On Classification of Solar Coronal Mass Ejections Observed by LASCO/SOHO during period 1996-2011

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Abstract. A study is performed to address the question of whether two types of CME events exist or not. From the study, we find that ~49.4% of CME events are decelerated while ~50.6% of CMEs is accelerated during their journey from solar surface to corona and beyond. Thus we classified CME events as two types of CMEs: accelerated CMEs and decelerated CMEs. The kinematics study of linear speed of CMEs and acceleration of CMEs support the view of existence of two types of CMEs.

1. INTRODUCTION

Early measurements of the speeds of coronal mass ejections (CMEs) suggested that there are two distinct types of the speed profiles: slow CMEs, which are associated with eruptive prominences, and fast CMEs, which originate in solar active regions (Gosling et al.

1976). MacQueen & Fisher (1983) suggested the CME classification into two types by analyzing the height-speed plots of 12 loops like CMEs observed with the Mauna Loa K-Coronameter covering 1.2–2.4 $R_\odot$. They found that flares associated CMEs showed higher speeds and little accelerations, whereas eruptive-filament–associated CMEs exhibited lower speeds and large accelerations. St. Cyr et al. (1999) statistically studied, using MK3 (1.1–2.2 $R_\odot$) and Solar Maximum Mission (SMM; 2.0–5.6 $R_\odot$) data from 1980 to 1989 and reported two classes of CMEs. According to this study, 59% of the CMEs (17 out of 29 events) associated with active regions moved with constant speeds, whereas 76% of the CMEs (13 out of 17 events) associated with prominence eruptions moved with constant accelerations. Sheeley et al. (1999) also classified CMEs into two classes: (1) gradual CMEs, which have speeds in the range 400–600 km /s are associated with erupting prominences, and (2) impulsive CMEs, which are associated with solar flares and have speeds greater than or equal to 750 km/ s. Low & Zhang (2002) found that the speed-height profiles of all CMEs taken together do not form two discrete populations but rather represent a continuous spectrum which indicates that the classification of CMEs into two distinctive groups is not distinct.

Low & Zhang (2002) presented a qualitative theory in which the two kinds of CMEs are represented by different initial states of the erupted magnetic configuration; on other hand Chen & Krall (2003) concluded that one mechanism is sufficient to explain the bimodal speed distribution. Yurchyshyn et al (2005) analyze the statistical properties of 4315 LASCO/ SOHO CMEs and they found that to a good approximation they can be fitted with a single lognormal distribution, and further concluded that, statistically, there is no physical distinction between the accelerating and the decelerating events.

In present investigation we have used CMEs data observed by LASCO/ SOHO satellite during the period of time interval January 11, 1996 to December 31, 2011 (~16 years) to understand the question of whether CMEs belongs to two classes or single class

2. OBSERVATIONAL DATA AND ANALYSIS

Data Source:

http://cdaw.gsfc.nasa.gov/CME_list/

Total number of CMEs = 17809
CMEs exclude from study= 12311
CMEs available for study= 4785
Number of accelerated CMEs = 2423
Number of decelerated CMEs = 2362

In Table 1 we have shown the various parameters of CMEs observed during the time interval of 1996-2011.

TABLE 1

NUMBER OF CMEs, NUMBER OF CMEs WITH ID, NUMBER OF ACCELERATED CMEs AND NUMBER OF DECELERATED CMEs FOR PERIOD OF 1996-2011

Year	**No. of CMEs**	**No. CMEs with ID**	**Accelerated CMEs number**	**Decelerated CMEs number**
1996	206	174	22	10
1997	385	249	86	50
1998	716	426	170	120
1999	1016	605	193	218
2000	1663	891	321	451
2001	1449	789	383	327
2002	1700	941	336	423
2003	1130	773	180	217
2004	1102	732	191	179
2005	1249	878	211	160
2006	1046	950	66	30
2007	1442	1387	35	20
2008	863	30	11	12
2009	746	713	23	10
2010	1117	1008	71	38
2011	1979	1765	124	90
Total	17809	12311	2423	2362

In order to understand data of Table 1 graphically, we have plotted a histogram between Year (1996-2011) versus yearly number of CMEs observed between 1996-2011 in upper left frame of Figure 1, in upper right frame of Figure 1 we have plotted a histogram between year versus yearly number of CMEs having incomplete data (ID), in lower left frame of Figure 1 we have plotted a histogram between year versus yearly number of accelerated CMEs and in lower right frame of Figure 1 we have plotted a histogram between year versus yearly number of decelerated CMEs.

