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The role of aerodynamic drag in dynamics of coronal mass ejections

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Abstract. Dynamics of coronal mass ejections (CMEs) is strongly affected by the interaction of the erupting structure with the ambient magnetoplasma: eruptions that are faster than solar wind transfer the momentum and energy to the wind and generally decelerate, whereas slower ones gain the momentum and accelerate. Such a behavior can be expressed in terms of "aerodynamic" drag. We employ a large sample of CMEs to analyze the relationship between kinematics of CMEs and drag-related parameters, such as ambient solar wind speed and the CME mass. Employing coronagraphic observations it is demonstrated that massive CMEs are less affected by the aerodynamic drag than light ones. On the other hand, in situ measurements are used to inspect the role of the solar wind speed and it is shown that the Sun-Earth transit time is more closely related to the wind speed than to take-off speed of CMEs. These findings are interpreted by analyzing solutions of a simple equation of motion based on the standard form for the drag acceleration. The results show that most of the acceleration/deceleration of CMEs on their way through the interplanetary space takes place close to the Sun, where the ambient plasma density is still high. Implications for the space weather forecasting of CME arrival-times are discussed.

Keywords. Sun: coronal mass ejections (CMEs), Sun: corona, (Sun:) solar wind, (Sun:) solar-terrestrial relations, (magnetohydrodynamics:) MHD

1. Introduction

Coronal mass ejections (CMEs) are large-scale solar eruptions during which the magnetic flux of some 10^{23} Wb is launched into the interplanetary space at velocities in the order of 1000 km s^{-1}, carrying along $10^{11} - 10^{13}$ kg of coronal plasma (e.g., Gosling 1990, Webb *et al.* 1994).

After the CME take-off, which is governed by the Lorentz force, in the high corona and interplanetary space the CME dynamics becomes dominated by the aerodynamic drag (Vršnak *et al.* 2004a). Consequently, CMEs faster then solar wind decelerate, whereas slower ones are accelerated, both eventually being adjusted to the solar wind speed (e.g., Lindsay *et al.* 1999, Gopalswamy *et al.* 2001, Manoharan 2006, Vršnak & Žic 2007). In this paper the influence of the aerodynamic drag on the CME kinematics in the high corona and interplanetary space is analyzed, and implications for the space weather forecasting are discussed.

2. Empirical relationships

In Fig. 1a mean accelerations a of CMEs measured in the LASCO (Large Angle and Spectrometric Coronagraph; Brueckner *et al.* 1995) C2/C3 field-of-view, covering $2 - 30\, r_\odot$, are presented as a function of their mean plane-of-sky speeds v. The sample includes 3091 CMEs observed in the period from January 1997 to June 2006 (the total number of reported CMEs for this period is 11108, but we excluded events where the estimates of the acceleration and mass are marked as uncertain). The graph reveals a distinct anti-correlation between a and v, i.e., the statistical tendency showing that slow CMEs are on average accelerated, whereas fast ones are decelerated. The intercept of the linear least-squares fit with the abscissa, $v_0 \approx 400$ km s^{-1}, is in the range of an average solar wind speed. Note that there are practically no slow CMEs with $a < 0$. On the other hand, it should be also noted that there are fast CMEs that still accelerate in the considered height range, indicating that the Lorentz force in some events still plays a significant role in the CME dynamics.

The $a(v)$ anti-correlation presented in Fig. 1a indicates that the aerodynamic drag is a dominant force in the majority of events. The aerodynamic drag is usually expressed in the form (Cargill *et al.* 1996, Cargill 2004):

$$a = -\gamma(v - w)|v - w|\,, \tag{2.1}$$

where v is the CME velocity and w is the ambient solar wind speed. The parameter γ reads:

$$\gamma = c_d \frac{A\rho_w}{m}\,, \tag{2.2}$$

where c_d is the dimensionless drag coefficient (for details see Cargill 2004), A is the effective CME area perpendicular to the direction of propagation, m is the CME mass, and ρ_w represents the ambient solar wind density.

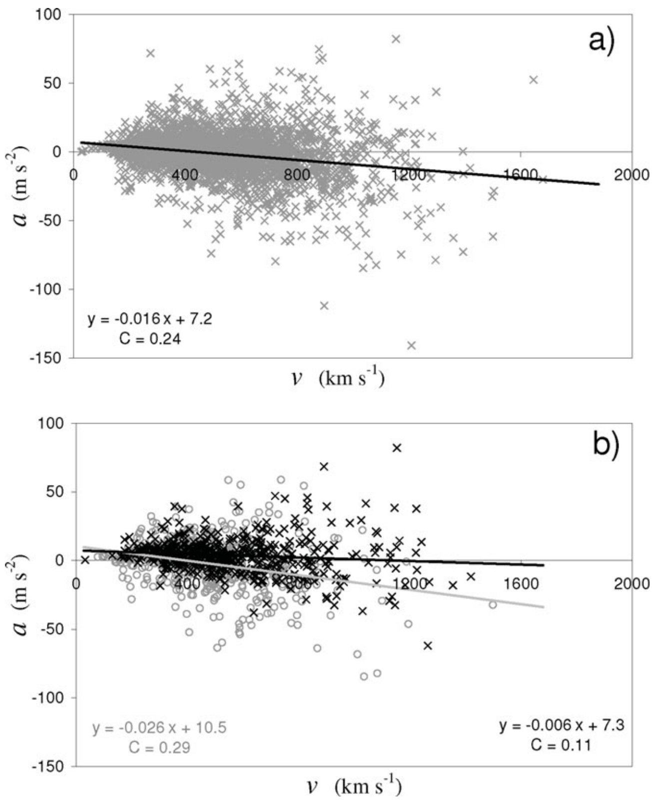

Figure 1. a) The anti-correlation of the CME acceleration and velocity in the LASCO field--of-view. b) The $a(v)$ anti-correlation shown separately for CMEs of low masses (gray) and large masses (black). Linear least square fits are given in the insets, together with the correlation coefficient C.

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Thus, we expect that the CME acceleration (after the Lorentz force and the gravity become negligible) should depend on the solar wind speed w and density ρ_w, as well as on the CME speed v, mass m, and size A. Although all of these parameters differ from one event to another, it can be expected that basic relationships should be reflected in the statistical analysis of the kinematical properties of CMEs.

In Fig. 1b we show the $a(v)$ relationship separately for 500 CMEs of the smallest and the largest masses (mean masses are $\overline{m} = 7 \times 10^{10}$ and 7×10^{12} kg, respectively). The low-mass subsample shows a considerably steeper slope k of the $a(v)$ fit (the difference has statistical significance larger than 99%), consistent with the expectation that the effect of drag decreases with increasing mass. Vršnak *et al.* (2008) have shown that the $k(m)$ dependence follows closely the theoretically expected trend $k \propto m^{-1/3}$.

To demonstrate the role of the solar wind speed, we have to involve the interplanetary propagation of CMEs, since measurements of the wind speed are not available near the Sun. In Fig. 2a we first show the the Sun–Earth transit time (TT) as a function of the CME plane-of-sky speed measured in the LASCO C2/C3 field of view. We utilized the sample of 91 events listed by Schwenn *et al.* (2005). Obviously, initially faster CMEs reach the Earth sooner. In Fig. 2b we show a dependence of TT on the solar wind speed w measured at 1 AU (here w represents the mean of the wind speed ahead and behind the CME; for details see Vršnak & Žic 2007). Comparing Fig. 2a with Fig. 2b we find that $TT(w)$ has higher correlation coefficient then $TT(v)$, implying that the solar wind speed plays more important role in determining the transit time than the CME take-off speed

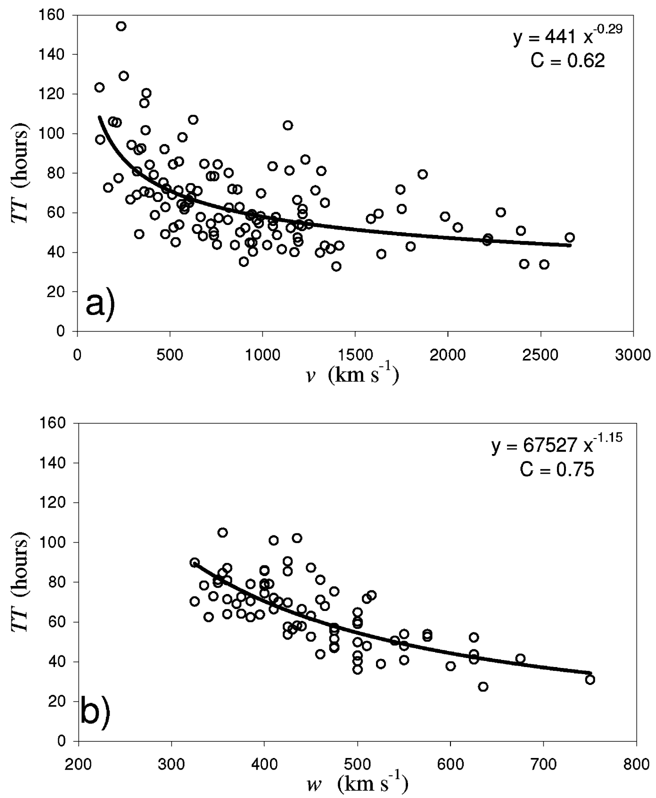

Figure 2. a) Relationship between the Sun-Earth transit time and the CME take-off speed. b) Transit time versus the ambient solar wind speed. Power-law least square fits are given in the insets, together with the correlation coefficient C.

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itself. Furthermore, this implies that most of the drag acceleration/deceleration occurs relatively close to the Sun, so that the ejection travels through the interplanetary space at a velocity close to the solar wind speed.

3. Model results and interpretation

Physical background of the empirical results presented in Sect. 2 can be explained employing a simple kinematical model based on Eq. 1. To define the parameter γ (Eq. 2), we assume that the CME dimensions are proportional to the radial distance r. Specifically, in the following we consider a cone-shaped CME of angular (full) width $\phi = 1\,\mathrm{rad}$. For the solar wind density $\rho_w(r)$ we take the empirical density model proposed by Leblanc *et al.* (1998). Given the equation of the continuity (the mass conservation), from that we also get the radial dependence of the solar wind speed $w(r)$. Furthermore, we assume $c_d = 1$ (Cargill 2004). Finally, we assume that Eq. 1 becomes valid beyond the distance r_0. After substituting $a = \mathrm{d}^2r/\mathrm{d}t^2$ and $v = \mathrm{d}r/\mathrm{d}t$ we get a differential equation whose solutions $v(t)$ and $r(t)$ depend on the "initial" CME speed v_0 at r_0. From $v(t)$ and $r(t)$ we also get $v(r)$ and the Sun-Earth transit time TT.

In Fig. 3a we show how the CME velocity decreases with the radial distance for different CME masses. The solar wind speed is normalized to the 1 AU value $w_0 = 400$ km s^{-1} and the velocity of the CME at $R_0 \equiv r_0/r_\odot = 10$ is taken to be $v_0 = 1000$ km s^{-1}. The same situation is considered in In Fig. 3b, but the solar wind speed $w_0 = 600$ km s^{-1}. Inspecting Figs. 3a and b we see that the speed of low mass CMEs ($m \lesssim 10^{12}$ kg) becomes very close to the solar wind speed already in the LASCO field-of-view ($R < 30$). Given that more than 55% of CMEs has mass $m < 10^{12}$ kg (72% has $m < 2 \times 10^{12}$ kg), this explains why velocities of the majority of LASCO-CMEs are grouped around the solar wind speed (e.g., Yashiro *et al.* 2004). In the same way, this explains why the Sun-Earth

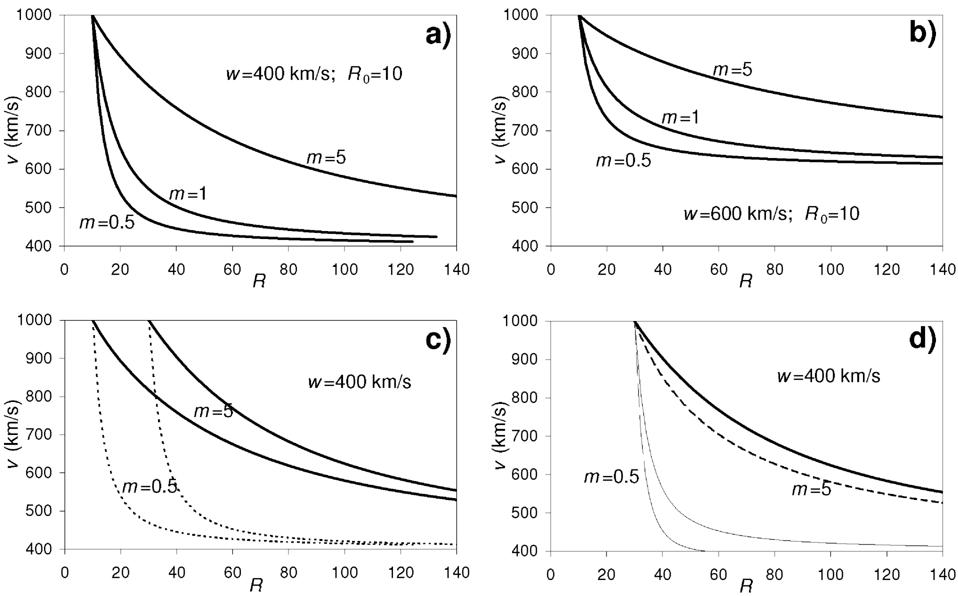

Figure 3. Calculated CME velocity as a function of the radial distance, which is expressed in units of the solar radius $r_\odot$. CME masses m expressed in 10^{12} kg are written by the curves. For details see the main text.

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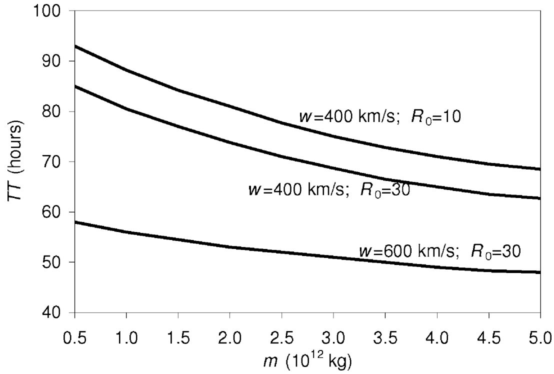

Figure 4. Sun-Earth transit time presented as a function of the CME mass for two solar wind speeds ($w = 400$ and 600 km s^{-1}) and two take-off radial distances $R_0 = 10$ and 30.

transit time is better correlated with the solar wind speed than with the CME take-off velocity. In massive CMEs the adjustment to the solar wind speed lasts longer, which means that the shortest transit times should be expected for fast and massive CMEs, when traveling in fast solar wind, i.e., when being launched from the vicinity of equatorial coronal holes.

Figure 3c shows how the kinematical curves $v(R)$ depend on the height at which the drag becomes effective, i.e., how they depend on the range beyond which the Lorentz force does not compensate the drag anymore. This is illustrated by showing calculations with the initial conditions $v_0 = 1000$ km s^{-1} at $R_0 = 10$ and $R_0 = 30$, respectively. Again we see that the velocity of low-mass CMEs becomes adjusted roughly to the solar wind speed within $\Delta R \approx 20$.

In Fig. 3d we demonstrate how the kinematical curves depend on the solar wind density model. For that purpose we compare the results obtained using the model by Leblanc *et al.* (1998) with outcome for the "hybrid" model proposed by Vršnak *et al.* (2004b). The latter model (results presented by dashed curves) is characterized by a considerably higher density and a steeper density decrease at low heights, so the velocity decrease in the case of light CMEs is extremely fast.

Finally, in Fig. 4 we inspect how the Sun-Earth transit time TT depends on various model parameters. For that purpose we draw three $TT(m)$ curves, calculated employing the density model by Leblanc *et al.* (1998) and taking $v_0 = 1000$ km s^{-1}. We consider solar wind speeds $w_0 = 400$ and 600 km s^{-1}, in combination with $R_0 = 10$ and 30. The graph reveals that differences in TT are larger for low-mass CMEs than for massive ones. Furthermore, one finds out that the difference in solar wind speed is more important than the value of R_0, and that a 50% change of the solar wind speed has larger effect on TT than changing the mass by one order of magnitude.

4. Discussion and conclusion

Comparing empirical relationships with the theoretical results we have demonstrated that the aerodynamic drag is a dominant force that acts on CMEs in the high corona and interplanetary space. Thus, the kinematics of CMEs after the main acceleration stage is determined by the speed and density of the ambient solar wind and by the CME take-off velocity, size, and mass. In the majority of events the CME speed becomes comparable to the solar wind speed close to the Sun, a few tens of solar radii after the Lorentz

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force becomes negligible. Such a behavior was found also in numerical simulations by Gonzalez-Esparza *et al.* (2003).

Consequently, the solar wind speed is the main parameter that determines the Sun-Earth transit time in most events. This can explain the so-called "Brueckner's 80 h rule" ($TT \approx 80$ h in most events; see Brueckner *et al.* 1998), since it can be presumed that most of CMEs propagate through slow solar wind, and for events with $m < 10^{12}$ kg a typical transit time should be around 80 h (Fig. 4). The shortest transit times ($TT < 1$ day) can be achieved only by massive CMEs of a very high take-off velocity ($v_0 > 2000$ km s^{-1}). Furthermore, a CME has to move through fast solar wind streams and the Lorentz force has to act over large distances to postpone the drag-dominant phase until the solar wind density becomes low.

References

Brueckner, G. E., Howard, R. A., Koomen, M. J., *et al.* 1995, *Solar Phys.*, 162, 357

Brueckner, G. E., Delaboudiniere, J.-P., Howard, R. A., *et al.* 1998, *Geophys. