1443	70	1683	71	70	S15W17	−221	35
2001/11/22b	1437	100	1833	82	73	N06W16	−221	33
2001/11/28	500	75	850	30	76	S10E09	–	–
2001/12/13	864	104	910	49	76	N13W05	−39	87
2001/12/14	1506	130	1493	143	43	S22E42	−39	39
2001/12/28	2216	131	2073	164	43	S28E52	–	–

Table 1 (*Continued*)

Date	V (km s^{-1})	Width (deg)	V_{space} (km s^{-1})	Error (km s^{-1})	γ (deg)	Source location	Dst (nT)	TT (hours)
2002/01/04	896	131	1096	160	40	N41E30	–	–
2002/01/14	1492	138	1600	109	55	S15W31	–	–
2002/02/20	952	77	965	90	65	S02W24	–	–
2002/03/10	1429	93	1475	137	62	S09E26	–	–
2002/03/11	950	107	955	34	54	S18E31	–	–
2002/03/14	961	99	1000	46	65	S25E01	−37	93
2002/03/15	957	114	1030	47	79	N10W02	−37	62
2002/03/18	989	101	947	42	64	N11W22	–	–
2002/03/22	1750	81	1725	149	61	S11W27	−100	39
2002/04/15	720	80	1033	31	87	S01W02	−127	56
2002/04/17	1240	61	1720	48	76	N06W12	−149	60
2002/04/21	2393	100	2381	325	56	S10W32	−57	49
2002/05/07	720	68	831	39	76	S05E13	−110	79
2002/05/08	614	50	961	56	83	S05W05	−110	69
2002/05/16	600	60	1022	38	77	S10E08	−58	67
2002/05/22	1557	68	1724	86	71	S12W14	−109	32
2002/07/15	1151	67	1081	28	69	N18E10	–	–
2002/07/18	1099	104	1110	66	66	N20W13	−38	94
2002/07/20	1941	125	1683	255	46	N01E44	−38	32
2002/07/23	2285	106	2018	328	81	S08E29	–	–
2002/07/26	818	80	846	36	65	S21E13	–	–
2002/08/16	1585	88	1576	68	74	S14E06	−106	54
2002/08/22	998	119	1151	133	52	S27W27	−45	106
2002/08/24	1913	117	1890	217	48	S20W37	−45	57
2002/09/05	1748	41	2638	52	75	S08E12	−181	45
2002/11/09	1838	92	1673	96	63	S16W22	−43	48
2002/11/24	1077	70	1433	70	81	N06E06	−64	50
2002/12/19	1092	75	1155	49	72	N06W17	−75	68

4. Implication for Space Weather Forecasting

For space weather forecasting it is crucial to predict, with good accuracy, onsets (TT) and magnitudes (Dst) of magnetic storms. In the next two subsections, we consider these issues using the determined space velocities.

4.1. Predictions of Onsets of Geomagnetic Disturbances

Figure 1 shows the scatter plots of the plane of the sky speeds (from the SOHO/LASCO catalog) versus travel times. Diamond symbols represent events originating from the western hemisphere and cross symbols represent events originating from the eastern hemisphere. The dashed line is a polynomial fit to data points (a third-degree polynomial function). The correlation coefficients are 0.68 for the western and 0.49 for the eastern events, respectively. The standard error in determination of the travel time is $\pm$ 16 hours.

