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Kinematic Differences between Gradual and Impulsive Coronal Mass Ejections: The Role of Flares

(Perbezaan Kinematik antara Lentingan Jisim Korona Berperingkat dan Impulsif: Peranan Nyalaan)

Z.S. HAMIDI[1,2,*], N. MOHAMAD ANSOR[1,2] & N.N.M. SHARIFF[2,3]

[1]*School of Physics and Material Science, Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*
[2]*Institute of Science, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*
[3]*Academy of Contemporary Islamic Studies (ACIS), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

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ABSTRACT

Coronal Mass Ejections (CMEs) are significant solar events that involve intense explosions of magnetic fields and mass particles out from the corona. These events are known to be the main driver of space weather and other disturbances experienced by the Earth. Generally, there are two types of CMEs – gradual and impulsive, and each type has different properties which is important to be studied on as they have potential to cause breakdowns in our systems. This study is aimed to analyze and differentiate the kinematic behavior of gradual and impulsive CME with the association of weak and strong flares. Data collection is made through SOHO LASCO catalogues and STEREO database which include velocity, acceleration and angular width as well as images. At the end of this study, it can be deduced that impulsive CME (specifically associated with strong flare) is the most prominent event that has greatest angular width and average velocity. The associated flare has contributed more heat energy to speed up the magnetic energy conversion which results to high velocity of plasma discharge. Since fast CME carries huge amount of momentum during the ejection, impulsive CMEs also experience decelerations due to loss of momentum that has been transferred to background solar wind.

Keywords: Coronal Mass Ejections; gradual CME; impulsive CME; solar flare

ABSTRAK

Letusan Jisim Korona (CME) ialah peristiwa suria yang ketara yang melibatkan letupan kuat medan magnet dan zarah jisim keluar daripada korona. Peristiwa ini diketahui sebagai pemacu utama cuaca angkasa dan gangguan lain yang dialami oleh Bumi. Secara umumnya, terdapat dua jenis CME – beransur-ansur dan impulsif, dan setiap jenis mempunyai sifat berbeza yang penting untuk dikaji kerana ia berpotensi menyebabkan kerosakan dalam sistem Bumi kita. Kajian ini bertujuan untuk menganalisis dan membezakan tingkah laku kinematik CME beransur-ansur dan impulsif dengan perkaitan suar lemah dan kuat. Pengumpulan data dibuat melalui katalog SOHO LASCO dan pangkalan data STEREO yang merangkumi halaju, pecutan dan lebar sudut serta imej. Pada akhir kajian ini, dapat disimpulkan bahawa CME impulsif (khususnya dikaitkan dengan suar kuat) adalah peristiwa paling menonjol yang mempunyai lebar sudut dan halaju purata yang paling besar. Nyalaan yang berkaitan telah menyumbangkan lebih banyak tenaga haba untuk mempercepatkan penukaran tenaga magnetik yang menghasilkan halaju tinggi nyahcas plasma. Memandangkan CME pantas membawa jumlah momentum yang besar semasa lonjakan, CME impulsif juga mengalami nyahpecutan akibat kehilangan momentum yang telah dipindahkan ke angin suria latar belakang.

Kata kunci: CME beransur-ansur; CME impulsif; Letusan Jisim Korona; suar suria

INTRODUCTION

A Coronal Mass Ejection (CME) is defined as a huge explosion of Sun's magnetic field and mass particles out of the corona. As one of the strongest sources of geomagnetic storms at the middle and high latitudes on Earth, CMEs are referred to as the primary cause of space weather (Mohamad Ansor & Hamidi 2022). During the ejection, a huge amount of plasma and magnetic flux are expelled into the interplanetary space travelling at a mean velocity up to hundreds of km/s (Webb & Howard 2012) before interacting with Earth's atmosphere and causing disturbances. The first CME was observed on 14th December 1971 through white-light coronagraph on board NASA's seventh Orbiting Solar Observatory (OSO-7)

(Tousey 1973). When this event occurs, the Sun's coronal structure undergoes a visible change that appears as a distinct and bright white-light feature moving outward in the coronagraph field of view (Hudson et al. 2006). Further, variations in solar activity, such as solar flares and CMEs, have altered the amount of heat that the Earth receives (Mohamad Ansor, Hamidi & Shariff 2019).

