An Insight into the Coupling of CME Kinematics in Inner and Outer Corona and the Imprint of Source Regions

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Abstract

Despite studying coronal mass ejections (CMEs) for several years, we do not yet have a complete understanding of their kinematics. To this end, it is essential to understand the change in kinematics of the CMEs as they travel from the inner corona (<3 R_s) up to the higher heights of the outer corona. We conduct a follow-up statistical study of several 3D kinematic parameters of 59 CMEs previously studied by Majumdar et al. (2020). The source regions of these CMEs are identified and classified as active regions (ARs), active prominences (APs), or prominence eruptions (PEs). We study several statistical correlations between different kinematic parameters of the CMEs. We show that the CMEs’ average kinematic parameters change as they propagate from the inner to the outer corona, indicating the importance of a region where the common practice is to perform averaging. We also find that the CME parameters in the outer corona are highly influenced by those in the inner corona, indicating the importance of the inner corona in the understanding of the kinematics. Furthermore, we find that the source regions of the CMEs tend to have a distinct imprint on the statistical correlations between different kinematic parameters, and that an overall correlation tends to wash away this crucial information. The results of this work supports the possibility of different dynamical classes for the CMEs from ARs and prominences, which gets manifested in their kinematics.

Unified Astronomy Thesaurus concepts: Solar coronal mass ejections (310)

1. Introduction

Coronal mass ejections (CMEs) are large-scale eruptions of plasma and magnetic field from the solar corona into the heliosphere (Webb & Howard 2012). Their speed ranges from a few hundreds to a few thousands of km s⁻¹, and their acceleration ranges from a few tens to a few 10⁴ m s⁻² (for a review, see Webb & Howard 2012). CMEs are also the major drivers of space weather, as they are capable of producing shock waves, interplanetary disturbances that cause huge technological damages (Gosling 1993). Thus, CMEs are of interest from both scientific and technological points of view, and hence, understanding their kinematics is essential. It is understood that the kinematics of CMEs are governed by the interplay of three forces: the Lorentz force, the gravitational force, and the viscous drag force (Wood et al. 1999; Zhang et al. 2001; Vrtanak et al. 2007; Webb & Howard 2012). As a result of these forces, CMEs follow a three-phase kinematic profile. According to Zhang & Dere (2006), the first, initial phase is a slow rise phase, followed by an impulsive acceleration phase (observed as rapid increase in their velocity), and then by the final phase, where CMEs propagate with little or no acceleration. The first two phases are usually finished in the low coronal heights (<3 R_s) (Temmer et al. 2008; Bein et al. 2011; Patel et al. 2021). In later stages of their evolution, CMEs experience drag due to solar wind, resulting in deceleration (Gopalswamy et al. 2000; Moon et al. 2002; Webb & Howard 2012). So, as kinematics of CMEs change from the inner to the outer corona, averaging the different kinematic parameters over their entire trajectories could wash away a lot of crucial information that might hold clues to the coupling of kinematics of CMEs in the inner corona to the heliosphere.

CMEs are also known to arise from different source regions: active regions (ARs) and prominence eruptions (PEs) (Subramanian & Dere 2001; Moon et al. 2002; Majumdar et al. 2020). CMEs associated with ARs are known to be mostly impulsive, whereas CMEs associated with PEs are gradual CMEs (MacQueen & Fisher 1983; Sheeley et al. 1999). Recently Pant et al. (2021) reported the influence of different source regions on the width distribution of CMEs. Now, whether these different source regions have any clear imprint on different kinematic properties of CMEs is still not clearly known.

