CHAPTER-5

On Some Properties of Prominence Eruptions and the Associated CMEs in Solar Cycle 23

5.1 Introduction

It is well established that quite often prominence eruptions (PEs) are associated with coronal mass ejections (CMEs). There is a very close association between prominences and CMEs. In white light the CME is displayed as classical three part structure, i.e., a bright leading edge, dark cavity and then prominence or core material (Hundhausen, 1984). The prominences are generally long-lived and can be tracked on the solar disk for several days prior to their eruption. Detailed studies of prominences have been made by several authors (Tandberg-Hanssen, 1995, 2011 and references therein).

Coronal mass ejections are an important aspect of coronal and interplanetary dynamics. They cause large geomagnetic storm and can drive transient interplanetary shocks and energetic particle events. CMEs are often seen as spectacular eruptions of matter from the Sun, which propagate outward through the heliosphere and often interact with the Earth's magnetosphere (Hundhausen 1997, Mittal and Narain 2009, 2010 and references therein). It is well known that these interactions can have substantial consequences on the geomagnetic environment of the earth, sometimes resulting in damage to satellites

(Mittal et al. 2010). General information on CMEs has been well reviewed by several authors (Gosling 1997, Howard et al. 1997 and Hundhausen 1999, Webb and Howard 2012.)

In this paper, we have performed a statistical analysis for a large number of PEs and the associated CMEs observed by Nobeyama Radioheliograph (NORH), the Solar and Heliospheric Observatory (SOHO) using the Large Angle and Spectrometric Coronagraph (LASCO) during 1997-2006. SOHO/LASCO made measurements up to a heliocentric distance of about 32 solar radii (Brueckner et al. 1995). We have studied the solar cycle variation of different properties of PEs and the associated CMEs such as average and median speeds, angular width and the latitude of solar sources for cycle 23.The present study is important as PEs associated CMEs may provide an excellent source of advanced warning of geoeffective solar eruptions. This study provides a diagnostic tool for studying the association rate between PEs and CMEs. The predicting of prominences associated with CMEs is important for preventing damage to instruments in the space and at the earth.

5.2. Data and Analysis

The "Nobeyama Radio Heliograph" (NORH) is a Japanese interferometric array which observes the Sun in two frequencies, 17 and 34 GHz; from 22:30 to 6:30 UT, it provides high- quality data for up to 8 hours per day with little interruption due to weather conditions. We use only 17GHz images archived at the Nobeyama Radio Observatory for this study. Further details are available in

Gopalswamy (2003). We considered all the PE eruption events from 1997 to 2007, covering the minimum to the maximum periods of the solar cycle 23. During this period, 376 events were observed; out of which only 195 events are associated with CMEs.

The speeds and accelerations of prominences in this study are obtained from the NORH images. To estimate the velocity of prominence we downloaded all images of PEs from NORH data. All images are opened in software. We have selected two images in different times, which must show a height difference. On division by the actual height difference to the time difference (in seconds), the actual velocity of prominence in km/sec is obtained. The position angle is measured counter clockwise from the solar north pole to the bisector normal to the PE width. For association between prominences and CMEs, we have taken the SOHO/LASCO JAVA script movies and study height- time history between them. This procedure obviously cannot detect those prominences, which spend less than 30 minutes within the NORH field of view (FOV).

The acceleration, speed, width and position angle of the CMEs used in this study were obtained from the online SOHO/LASCO CME catalogue (http://cdaw.gsfc.nasa.gov/CME-list). We have used the data of CMEs from 1997 to 2006, which includes all the CMEs identified by LASCO operators during the period. The LASCO has some advantages over previous coronagraphs. It has much improved instrumental capabilities characterized by very low stray-lights, low noise levels, and a large dynamic range. In Yashiro et al. (2004), CME speeds were determined from linear fits to the height- time measurements, and accelerations were obtained from quadratic fits. Thus the speeds used in this study are corresponding to the representative speeds in the LASCO field of view. This task was performed by Yashiro et al. (2004), and the error was estimated at less than 10%. The position angle measured counter clockwise from the solar north pole to the bisector normal to the CME width.

5.3. Some properties of prominences and the associated CMEs

5.3.1. Speed of prominence and the associated CMEs

Mass motion is the basic characteristic of CMEs, which is quantified by their speeds. As the prominences are the inner core of CMEs, when a CME occurs, it leads the movement of the edge to a greater heliocentric distance. It is to be noted that the height-time measurements are made in the plane of the sky, so all the derived parameters are lower limits to the actual values. The height-time (h-t) plots fitted to first order polynomials give an average speed but it may not be suitable for all CMEs. Quadratic fitting to the h-t plot gives the constant acceleration which may also change with time (Gopalswamy, 2006).

The annual average and median speed of all types of prominences and the associated CMEs during the period 1997-2006 are shown in Table 1. The overall average and median speed of prominences are 51km/sec and 38km/sec respectively, and those of associated CMEs are 559km/sec and 526km/sec, respectively. The histogram of speeds in Fig. 5.1 and Fig. 5.2 exhibits the annual average and median speed distribution of PEs and the associated CMEs. The average speed of prominences varies from about 30km/sec to about 74km/sec and those associated CMEs varies from about 390km/sec to about 720km/sec. The speed distributions of PEs and the associated CMEs (Fig5.2) do not follow solar cycle 23. In the speed distribution of prominences (Fig5.1a), there is one peak in the year 1999 (in the rising phase of solar cycle 23) and another peak around 2001 (in maximum phase of solar cycle 23). In the speed distribution of associated CMEs (Fig5.1b) the maximum CME means speed occurs in the year 1998 and another peak occurs around 2003.

Table 5.1 Annual average and median speeds of prominences and the associated CMEs during 1997-2006.

year	number of events	Prominence Speed (km/sec)			Associated CMEs Speed (km/sec)		
		Average	Median	S.D.	Average	Median	S.D.
1997	8	39	34	30.92	408	374	207.19
1998	19	56	28	71.61	717	594	511.97
1999	28	73	74	56.66	596	542	269.08
2000	39	66	45	92.91	554	553	246.90
2001	34	66	52	62.95	505	490	201.51
2002	31	31	24	44.79	659	534	500.96
2003	10	44	31	43.81	669	667	287.68

2004	15	36	29	35.31	396	364	161.32
2005	8	42	22	31.83	623	633	217.09
2006	3	58	38	40.56	463	510	95.02

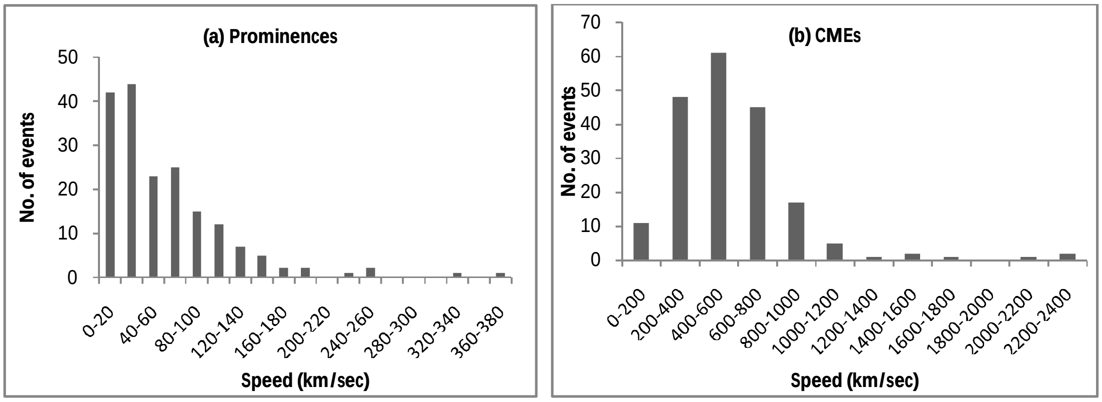


Fig5.1. Histogram shows the speed distribution of all prominences and the associated CMEs during 1997-2006.

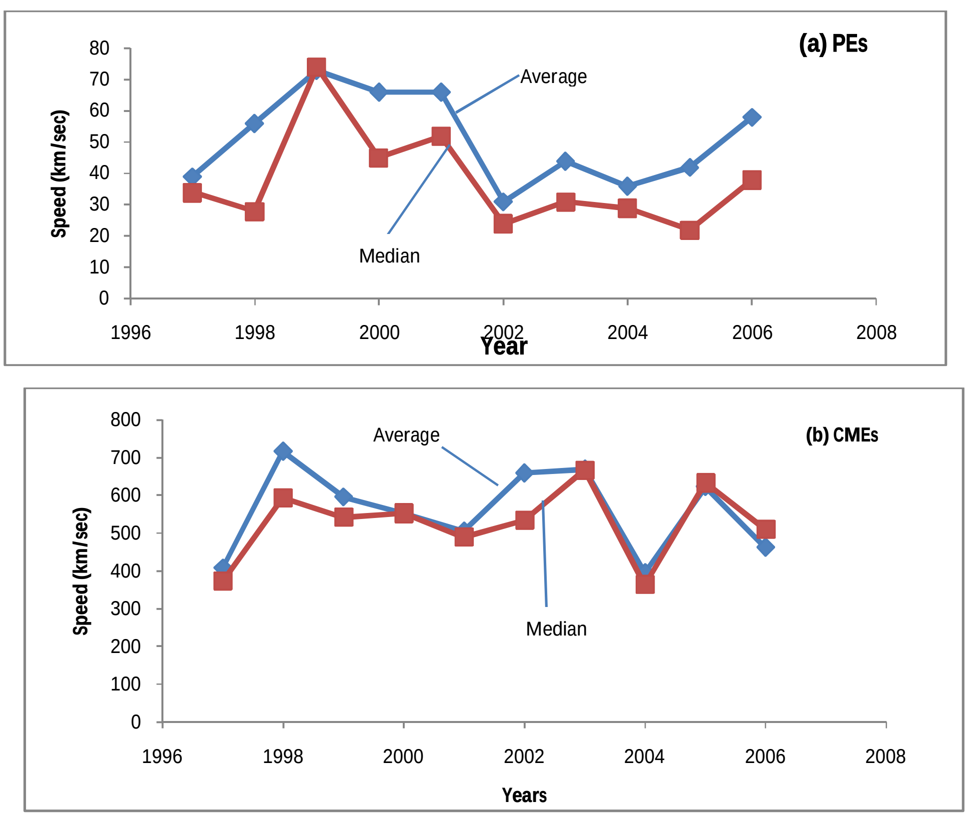


Fig5.2. Annual average and median speeds of prominences and the associated CMEs from 1997-2006.

5.3.2. Width of PEs and the associated CMEs

Width is measured as the position angle extent in the sky plane. For a prominence the angular width is measured from coordinate x and y where $x= r \cos\theta$, $y=r \sin\theta$ and $\theta= \tan^{-1} (y/x)$. For CME away from the limb, the measured width is likely to be an overestimated, but it should be true width for CME originating from close to the limb. Fig. 5.3 shows the histogram of apparent angular width for the period 1997-2006 and the annual average and median width distribution for the same period are shown in Fig5.4. The overall average and median width of prominences is 32^o and that of the associated CMEs are 74^o and 63^o, respectively. The average width of prominences varies from about 20^o to about 45^o and that of the associated CMEs varies from about 45^o to about 95^o. The average width of prominences is the smallest during solar minimum (1997-2006).The width distribution (Fig5.2) shows the solar cycle variation. The peak in width distribution of prominences (Fig5.4a) occurs around the year 2000 and declines slowly with minimum. In width distribution of associated CMEs (Fig5.4b), there is one peak in Year 2001 and another peak occurs in the year 1998.The numerical values of average, median, width and S.D. Of all types of prominences and the associated CMEs are shown in Table 5.2.

Table 5.2 Annual average and median widths of prominences and associated CMEs during 1997-2006.

year	number of events	Prominence (Width in degree)			Associated CMEs (Width in degree)		
		Average	Median	S.D.	Average	Median	S.D.
1997	8	35	38	12.21	64	65	24.81
1998	19	30	31	16.70	80	57	80.89
1999	28	40	43	18.20	77	60	61.62
2000	39	41	35	20.60	71	61	44.68
2001	34	40	44	17.11	94	72	74.33
2002	31	35	34	25.08	81	50	84.27
2003	10	26	30	15.57	80	76	65.16
2004	15	28	29	13.28	72	61	30.91
2005	8	24	24	10.90	45	48	19.86
2006	3	20	16	17.90	77	79	21.59

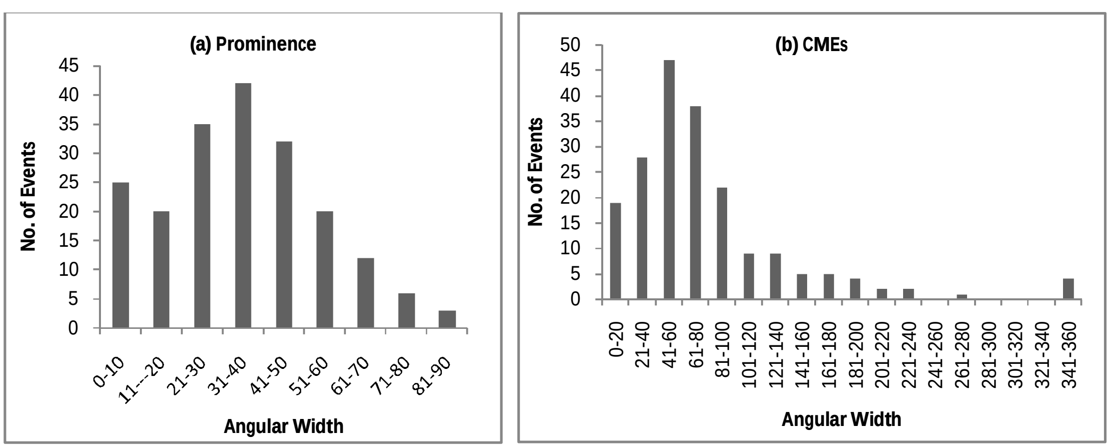


Fig5.3. Histograms show the width distribution of PEs and the associated CMEs during 1997-2006. In (b), last bin shows halo CMEs whose width is 360 degree.

