Research Article

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Some kinematics of halo coronal mass ejections

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Abstract: We present an investigation of halo coronal mass ejections (HCMEs) kinematics and other facts about the HCMEs. The study of HCMEs is very important because HCMEs are regarded as the main causes of heliospheric and geomagnetic disturbances. In this study, we have investigated 313 HCMEs observed during 1996-2012 by LASCO, coronal holes, and solar flares. We find that HCMEs are of two types: accelerated HCMEs and decelerated HCMEs. The mean space speed of HCMEs is 1283 km/s while the mean speed of decelerated HCMEs and accelerated HCMEs is 1349 km/s and 1174 km/s, respectively. The investigation shows that 1 (0.3%) HCME was associated with class A SXR, 14 (4.7%) HCMEs were associated with class B SXR-flares, 87 (29.4%) HCMEs were associated with class C SXR-flares, 125 (42.2%) HCMEs were associated with class M SXR-flares and 69 (23.3%) HCMEs were associated with class X SXR-flares. The speed of HCMEs increases with the importance of solar SXR-flares. The various results obtained in the present analysis are discussed in the light of the existing scenario of heliospheric physics.

Keywords: Sun, coronal mass ejections, solar flares

1 Introduction

Coronal mass ejections (CMEs) are regarded as the main causes of heliospheric and geomagnetic disturbances. The Halo Coronal mass ejections (HCMEs) propagating near the Sun-Earth direction, either toward or away from the Earth, and appear as an annulus surrounding the solar disk (Chen 2011). General information on CMEs has been well-reviewed by several authors (Chen 2011; Gosling 1997; Howard et al. 1997; Hundhausen 1999; Webb and Howard 2012). The HCMEs are important to us because they are geo-effective and the source regions of front side HCMEs are likely to be located within a few tens degrees of the center of the solar disk (Webb 2002; Gopalswamy 2004). Yashiro et al. (2004) reported that the average velocity of HCMEs is nearly two times of normal CMEs and this makes HCMEs as a very special class of CMEs. Andrews (2002) proposed that many faint and slow speed HCMEs are not observed by coronagraphs and maybe the reason that the average velocity of the observed HCMEs is high. Zhang et al. (2010) used Monte Carlo simulations to investigate how the brightness of CMEs with an average velocity of 523 km/ s is reduced when they are observed as halo events. According to Gopalswamy et al. (2010a,b) partial and full HCMEs occur at a rate of ~10% and ~ 4% of all CMEs, respectively. Verma (2011) studied the relationship of X-class soft X-ray flares with CMEs and HCMEs and found that energetic X-class solar flares are related to 79% solar CMEs and 46% HCMEs, respectively.

Early measurements of the speeds of CMEs suggested that there are two distinct types of speed profiles: slow CMEs, and fast CMEs (Gosling et al. 1976). Sheeley et al. (1999) also classified CMEs into two classes: gradual CMEs having speeds 400 to 600 km/s, associated with erupting prominences, and impulsive CMEs having > or equal 750 km/s, associated with solar flares. Moon et al. (2002) support the concept of two types of CMEs: flares and eruptive filament associated CMEs. Low & Zhang (2002) found that the speed-height profiles of all CMEs do not form two discrete populations but show a continuous spectrum that does not support the view of two classes of CMEs. 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. Chen & Krall (2003) concluded that one mechanism is sufficient to explain the bimodal speed distribution. Yurchyshyn et al. (2005) analyze the statistical properties of CMEs and they found that the speed distributions for accelerating and decelerating events are nearly the same and they can be fitted with a single lognormal distribution. Zagainova & Fainshtein (2015)
presented a detailed study of CMEs relation with powerful flares which not related to eruptive filaments. Fainshtein et al. (2018) also studied the kinematic characteristics of two types of HCMES (accelerating and slowing down). Recently, Michalek et al. (2019) found that CMEs can be divided into two categories: regular and specific events. The regular events are pronounced and follow the pattern of sunspot numbers. On the other hand, special events are poorer and more correlated with the general conditions of the heliosphere and corona. Reeves et al. (2019) presented a model to simulate a coronal mass ejection using a three-dimensional magnetohydrodynamic code that includes coronal heating, thermal conduction, and radiative cooling in the energy equation. Must recently, Verma & Mittal (2019) find that all HCMEs were observed when there were CHs and solar flares within 10° to 60°. They also find that the 128 (40.8%) and 88 (23.6%) HCMEs events were observed when there were CHs and solar flares within 10° and 20°, respectively. Verma & Mittal (2019) are of the view that the HCMEs may have been produced by some mechanism, in which the mass ejected by solar flares or active prominences, gets connected with the open magnetic lines of CHs (source of high-speed solar wind streams) and moves along them to appear as an HCMES. Verma & Mittal (2019) are also of the view that CMEs formation is a two-step process: The first step, Triggering include releasing of materials by flares (etc.) involved in CMEs formation is a necessary condition while in the second step, the reconnection of a bipolar magnetic field of flares or active prominence region with an open magnetic field of CHs is a sufficient condition.