A major concern in the study of CME kinematics regards measurements that are carried out in the plane of the sky that leads to projection effects (Balmaceda et al. 2018). A primary step to minimize such projection effects is to connect the CMEs to their source regions on the disk of the Sun. An even better way to remove the projection effects is to use 3D reconstruction techniques. To this end, several works based on the tracking of CMEs in 3D have been reported (Thernisien et al. 2006, 2009; Mierla et al. 2008; Moran et al. 2010; Joshi & Srivastava 2011; Sarkar et al. 2019). A method based on forward modeling to fit the CME flux rope on multi-vantage-point images was also developed, assuming the self-similar expansion of the CMEs (Thernisien et al. 2006, 2009), and was termed the graduated cylindrical shell (GCS) model. Therefore, a study based on the fitted parameters of the model will be free from projection effects. Recently, Majumdar et al. (2020) connected 3D profiles of width evolution and acceleration to report on the observational evidence of the imprint of the height of influence of the Lorentz force on the 3D kinematics. These 3D parameters are of the most significant relevance in the context of arrival time prediction of CMEs. Several models have been developed that...
take the average speed of the CME as input to predict their arrival times (for a review, see Zhao & Dryer 2014; Riley et al. 2018).

Since the kinematics of the CMEs change as the CMEs propagate outwards, it is important to look at the coupling of the kinematics of the CMEs from the inner to the outer corona. It has been reported several times in the past that quiescent prominences and active regions tend to classify the ejected CMEs from them into two dynamical classes, with quiescent prominences tending to be gradual CMEs and active regions tend to be impulsive CMEs (Sheeley et al. 1999). It is worth looking at the manifestation of this distinction in the behavior of different kinematic parameters that reflect the kinematics of a CME. In this work, keeping in mind the above existing shortcomings in our understanding of CME kinematics, we look into the correlation between different 3D kinematic parameters of the CMEs as they evolve from the inner to the outer corona. With the additional information of the source region of the CMEs, we also look into the imprint of the source regions (if any) on the behavior of these different 3D kinematic parameters. We study the same 59 events studied by Majumdar et al. (2020) and follow the same analysis. In this context, it should be noted that a shock spheroid model is also available as a part of the GCS model (as reported earlier by Hess & Zhang 2014) for fitting the shock front ahead of the flux rope. Since we were not interested in the shock dynamics and our aim was focused on the CME kinematics, we only used the flux-rope GCS model in our work. Like Majumdar et al. (2020), two vantage point observations are used for fitting the GCS model. It must be noted that provision for the use of a third vantage point in the form of observations from the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) can be used for better constraining parameters like the tilt angle (see Thernisien et al. 2009). Since the aim of this work was to study the radial kinematics of CMEs, the tilt-angle parameter was not used in our analysis, reducing the need for the third vantage point. Also, the field of view (FOV) of LASCO starts well beyond the starting FOV of COR-1, and since we do not want to include extreme ultraviolet observations with white light, in order to keep consistency, we did not include LASCO observations for the GCS fitting. In Section 2 we outline the data source used and the working method, followed by our results in Section 3. We summarize the main conclusions from our work in Section 4.

2. Data and Method

2.1. Data Source and Data Preparation

The data used for this work is primarily taken from COR-1 and COR-2 on board the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) package (Howard et al. 2002) of the twin-spacecraft Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008). Also, data from different passbands of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO; Lemen et al. 2011) and the Extreme ultraviolet Imaging Telescope (EIT; Delaboudiniere et al. 1995) on board SOHO were used to identify the source regions of CMEs coming from the front side of the Sun. For more details on the data source, please refer to Majumdar et al. (2020).

2.2. Parameter Description

To understand the relationship between the different parameters associated with kinematics of a CME as the CME propagates from the inner to the outer corona, we list out the different parameters used in this work in Table 1 and define them as follows.

1. $a_{\text{max}} (V_{\text{max}})$—peak acceleration (velocity) of the CME in the entire (COR-1 and COR-2) FOV
2. $V_{\text{max}}$—velocity of the CME at $a_{\text{max}}$
3. $V_{\text{lin}}$—average velocity of the CME from linear fit to the height–time data for the entire FOV.
4. $V_{\text{init}} (a_{\text{lin}})$—mean velocity (acceleration) in the inner corona ($<3 R_\odot$) computed by taking the mean of the velocity (acceleration)–time data points, obtained from derivatives of the height–time data.
5. $a_{\text{mean}} (V_{\text{mean}})$—overall mean acceleration (velocity) in the entire FOV by computing the mean of the acceleration (velocity)–time data points, obtained from derivatives of the height–time data.
6. $a_{\text{const}}$—constant acceleration in the entire FOV, found from quadratic fit to the height–time data for the entire FOV.
7. $h_{\text{max}} (h_{v_{\text{max}}})$—height at which peak acceleration (velocity) was attained.

