DYNAMICS OF CORONAL MASS EJECTIONS IN THE NEAR-SUN INTERPLANETARY SPACE

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ABSTRACT

Kinematics of more than 5000 coronal mass ejections (CMEs) measured between 2 and 30 solar radii is investigated. A distinct relationship between the late-phase acceleration of CMEs and their velocities is found. It can be represented in the form \( a_{\mu}(v^{-2}) = -0.02(v - 400) \), where the relationship is interpreted in terms of coupling of the CME motion and the solar wind, i.e., by the action of the aerodynamic drag. The results indicate that in the considered radial distance range the Lorentz force acceleration becomes weak, in the majority of the events spanning between 0 and 10 m s\(^{-2}\). Implications for the interplanetary motion of CMEs are discussed, emphasizing the prediction of the 1 a.u. arrival time.

Key words: Sun: CMEs; corona; interplanetary medium; MHD.

1. INTRODUCTION

Coronal mass ejections (CMEs) are supposed to be driven by the Lorentz force, which implicitly includes the presence of an electric current \( I \). The inductance \( L \) of such a current system increases during the eruption due to the enlargement of the expanding structure (see, e.g., Vršnak 1990, or Chen 1996). On the other hand, it can be assumed that the magnetic flux \( \Phi \) through the "circuit" is not changing much, except maybe in a limited time interval due to the reconnection below the erupting flux tube (e.g., Vršnak, 1990; Lin and Forbes, 2000), or by an injection of the poloidal flux from the subphotospheric layers (e.g., Chen, 1996). This implies that, in general, the current has to decrease since \( \Phi = LI \). Consequently, the Lorentz force decreases, eventually ceasing at large heliocentric distances.

The free energy of the system \( W = LI^2 \propto L^{-1} \) decreases, and if only the Lorentz force and gravity are considered, it should be transformed directly into the kinetic and potential energy. However, CMEs travel through the ambient coronal/interplanetary (C/IP) plasma, causing the emission of MHD waves and appearance of the "aerodynamic" drag. The drag can have complex characteristics depending on the orientation of the ambient magnetic field (Cargill et al., 1996). The coupling is occasionally "visualized" by the type II radio bursts excited in the dekameter-to-kilometer wavelength range by the IP shocks that are driven by CMEs (e.g., Gopalswamy et al., 2001). As the Lorentz force and the gravity decrease, the drag might become a dominant force.

Indeed, Gopalswamy et al. (2000) inferred that in the IP space the CMEs that are faster than the solar wind decelerate, whereas the slower ones are additionally accelerated by the wind. The net acceleration was found to be proportional to the CME speed, which was further strengthened in a following paper (Gopalswamy et al., 2001b) where the projection effect was eliminated and different distances from the Sun were considered. On the other hand, Gopalswamy et al. (2001a) analyzed the relationship between acceleration and speed for fast (> 900 km s\(^{-1}\)) and wide (> 60°) CMEs associated with dekametric- hectometric type II bursts, and found that in the upper corona faster CMEs show a stronger deceleration. A similar result was obtained by Vršnak (2001a) who in addition showed that the deceleration rate statistically depends not only on the speed of ejecta, but also on the height, i.e., the external plasma density. An empirical scaling law was established describing the decrease of the average drag with radial distance, which provides a better prediction of the Sun-Earth transit time (Vršnak and Gopalswamy, 2002).

In the papers by Vršnak (2001a) and Gopalswamy et al. (2001b) the acceleration/speed relationship was studied on relatively small samples of events of specific characteristics: The former one embraced only fast events showing an exponential-like decay of speed, whereas the second one considered only fast and wide CMEs associated with type II bursts. In this paper we extend the investigation to a general sample of CMEs utilizing a large set of events observed between 1996 and 2001 by the Large Angle Spectroscopic Coronograph (LASCO) aboard the So-
lar and Heliospheric Observatory (Brueckner et al., 1995). The aim is to get a better insight into the coupling of the CME motion and the ambient magnetoplasma, and to infer the role of the Lorentz force in the dynamics of CMEs in the near-Sun IP space. The final goal is to improve the prediction of the CME arrival time at the Earth (Gopalswamy, 2002).