In the present paper, we propose to investigate the HCMEs observed by LASCO/ SOHO satellite during the interval period of January 06, 1997, to September 30, 2012, to understand some facts about HCMEs. We have also plan to classify the HCMEs events as accelerating HCMEs and decelerating HCMEs to understand them in a better way. In section 1 of the paper, we try to give an introduction to various facts of HCMEs related to research work. In section 2 of the paper, we mentioned observational data and analysis. In section 3 we have discussed the results obtained in the present investigation. A summary and conclusions are delivered in the last section 4.

2 Observational Data and Analysis

After the launch of the SOHO satellite in December 1995, the LASCO telescope with C1, C2, and C3 coronagraph, observed thousands of CMEs (Brueckner et al. 1995). LASCO data is available online (https://cdaw.gsfc.nasa.gov/CME_list/index.html) as described by Gopalswamy et al. (2010a,b). The LASCO instrument is a set of three coronagraph telescopes and recording white light images of the solar corona from 1.1 through 30 solar radii since its launch. The C1 coronagraph record images of the corona from 1.1 to 3 solar radii, the C2 coronagraph record images of the corona from about 1.5 to 6 solar radii, and C3 coronagraph record images of the corona from about 3.5 to 30 solar radii. The LASCO C1 coronagraph failed in June 1998. Our data sample includes 518 HCMEs observed from 1996 April 29 to 2012 September 30. The list of HCMEs is downloaded from the 'CDAW CME catalog available online (https://cdaw.gsfc.nasa.gov/CME_list/HALO/index.html). Meanwhile, the first halo CME recorded by SOHO occurred on 29 April 1996, and its source was located on the backside of the Sun. An HCME with the source on the visible disk and the associated solar flare was recorded on 6 January 1997. During the above period, LASCO coronagraph recorded 518 HCMES but 205 HCMES were excluded from the study because of their association with back-sided disk events and thus we are left with 313 halo CME events for the present study. HCMEs data can be obtained from other space missions but we have used only CDAW catalog data to study the kinematics of HCMEs. The HCMEs list downloaded from the above website show many parameters of each halo CME event. The HCMEs catalog lists many parameters of each event. In particular, the date and time of the first appearance of the CME in C2, and the associated solar flare, the onset time of the flare, the soft X-ray class of the associated source (flares, etc.), the soft X-ray class of the associated SXR flare, the onset time of the flare, the related daily movies and plots and remark about the event.

2.1 HCMEs and solar flares

The various detail of HCMEs observed between 1996 and 2012 is shown in Table 1. Column 1 shows the year of observation, the columns 2-6 show the numbers of all CMEs, HCMEs, HCMEs with incomplete data (ID), accelerating HCMEs, and decelerating HCMEs. From Table 1 it is clear that the numbers of HCMEs are increasing from solar minimum to solar maximum, following sunspot cycle indicating CMEs belong to a class of solar active phenomena. It is also clear from Table 1 that the numbers of HCMEs are only 2.67% of CMEs observed in the period 1996-2012. In this investigation, we have considered 313 HCMEs for study but the location and class of 17 SXR flares associated with HCMEs are not known and thus we excluded 17 halo CME events.
Table 1. Number of CMEs, Number of HCMEs, Number of HCMEs with ID, Accelerated HCMEs Number and Decelerated HCMEs Number for Each Year During Period 1996-2012.