As it is well known, the general categories of CMEs are gradual and impulsive. It was firstly introduced by Sheeley et al. (1999) when they implemented a new technique to acquire height-time plots and some visual observations on LASCO. The results of the analysis lead to the suggestion of two classifications, namely gradual and impulsive, which are based on certain characterizations. Table 1 presents the characterizations of gradual and impulsive CME.

The gradual CME is defined as an extremely weak event that accelerates at a rate of no more than 20 m/s^2 and continues to accelerate positively for up to 10 h. Their leading edges travel more faster at 400-600 km/s as compared to their cores at 300-400 km/s before becoming invisible in the field of view at 30 R_{sun} and beyond. Slowly accelerating CMEs are often diminishing in a short period of time and reaching a constant speed more quickly. However, impulsive CMEs are fast-moving events with average speeds exceeding 750 km/s and accelerate at a few hundred m/s^2 but do not last as long as gradual CMEs. It is common for impulsive CMEs to exhibit deceleration, whereby they can slow down continuously by 500 km/s in one hour. There are several factors that contribute to deceleration of impulsive CMEs, including shock waves, drag forces, and rapid growth of current sheets (Lin & Forbes 2000; Temmer et al. 2023). These findings by Sheeley et al. (1999) are agreed by several following studies that also observed acceleration on gradual CMEs and deceleration on impulsive CMEs after they analyzed the events based on those two classifications (Hamidi & Shariff 2014; Zhang et al. 2004).

In addition to gradual and impulsive, CMEs have also been classified into various categories based on their properties and flares association. According to an observational study of 6621 CMEs, the four classifications display different kinematics and physical attributes, apart from their distinct initiation methods (Nicewicz & Michalek 2016). The same method has also been applied to examine the properties of CMEs associated with flares during the rising phase of Solar Cycle 24 and the authors have produced two classifications - low group flare-CMEs and high group flare-CMEs (Mohamad Ansor, Hamidi & Shariff 2023). High group flare-CMEs are associated with M and X flares, whereas low group flare-CMEs are associated with A, B, and C flares. In order to distinguish the properties of flare-associated CMEs, it is necessary to understand the relationship between CMEs and flares associations. This relationship has also been extensively studied in order to distinguish the properties of flare-associated CMEs (Andrews & Howard 2001; Sheeley et al. 1999) and non-flare associated CME (Compagnino, Romano & Zuccarello 2017; Syed Ibrahim et al. 2018). Concluding on the previous studies, CMEs have been widely categorized into many types mainly based on their kinematic properties. By considering the role of associated flares in contributing energy to the CMEs, this study is aimed to investigate the differences in gradual and impulsive CMEs characteristics when they are associated with weak and strong flares, by analyzing their height-time, height-velocity, and height-acceleration profiles. Besides, this study signifies the importance of understanding the energy of associated flares as it affects the CME to arise as a gradual that does not affect the Earth's magnetosphere, or impulsive that can trigger geomagnetic storms upon arrival. Results present the overall pattern of height-time, velocity and acceleration progression for both events in order to differentiate and recognize the effects of flares towards the correlated CMEs.

METHODS

According to their associated class flare, CMEs throughout Solar Cycle 24 have been classified into low group flare-CMEs and high group flare-CMEs. During the present study, a gradual and impulsive characterization is conducted for both groups, and a qualitative analysis is conducted through a descriptive approach. An impulsive CME is selected by selecting one significant event as the representative from each group (low flare-CME and high

TABLE 1. Properties of gradual and impulsive CME

Gradual	Impulsive
Formed when prominences & their cavities rise up from below coronal streamers	Often associated with flares & Moreton waves on visible disk
Accelerates gradually to speeds of range 400-600 km/s	Moves uniformly at speeds higher than 750 km/s
Very weak (< 20 m/s^2) but persistent (lasts for ten of hours) towards positive acceleration	Short but strong acceleration (a few hundred of m/s^2)

flare-CME). A similar procedure is followed when selecting data for gradual CMEs. Following the selection of events, height-time, height-velocity, and height acceleration profiles are analyzed in order to gain a better understanding of their development and kinematic behavior under different intensities of flares. The scope of this research is limited to only one event per group for gradual and impulsive type, as this acts as a representative study to illustrate the behavior of CMEs with different classes of associated flares. The data selection is made based on the most significant event whereby each CME shows the closest readings of average velocity and average acceleration as compared to the established characteristics by Sheeley et al. (1999). A single-event analysis conducted in this study is important to individually look through the progression of each properties in comparison with another event to comprehend the differences between them.

Qualitative analysis is carried out by observing the development of each event based on LASCO images and how the leading edge, cavity and core of each CME propagate out of the visible disk, together with the differences in features size and brightness. As velocity and acceleration are the main properties of CMEs, their profiles are studied by looking at the overall trend when they start propagating, reaching their maximum height and proceed to increase or decrease in magnitude towards the end. It is crucial to identify if there is any prominent increment or decrement phase in velocity or acceleration which can correlate to the position of leading edge whether it is drastically climbing or in a gradual state.

The height-time profile for each event is directly quantified by SOHO LASCO and obtained from the database. To plot height-velocity and height acceleration profiles, we use the following equations to evaluate velocity and acceleration at each point. The actual position of the CME is firstly measured based on LASCO images and calculated using Equation (1) (Solar and Heliospheric Observatory 2020), before evaluating velocity and acceleration.

$$\frac{d_{screen}}{d_{actual}} = \frac{s_{screen}}{s_{actual}} \tag{1}$$

whereby d_{screen} is diameter of the Sun measured on the screen; d_{actual} is the actual diameter of the Sun = 1.4×10^6 km, s_{screen} is the position of the CME measured on the screen and s_{actual} is the actual position of the CME. Subsequently, the values of actual position of CME are used to calculate velocity using Equation (2). The following evaluation of velocity and acceleration are fully referred to data points that are provided by SOHO LASCO database.

$$v = \frac{s_2 - s_1}{t_2 - t_1} \tag{2}$$

whereby s_2 is the actual position at time t_2; s_1 is the actual position at time t_1; t_2 is the time at point 2; and t_1 is the time at point 1. The evaluation of velocity is then followed by evaluation of acceleration based on Equation (3). Since the data points is obtained from SOHO LASCO database, total data points are differed for each event, yet they still produce relevant graphs for this analysis.

$$a = \frac{v_2 - v_1}{t_2 - t_1} \tag{3}$$

whereby v_2 is the velocity at time; t_2 and v_1 is the velocity at time, t_1. After the values of velocity and acceleration for each event are evaluated, height-velocity and height-acceleration are then plotted to generally illustrate the entire development and progression and the differences between them.

RESULTS AND DISCUSSION

Gradual CMEs are weak events that move with constant acceleration along the field of view at low velocity. In this study, we analyze two gradual events, one of which is associated with a weak flare and the other with a strong flare. A few frames of gradual CME development as captured by SOHO LASCO C2 are shown in Figure 1. On 23rd December 2014, a low group flare-CME occurred with an angular width of 14°, starting at 0448UT and lasting for more than 5 h. During the CME timeframe, a C2.1 flare was observed at AR2242 at 0445 UT and ended at 0608 UT. A high group flare-CME with an angular width of 129° occurred on 5th September 2017 at 1748 UTC and eased off at 2200 UTC. On this day, M2.3 flare was recorded at 1737 UT, pulled off its peak at 1743 UT and ended at 1751 UT, which is evidently associated with gradual CME as it surfaced from the same region.

Compared to high group flare-CMEs, gradual events of low group flare-CMEs are seen to be less prominent due to their smaller scale. First image (Row 1) shows the point of initiation of the first event, where the leading edge is already ascending into the space, followed by the cavity, or dark region, and the evolving core of the CME. As a result of the ejection, the magnetic field has reached its maximum stability, as well as the active region that holds up the maximum energy. In the second image, the whole structure gains a slight but not very significant, change in height as the CME rises, before breaking in its structure, with mass particles stopping from traveling outward, indicating end of ejection (third image). As the second event of high group flare-CME unfolds, the image of each component of CME becomes more obvious. The associated M2.3 flare and leading edge are captured at the same time during the initiation phase, when the cavity and its core are not yet present. 1 h after initiation, the leading edge, cavity, and core are finally visible as they evolve into interplanetary space. In the final stage, the CME structure has spread out of view and no emissions are visible on the limb, so the ejection in that area has ceased. Figure 2 shows