2. THE DATA

The events used for the analysis are listed in the LASCO CME catalogue (Yashiro and Michalek, http://caw.gsfc.nasa.gov/CME_list/), where the basic kinematical parameters are provided. We utilize the distance-time measurements $R(t)$, where $R = r/r_\odot$ is the projected heliocentric distance $r$ normalized with respect to the solar radius $r_\odot$. The parameters treated in the following are: The mean radial distance $ar{R} = (R_1 + R_2)/2$, where $R_1$ and $R_2$ are the first and the last distance at which the CME was measured; The average velocity $\bar{v}$ obtained using the linear fit to $R(t)$; The average acceleration (hereinafter $\bar{a} \equiv \bar{\alpha}$) obtained from the 2nd degree polynomial fit which is also used to get the velocity as $\bar{v} = \bar{R} > 3$ (hereinafter $\bar{v}_2$). The events which were measured at $n \geq 3$ instants, providing an estimate of $\bar{a}$, show the distribution of accelerations centered at $\bar{a} = 0$ with a standard deviation of $\sigma(\bar{a}) = 31$ m s$^{-2}$. The average of mean distances amounts to $\bar{R} = 9 \pm 4$, with $\bar{R}_1 = 3.4 \pm 1.0$ and $\bar{R}_2 = 14 \pm 7$.

From the original data set we formed two subsamples, one embracing the events with $n \geq 4$ and another with $n \geq 6$ (hereinafter n4-set and n6-set, respectively). Such a sampling provides an insight into the influence of the accuracy of acceleration and velocity estimates. The mean error of the values of $\bar{a}$ in the n4-set is 7.6 m s$^{-2}$, and it drops to 4.7 m s$^{-2}$ in n6-set. The fraction of events with errors larger than 10 m s$^{-2}$ is 18% and 10% for the two subsamples, respectively.

The basic outcome of the subsampling turned out to be elimination of the majority of events showing $|\bar{a}| > 100$ m s$^{-2}$, indicating that such extreme accelerations are artifacts caused by the unreliability of the n4-set data. Still, 19 events showing $|\bar{a}| > 100$ m s$^{-2}$ remained in the n4-set, and four in the n6-set. We stress that the influence of these events on the results is insignificant in both cases.

Finally, some events drop out when the velocities $\bar{v}_2$ are considered, since some of the curves with $\bar{a} > 0$ and the first measurement at a relatively large $R$ do not have an intercept with the $R = 3$ level. In this way we get the subsamples which we denote n4v3-set and n6v3-set, embracing 4463 and 3581 events, respectively.

The dependence of the acceleration on the velocity at $\bar{R} = 3$, $\bar{a}(\bar{v}_2)$, is shown in Figure 1a for the n4v3-set, and the bin-averaged values are presented in Figure 1b. (A graph $a(\bar{v})$ can be found in the recent paper by Moon et al. (2002)). The linear least squares fits $\bar{a} = c_2 \bar{v} + c_1$ are drawn by full lines and the corresponding 99% confidence limits are drawn dashed. Note an absence of events in the range $\bar{v} < 150$ km s$^{-1}$, $\bar{a} > 0$ in Figure 1a, revealing that slow events decelerate very rarely.

The error bars in Figure 1b represent the mean errors $M(\bar{a}) = \sigma(\bar{a})/\sqrt{n}$ where $\sigma(\bar{a})$ is the standard deviation and $n$ is the number of the events in a given bin. The fit in Figure 1b is obtained attributing equal weights to all bin-averaged values in order to eliminate the effect of data grouping. Note that in Table I we show for the bin-averaged values the fit parameters which are obtained excluding the last two bins ($1500 < \bar{v} < 2000$ km s$^{-1}$ and $2000 < \bar{v} < 2500$ km s$^{-1}$). In these two bins only a small number of events is found (e.g., in the n4v3-set $n = 44$ and 5, respectively) resulting in considerably larger errors of the means (Figure 1b).
Table 1. Summary of correlations between accelerations and velocities