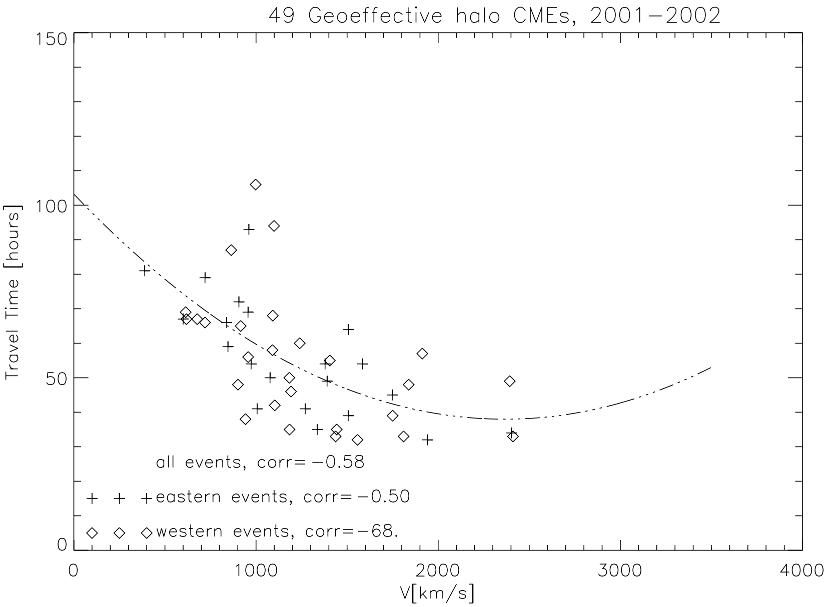

Figure 1 The scatter plot of the sky-plane speed versus the HCME travel time. Diamond and cross symbols represent events originating from the western and eastern hemispheres, respectively. The dot-dashed line is a polynomial fit to all the data points.

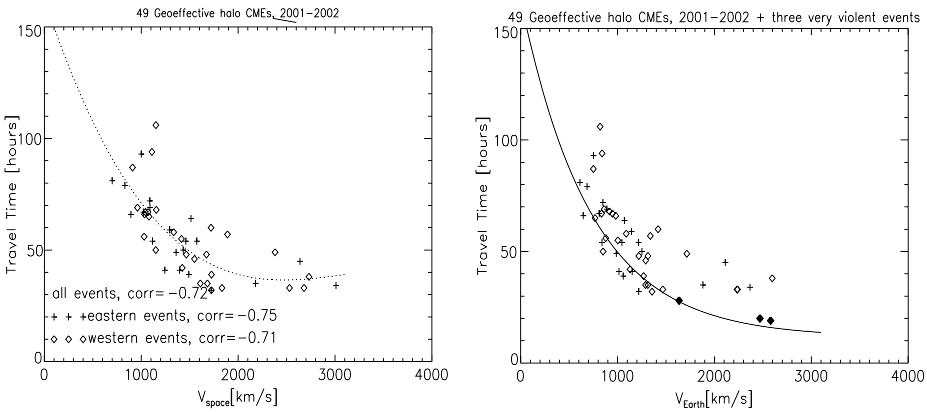

Figure 2 The scatter plots of the space (left panel) and Earth-directed velocities versus the HCME travel time. Diamond and cross symbols represent events originating from the western and eastern hemispheres, respectively. The dot-dashed line (left panel) is a polynomial fit to all the data points. The continuous line (right panel) is the ESA model representation. The three additional dark diamonds (only on the right panel) show the HCMEs (14 July 2000, 28 October 2003, and 19 October 2003) of historical importance.

For comparison, we present in Figure 2 (left panel) a similar plot except for the space speeds. The figure clearly shows that the space speeds are strongly correlated with TT. Now the correlation coefficients are more significant: 0.71 for the western and 0.75 for the eastern events. The standard error in determination of the travel time is only ± 10 hours. In Figure 2 (right panel) we also show a similar plot but for the space speeds projected in the Earth direction. To illustrate that our considerations are consistent with previous results we compare them with the ESA model (the continuous line; Gopalswamy *et al.*, 2005b). For these plots we used only the 49 geoeffective (Dst ≤ -30 nT) events. For comparison, in Figure 2 (right panel) we added the three events (14 July 2000, 28 October 2003, and 19 October 2003) of historical importance, represented by the dark diamonds.

4.2. Magnitudes of Geomagnetic Storms

Magnitudes of geomagnetic disturbances depend not only on the velocities of CMEs but also on the location of source region on the solar disk (*e.g.,* Gopalswamy, Yashiro, and Akiyama, 2007). For our cone model positions of the source regions are characterized by the parameter γ, which is the angular distance of the CME from the plane of the sky. This parameter decides which part of a HCME hits Earth. Events with small γ strike Earth with their flanks whereas those with large γ hit Earth with their central parts. Figure 3 shows the scatter plot of the plane of the sky speeds multiplied by γ versus Dst index. The parameter γ was determined from the location of the associated flares. There is a slight correlation between $V\gamma$ and Dst. The correlation coefficients are ~ 0.49 for the western and ~ 0.30 for the eastern events, respectively.