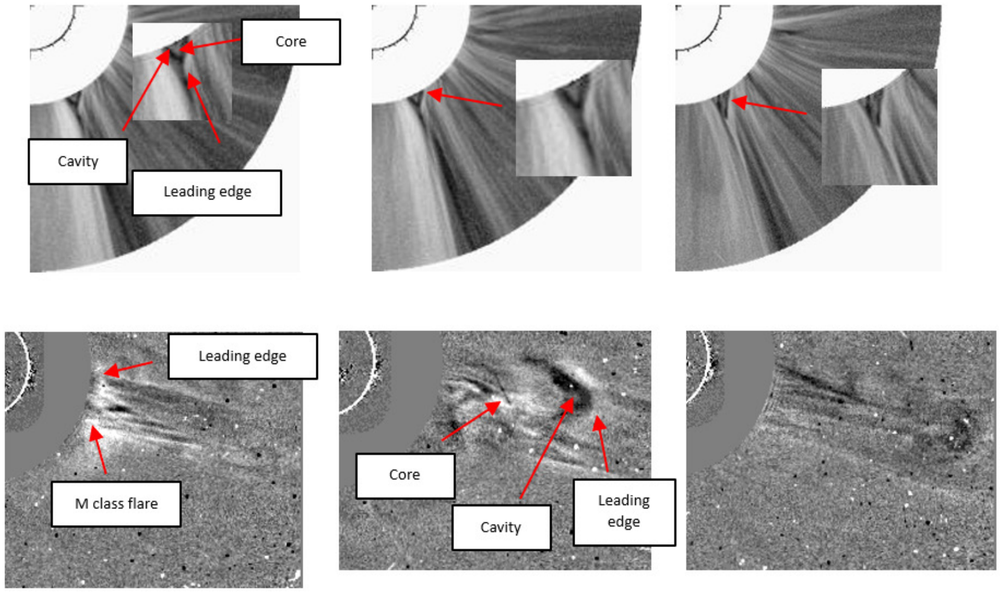

FIGURE 1. Development of gradual CME of low group flare-CME (first row) on 23rd December 2014 and high group flare-CME (second row) on 5th September 2017 as captured by LASCO C2

height-time, height-velocity, and height-acceleration for low-group flare-CMEs (left) and high-group flare-CMEs (right) for further analysis of their kinematic behavior.

Gradual CME of low group has an initial height at 4.56 R_{sun} before continuing its propagation at 4.82 R_{sun}. Since this event is classified as a slow CME, there is no large changes observed in its height as each data point does not increase more than one R_{sun}. The maximum height achieved is about 5 R_{sun} before proceeding to ascend slowly until it reaches the final height at 7.09 R_{sun} and emerging with background solar wind afterwards. Meanwhile, impulsive CME is initially ejected at a lower height of 2.96 R_{sun} and undergoes a steady climb as it goes outwards of the corona. The moment when the whole structure is visible on screen as seen in Figure 1, the height of leading edge is at 5.29 R_{sun} and the maximum height before the CME (out of the view) is 13.37 R_{sun}. As a whole, the pattern of the height changes is quite steady, with little variation between each increment, much like the low group despite different classes of associated flare.

Low group flare-CME height-velocity evolution shows a steady, slightly rising trend from the beginning, peaking at 440 km/s. It is anticipated that the velocity change would slow down as the mass increases above 12 R_{sun} and the whole profile does not exhibit a sharp increase as it propagates outward while maintaining its velocity with average velocity of 314.5 km/s. High group flare-CME obtained higher magnitudes of average and peak velocity of 466 km/s and 520 km/s, respectively. On the most significant part, the leading edge changes its velocity drastically from 435 km/s to 450 km/s at a height of 4.09 R_{sun} towards 5.29 R_{sun}, simultaneously when the leading edge climbs to its highest point for 1.20 R_{sun} in 18 min. The kinematics of a CME can be described in three phases - initiation, acceleration and propagation. Initiation phase is indicated by a slow rise of coronal structure and usually lasts for about an hour, acceleration phase is when the CME undergoes a drastic increment of velocity in radial direction, and propagation phase displays no outstanding changes in acceleration while slight decelerations are observed. Therefore, the rapid changes in velocity as seen in the high group event specifies the acceleration phase the event is going through together with the rising of X-ray flux of accompanied flare.

For height-acceleration progression, low group flare-CME accelerates within 3 m/s^2 until 42 m/s^2, emerging at 23 m/s^2 and approaching its peak at 42 m/s^2, without large changes in acceleration throughout its propagation. On the other hand, high group flare-CME has smaller magnitudes and range of acceleration going within 2 m/s^2 until 14 m/s^2. The evaluated average acceleration is 7.8 m/s^2 and peak acceleration is observed when the leading edge climbs from 4.09 R_{sun} to 5.29 R_{sun} while travelling at 14 m/s^2. Following its peak, the CME begins to slow down towards below 10 m/s^2 as height increases until it comes to an end.

