On distribution of CMEs speed in solar cycle 23

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Abstract:

We have analyzed the data for more than 12900 CMEs which were obtained by SOHO/LASCO during the period of 1996-2007. The online CME catalogue contains all major CMEs detected by LASCO C2 and C3 coronagraphs. Basically we determine the CME speeds from the linear and quadratic fits to the height-time measurements. It is found that linear (constant speed) fit is preferable for 90% of the CMEs. The distribution of speeds of CMEs in solar cycle 23 is presented along with those obtained by others. As expected, the speeds decrease in the decay phase of the cycle 23. There is an unusual drop in speed in the year 2001 and an abnormal increase in speed in the year 2003 due to the high concentration of CMEs, X-class soft X-ray flares, solar energetic particle (SEP) events and interplanetary shocks observed during October-November period called Halloween events.

Key words: Sun, coronal mass ejections, solar cycle, speed

Introduction

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Coronal mass ejections (CMEs) are a topic of extensive study, since they were first detected in the coronagraph images obtained on 14-December-1971 by NASA's OSO-7 spacecraft (Tousey 1973). In fact, CMEs are large scale magnetized plasma structures ejected from regions where the magnetic field lines of the Sun are closed, such as active and filament regions, active region complexes and trans-equatorial interconnecting regions (Gopalswamy, 2006). It has been recognized that such ejections should carry magnetic fields (see, e.g., Gold 1962).

CMEs originating on the solar disk, particularly close to the central meridian are important from space weather point of view (Sharma et al., 2008). They appear as enhancements surrounding the occulting disk hence were called Halo CMEs (Howard et al., 1982). These CMEs can affect Earth's magnetospheric environment and technological systems (see, e.g., Webb et al. 2000, Gopalswamy et al. 2001, Bothmer & Daglis, 2006). The strongest geomagnetic disturbances are caused by CMEs traveling towards Earth (Vennerstroem, 2001).

The initial detection of CMEs was followed by extensive observations using both space based and ground based instruments. Space based observations included the coronagraph on board *Skylab* in 1973 and 1974 (MacQueen et al. 1976), the Solwind coronagraph on the U.S. Air Force satellite *P78-1* from 1979 to 1985 (Koomen et al. 1975); the coronagraph/polarimeter on the Solar Maximum Mission (SMM) in 1980 and 1984 to 1989 (MacQueen et al. 1980) and recently the Large Angle and Spectrometric Coronagraphs (LASCO) on the Solar and Heliospheric Observatory (SOHO) from 1996 to present (Brueckner et al. 1995).

The most extensive set of ground based observations of CMEs have been obtained using the Mark- III K-Coronameter (MK3) which has been replaced by the Mark-IV K-Coronameter (MK4), at the Mauna Loa Solar Observatory (MLSO) since 1980 (MacQueen & Fisher 1983; St. Cyr et al. 1999). However LASCO has a significant advance over previous instruments as it has a wide field of view starting from about 1.5Rs to 32Rs, increased sensitivity and increased dynamic range (Brueckner et al. 1995). The SOHO satellite placed at the L1 Lagrangian point; can continuously observe the Sun (not just optical wavelengths). This represents an unprecedented uniformity in data coverage from solar minimum to maximum and beyond with a single spacecraft (Howard et al. 1997).

Early measurements of the speeds of the CMEs suggested that there are two different types of the speed profiles, namely, slow CMEs which are associated with eruptive prominences and fast CMEs which originate in solar active regions (Gosling et al., 1976). It emerges that the fast CMEs propagate at constant speed and the slow CMEs are accelerating (MacQueen & Fisher 1983). The CMEs are initiated at a height of 1.3-1.5 solar radii and accelerated until the height of 3.7-4.7 solar radii. In the onset phase of CMEs in the low corona at times they are likely to be accelerated (Zhang et al., 2001). Based on their kinematical behavior the CMEs can be grouped into "Gradual CMEs and Impulsive CMEs" (Sheeley et al., 1999). The Gradual CMEs have speeds < 400 km/s throughout the LASCO field of view and are associated with eruptive prominences. On the other hand the Impulsive CMEs have speeds constant or greater than 750 km/s above certain heights and are decelerating. They are associated with solar flares (Mittal and

Narain, 2006). Many times prominences may be just missed during the observations in fast events.