| Year | No. of CMEs | No. of HCMEs | No. of HCMEs with ID | Accelerated HCMEs Number | Decelerated HCMEs Number |
|------|-------------|--------------|---------------------|--------------------------|--------------------------|
| 1996 | 206         | 4            | 04                  | 0                        | 0                        |
| 1997 | 385         | 17           | 06                  | 7                        | 4                        |
| 1998 | 716         | 29           | 09                  | 11                       | 9                        |
| 1999 | 1016        | 27           | 12                  | 2                        | 13                       |
| 2000 | 1663        | 58           | 16                  | 17                       | 25                       |
| 2001 | 1449        | 63           | 19                  | 19                       | 25                       |
| 2002 | 1700        | 52           | 21                  | 13                       | 18                       |
| 2003 | 1130        | 30           | 12                  | 3                        | 15                       |
| 2004 | 1102        | 40           | 19                  | 12                       | 9                        |
| 2005 | 1249        | 59           | 22                  | 13                       | 24                       |
| 2006 | 1046        | 14           | 5                   | 6                        | 3                        |
| 2007 | 1442        | 3            | 2                   | 0                        | 1                        |
| 2008 | 863         | 1            | 1                   | 0                        | 1                        |
| 2009 | 746         | 1            | 0                   | 1                        | 0                        |
| 2010 | 1117        | 11           | 2                   | 5                        | 4                        |
| 2011 | 1979        | 41           | 22                  | 9                        | 10                       |
| 2012 | 1616        | 68           | 36                  | 15                       | 17                       |
| Total| 19425       | 518          | 205                 | 133                      | 180                      |

(**ID: incomplete data)**

The data of 296 HCMEs associated with SXR flares whose locations and importance class are known and the data 295 HCMEs are used to study the disk distribution of HCMEs and relation between the speed of HCMEs associated SXR flares. We investigated the relationship between the space speed of HCMEs and the importance of SXR solar flares. We also found that the space speed of HCMEs is positively associated with the class of SXR flares as shown in Table 2. The columns 2-6 lists the number and the mean and median space speed of the HCMEs associated with an X-ray class A, B, C, M, and X flare, respectively. The values are given for all (row 2), decelerating (row 3), and accelerating (row 4) HCMEs.

The locations and classes of 313 HCMEs associated with SXR flares are investigated and found that the location and class of 17 HCMEs associated with SXR flares are not known. The solar disk locations of SXR flares associated with HCMEs are shown in Figure 1. In Figure 1 we have plotted solar disk locations SXR flares associated with HCMEs on the x-axis as an east (−90° to 0°) to the west (0° to 90°) longitude in degree and on the y-axis as south (−90° to 0°) – north (0° to 90°) latitude in degree. It is clear from Figure 1 that the source locations of ~95% HCMEs associated solar SXR flares occur within ±30° solar latitude while solar longitude (east-west longitude) shows that the ~70% HCMEs related solar events sources are mostly concentrated within ±40° solar longitude. Gopalswamy et al. (2010a,b) in their study for 247 CMEs shows that about 70% of events occur near the central meridian in the range of ±30° solar longitude. Hence our result is in good agreement with the previous study of Gopalswamy et al. (2010a,b).

The solar soft X-ray classes of 296 HCMEs associated with SXR flares are known and the plot of the class of SXR flares versus the number of HCMEs is shown in Figure 2. The Figure 2 and Table 2 show that 1 (0.3%) HCME was associated with class A SXR, 14 (4.7%) HCMEs were associated with class B SXR flares, 87 (29.4%) HCMEs were associated with class C SXR flares, 125 (42.2%) HCMEs were associated with class M SXR flares and 69 (23.3%) HCMEs were associ-
Table 2. Relation between Speed of HCMEs and Class of SXR Flares.