For comparison, Figure 4 shows a $V\gamma$ plot but for the space parameters. Now the parameters ($V_{\rm space}, \gamma$) were estimated from the model (see Michalek, 2006). From inspection of the figure it is clear that the correlation between ($V_{\rm space}\gamma$) and Dst is more significant. The correlation coefficients are ~ 0.85 for the western and ~ 0.58 for the eastern events, respectively. It is clear that the space parameters, determined from the

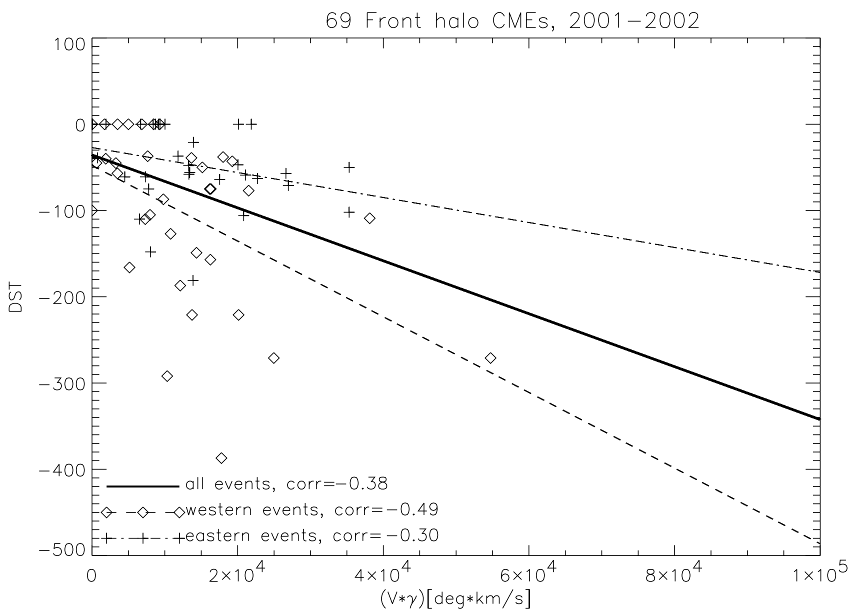

Figure 3 The scatter plot of the sky-plane speeds multiplied by γ versus Dst index. Diamond and cross symbols represent events originating from the western and eastern hemispheres, respectively. The solid line is a linear fit to all the data points, the dot-dashed line is a linear fit to the eastern events, and the dashed line is a linear fit to the western events.

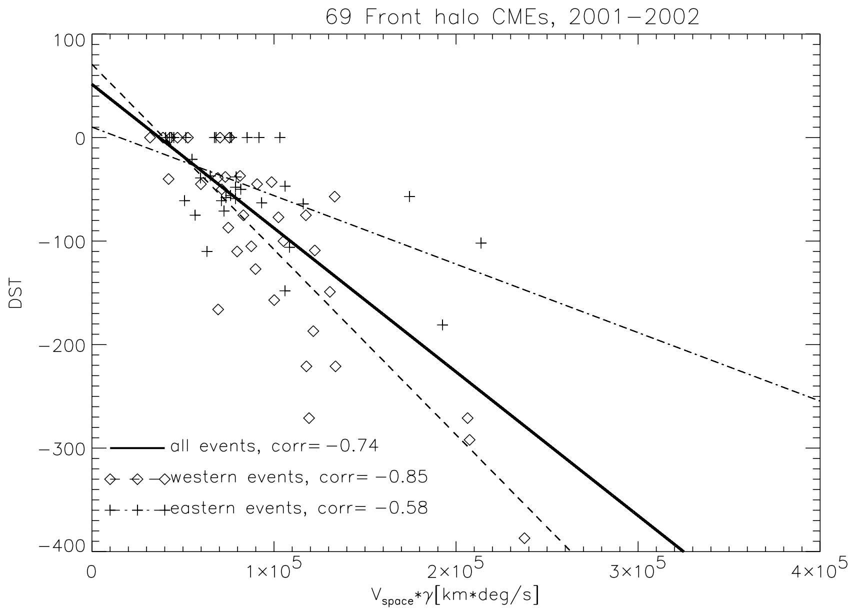

Figure 4 The scatter plot of $V_{\text{space}}\gamma$ versus Dst index. Diamond symbols represent events originating from the western and eastern hemispheres, respectively. The solid line is a linear fit to all the data points, the dot-dashed line is a linear fit to the eastern events, and the dashed line is a linear fit to the western events.