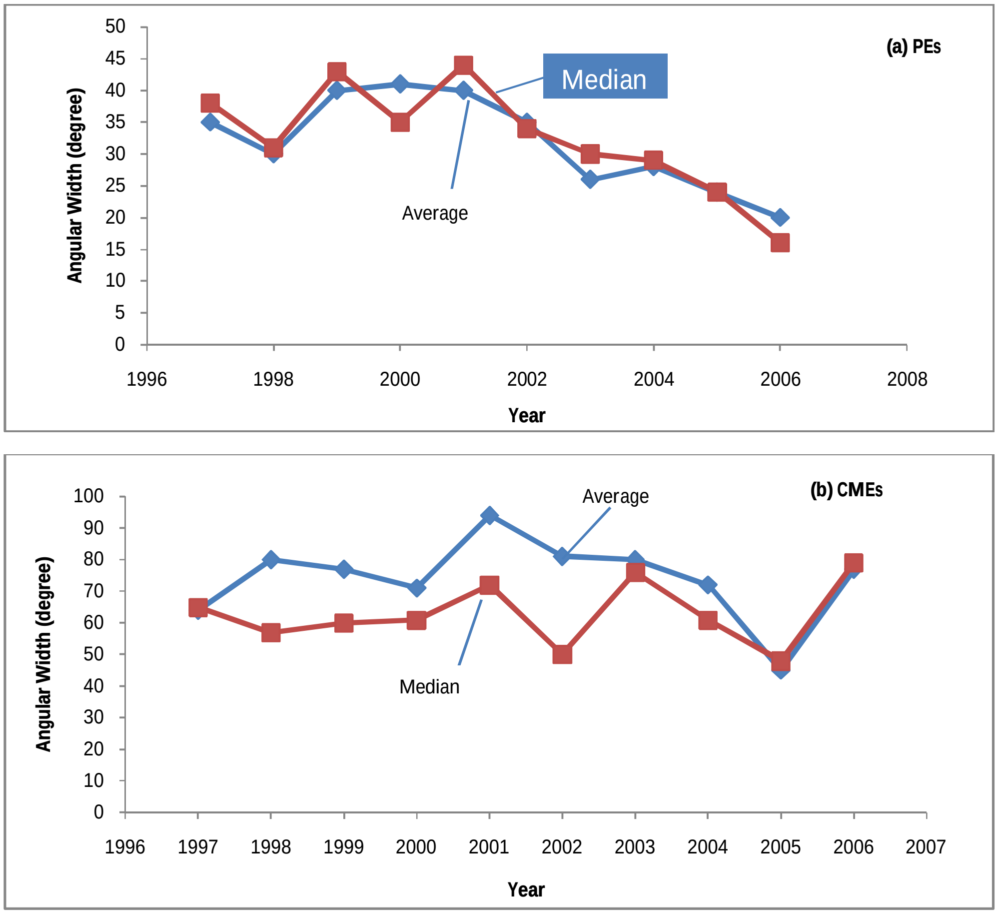


Fig5.4. Variation of annual average and median widths of PEs and the associated CMEs during 1997-2000.

5.3.3 Latitudes of PEs and the associated CMEs

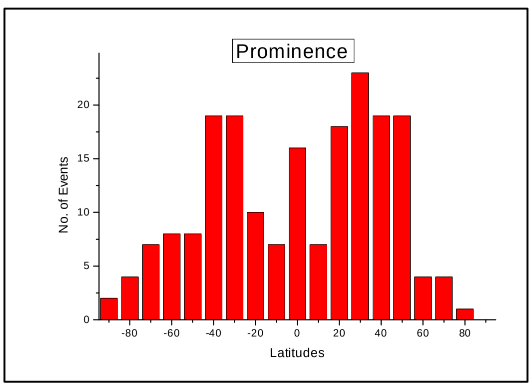
The latitudes are obtained from the central position angle. We have converted the observed position angle of the PE and CME events to heliographic latitudes. For example a prominence eruption from P.A. = 90 or 270 will be considered to have zero latitude, from P.A. = 0 or 360, it will be considered to be originated from a latitude of 90, and so on (Gupta et al. 2014). Figure 5.5 represents the latitude distributions of the 10 years (1997- 2006) period involving 195 prominences along with those associated with CMEs. The latitudinal distribution of the central position angles of prominences and corresponding CMEs tends to cluster about the equator at minimum, but broadens to cover all latitudes near solar maximum. During the decline phase of cycle 23 (2003 -2006), the latitudes of PEs and associated CMEs are generally close to the equator and afterward spread to all latitudes. The number of prominences is larger in the northern hemisphere, but associated CMEs are larger in the southern hemisphere. It is clear from Fig5.5 that an equal number of prominence and associated CMEs ejected from close to the equator.

Table 5.3 shows annual averages of latitudes of all types of PEs and the associated CMEs. The average magnitudes of latitudes of prominence and the associated CMEs are 32^o and 27^o, respectively. The solar maximum of cycle 23 which falls in the year 2000 and 2002 coincides with the maximum in the average magnitude of the latitude distribution (cf. Fig 5.6).

Table 5.3. the average magnitude of latitudes of prominences and the associated CMEs during 1997-2006.

Year	prominence Average $\lvert latitude \rvert$ (deg)	Associated CMEs Average $\lvert latitude \rvert$ (deg)
1997	36	13

1998	30	22
1999	40	36
2000	42	45
2001	40	36
2002	35	43
2003	25	25
2004	27	27
2005	24	18
2006	20	8



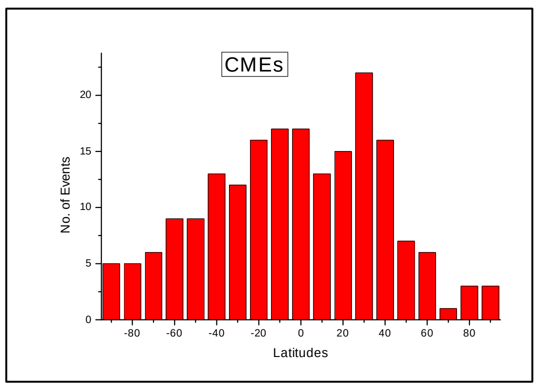


Fig.5. Histogram shows the latitudes of all type Latitudes of PEs and the associated CMEs from 1997 to 2006.

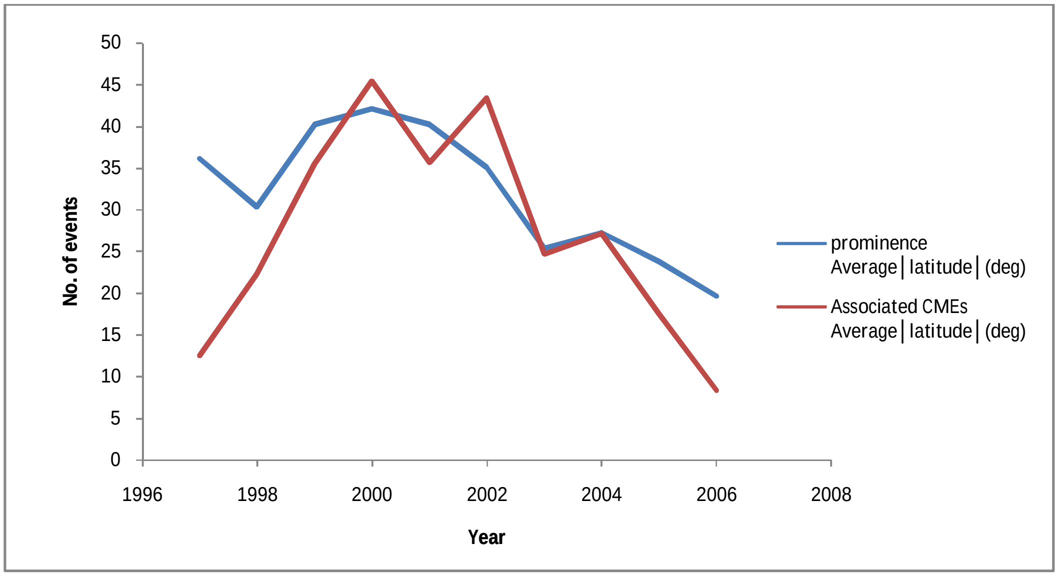


Fig.6. Annual average latitudes of prominence and the associated CMEs from 1997 to 2007

5.3.4. Acceleration of PEs and the associated CMEs

All prominences and CMEs have positive acceleration in the beginning as they lift off from the rest. Close to the Sun, the solar wind speed is negligible.

Fig5.7 is the histogram of acceleration of prominence and associated CMEs observed during the period 1997-2006, i.e. of cycle 23. It is clear from Fig5.7 (a) that a majority (53%) of PEs are decelerated, about 6% of them move with little acceleration and the remaining 40% have positive acceleration. Thus prominences have a clear bias towards negative acceleration (deceleration). In Fig5.7 (b), a majority (49%) of associated CMEs are accelerated; about 4% show little acceleration and the remaining 45% have negative acceleration. Thus CMEs have a clear bias towards positive acceleration. In all there are 174 CMEs whose acceleration could be determined. Fig5.8 shows a scatter plot between the measured acceleration (in m/sec^2) and speed (in km/sec) of all types of prominences and associated CMEs for which the acceleration estimated are possible. The correlation coefficient for acceleration vs. speed of prominences and associated CMEs are -0.7 and -0.16, respectively. Despite the larger scatter, the acceleration has a reasonable correlation with speed.

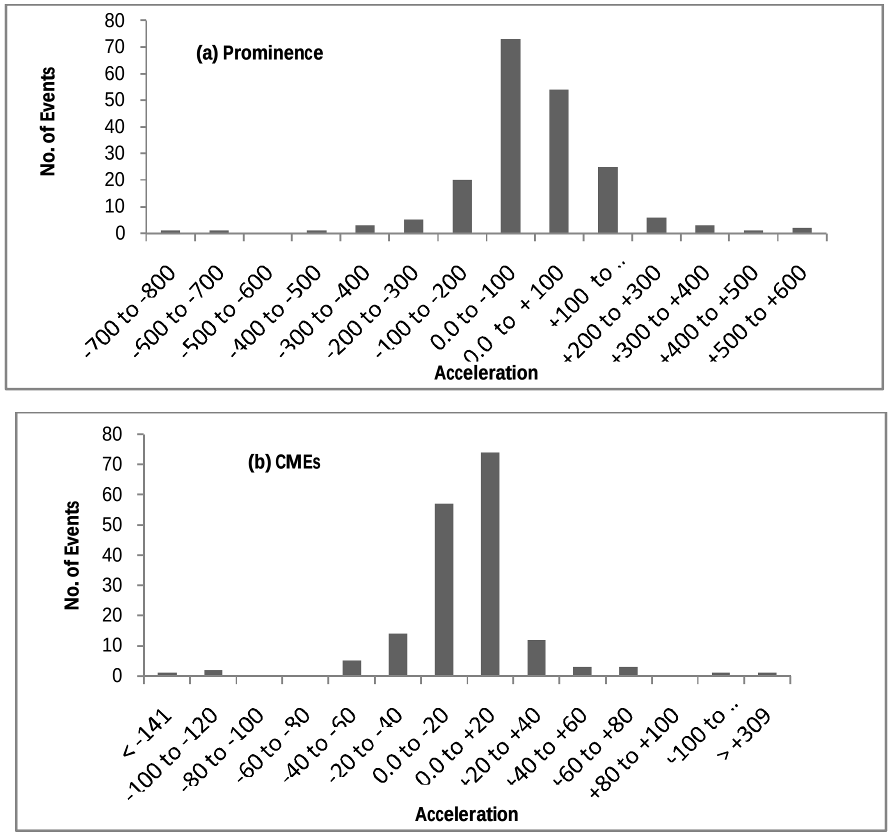
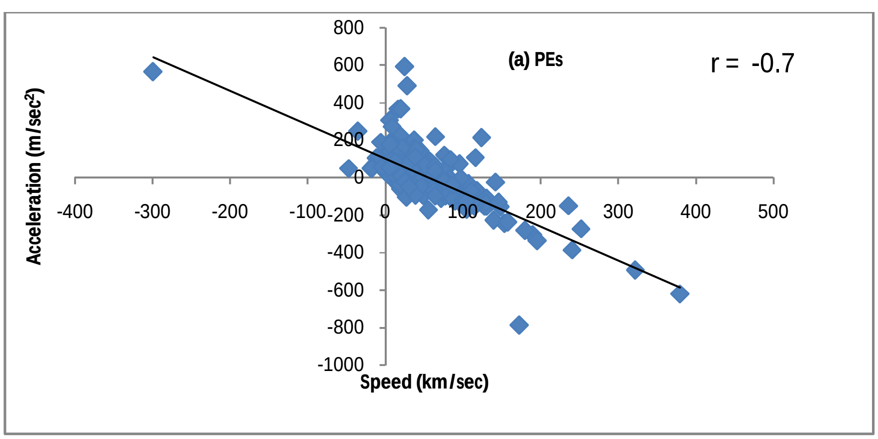


Fig5.7. Histogram of acceleration of PEs and the associated CMEs from 1997 to 2006. (a) Shows clear bias towards deceleration. (b) Shows clear bias towards acceleration.



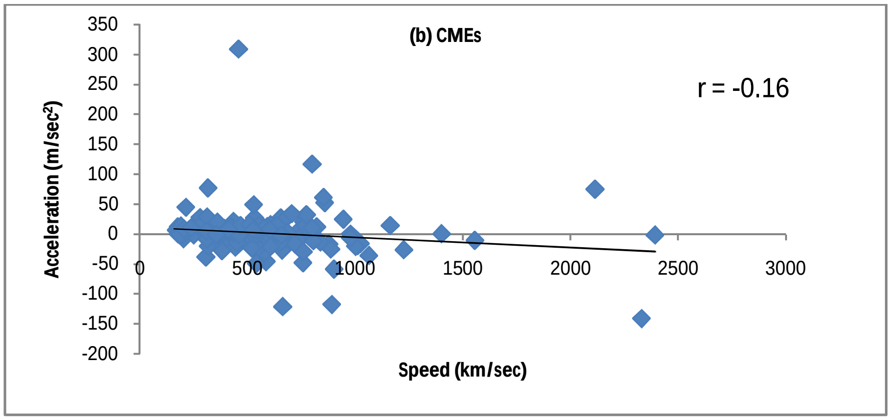


Fig5.8. Acceleration as a function of speed of all types of PEs and the associated CMEs from 1996 to 2006. "r" is the correlation coefficient of the distributions.

5.3.5. Solar cycle variations of PEs and associated CMEs

In Fig5.9 we have exhibited year wise mean sunspot number and number of prominence and associated CMEs. The solar maximum of cycle 23 falls in the year 2000. The number of prominence and associated CMEs in the year 2000 and 2002 is the largest, as expected. Thus the occurrence of prominence and associated CMEs is well correlated with solar cycle variation. The number of prominence and associated CMEs is minimized (08) at solar minimum (1997) and maximum (39) at solar maximum (year 2000). The situation is somewhat similar at the next solar minimum year (2007).

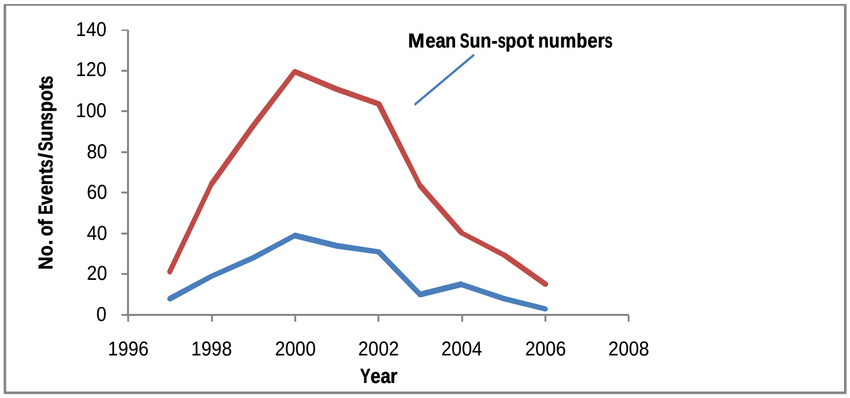


Fig.9. Annual variation of mean sunspot number and the number of PEs associated CMEs.

Discussion and conclusions

In this paper, we have made a comprehensive statistical study on prominence Eruptions and the associated CMEs from 1997 to 2006. During the period 1997-2006 more than 14000 CMEs were observed by SOHO/LASCO, whereas NORH has found 376 prominence eruption events, out of them 195 prominences are associated with CMEs. Nishant et al 2010 has studied the properties of 390 prominence eruptions associated with CMEs during 1996 to 2009. Our study is more comprehensive and detailed than that of others.

The matter presented above leads us to conclude the following:

1. The average speed and apparent width of prominence are 51 km/sec and 32^{o}, respectively, whereas the respective quantities for associated CMEs are 559km/sec and 74^{o} for the period 1997 to 2006. Clearly the associated CMEs are faster and wider than prominences.
2. The average median speed and apparent width of prominence are 38km/sec and 32^{o}, respectively, whereas the respective quantities for associated CMEs are 526km/sec and 63^{o}. These results show that the median speed and median width are lower than the respective average values.
3. Speed distributions of PEs and the associated CMEs show that there is no clear trend because speed varies year to year.

4. The variation of the annual average speed of PEs and the associated CMEs does not agree with solar cycle 23.
5. The apparent width distribution of prominence is biased towards lower widths and shows the solar cycle variation, whereas the associated CMEs has no clear bias and do not show solar cycle variation.
6. Around solar minimum the prominences tend to occur at lower latitudes which increase towards maximum. The associated CMEs also have similar behavior. The average latitudes of PEs and associated CMEs are well-correlated with the solar cycle.
7. The average latitude of PEs and associated CMEs are 32^o and 27^o, respectively. Prominences and the associated CMEs approximately have same latitudes, i.e. both occur roughly at the same position.
8. About 48% of all prominence come from the northern hemisphere and about 43% come from the southern hemisphere. Only 8% prominence comes from equatorial regions, whereas 44% of associated CMEs come from the northern hemisphere and about 47% come from the southern hemisphere. Only 9% CMEs come from the equatorial regions.
9. About 6% of prominences show little acceleration, i.e. they move with constant speed, but about 53% of prominence decelerated i.e. their speed goes on decreasing as they move away from the Sun. The remaining 40% have positive acceleration, i.e. their speed goes

on increasing. The distributions of PEs are biased towards deceleration. The associated CMEs show 4% little acceleration whereas 45% of CMEs are decelerated. The remaining 49% have positive acceleration. The associated CMEs have a clear bias towards positive acceleration.

10. The correlation coefficients for acceleration vs. speed of PEs and associated CMEs are -0.7 and -0.16, respectively i.e. they have reasonable correlation.

11. The variation in the number of prominence and associated CMEs are well- correlated with the solar cycle variation.