| Detailed of HCMEs | HCMEs associated class A SXR flares | HCMEs associated class B SXR flares | HCMEs associated class C SXR flares | HCMEs associated class M SXR flares | HCMEs associated class X SXR flares |
|-------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| HCMEs No.         | 1                                   | 14                                  | 87                                  | 125                                 | 69                                  |
| Mean Speed        | 136±0                               | 547±150                             | 823±340                             | 1119±505                            | 1581±663                            |
| Median Speed      | 136                                 | 534                                 | 791                                 | 1079                                | 1543                                |
| Decelerated HCMEs No. | 0                           | 7                                   | 43                                  | 79                                  | 46                                  |
| Mean Speed        | 587±145                             | 788±284                             | 1126±477                            | 1597±654                            |
| Median Speed      | 586                                 | 693                                 | 1092                                | 1583                                |
| Accelerated HCMEs No. | 1                           | 7                                   | 44                                  | 46                                  | 23                                  |
| Mean Speed        | 136±00                              | 507±154                             | 855±384                             | 1101±544                            | 1572±704                            |
| Median Speed      | 136                                 | 505                                 | 835                                 | 1073                                | 1385                                |

![Figure 2. The plot of the class of SXR flares associated with HCMEs versus the number of HCMEs associated with SXR flares.](image)

2.2 Kinematics of HCMEs

As mentioned earlier we have 313 HCMEs whose space speed, accelerations, and onset time of flares are known. The CME space speeds that are corrected using the cone model by Xie et al. (2004). Further, out of 313 halo CME events, the 133 halo CME events show average positive accelerations while 180 halo CME events show average negative accelerations or decelerations during their journey from the solar surface to solar corona and beyond. The space speed of HCMEs is an important parameter to understand the origin of HCMEs. The space speed of 20 HCMEs is not known and thus after excluding 20 halo CME events, we are left with 292 HCMEs for space speed distribution study. The detail of HCMEs number used in the plot is indicated in Figure 3. The plot of space speed of HCMEs versus the number of HCMEs is shown in Figure 3.

In the upper part of Figure 3, we have shown a plot of space speed of HCMEs versus the number of HCMEs and upper part of Figure 3 also show the number of HCMEs, mean and median values of space speed of HCMEs as 1283 km/s and 1151 km/s, respectively.

In the middle part of Figure 3, we have shown space speed of decelerating HCMEs versus the number of HCMEs and middle part of Figure 3 also show the number of HCMEs, mean and median values of space speed of decelerating HCMEs as 1349 km/s and 1260 km/s, respectively. In the lower part of Figure 3, we have shown a plot of space speed of accelerating HCMEs versus the number of HCMEs and lower part of Figure 3 also show the number of HCMEs, mean and median values of space speed of HCMEs as 1174 km/s and 1051 km/s, respectively.

All CMEs have acceleration at the beginning as CMEs liftoff from rest and in this situation, the propelling force of the CMEs exceeds gravity force and other restraining forces. In Figure 4, we have shown a plot of the space speed of HCMEs versus the acceleration of HCMEs. This figure also shows that the most HCMEs with space speed < 1500 km/s has the accelerations < 50 to −50 (m/s²) while HCMEs with space speed > 1500 km/s have also higher accelerations >50 to −50 (m/s²). We try to fit a linear equation and a two-degree polynomial equation to Figure 4 data and we find a very small correlation value which indicates that space speed of HCMEs and acceleration of HCMEs has no relation. From Figures 4, we could not draw any specific conclusion between the space speed of HCMEs and the acceleration of...
Figure 3. The upper part of the figure shows a plot of the space speed of HCMEs versus a number of the HCMEs, the middle part of the figure shows a plot of the space speed of HCMEs versus a number of the decelerate halo CMEs and the lower part of the figure shows a plot of the space speed of HCMEs versus a number of the accelerated HCMEs.

Figure 4. A plot of space speed of HCMEs (km/s) versus acceleration of the HCMEs (m/s²).

HCMEs which shows poor correlation coefficient; therefore we decided to investigate HCMEs in two parts: decelerating HCMEs and accelerating HCMEs speed, separately.

In Figure 5, we have shown a plot of space speed of HCMEs versus the acceleration of decelerating HCMEs. The linear equation (Y = -0.037X + 22.51) is fitted to Figure 5 data and we have calculated the value of the correlation coefficient as R = 0.65, which indicates that the acceleration of decelerating HCMEs and the space speed of HCMEs has a fair correlation. The two-degree polynomial equation (Y = -4E-06X² - 0.024X + 18.06) is also fitted to Figure 5 data and we have also calculated the value of the correlations coefficient as R = 0.65, which indicate that the acceleration of decelerating HCMEs and the space speed of HCMEs has a fair correlation.