It is accepted that magnetic reconnection plays a major role in the origin of coronal ejecta, which are driven through the ambient solar wind by magnetic and pressure forces (Vrsnak 1990, Chen 1996). After the driven forces cease to act and the maximum acceleration is reached within several solar radii, fast ejecta have a tendency to decelerate, while the slow ones get an additional acceleration due to interaction with ambient magnetic fields. CMEs propagating in interplanetary space asymptotically approach the velocity of the ambient solar wind because of the viscous drag in the corona (Yurchyshyn et al., 2005). It is to be noted that, the origin of CMEs and their propagation in the solar corona and interplanetary space are complex nonlinear phenomena, in which dissipative processes associated with the electric resistivity and viscosity should not be neglected.

Low and Zhang (2002) have given a qualitative theory in which the two kinds of CMEs are represented by different initial states of the erupted magnetic configuration. Contrary to MacQueen & Fisher (1983) and Sheeley (1999), Chen and Krall (2003) use a theoretical model of CMEs based on a three-dimensional (3-D) magnetic flux rope and find that the resulting distribution of model speed-height profiles is similar to that observed if an upper limit on the amount of injected flux is imposed. Then Chen and Krall (2003) purposed that one driving mechanism is sufficient to produce “two populations” of CMEs and account for the observed properties and distribution of CME acceleration. It is significant that this distribution of CMEs is consistent with the observed parameters of magnetic clouds at 1 AU.

In this paper we exhibit the distribution of speeds of CMEs in the solar cycle 23 during 1996-2007 period. The next section contains data used and the results obtained by us. The last section deals with the discussion of results and conclusions.

Data and Results

The SOHO mission's LASCO instrument routinely records CMEs. It has detected more than 12900 CMEs during 1996-2007 period which have been catalogued on website http://cdaw.gsfc.nasa.gov/CME_list . For each event the catalogue contains height-time plots (fitting measurements of the apparent height of a morphological feature at different times, a height-time, diagram), plane of sky speeds (The speed with which the CME spreads in the sky plane) and the corresponding accelerations. The CME speed is determined from both the linear and the quadratic fits to the height-time measurements. The speed of CME is usually measured by constructing a time-height diagram for the fastest moving feature of the CME front as it appears projected on the plane of the sky. The plane of the sky values can deviate from the real radial speed of the CME front, depending on the actual direction of the motion. In our study we analyze the linear (constant speed) fit which is preferable for 90% of the CMEs. It may be remarked that there is a data gap during the period July-Sept., 1998, because during this period SOHO satellite became inoperational (Gopalswamy et al. 2008). The SOHO/LASCO continuously records CMEs using its two telescopes C2 and C3. The C1 telescope which can observe CMEs closer to the Sun was disabled in June 1998.

Coronagraphs obtain images with a certain time cadence, so when a CME occurs, the leading edge progressively appears at a greater heliocentric distance. On measuring the heliocentric distance of the leading edge of the CMEs in each LASCO image obtains CMEs height as a function of time. On tracking a CME feature in successive frames, one can derive the speed of the feature. It is to be noted that the height-time measurements are made in the sky plane, so all the derived parameters such as speed etc are lower limits to the actual values. The height-time plots are then fitted to first order polynomials that characterize the motion of the CMEs. The measured sky plane speed ranges from a few km/s to ~ 3300 km/s with an average value of ~ 435 km/s, while Gopalswamy (2004) shows the average value is 459 km/sec.

The speed distributions (the number of events as a function of speed) for the years 1996 to 2007 are exhibited in the figures 1. The speed-distribution for the complete period 1996-2007 is presented in Fig.2. The fractions in figures 1 and 2 mean number of events having a given speed divided by the total number of events.