3. Results

We derived the parameters mentioned in Section 2.2 from the velocity and acceleration calculations of the 59 CMEs described in Majumdar et al. (2020), studied their correlations, and established several empirical relations among them. Some of the CMEs studied in Majumdar et al. (2020) show deceleration very close to the Sun (see Figure 2 of Majumdar et al. 2020). It should be noted that we used coronagraph images with an FOV starting from 1.4 $R_\odot$ (in the plane of the sky), and in some cases the CMEs have already reached 2 $R_\odot$ (projected height) for the first measurement. According to Gui et al. (2011), the impulsiveness of the CMEs occurs below 1.5 $R_\odot$. As the aforementioned CMEs are well beyond this height for the initial points of measurement, it is possible for deceleration to occur at the start of the coronagraph FOV. Furthermore, Sachdeva et al. (2017) reported that for fast CMEs, solar wind drag can act earlier, leading to deceleration. It should also be noted that the width mentioned in Table 1 of Majumdar et al. (2020) is the value of the half-angle parameter measured at a particular instant of time and height (as mentioned in the table), beyond which the parameter experiences further evolution. Further, while comparing the GCS width with the width given in the Coordinated Data Analysis Workshop (CDAW) catalog (Gopalswamy et al. 2009), it must be kept in mind that the complete width of the CME as measured from the GCS model is estimated as 2(half angle + $\sin^{-1}$aspect ratio)), while CDAW provides the final projected width. For halo or partial-halo CMEs, the projected width becomes an overestimate. In Table 1 of this work, we provide the Pearson’s correlation coefficient (CC) and, for better appreciation of our results, the Pearson’s critical correlation coefficients (CCCs). We also provide the associated $p$-value which shows the statistical significance of the correlation. The average significance level ($\alpha$) for the correlations was found to be 0.05 on average, thus correlations...
with p-values lesser than 0.05 and CCs higher than CCCs implies a statistically significant result. In Figure 1(a) we plot $a_{\text{max}}$ versus $V_{\text{max}}$. We find that the two parameters are positively correlated with a CC of 0.63 and can be described by the following relation:

$$a_{\text{max}} = 10^{-0.35} V_{\text{max}}^{1.21}.$$  

A similar result was also reported by Bein et al. (2011) but it must be noted that their numbers suffered from projection

Table 1

Summary of the Fitted Parameters with the Correlation Coefficients (CCs), Critical Correlation Coefficients (CCCs), P-values and Fitted Relations.

| Parameters Studied | Correl. Coeff. (CC) | Crit. Correl. Coeff. (CCC) | P-values | Empirical Relation |
|--------------------|----------------------|----------------------------|----------|-------------------|
| (a) $a_{\text{max}}$ versus $V_{\text{max}}$ | 0.63 (overall) | 0.25 | $7.8 \times 10^{-3}$ | $a_{\text{max}} = 10^{-0.35} V_{\text{max}}^{1.21}$ |
|                    | 0.45 (AP)           | 0.46 | 0.053 | $a_{\text{max}} = 10^{-1} V_{\text{max}}^{0.98}$ |
|                    | 0.91 (AR)           | 0.44 | $4.3 \times 10^{-8}$ | $a_{\text{max}} = 10^{-2.71} V_{\text{max}}^{0.98}$ |
|                    | 0.41 (PE)           | 0.44 | 0.075 | ... |
| (b) $V_{\text{max}}$ versus $a_{\text{max}}$ | 0.57 (overall) | 0.25 | $3.2 \times 10^{-6}$ | $V_{\text{max}} = 10^{1.30} a_{\text{max}}^{0.43}$ |
|                    | 0.42 (AP)           | 0.46 | 0.07 | ... |
|                    | 0.77 (AR)           | 0.44 | $7.4 \times 10^{-5}$ | $V_{\text{max}} = 10^{1.31} a_{\text{max}}^{0.44}$ |
|                    | 0.57 (PE)           | 0.44 | 0.009 | ... |
| (c) $V_{\text{lim}}$ versus $V_{\text{mi}}$ | 0.68 (overall) | 0.25 | $2.6 \times 10^{-3}$ | $V_{\text{lim}} = 10^{1.51} V_{\text{mi}}^{0.46}$ |
|                    | 0.78 (AP)           | 0.46 | $9.8 \times 10^{-5}$ | ... |
|                    | 0.63 (AR)           | 0.44 | 0.003 | ... |
|                    | 0.78 (PE)           | 0.44 | $5.8 \times 10^{-5}$ | ... |
| (d) $V_{\text{max}}$ versus $V_{\text{mi}}$ | 0.73 (overall) | 0.25 | $4.6 \times 10^{-11}$ | $V_{\text{max}} = 10^{0.05} V_{\text{mi}}^{0.72}$ |
|                    | 0.88 (AP)           | 0.46 | $5.1 \times 10^{-7}$ | ... |
|                    | 0.67 (AR)           | 0.44 | 0.001 | ... |
|                    | 0.66 (PE)           | 0.44 | 0.002 | ... |
| (e) $a_{\text{const}}$ versus $V_{\text{mi}}$ | $-0.67$ (overall) | $-0.25$ | $8.9 \times 10^{-4}$ | $a_{\text{const}} = 545.6 V_{\text{mi}}^{-0.52}$ |
|                    | $-0.62$ (AP)        | $-0.46$ | 0.006 | ... |
|                    | $-0.61$ (AR)        | $-0.44$ | 0.005 | ... |
|                    | $-0.30$ (PE)        | $-0.44$ | 0.202 | ... |