In Figure 6, we have shown a plot of space speed of HCMEs versus the acceleration of accelerating HCMEs. The linear equation (Y = -0.025X - 10.30) is fitted to Figure 6 data and we have also calculated the value of the correlation coefficient as R = 0.65, which indicates that the acceleration of accelerating HCMEs and the space speed of HCMEs has a fair correlation.
data and we have also calculated the value of the correlation coefficient as \( R = 0.55 \), which indicates that the acceleration of HCMEs and space speed of HCMEs has a fair correlation. The two-degree polynomial equation \( Y = 4E - 06X^2 + 0.015X - 4.21 \) is also applied to Figure 6 data and we have also calculated the value of the correlation coefficient as \( R = 0.55 \), which indicate that the acceleration of accelerating HCMEs and space speed of accelerating HCMEs has a fair correlation. An investigation relation between space speed of HCMEs and acceleration of decelerating HCMEs in Figures 5 and an investigation of space speed of HCMEs and acceleration of accelerating HCMEs in Figures 6, clearly indicates that the HCMEs may be of two types: accelerating HCMEs and decelerating HCMEs and support the Yashiro et al. (2004) results.

![Figure 6](image)

**Figure 6.** A plot of the space speed of HCMEs (km/s) versus the acceleration of accelerated HCMEs (m/s²). The linear equation and two-degree polynomial are fitted to the space speed of accelerated HCMEs and the acceleration of accelerated HCMEs.

### 3 Result and Discussions

#### 3.1 On Distribution of HCMEs

The distribution of the HCMEs source is shown in Figure 1. From Figure 1 It is obvious that 95% of HCMEs associated solar flares are located between \( \pm 30^\circ \) solar latitude on the solar disk and 70% of HCMEs associated solar flares located between \( \pm 40^\circ \) solar longitude on the solar disk. This shows that majority of HCMEs associated with solar flares are located near the center of the disk and support the earlier results (Webb 2002; Gopalswamy 2004; Yashiro et al. 2004). According to Gopalswamy (2004) full HCMEs for period 1996-2003, occur at a rate of \( \sim 4\% \) of all CMEs but in the present study, we find that full HCMEs for period 1996-2012 occur at the rate of out of \( \sim 2.67\% \) which is less than the value reported by Gopalswamy (2004). The Table 2 shows that 1 (0.3%) HCMEs was associated with class A SXR flare, 14 (4.7%) HCMEs were associated with class B SXR flares, 87 (29.4%) HCMEs were associated with class C SXR flares, 125 (42.2%) HCMEs were associated with class M SXR flares and 69 (23.3%) HCMEs were associated with class X SXR flares. Earlier Gopalswamy et al. (2010a,b) investigated the relation between HCMEs and SXR flares their results are presented in the form of Figure 2 which shows HCME counts of B, C, M, X-class flares. Komitov et al. (2010) showed that out of 14775 SXR flares observed during period 1996-2009 the number of class X SXR flares were 126 (0.85%), number of class M SXR flares were 1443 (9.77%) and number of class C SXR flares were 13206 (89.38%). This clearly shows that HCMEs are mostly associated with class M and X SXR flares but sometimes smaller SXR flares of class A, B, and C can also produce HCMEs.