To show the annual variation of median/average speeds and associated statistical errors over the solar cycle 23 the results are exhibited in Fig.3. During solar minimum (1996-1997) the average speed is about 290 km/s whereas during the solar maximum (1999-2002) it is in the range 495-508 km/s. Normally CME speed increases from a lower value to high value from solar minimum to maximum, but surprisingly, there is a dip in speed for the year 2001. For completeness, year wise median and average values and errors of solar speeds are given in Table-1, also.

Discussion and Conclusions

Mass motion is the basic characteristic of CMEs which is quantified by their speeds. Early compilation of the Solwind CMEs speeds indicated that the average CME speeds increased towards solar maximum although SMM data did not indicate such a variation.

The highest speed (485 km/s) during the SMM era was found during solar minimum (1985). In fact Hundhausen (1999) remarked that the “speeds vary widely, even when averaged over intervals as long as a year.” The mean speed obtained from the SMM data for the year 1985 is abnormally high in contrast to the Solwind value. This discrepancy may be due to poor data coverage and the inability to measure the speeds of many of the observed CMEs (Gopalswamy et al 2003).

Tracking a CME feature (usually the bright leading edge) in consecutive coronagraph images allows for the speed of the CME to be estimated. However this coronagraph derived speed is the component of the CME speed in the plane of the sky. Thus for non-limb CME such as a halo event), measurements of speed and direction will suffer to some degree from a projection effect (Gopalswamy et al., 2000). So tracking a halo gives the expansion speed of a CME rather than its radial speed away from the Sun and the precise trajectory and velocity of the CME hence can not be determined with any guaranteed accuracy.

The speed is normally determined from a linear fit to the height-time (h-t) plots but CMEs often have finite acceleration, so that the linear fit speed should be understood as the average value within the coronagraphic field of view. Quadratic fit to the h-t plot gives the constant acceleration, which is again an approximation because the acceleration may change with time (Gopalswamy, 2006).

Figure 3 and Table 1 show that the median/average speeds of CMEs and associated errors vary with the solar cycle. It increases towards solar maximum and decreases afterwards except for a dip around the year 2001. This could be due to poor data coverage and the inability to measure the speeds of many of the observed CMEs. Our results are in good agreement with the previous results.

Our figure 2 shows that the largest fraction of CMEs (about 10%) have a speed of about 270 km/s. The number of CMEs having speeds greater than 1000 km/s is quite small (less than 4%).

It may be concluded that:

During the period 1996-2007 a large number of CMEs have speeds smaller than 600 km/s but greater than 100 km/s.

The CME speeds vary in solar cycle 23. The annual mean speed increased from 270 km/sec. in 1996 to about 500 km/sec. in 2000. The average speed of CMEs showed a dip in the year 2001, as did the CME rate and continued to increase to the second maximum in 2002. However the speed did not decline after the 2002.

Increase in speed in 2003 is mainly because of the exceptional active regions (10484, 10486 and 10488) that produced fast and wide CMEs and abnormally energetic events called Halloween events which occurred during October-November, 2003. The speed then started to decline with time of the solar cycle.

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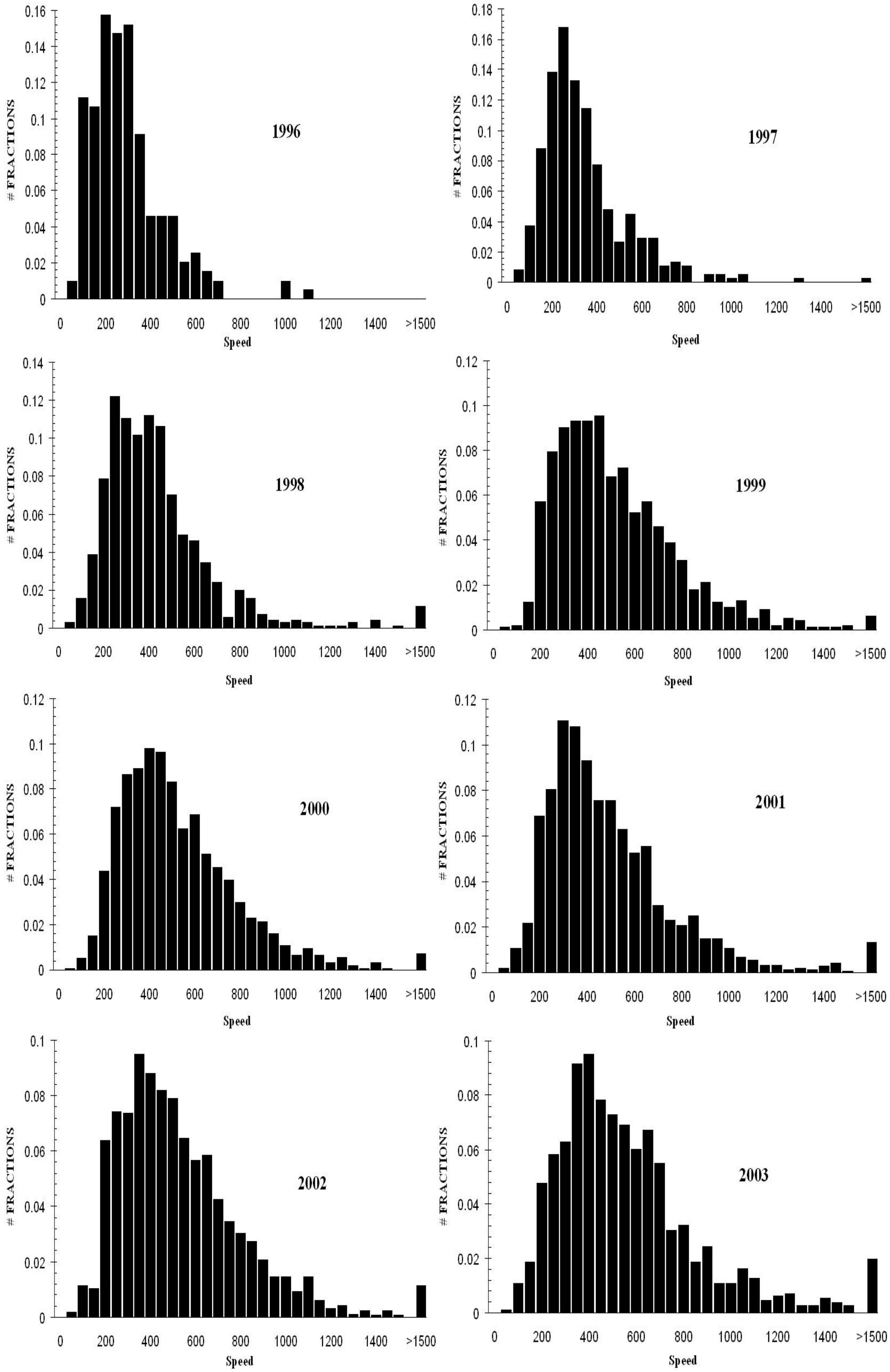