Note. Apart from the overall empirical relation, the same is also shown separately only for the source regions for which the CC is distinctly different and higher than the CC of others. In (a) and (b) the CC for AR is much higher than others. In (c) and (d), the individual CCs are similar, while in (e) the CC for AR and AP are similar to the overall CC, and the CC for PE is much poorer.

Figure 1. Plot of (a) $a_{\text{max}}$ vs. $V_{\text{max}}$ and (b): $V_{\text{max}}$ vs. $a_{\text{max}}$ of all the CMEs. The dashed curves denote the fitted power-law relation. The data points and fitted curves are color-coded according to the source regions.
effects and were obtained by combining EUV and white light (WL) observations, bringing additional ambiguity regarding whether the same physical feature is being tracked in EUV and WL (for a discussion, see Song et al. 2019, and references therein), as the former corresponds to the temperature structure of a CME while the later corresponds to the density structure (Ying et al. 2020). In our work, we do away with both of these limitations, as our measured numbers are in 3D and the measurements are done uniquely in WL. Thus, we find that the power law remains unchanged in 3D. Since we also have the information of the source regions of the CMEs, we also find the correlations between these quantities for CMEs coming from different source regions. From this, we find that $a_{\text{max}}$ and $V_{\text{max}}$ are strongly correlated (CC = 0.91) for CMEs coming from ARs, while the ones coming from APs and PEs show weaker correlations of 45% and 41%, respectively. This indicates a difference in the CCs for CMEs connected to ARs and CMEs connected to prominences (APs and PEs). We also find that the two quantities for CMEs from ARs are now related by the relation,

$$V_{\text{lin}} = 10^{1.51} V_{\text{m}}^{0.46}.$$  

Thus, in addition to arriving at a similar conclusion in 3D as was reported earlier by Bein et al. (2011) in 2D, with the aid of the source region information, we now understand that the source regions have a distinct imprint on the correlation between these parameters, and that concluding based on just the overall correlation washes away this crucial information. For a better understanding, we also plot in Figure 1(b) $V_{\text{lin}}$ versus $a_{\text{max}}$. In this case too we find an overall positive correlation of 0.57. This positive correlation can be described by the relation,

$$V_{\text{max}} = 10^{1.30} a_{\text{max}}^{0.43}. \quad (3)$$

Similar behavior was also reported by Joshi & Srivastava (2011) based on fewer samples, although they did not report any such power-law relation (or any CC). Looking further into the CCs for CMEs coming from different sources, we find that CMEs coming from ARs show a relatively higher correlation with a CC of 0.77, while it is lesser for CMEs coming from APs and PEs (with CCs of 0.42 and 0.57, respectively). This, in support of our previous result, also hints toward the possibility that the dynamics of the CMEs connected to ARs are different from CMEs connected to prominences. Figure 2(a) shows the plot between $V_{\text{lin}}$ and $V_{\text{m}}$. We find that the two quantities are positively correlated, with an overall CC of 0.68, and they are related by the relation,