<table>
<thead>
<tr>
<th>set</th>
<th>N</th>
<th>$c_1$ [10^{-8} m s^{-1}]</th>
<th>$c_2 = a_{rel0}$ [m s^{-1}]</th>
<th>$v_{rel0}$ [m s^{-1}]</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>n4</td>
<td>4609</td>
<td>-0.0101 ± 0.0012</td>
<td>4.29 ± 0.63</td>
<td>403 ± 14</td>
<td>0.13</td>
</tr>
<tr>
<td>n6</td>
<td>3697</td>
<td>-0.0101 ± 0.0010</td>
<td>4.50 ± 0.52</td>
<td>445 ± 7</td>
<td>0.16</td>
</tr>
<tr>
<td>n4v3</td>
<td>4463</td>
<td>-0.0288 ± 0.0010</td>
<td>12.12 ± 0.52</td>
<td>421 ± 5</td>
<td>0.41</td>
</tr>
<tr>
<td>n6v3</td>
<td>3651</td>
<td>-0.0241 ± 0.0008</td>
<td>10.47 ± 0.42</td>
<td>431 ± 3</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>complete sets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n4</td>
<td>11</td>
<td>-0.0113 ± 0.0016</td>
<td>3.43 ± 1.16</td>
<td>303 ± 65</td>
<td>0.903</td>
</tr>
<tr>
<td>n6</td>
<td>11</td>
<td>-0.0108 ± 0.0016</td>
<td>3.77 ± 1.02</td>
<td>330 ± 45</td>
<td>0.917</td>
</tr>
<tr>
<td>n4v3</td>
<td>11</td>
<td>-0.0266 ± 0.0007</td>
<td>10.82 ± 0.69</td>
<td>407 ± 15</td>
<td>0.960</td>
</tr>
<tr>
<td>n6v3</td>
<td>11</td>
<td>-0.0244 ± 0.0009</td>
<td>10.38 ± 0.56</td>
<td>425 ± 7</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bin-averaged</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The same regression analysis as the one shown in Figure 1 is performed for all other data sets and the results are presented in Table I. The relationship $a(R)$ is shown in the rows denoted by n4 and n6, whereas rows n4v3 and n6v3 represent $a(V)$ correlations. The first two columns provide the data set label and the number of events in the sample. In the 3rd, 4th, and 5th column of Table I the slope $c_1$, the intercept with the $y$-axis $a_{rel0} = c_2$, and the intercept with the $x$-axis $v_{rel0} = -c_2/c_1$ are given, respectively. In the last column of Table I the correlation coefficients $C$ are presented. According to the F-test the statistical significance $P_a$ is larger than 99% for all correlations listed in Table I ($P_a = 100 - P_a$ gives the probability for $C = 0$).

In Figure 2 we compare the scaling law $\gamma(R)$ established by Vršnak (2001a) with the slopes of the $a(R)$ relationships obtained, as well as with those found by Gopalswamy et al. (2000) and Gopalswamy et al. (2001b) for the interplanetary space. The slopes are now expressed in $s^{-1}$, amounting to $k = 10^{-5} c_1$ (these values would be obtained if the velocities were expressed in $m s^{-1}$ in the regression analysis). The values for the n4v3-set and n6v3-set are positioned at $R = (R) = 9$ and overlap each other. The slopes from Gopalswamy et al. (2000) and Gopalswamy et al. (2001b) are drawn at $R = 40$ and $R = 46$, corresponding to the geometrical mean (see the argumentation in Vršnak (2001a)) of the considered distance ranges ($0.76$ and $1$ AU, respectively). The fit through the processed data-points matches quite closely to the scaling $\gamma = 2 \times R^{-1.5}$ that was inferred by Vršnak and Gopalswamy (2002) from the Sun-Earth transit times.