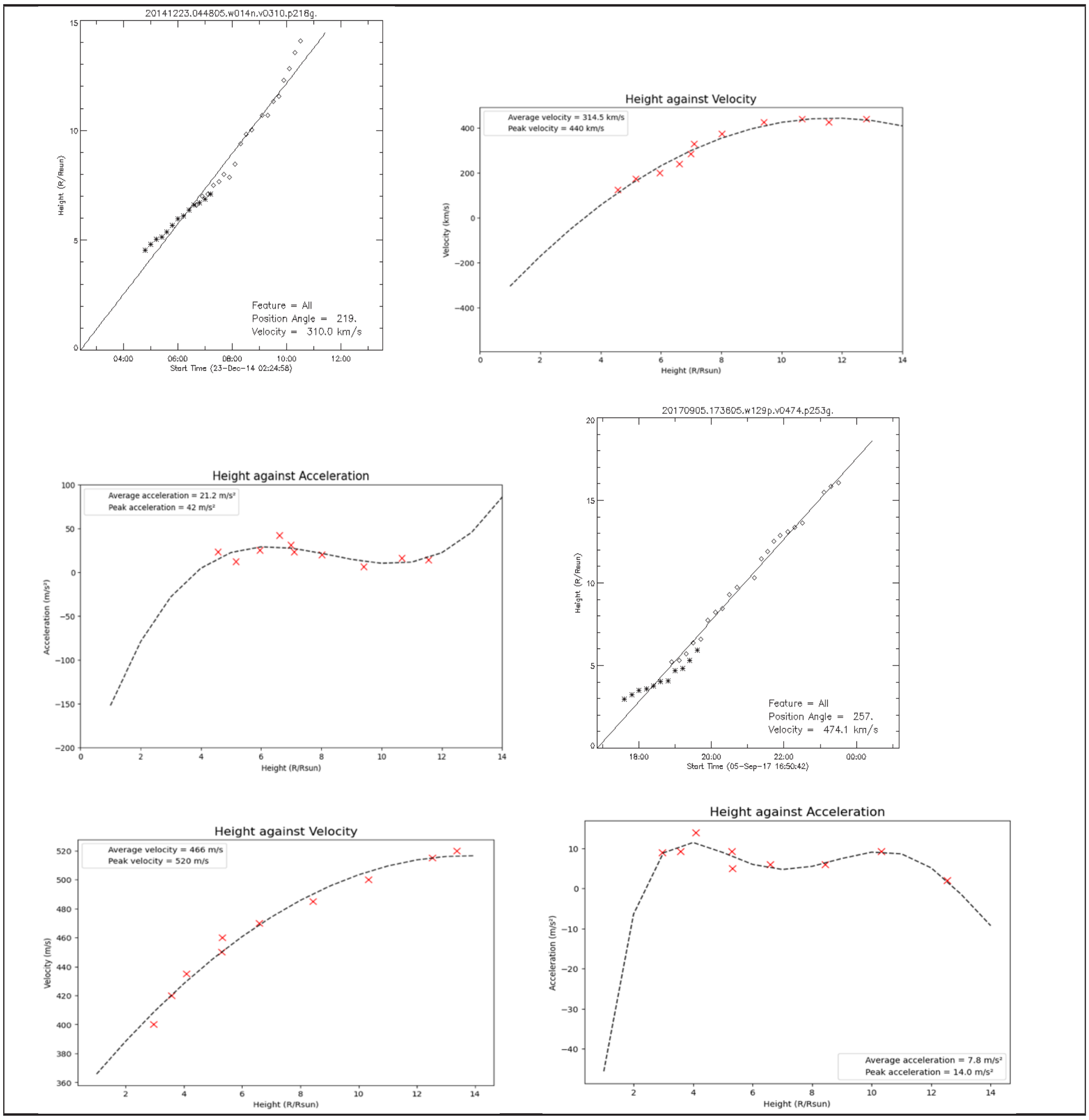

FIGURE 2. Height-time, height-velocity and height-acceleration for low group flare-CME (left) and high group flare-CME (right)

Moving on to impulsive CMEs, the first flare-CME selected from the low group occurred on 11th June 2014 with the accompanying C3 flare. In the first row of Figure 3, the CME emerged with an angular width of 30° at 0924 UT, sustained for one hour, and ended at 1030 UT, while the C3 flare developed from the same active region at 0931 UT, reaching peak flux at 0934 UT, and ending at 0945 UT. Second row images show a full halo CME from high group that happened on 27th January 2012. It initiated at 1827 UT, propagating for almost 2 h before ceasing at 2018 UT. This event coincides with X1.7 flare which started prior to CME, at 1737 UT, making to its maximum at 1837 UT and settled down at 1856 UT.