$$V_{\text{lin}} = 10^{0.51} V_{\text{m}}^{0.46}. \quad (4)$$

The CMEs from ARs have a CC of 0.63, while the CMEs connected to prominence eruptions (APs or PEs) have a higher correlation of 0.78. This indirectly indicates that such CMEs connected to erupting prominences experience a small and gradual acceleration that continues during their propagation in the higher heights, while the ones from ARs are more prone to an initial impulsive acceleration, followed by a decelerating or constant velocity profile. Although this was reported in earlier work (Sheeley et al. 1999; Moon et al. 2002; Webb & Howard 2012), it is important to note that this result is based on 3D quantities with the relative contribution of different source regions to the overall correlation. Also, from our results, we show that similar conclusions which are well known from previous studies as mentioned above on the kinematics of gradual and impulsive CMEs can also be obtained from a...
different perspective by studying the statistical kinematic properties.

Figure 2(a) also shows the importance of considering the kinematics in the inner corona and how the kinematic parameters in the outer corona are influenced by those in the inner corona. Also, several models of CME arrival time predictions use \( V_{\text{in}} \) as input to calculate their arrival times (for a review, see Zhao & Dryer 2014; Riley et al. 2018). An important aspect in this regard is the lead time of the forecast, which is the difference between the observed arrival time of CME, and the time of submission of the forecast (Riley et al. 2018). With the help of Equation (4), the lead time can be minimized by estimating \( V_{\text{in}} \) from \( V_{\text{mi}} \), thereby reducing the absolute dependency on observations of the outer corona for arrival time predictions. Please note that an estimate of the gain in lead time would be possible only with the availability of near-real-time data. Apart from that, it would also depend on the telemetry rate of the instruments involved, which would dictate the accessibility of the near-real-time data. Having said that, we would also like to emphasize that our result will help in the implementation of inner coronal observations from space missions like ADITYA-L1 (Prasad et al. 2017; Seetha & Megala 2017) and PROBA-3 (Renotte et al. 2014) (which do not have outer coronal observations) solely for the purpose of arrival time estimation of CMEs.

In Figure 2(b), we plot \( V_{\text{max}} \) versus \( V_{\text{m}} \) and find that the two quantities are positively correlated, with an overall CC of 0.73, and they can be related by the relation,

\[
V_{\text{max}} = 10^{1.05} V_{\text{m}}^{0.72}.
\]  

(5)

This throws light on the kind of acceleration profiles experienced by the CMEs. The CMEs experiencing impulsive acceleration also experience a high retardation (see Figure 2 in Majumdar et al. 2020) that will largely affect \( V_{\text{m}} \), while the CMEs experiencing uniform acceleration do not experience such high retardation. Again, looking at the source region contributions, we see that the CMEs from ARs have a comparatively lower CC of 0.67, with a similar CC value for the CMEs from PEs, while the CMEs from APs show a higher CC of 0.88. This thus re-establishes that CMEs connected to ARs are mostly impulsive ones and experience higher deceleration than those connected to APs, leading to a lower correlation in the former. A lower correlation in the case of CMEs from PEs again indicates that they are gradual events where a steady small acceleration prevents the mean velocity from being more strongly correlated with the peak velocity (as the latter keeps increasing). It is important to note that this was already pointed out by Majumdar et al. (2020), and we reaffirm those results in a more statistical manner here. The above relation (Equation (5)) could also be empirically used to estimate one of the quantities when the other is known. For example, if we have inner corona observations in the future from Aditya-L1/VELC or STEREO/COR-1A, then \( V_{\text{max}} \) could be measured in the inner corona, and the mean speed \( V_{\text{m}} \) could be quickly estimated based on such empirical relations. \( V_{\text{m}} \) has other applications, such as in drag-based models for CME propagation.