4. DISCUSSION

Figure 1 and Table I reveal a well defined correlation between the accelerations and speeds of CMEs. The largest correlation coefficient is found for the n6 samples where the accuracy of used accelerations and velocities is highest. The acceleration becomes $a = 0$ between $v \approx 350$ - 450 km s$^{-1}$ in most of the data sets considered. The values closer to the lower limit are obtained from the correlations based on the equal-weight fits of the bin-averaged data, whereas those closer to the upper limit are found using the complete data sets. Inspecting Table I one finds that the relationship can be expressed generally as:

$$a = -0.02 \pm 0.01 (v - 400 \pm 50),$$

where $a$ is expressed in $m s^{-2}$ and $v$ in $km s^{-1}$. A relationship of this form is indicative of the aerodynamic drag (Cargill et al., 1996; Vršnak, 2001a). Indeed, the velocity $v_{rel0} = 400$ km s$^{-1}$ is very close to a typical solar wind speed at these radial distances (Sheeley et al., 1997). So, roughly speaking, CMEs faster than the solar wind decelerate, whereas slower ones accelerate due to coupling with the solar wind.

Results presented by Gopalswamy et al. (2001b) and Vršnak (2001a) indicate that the acceleration/speed relationship might be better approximated by a quadratic dependence. However, fitting the data used herein with the function $a = a(v - v_0) [v - v_0]$ which is more appropriate to describe the drag (Cargill et al., 1995), did not show a reasonable outcome. In fact, this can be seen straightforwardly from the distribution of data-points in Figure 1.

Finally, let us investigate the quantity $f_L = a + g - f_d$, where $g$ is the acceleration of gravity and $f_d$ is an estimate of the drag acceleration. Presumably, $f_L$ reveals the Lorentz force acceleration. The value of $g$ is evaluated for the mean radial distance $R$ at which a particular CME was measured. The drag acceleration is estimated from $f_d = \gamma (v - v) \gamma (v - v)$ by substituting $v = v$ for the speed of a given CME, $w = 400$ km s$^{-1}$ for the solar wind, and $\gamma = 1.16 \times 10^{-6} \times R^{-1.55}$ (Vršnak, 2001a). In Figure 3 we show the distribution of $f_L$ for the n6v3-set. We emphasize that very similar distributions are obtained utilizing any other considered subsample, or using $v = v_3$ instead of $v = v$.

In the majority of the events, $f_L$ lies between 0 and 10 m s$^{-2}$. Yet, in 13% of events $f_L$ appears to be larger than 20 m s$^{-2}$ (see also Vršnak (2001b)). In extreme cases (0.2%) $f_L$ is larger than 100 m s$^{-2}$. In 22% of events the inferred $f_L$ is negative, reaching down to $f_L \approx -60$ m s$^{-2}$. In about 80% of events $f_L$ lies between $-10$ and 20 m s$^{-2}$. The fraction of events found in the range $f_L > 50$ m s$^{-2}$,
However, the existence of fast events whose velocity is still increasing suggests that in a certain fraction of events the Lorentz force is still comparatively strong. On the other hand, the deceleration of slow events could be caused either by the gravity or by a negative Lorentz force (Wang and Sheeley, 2002). The reality of $f_L < 0$ is evidenced by the “fall-back” events described by Wang and Sheeley (2002) and by the existence of an upper equilibrium observed in some events (Vršnak et al., 1990; Vršnak, 2001b). Such a behaviour is anticipated in the flux rope model by Vršnak (1990).

The slopes of $a(v)$ correlations for the n4v3-set and n6v3-set, expressed in $s^{-1}$, amount to $k = 10^{-3} c_1 = 1.3 \times 10^{-5} s^{-1}$. The value of $k$, though somewhat smaller, is very close to the value of the drag parameter $\gamma_1$ defined by Vršnak (2001a): At $R = 10$ one finds (see Table IV and Figure 5a in Vršnak, 2001a) $\gamma_1 = 2.5 \times 10^{-6} s^{-1}$. Combining these results with the values of $k$ found by Gopalswamy et al. (2000) and Gopalswamy et al. (2001b) for the IP space (Figure 2), justifies the extrapolation of the power-law scaling of $\gamma$ up to 1 AU, as proposed by Vršnak and Gopalswamy (2002) in evaluating the Sun-Earth transit time.

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