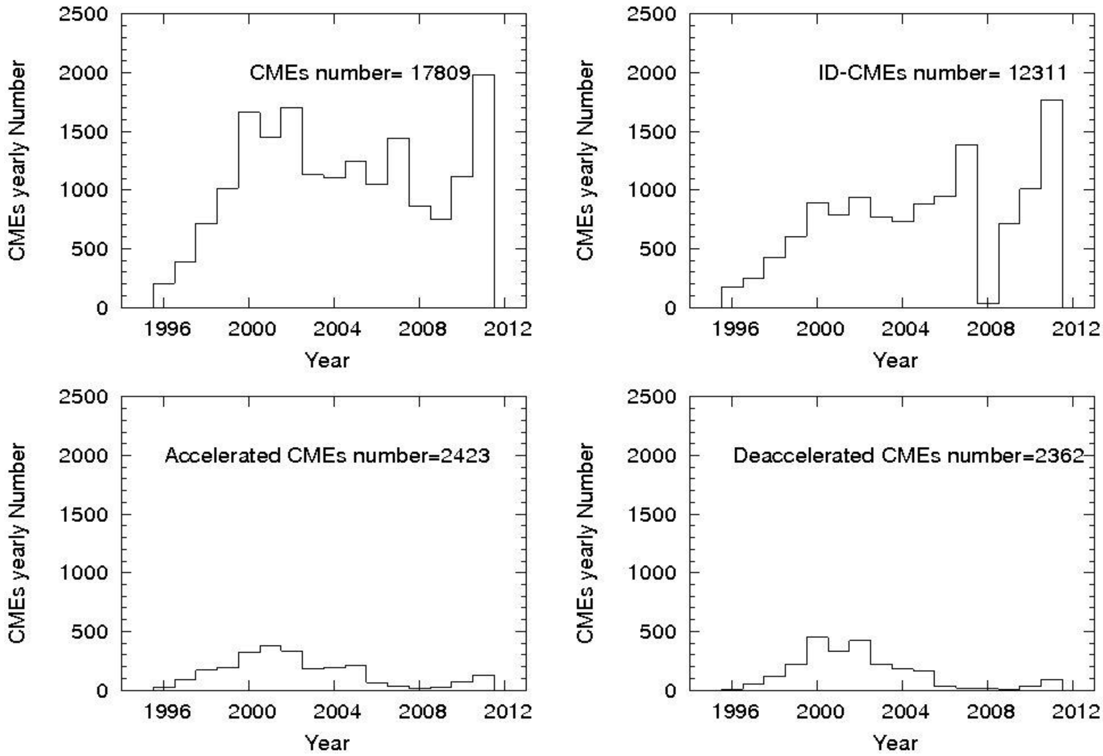

Fig. 1. Top left figure shows a plot of year versus total CMEs yearly number, top right figure shows a plot of year versus CMEs yearly number with incomplete data, bottom left figure shows a plot of year versus CMEs yearly number for accelerated class of CMEs, and bottom right figure shows a plot of year versus CMEs yearly number for decelerated class of CMEs.

The yearly average acceleration (m/s^2) of decelerated CME events and accelerated CME events are shown in column 6 of Tables 2 and 3, respectively. The various rows column 1 of Table 2 show year of CMEs observations, the rows of column 2 of Table 2 show number of accelerated CMEs observations in each year, the rows of column 3 of Table 2 show average width of accelerated CMEs observed in each year, the rows of column 4 of Table 2 show average linear speed (LS) of accelerated CMEs observed in each year and the rows of column 5 of Table 2 show average initial speed (IS) of accelerated CMEs observed in each year, and the column 6 of Table 2, shows that the value of yearly average of accelerations for accelerated CME events for time interval 1996 to 2011.

TABLE 2

CMEs NUMBERS, WIDTH, LINEAR SPEED, INITIAL SPEED AND ACCELERATION OF ACCELERATED CMEs FOR PERIOD OF 1996-2011.

Year	Accelerated CMEs Number	Average Width of CMEs	Average LS of CMEs	Average IS of CMEs	Average Acceleration Of CMEs
1996	22	91	365	258	9.3
1997	86	86	387	290	7.14
1998	170	80	452	352	8.74
1999	193	88	510	426	9.27
2000	321	84	501	418	9.83
2001	383	93	521	421	10.85
2002	336	81	542	453	11.75
2003	180	77	595	512	9.85
2004	191	95	477	386	10.12
2005	211	80	464	368	10.51
2006	66	90	418	314	9.3
2007	35	61	325	227	7.56
2008	11	91	370	242	7.28
2009	23	77	278	156	5.5
2010	71	97	421	273	9.88
2011	124	139	562	449	9.9

The various rows of column 1 of Table 3 show years of CMEs observations, the rows of column 2 of Table 3 show number of decelerated CMEs observations in each year, the rows of column 3 of Table 3 show average width of decelerated CMEs observed in each year, the rows of column 4 of Table 3 show average linear speed (LS) of decelerated CMEs observed in each year and the rows of column 5 of Table 3 show average initial speed (IS) of decelerated CMEs and the column 6 of Table 3 shows that the value of yearly average of accelerations (m/s^2) for decelerated CME events for time interval 1996 to 2011.

TABLE 3

CMEs NUMBERS, WIDTH, LINEAR SPEED, INITIAL SPEED AND ACCELERATION OF DECELERATED CMEs FOR PERIOD OF 1996-2011.

Year	Decelerated CMEs Number	Average Width of CMEs	Average LS of CMEs	Average IS of CMEs	Average acceleration of CMEs
1996	10	84	410	443	-5.27
1997	50	111	448	510	-7.69
1998	120	89	549	621	-9.27
1999	218	99	622	706	-12.4
2000	451	84	616	693	-12.51
2001	326	97	612	685	-10.6
2002	423	82	624	709	-13.76
2003	217	91	761	856	-16.34
2004	179	93	622	693	-12.67
2005	160	123	710	804	-18.06
2006	38	77	549	626	-14.29
2007	20	103	517	583	-6.98
2008	12	68	566	649	-12.81
2009	10	51	402	434	-3.92
2010	38	110	676	757	-10.54
2011	90	171	740	836	-14.94

We have plotted a histogram between accelerations of CMEs along x-axis and number of CMEs along y –axis. As shown in Figure 2. In plotting Figure 2 we have counted number of CMEs at acceleration gap of 20 (m/s^2). It is clear from Figure 2 that the number of CMEs with acceleration range -1 to -20 (m/s^2) is 1840, which is a ~78% of decelerated CMEs. Similarly, In Figure 2 we also noted that the number of CMEs with acceleration range 1 to 20 (m/s^2) is 2020 which is a ~83% of accelerated CMEs. The Figure 2 also indicate that out of 4787 CMEs with known accurate values of acceleration, 3860 CMEs are observed with acceleration are between -20 m/s^2 to 20 m/s^2 which is 80.7% of total CMEs.

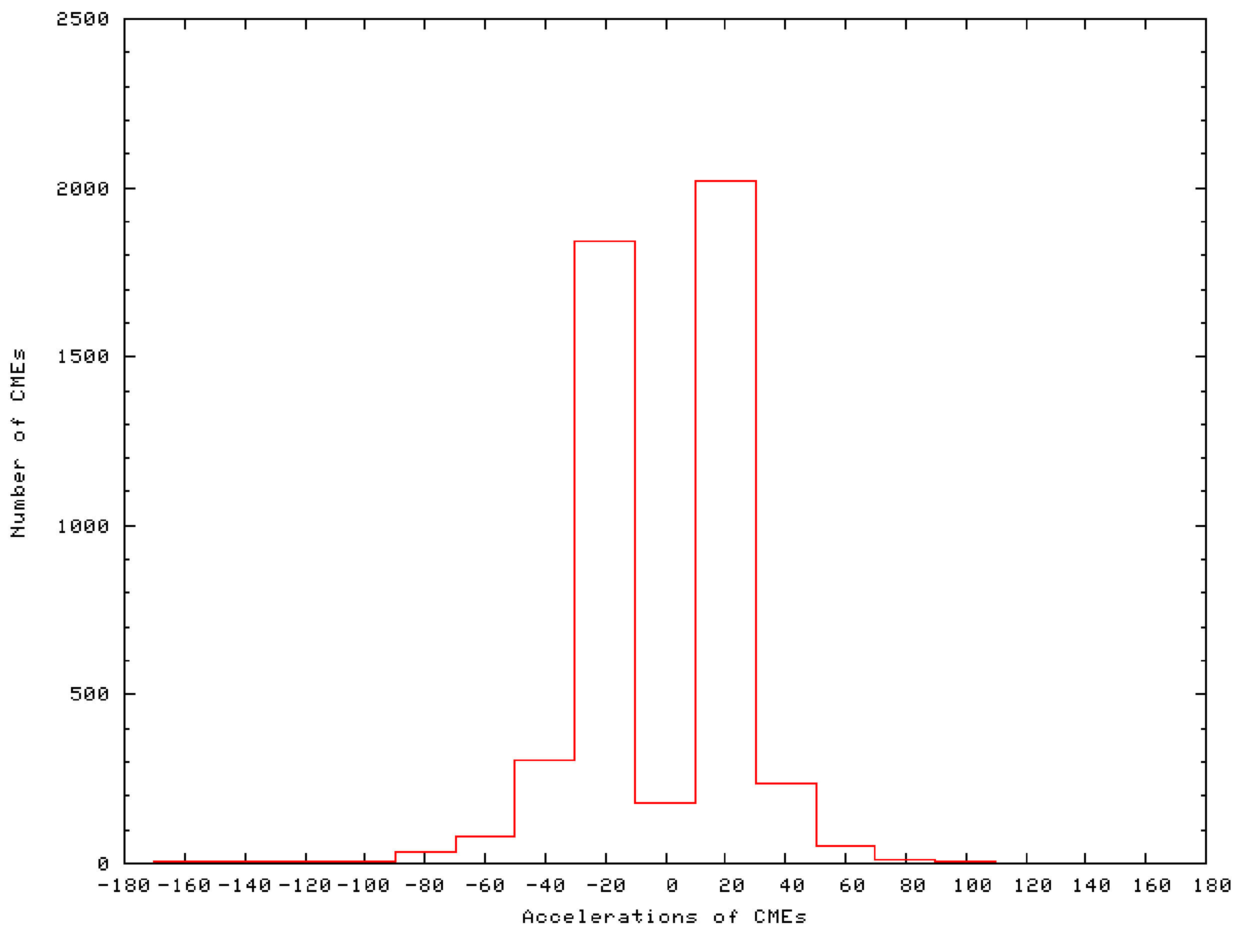

Fig. 2 shows plot of acceleration of CMEs (ms^{-2}) and number of CMEs.

In Figure 3, we have plotted CMEs linear speed or CMEs initial speed (km/s) versus number of CMEs for accelerated class CMEs and number of CMEs for decelerated class of CMEs. In upper left panel of Figure 3 we have plotted a figure between CMEs linear speed versus number of accelerated CMEs while in upper right panel of Figure 3 we have plotted a figure between CMEs initial speed versus number of accelerated CMEs. Similarly, in lower left panel of Figure 3 we have plotted a figure between CMEs linear speed versus number of decelerated CMEs while in lower right panel of Figure 3 we have plotted a figure between CMEs initial speed versus number of decelerated CME events.

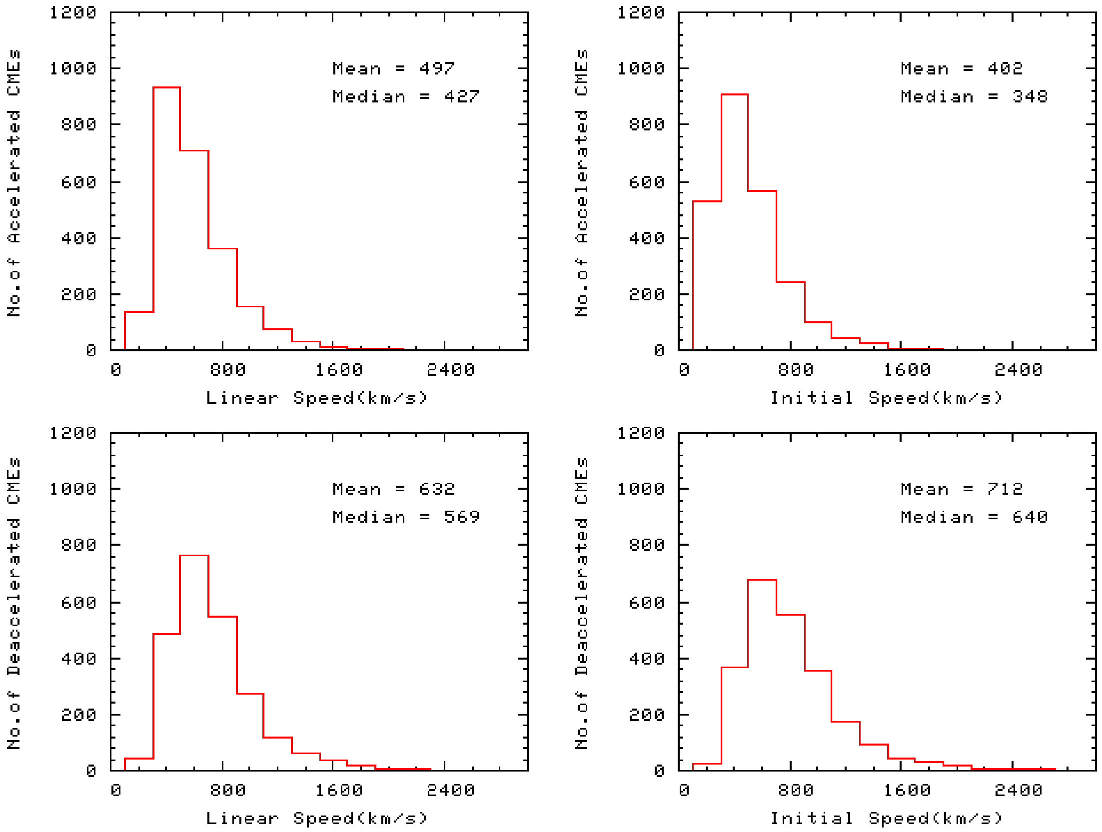

Fig. 3 The upper panel left side shows plot of linear speed and number of accelerated CMEs, upper panel right side shows plot of initial speed and number of accelerated CMEs. The lower panel left side shows plot of linear speed and number of decelerated CMEs, lower panel right side shows plot of initial speed and number of decelerated CMEs. The mean and median values of speed are shown in each panel.

. It is also evident from upper panel and lower panel of Figure 3 that the peak of linear speed of decelerated CMEs is showing larger values compare to peak of linear speed of accelerated CMEs. Similarly, It is also evident from upper panel and lower part of Figure 3 that the peak of initial speed of decelerated CMEs is showing larger values compare to peak of initial speed of accelerated CMEs.

In Figure 4 we have plotted linear speed of CMEs (km/s) along x-axis and accelerations of CMEs (m/s^2) along y-axis and also fitted a linear equation (Y=0.016X+7.688) to CMEs data as shown in Figure 4. The value of accelerations of CMEs data used in Figure 4 has a positive values and negative values of CMEs acceleration The value of correlation coefficient (R) for linear equation is R=0.27 which is very poor correlation.

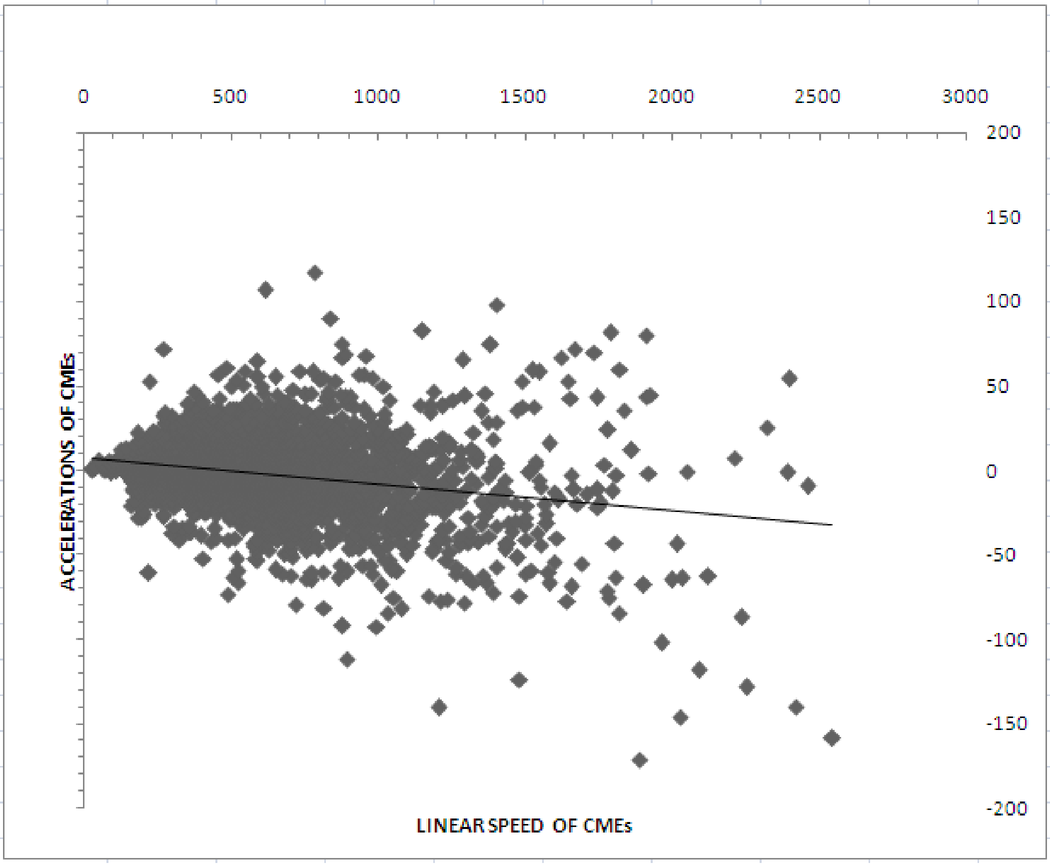

Fig. 4 shows plot of linear speed of CMEs (km/s) and acceleration of CMEs (ms^{-2}).

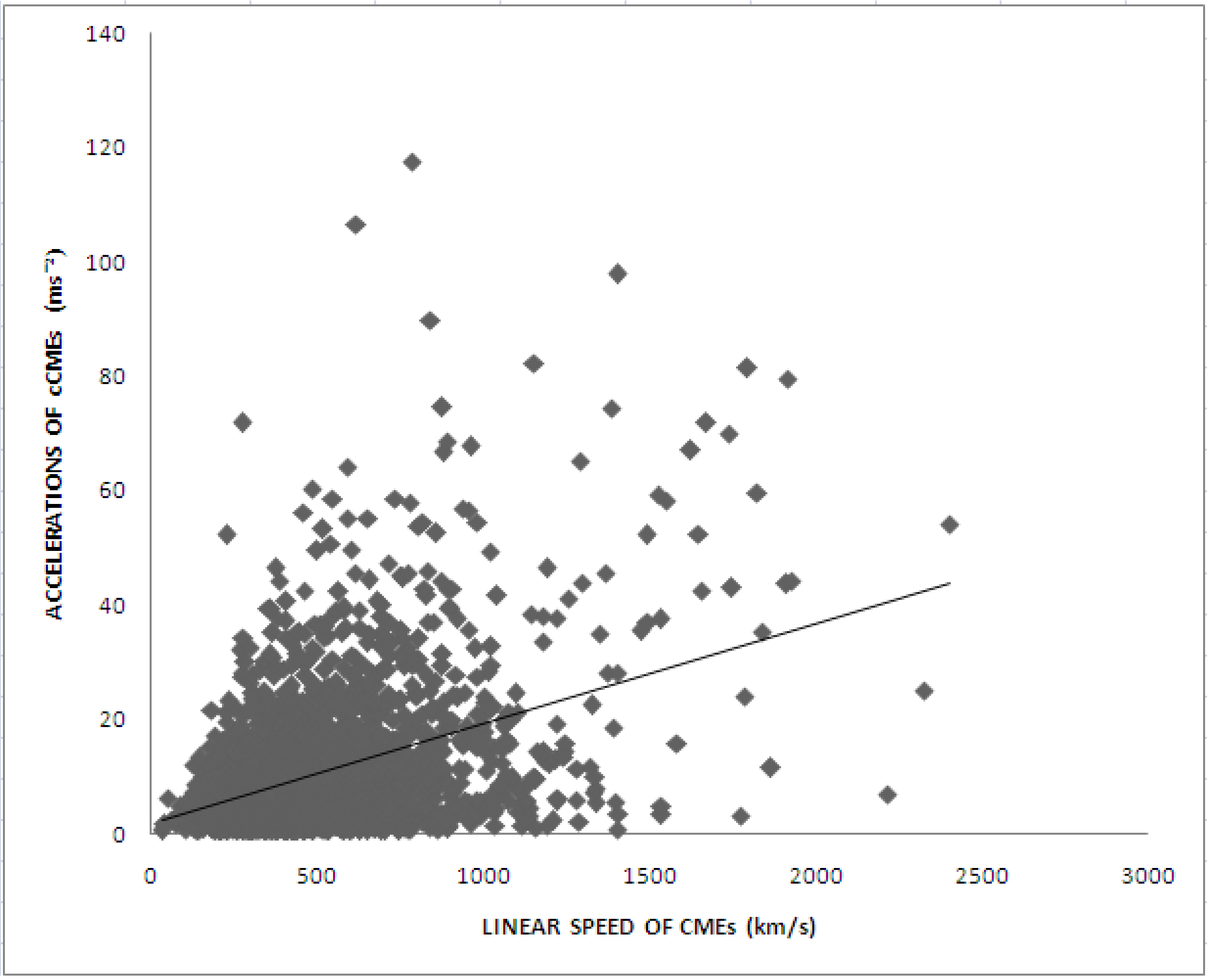

Fig. 5 shows plot of linear speed of CMEs and acceleration of accelerated CMEs.

This also suggests that the linear speed and acceleration of CMEs does not follow single mechanism of CMEs. To understand the kinematics of CMEs in better way we have divided CMEs data into two parts: positive accelerated or accelerated CMEs and negative accelerated or decelerated CMEs. In Figure 5 we have linear speed of positive accelerated CMEs along x-axis and acceleration of positive accelerated CMEs along y-axis. We have also fitted a linear equation (Y=0.028X+2.584) to positive accelerated CMES data and the equation is shown in Figure 5. The value of correlation coefficient (R) for linear equation is R=0.55 which indicate a fair correlation. This also indicates that the linear speed and acceleration of accelerated CMEs follow same mechanism and is a separate class of CMEs.

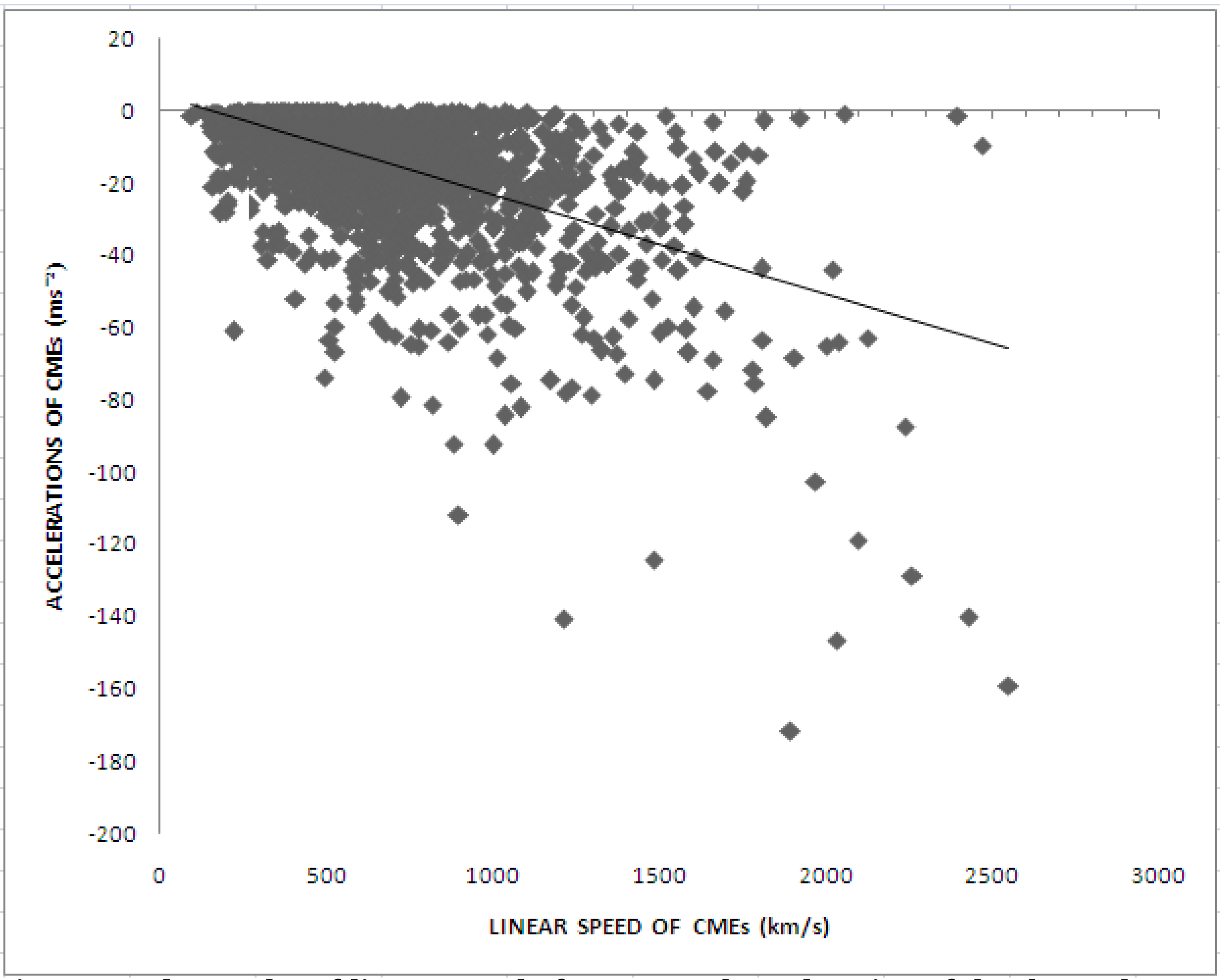

Figure 16 Shows plot of linear speed of CMEs and acceleration of decelerated CMEs

In Figure 6 we have plotted linear speed of decelerated CMEs along x-axis and acceleration of decelerated CMEs along y-axis. We have also fitted a linear equation (Y=0.037X+4.057) to decelerated CMEs data and the equation is shown in Figure 6. The value of correlation coefficient (R) for linear equation is R=0.61 which is a fair correlation. This also suggests that the linear speed of decelerated CMEs and acceleration of decelerated CMEs follow same mechanism and is a separate class of CMEs. These analyses clearly indicate that the accelerated CMEs and decelerated CMEs are two separate classes of CMEs.

3. RESULTS AND DISCUSSIONS

In Figures 4, 5 and 6, we have plotted linear speed of CMEs (km/s) along x-axis and accelerations of CMEs (m/s^2) along y-axis. The Figure 4 shows the value of correlation coefficient (R) for linear equation is R=0.27 which is very poor correlation. This also suggests that the linear speed and acceleration of CMEs does not follow single mechanism of CMEs. In Figure 5 we have linear speed of positive accelerated CMEs along x-axis and acceleration of positive accelerated CMEs along y-axis. We have also fitted a linear equation (Y=0.028X+2.584) to positive accelerated CMES data and the equation is shown in Figure 5. The value of correlation coefficient (R) for linear equation is R=0.55 which indicate a fair correlation. This also indicates that the linear speed and acceleration of accelerated CMEs follow same mechanism and is a separate class of CMEs. In Figure 6 we have plotted linear speed of decelerated CMEs along x-axis and acceleration of decelerated CMEs along y-axis. We have also fitted a linear equation (Y=0.037X+4.057) to decelerated CMEs data and the equation is shown in Figure 6. The value of correlation coefficient (R) for linear equation is R=0.61 which is a fair correlation. This also suggests that the linear speed of decelerated CMEs and acceleration of decelerated CMEs follow same mechanism and is a separate class of CMEs. These analyses clearly indicate that the accelerated CMEs and decelerated CMEs are separate class of CMEs.

Earlier, Verma and Pande (1989), Verma (1992), Verma (1998) and Verma (2002) suggested that the CME events are perhaps have been produced by some mechanism, in which the mass ejected by some solar flares or active prominences, gets connected with the open magnetic lines of CHs (coronal holes: source of high speed solar wind streams) and moves along them to appear as CMEs. Verma and Pande (1989) and Verma (1992) investigated 79 CMEs observed by P78-1 satellite during 1979-1982 and found that 61% CMEs were associated with coronal holes. Verma and Pande (1989) and Verma (1992) also suggested that mass ejected during solar flares and active prominences may move along the open magnetic field of coronal holes to appear as CMEs. Verma (1998) analyzed 154 CMEs observed by P78-1 satellite during the period of 1979-1982 and 1984-1985 and also found that 81 CMEs were associated with coronal holes. Verma (2002) analyzed 196 CMEs observed by LASCO/ SOHO during 2000 and found that CMEs are associated Hα flares and coronal holes. Verma (1998) and Verma (2002) also presented possible scenario of CMEs origin in the presence of coronal holes shown hereasFigure7.