There is no doubt that both impulsive and gradual CMEs are more noticeable in terms of their structure and produce larger brightness and distinct images of each component. At the beginning of the low group flare-CME ejection (Row 1), all components of the CME can be seen exiting out of the Sun's surface located below the east limb. As can be seen in the second image taken at 0954 UT, the leading edge, cavity, and core of the CME keep going outwards of the corona during the first 30 min after launch.

Comparatively, the brightness of the structure is comparable to a gradual CME of the low group, as both events took place during a low-energy, dim-emitting condition with limited magnetic field and plasma release. A flare-CME from a high group (Row 2) has a very distinctive structure and brightness, especially its intense leading edge which is perfectly shaped, followed by a cavity and a core. Accordingly, this CME is seen as the strongest of all the events due to its 360° angular width and its association with the strongest flare, X1.7, as evidenced by the radial outspread compared to the other events. As shown in Figure 4, height-time, height-velocity, and height-acceleration of impulsive CMEs are shown for flare-CMEs of the low group (left) and flare-CMEs of the high group (right).

The first ejection of low group flare-CME takes place at a height of 2.92 R_{sun}, when the core is not yet visible in the field of view. The leading edge obtains its maximum climb rate across the whole documented distance of its propagation in the following 12 min, reaching a height of 4.02 R_{sun}. Prior to ceasing and combining with the background solar wind to spread at the speed of the solar wind, the event's highest height is measured at 7.71 R_{sun} at 1030 UT. The flare-CME in the high group had a higher initial height at 3.76 R_{sun} and has an almost constant variation in height across all sites. According to the overall perspective, the height growth for this event is more constant since the leading edge is changing steadily, with the exception of the first, second, and third points and during the standstill. The leading edge of this event reached a distance of 28.33 R_{sun}, four times greater than the first impulsive event.

The height-velocity profile for low group shows a gradual decline across its propagation with an initial velocity of 1050 km/s, a decrease to 950 km/s, and further deceleration until 600 km/s before combining with solar wind. Maximum velocity coincides with initial velocity, 1050 km/s, with an average velocity of 820 km/s. The high group flare-CME, in contrast, possesses a gradual trend towards positive direction with a wider range of velocity between 1950 km/s and 2820 km/s. Its average velocity is much higher than the low group's which is 2402 km/s, and its peak velocity is 2820 km/s. In both events, the height-acceleration profiles indicate deceleration with different patterns - the flare-CME in the low group steadily decelerates, while the flare-CME in the high group fluctuates slightly, but still shows deceleration. Assuming that CME associated with strong flares experience more deceleration, the average acceleration for low and high groups is -128.17 m/s^2 and -149.6 m/s^2, respectively.

For a better view of comparison, Table 2 presents the properties of gradual and impulsive CMEs for both groups which include angular width, average velocity, average acceleration, initial and final height and rate of change of height.

Overall, flare-CMEs associated with low-class flares have smaller angular widths, while flare-CMEs associated with high-class flares have wider angular widths. A gradual flare-CME of high class has a smaller angular width than an impulsive flare-CME, but is still more extensive than a gradual flare-CME of low class. Due to the heat energy contribution from flares, high group flare-CMEs of gradual