#### 3.2 On Kinematics of HCMEs

The investigation of Yashiro et al. (2004) indicates that the average velocity of HCMEs is twice normal CMEs and this is the main reason to make HCMEs a very special class of CMEs. In the present study, we have also found that the mean value of space speed of HCMEs is 1283 km/s while the mean value of accelerated HCMEs and decelerated HCMEs is 1173 km/s and 1349 km/s, respectively. As mentioned in section 1 of the paper, there is controversy about two types of CMEs and to examine it we have carried a comprehensive detailed study to address the question of whether two classes of CME events exist or not. The acceleration and speed of HCMEs are important tools to know the kinematics of HCMEs. The plot of the space speed of HCMEs and the acceleration of HCMEs is shown in Figure 4 and we try to fit a linear and two degrees polynomial equation to Figure 4 data and we found a very small value of the correlation coefficient as \( R < 0.2 \), clearly shows that there is no relation between the speed of HCMEs and acceleration HCMEs. Figure 4 also tells us that the most HCMEs with space speed < 1500 km/s has the accelerations < 50 to \(-50\) (m/s²) while HCMEs with space speed > 1500 km/s have higher accelerations > 50 to \(-50\) (m/s²) Thus we conclude that the there is no relation between the space speed of HCMEs and the acceleration of HCMEs. Figures 4 show that the space speed HCMEs and the acceleration of HCMEs do not follow linear or two-degree equations and thus ruled out the possibility.
of the origin of halo CMEs as a single step process. Now to understand HCMEs in detail we investigated the HCMEs by dividing HCMEs as accelerating HCMEs and as decelerating HCMEs. Figure 5 shows the plot of the space speed of HCMEs and the acceleration of decelerating HCMEs and we also fitted a linear equation and two-degree polynomial to these figures data. We calculated the value of correlations coefficients $R > 0.65$ for the space speed of HCMEs and the acceleration of decelerating HCMEs, which indicate that the speed of HCMEs and the acceleration of decelerating HCMEs have a fair level of correlations. Similarly, Figure 6 shows the plot space speed of HCMEs and acceleration of accelerating HCMEs and after fitting a linear equation and two degrees polynomial to these figures data, we find the value of correlations coefficient as $R > 0.60$, which indicate that space speed of HCMEs and acceleration of accelerating HCMEs has a fair level of correlations. These suggest that the HCMEs are of two types: accelerating HCMEs and decelerating HCMEs.

As mentioned earlier Verma & Mittal (2019) investigated the origin of HCMEs and found that HCMEs observed when there were CHs and solar flares within $10^\circ$ to $60^\circ$. They find that the 128 (40.8%) and 88 (23.6%) HCMEs events were observed when there were CHs and solar flares within $10^\circ$ and $20^\circ$, respectively. Verma & Mittal (2019) are of the view that the HCMEs may have been produced by some mechanism, in which the mass ejected by solar flares or active prominences, gets connected with the open magnetic lines of CHs (source of high-speed solar wind streams) and moves along them to appear as an HCMEs, earlier suggested by Verma and Pande (1989) and Verma (1998, 2002). Further, we are also of the view that CMEs formation is a two-step process: The first step, Triggering include releasing of materials by flares (etc.) involved in CMEs formation is a necessary condition while in the second step, the reconnection of the bipolar magnetic field of flares or active prominence region with an open magnetic field of CHs is a sufficient condition. The present work is the continuation of earlier work by Verma & Mittal (2019) and using the same set of data in the present investigation. As discussed above, we are of the view that the HCMEs are of two types: accelerated HCMEs and decelerated HCMEs and these HCMEs may be originated through the following mechanism:

1. Accelerated HCMEs may be originating through mass released by solar flares and early reconnection to open the magnetic field of coronal holes at a lower height in corona and moves as HCMEs to higher corona height including earth and beyond.
2. Decelerated HCMEs may be originating through mass released by solar flares and late reconnection to open magnetic field of coronal holes at a higher height and moves as HCMEs to higher corona height including earth and beyond.

The above hypothesis is based on various investigations carried out in the preceding paragraph and we suggest that a detailed theoretical investigation should be carried out to understand this phenomenon. The mechanism involved in the origin of CMEs using the reconnection scenario is discussed by Verma (1998, 2002) and Verma & Mittal (2019).

4 Summary and Conclusion

In this study, we have investigated 313 HCMEs observed during 1996-2012 by LASCO, coronal holes, and solar flares. We find that 95% of HCMEs associated solar flares are located between $±30^\circ$ solar latitude on the solar disk and 70% of HCMEs associated solar flares located between $±40^\circ$ solar longitude on the solar disk. We also find that 1 (0.3%) HCME was associated with class A SXR, 14 (4.7%) HCMEs were associated with class B SXR flares, 87 (29.4%) HCMEs were associated with class C SXR flares, 125 (42.2%) HCMEs were associated with class M SXR flares and 69 (23.3%) HCMEs were associated with class X SXR flares. The speed of HCMEs increases with the importance of solar SXR flares. We also find that HCMEs are of two types: accelerated HCMEs and decelerated HCMEs. The mean space speed of HCMEs is 1283 km/s while the mean speed of decelerated HCMEs and accelerated HCMEs is 1349 km/s and 1174 km/s, respectively.

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