We look into the correlation between \( a_{\text{const}} \) and \( V_{\text{mi}} \) in Figure 3(a). We find a clear anticorrelation between the two quantities with a CC of \(-0.67\), where the two quantities are related by

\[
a_{\text{const}} = 545.6 V_{\text{mi}}^{-0.52}.
\]  

(6)

This indicates the interaction of the CME with the solar wind and the drag experienced by the former due to the later. It is worthwhile to note that such acceleration-velocity anticorrelation has been previously reported (see Moon et al. 2002; Vršnak et al. 2004), but such reports only include results in the outer corona with projected values of acceleration and velocity (starting with projected height of at least \( 2 R_{\odot} \)). In our work, we report on a similar anticorrelation that exists in the inner corona as well, and our result is based on 3D acceleration and velocity. This anticorrelation thus shows that the influence of the drag forces comes into play as early as the inner corona. Further, when we look into the individual source region contributions, we find that the CMEs from ARs have a CC of \(-0.61\) and that CMEs from APs have a similar CC \((-0.62\), while this anticorrelation is relatively poor for PEs \((-0.30\). This distinct difference in the CC for CMEs from PEs and CMEs from active regions (ARs and APs) points to the contrasting acceleration experienced by the CMEs. Those with impulsive acceleration are faster, which increases drag, causing a higher retardation which is reflected in the higher value of anticorrelation in the case of CMEs connected to ARs. This is not the case for CMEs from PEs, which are predominantly gradual events, leading to a weaker anticorrelation reflecting a weaker drag. We thus find that the source region information is again important in the study of statistical kinematics of CMEs.

In Figure 4(a) we plot the distribution of \( V_{\text{mi}} \) and \( V_{\text{m}} \). We find that the distribution of \( V_{\text{m}} \) has been shifted toward the right side with respect to the distribution of \( V_{\text{mi}} \). Thus, for average quantities, it is important to specify the region where the average has been taken, as we can see that the numbers change from the inner to the outer corona. For a better illustration, in Figure 4(b) we plot \( V_{\text{m}} \) versus \( V_{\text{mi}} \). The solid line represents the
boundary where both quantities are equal. We see that for most of the CMEs, \( V_m \) is greater than \( V_{mi} \), implying that the CMEs have gained speed while propagating in the outer corona. We also note that most CMEs that have \( V_{mi} \) greater than \( V_m \), come from ARs, thus re-indicating the presence of impulsive accelerations in the lower heights, followed by later deceleration. Also, the CMEs coming from PEs have \( V_m \) greater than \( V_{mi} \), thus confirming that they experience gradual acceleration for a longer duration that leads to a steady increase in their velocities as they propagate outwards. So, we note that working with a single average velocity of the CME for its entire trajectory often masks this important information. Similarly, in Figure 4(c) we plot the distribution of \( a_{mi} \) and \( a_m \). We find that the distribution of \( a_{mi} \) was relatively more spread out around the zero value, thus indicating acceleration and deceleration and the wide range of kinematics exhibited by CMEs.

Figure 4. (a): Distribution of \( V_{mi} \) and \( V_m \). (b): \( V_{mi} \) vs. \( V_m \). (c) Distribution of \( a_{mi} \) and \( a_m \). (d) Distribution of \( h_{max} \) and \( h_{vmax} \). The data points are color coded according to the source regions.
connected to different source regions, while the distribution of \( a_m \) is more narrowed around the zero value, with the mode of the distribution lying in the range of 0–100 m s\(^{-2}\). This shows that the CMEs experience very little acceleration in their higher heights. For a better understanding, in Figure 4(d) we plot the distribution of \( h_{\text{max}} \) and \( h_{\text{max}} \). In support to our former argument on Figure 4(c), here too we see that the distribution of \( h_{\text{max}} \) is not as spread out as the distribution of \( h_{\text{max}} \). We also see that the mode of the distribution of \( h_{\text{max}} \) lies at 2–3 \( R_\odot \), which is also supported by the results of Majumdar et al. (2020), suggesting that the Lorentz force on the 3D kinematics of CMEs stays dominant until a height range of 2.5–3 \( R_\odot \). This result also points to the fact that it is also the impact of the Lorentz force that is closely responsible for the CMEs attaining their peak accelerations during their propagation. While looking into the distribution of \( h_{\text{max}} \), we find that we do not see any such clear peak in the distribution, and that it is much more spread out. This is possibly because we have selected events from different classes: CMEs from ARs that show a presence of impulsive acceleration which occur for a shorter duration; and CMEs from PEs that show a presence of small gradual accelerations that occur for a longer duration.

4. Summary and Conclusions

We have studied the behavior of several 3D kinematic parameters of the 59 CMEs studied by Majumdar et al. (2020) and we extended their analysis in this work. Several correlations studied between different kinematic parameters showed the importance of considering inner corona observations in the understanding of CME kinematics, and how different kinematic parameters in the outer corona are influenced by the parameters in the inner corona. We also found that the overall correlations often wash away crucial information, and that individual correlations for CMEs from different source regions show the imprint of those source regions on the kinematics. In this regard, the change in the power-law exponent for the different CCs is not pronounced, which has led to a considerable overlapping of the data points for different source regions. Recently, Pant et al. (2021) reported on the clear influence of the source region on the width distribution of slow and fast CMEs, concluding on the possibility of different physical ejection mechanisms for the CMEs from ARs and PEs. In this work, we thus look into the correlations of several kinematic parameters, and we again find a clear imprint of the source regions (in the form of distinctly different individual CCs) on the overall correlations. Further, we find that while working with average kinematic quantities, it is important to specify the region where the average is taken, as the average values change with the CME propagating from the inner to the outer corona. It should also be noted that even within the inner corona, the average values change, and in this work, we point out that tagging a single average speed to a CME might not be the best way to comment on its speed. Hence, we show as an example that the average speed of a CME indeed changes as the CME travels from the inner to the outer corona. It is also worth noting that our results are based on 3D parameters and are therefore independent of projection effects. In the following, we conclude our main results,

1. A study of \( a_{\text{max}} \) and \( V_{\text{max}} \) further showed that a moderate overall correlation, the ones coming from ARs show a much higher positive correlation (CC 0.77), indicating that the maximum velocity and accelerations are better correlated for CMEs from ARs.

2. We found \( V_{\text{lin}} \) and \( V_{\text{mi}} \) to be positively correlated (CC 0.68), and that the former can be estimated from the later through Equation (4), thus enabling the use of inner coronal observations to CME arrival time predictions with better lead time of forecast. Further a study of \( V_{\text{max}} \) and \( v_m \) indirectly indicated the acceleration experienced by the CMEs from different source regions.

3. We also found an anticorrelation between \( k_{\text{const}} \) and \( V_{\text{mi}} \) with a CC of \(-0.67\) that shows evidence of the drag experienced by the CME due to interaction with the solar wind. Thus showing that the influence of the drag forces comes into play as early as in the inner corona. While the CMEs from ARs and PEs have similar CCs, the correlation for CMEs from PEs is much weaker with a CC of \(-0.30\).

4. From Figures 4(a) and (b), we found the average velocities change as the CMEs travel from the inner to the outer corona, and that the CMEs from PEs experience weak and gradual accelerations, while the ones from ARs experience impulsive accelerations followed by retardation. This was further supported by Figure 4(c), which showed that \( a_m \) is more confined around the zero value while \( a_m \) is relatively more spread about the zero value. Also, we found the distribution of \( h_{\text{max}} \) peaks around 2–3 \( R_\odot \), which supports the results of Majumdar et al. (2020) that the impact of Lorentz force stays dominant in 2.5–3 \( R_\odot \). This indicates the role of the Lorentz force in propelling the CMEs to their peak accelerations.

A number of upcoming space missions like ADITYA-L1, PROBA-3, and the recently launched Solar Orbiter (Müller et al. 2013) will be observing the inner corona, and we believe these results will provide rich inputs to their observation plans. Also, the above correlations between the parameters in the inner corona to the parameters in the outer corona will help better exploit the inner coronal observations. An extension of this study over a larger sample size will help better establish our claims. The results will also provide inputs to models that study CME ejection mechanisms, thus aiding in our present understanding of the same.

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