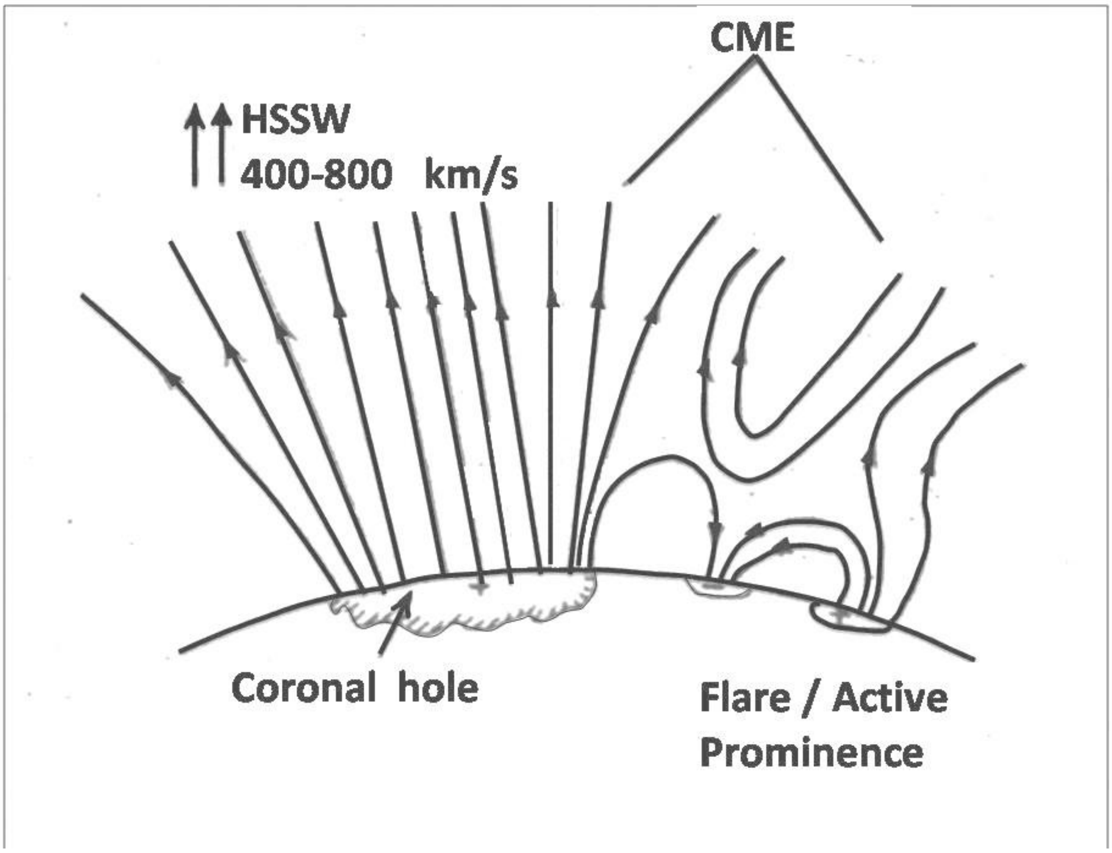

Fig. 11. Above figure shows the mechanism involved in origin of CMEs using reconnection scenario in presence of coronal hole and is adopted from the paper by Verma (1998) and Verma (2002).

As mentioned above in the present investigation we have found that the CMEs are of two types: accelerated type of CMEs and decelerated type of CMEs. Further, we are of the view that CMEs may be two types and the

CMEs may be originated through following mechanism:

1- Accelerated type of CMEs may be originating through mass ejection by small flares or activation/ eruptive prominences and early reconnection to open magnetic field of coronal holes at lower height in corona and moves as CMEs to higher coronal height including earth and beyond.
2- Decelerated types of CMEs may be originating through mass ejection by huge energy from solar flares or large eruptive prominence and late reconnection to open magnetic field of coronal holes at higher height and moves as CMEs to higher coronal height including earth and beyond.

The mechanism involved in origin of CMEs using reconnection scenario is shown in Figure 7 and is taken from paper by Verma (1998) and Verma (2002). The ejected mass to corona involved in CMEs phenomena in the accelerated class of CMEs and decelerated class of CMEs are initially produced by two separate class of mechanism but finally CMEs move to corona almost same average final speeds and beyond after reconnection with open magnetic lines of CHs. We are of the view that, for the formation of CMEs is a two step process: First step, Triggering include releasing of materials involved in CMEs formation is a necessary condition while in the second step, the reconnection of bipolar magnetic of flares or active prominence region with open magnetic field of CHs is a sufficient conditions. The necessary condition for the origin of CMEs that there should be some flares like solar active prominences which releases or ejects solar plasma material required for the formation of CMEs from a bipolar magnetic field area and the sufficient condition for the formation of CMEs, that there should a CHs in nearby area which produces high speed solar wind (400-800 km/s) and has open magnetic lines field.

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