asymmetric cone model, could be very useful for space weather applications. Correlation coefficients are almost twice as large as those obtained from the projected speeds. For these plots (Figures 3 and 4), we used all HCMEs from Table 1, even the non-geoeffective ones. These events generate false alarms. Nongeoeffective HCMEs are slow ($V < 900\ \text{km}\,\text{s}^{-1}$) or have source region closer to the solar limb. The limb HCMEs appear as halo events only because of compression of preexisting coronal plasma. The investigation confirms that the western events are more geoeffective than the eastern ones (*e.g.*, Zhang *et al.*, 2003). Our investigation suggests that the severest geomagnetic storms (with Dst < -200 nT) were generated by the western events, although east-hemisphere CMEs are capable of causing such strong storms as well (Gopalswamy *et al.*, 2005a; Dal Lago *et al.*, 2006).

5. Summary

The prediction of the magnitudes and onsets of geomagnetic storms is crucial for space weather forecasting. Unfortunately, parameters characterizing HCMEs are poorly correlated with geomagnetic disturbances because of projection effects. In the present paper, we applied the asymmetric cone model (Michalek, 2006) to obtain space speeds and source locations of all front-sided HCMEs observed by SOHO/LASCO in the period of time from the beginning of 2001 until the end of 2002. These parameters were used for prediction of the strength (Dst) and onsets (TT) of geomagnetic storms (Figures 2 and 4). The results are very promising. Correlation coefficients between the space speeds and parameters characterizing geomagnetic storms (TT and Dst) are very significant and almost twice as large as results for the projected speeds. The standard error in the prediction of the travel time is equal to ~ 10 hours, almost 60% lower than for the projected speeds. It is interesting to compare our results to other cone models. Xie *et al.* (2006) calculated absolute differences between predicted (using the ESA model; Gopalswamy *et al.*, 2005b) and observed shock travel times for the previous cone models (XOL, MGY, and ZPL). They found that the mean errors for those models were 6.5, 12.8, and 9.2 hours, respectively. In the present considerations, the mean difference between predicted (using the polynomial fit from Figure 2) and observed shock travel times is 8.4 hours, four hours less than in our previous cone model (MGY). Many authors have considered the relation between speeds and geoeffectiveness of CMEs (*e.g.,* Tsurutani and Gonzales, 1998; Lindsay *et al.*, 1999; Cane, Richardson, and St. Cyr, 2000; Wu and Lepping, 2002; Srivastava and Venkatakrishan, 2002; Yurchyshyn, Wang, and Abramenko, 2004). Those studies demonstrated that the initial speeds of CMEs are correlated with the Dst index but because they applied the plane of the sky speeds, the correlation coefficient were not significant. Recently, Michalek *et al.* (2006) showed that the correlation between the space speed of HCMEs and Dst index could be much more significant (with a correlation coefficient of ~ 0.60). In the present study we considered the correlation between $V_{\text{space}}\gamma$ and Dst index. We found that this correlation could be very significant (~ 0.85 for the western events). This confirms previous results that geoeffectiveness of HCMEs depends not only on the HCMEs speeds but also on the direction of their propagation (Moon *et al.*, 2005; Michalek *et al.*, 2006; Gopalswamy, Yashiro, and Akiyama, 2007). The present study shows that the asymmetric cone model could be very useful for space weather forecasting. There are two important advantages of this method. First, using our asymmetric cone model can help predict space weather with good accuracy. Second, to predict space weather we need observational data from one instrument only (a coronagraph along the Sun – Earth line such as the LASCO coronograph). The method also has some limitations. Faint HCMEs could not be used for this study because it is difficult to get the height – time plots around the entire occulting disk. Fortunately, such poor events are generally not geoeffective so they are not of immediate concern (we missed only one front-sided HCME). We consider a flat cone model (not an ice-cream-cone model), so in some cases the measured projected velocities, and as a consequence the space speeds, could be slightly overestimated. We need to keep in mind that the magnetic field direction at the front of magnetic cloud (or ICME) determines to a large degree the geoeffectiveness of events. Unfortunately, this in situ measurement can only be recorded at Earth's vicinity and it cannot be used for space weather forecasting owing to time constraints. When considering the asymmetric cone model, it is important to note that CMEs have more complicated 3D structures (Cremades and Bothmer, 2004) and more factors need to be determined to have a better understanding of what produces the geomagnetic storms at Earth.

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