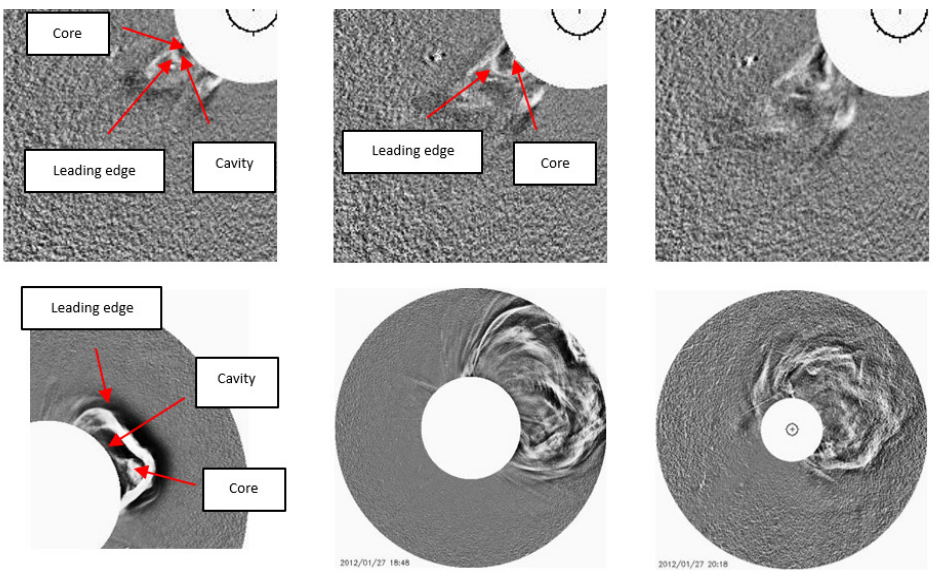

FIGURE 3. Development of impulsive CME of low group flare-CME (first row) on 11th June 2014 and high group flare-CME (second row) on 27th January 2012 as captured by STEREO COR-A and LASCO C2

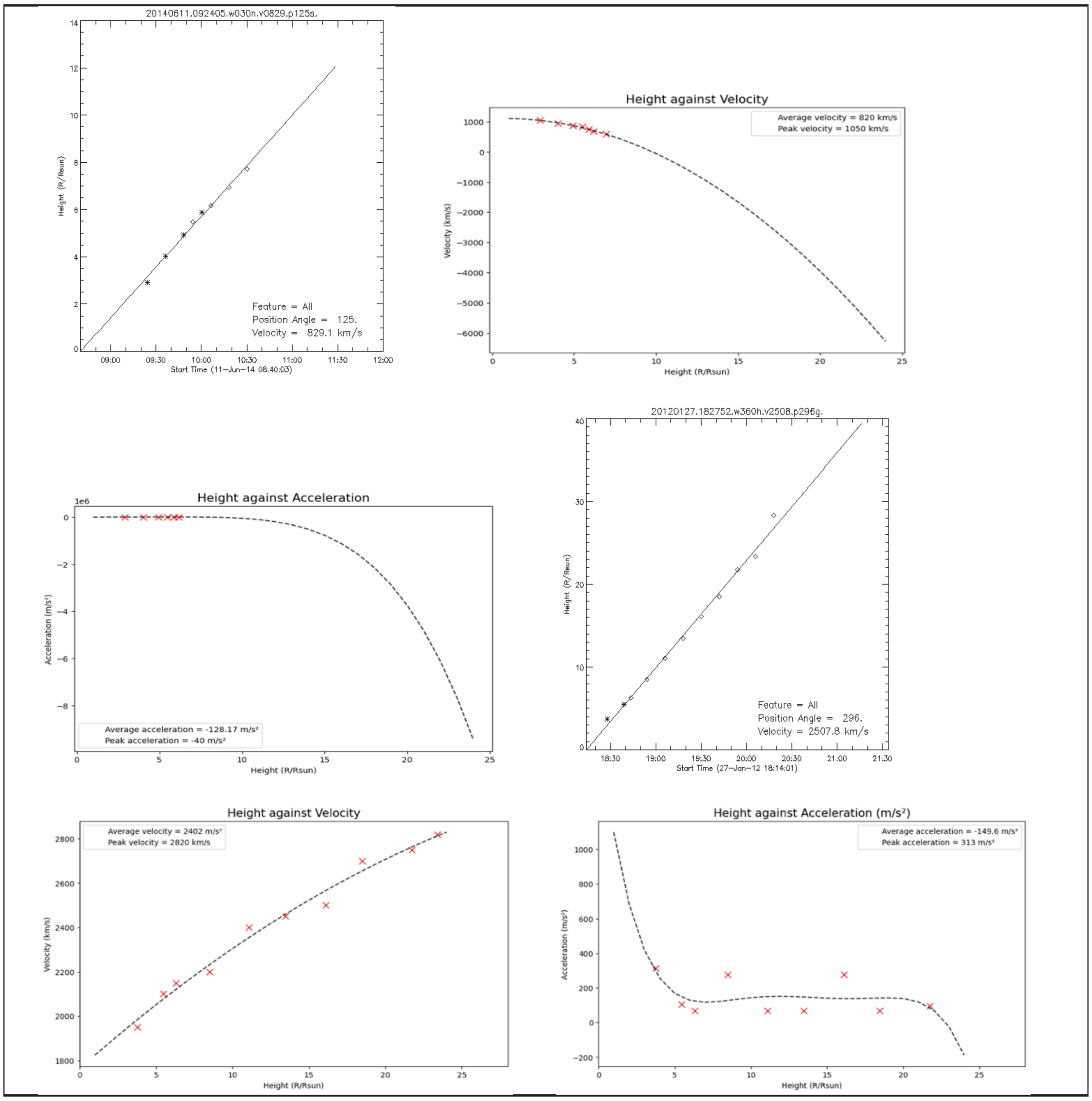

FIGURE 4. Height-time, height-velocity and height-acceleration for low group flare-CME (left) and high group flare-CME (right)