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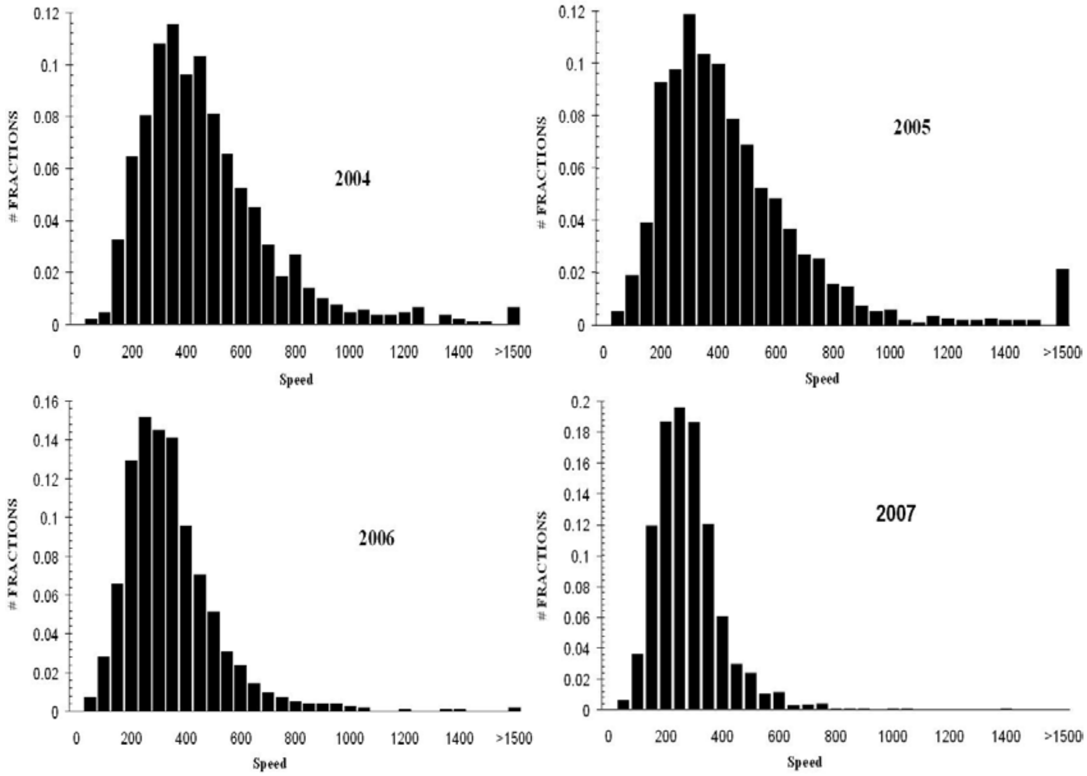

Figure: 1. The speed distributions of SOHO/LASCO CMEs from 1996-2007. The last bin includes all CMEs faster than >1500 km/sec.

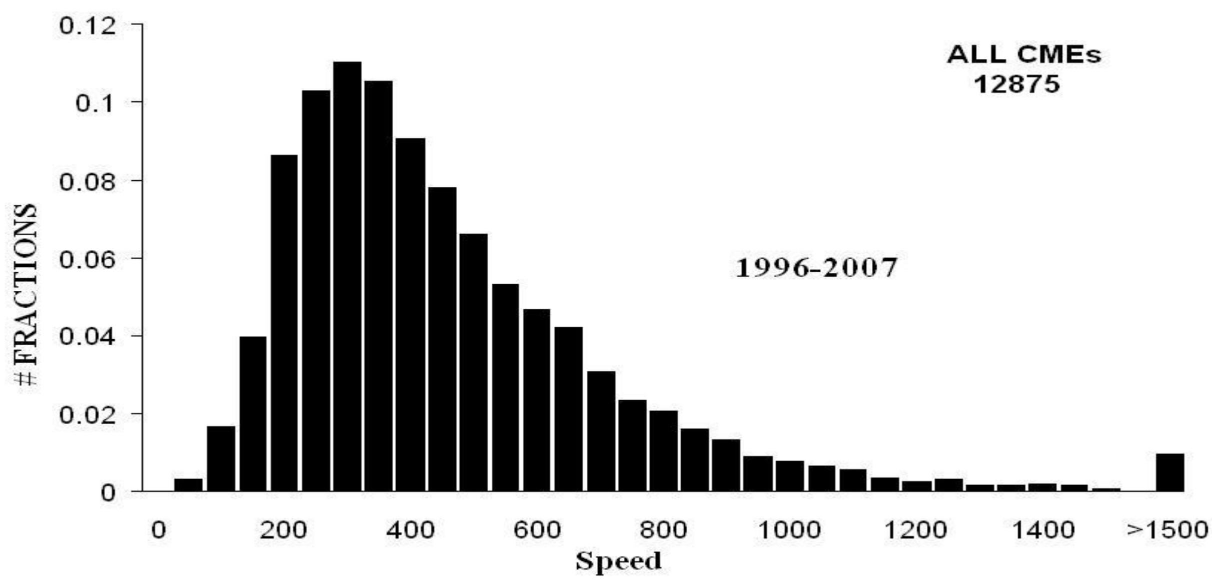

Figure: 2. Total distribution of speeds of SOHO/LASCO CMEs from 1996-2007. The last bin includes all CMEs faster than >1500 km/sec (up to 4% of all CMEs).

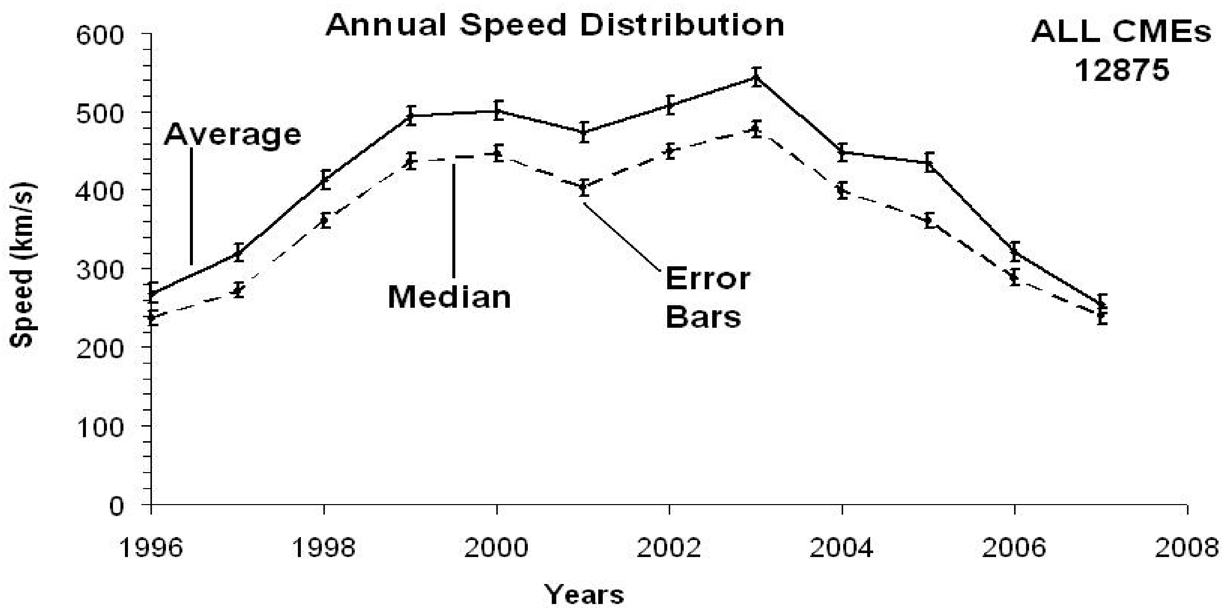

Figure: 3. Annual average and median speeds of SOHO/LASCO CMEs from 1996 to 2007 and associated error bars.

Table-1 Annual median and average CME speeds, along with the number of CMEs and associated errors during 1996-2007

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Median	237	272	361	436	447	403	450	478	399	361	289	240
Error of Median	15	12.67	12.48	10.4	8.27	9.56	8.9	12.4	10	12	7	4
Average	269	320	413	495	501	473	508	544	448	335	321	255
Error of Average	12	10.11	10	8.3	6.6	7.63	7.1	10	8	9.55	5.63	3.13
No. of CMEs	197	376	697	997	1587	1483	1644	1113	1084	1222	1034	1441