and impulsive are moving faster due to enhanced magnetic field energy conversion. Although impulsive events are accompanied by flare energy, they decelerate with higher magnitudes, while gradual events accelerate with lower magnitudes. The momentum of fast-moving CMEs is transferred to solar wind and the CMEs begin to decelerate as they lose momentum and both CMEs have decreased in speed due to continuous momentum transfer from the start to the end. The manifestation of acceleration by gradual event and deceleration by impulsive event have also been seen and discovered by several previous studies according to their modelling mechanism (Shen et al. 2012; Temmer et al. 2023; Vršnak et al. 2004). Meanwhile, high group flare-CMEs experience a faster rate of change of height than low-group events in respective groups since they cover more distance in a minute and expand faster. On top of that, both impulsive events are travelling much faster than gradual events due to higher average velocity, whereby Zhang et al. (2004) also obtained a parallel outcome.

Based on the flare model by Jain, Aggarwal and Kulkarni (2010), a CME is emerged from a region where

TABLE 2. Properties of gradual and impulsive CME

Type of CME	Gradual CME		Impulsive CME	
Group of flare-CME	Low group flare-CME	High group flare-CME	Low group flare-CME	High group flare-CME
Event date	23rd Dec 2014	5th Sep 2017	11th June 2014	27th Jan 2012
Associated flare	C2.1	M2.3	C3.0	X1.7
Angular width	14°	129°	30°	360°
Average velocity (km/s)	307	466	820	2402
Average acceleration (m/s^2)	22	7.8	-128.17	-149.60
Initial height (R_{sun})	4.56	2.96	2.92	3.76
Final height (R_{sun})	14.06	13.37	7.71	28.33
Rate of change of height (R_{sun}/min)	1.63×10^{-2}	2.94×10^{-2}	7.26×10^{-2}	0.22

the magnetic energy is dominant and that is fueled by magnetic sources. In another way, flares develop a magnetic field to increase their energy, just as they have the potential to contribute thermal energy to CMEs. Therefore, events that occur together with strong flares would gain more heat energy, increasing the energy conversion process which eventually results in accelerating particles at higher speed during CME onset. The associated C3 flare accompanying the low group in impulsive CME is the succeeding flare to X-class flare during its descent phase, which is believed to carry an extra energy that contributes to the corresponding CME to release at higher velocity.

CONCLUSION

This study examined the kinematic properties of gradual and impulsive CMEs selected from low group flare-CMEs and high group flare-CMEs, in order to observe similarities and differences with different classes of associated flares. Compared with gradual CMEs, impulsive CMEs have a greater average velocity; however, since insufficient momentum has been transferred to the ambient solar wind, they decelerate. High-group flares (such as those associated with CMEs with high flare groups) of gradual and impulsive appear to contribute to the high velocity of plasma discharge since they release more heat energy, thus speeding up the conversion of magnetic field energy. Due to the increased rate of height change, the impulsive CMEs can travel a greater distance (R_{sun}) in a minute as a result of their enhanced velocity. On acceleration, gradual CMEs record positive acceleration with 22 m/s^2 and 7.8 m/s^2 for low group and high group, respectively. Meanwhile, both impulsive events possess larger magnitudes of average acceleration but they go in negative manner - deceleration. Angular width goes correspondingly with accompanied flare energy, whereby events associated with M2.3 and X1.7 appear in larger width compared to C2.1 and C3 association. The most significant event is apparently the impulsive event of high group flare-CME that exhibits 360° of angular width as a result of its high average velocity, thus covering more distance than others. As properties of CMEs are important to understand for its dynamic behavior, future studies are recommended to include the starting of associated flare whether it gives a different perspective as when the flare occurs before or after CME onset. The different parts of CME (leading edge, cavity, core) might also give another discovery to the acceleration or deceleration behavior which is good to be examined in future studies.

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*Corresponding author; email: zetysh@uitm.edu.my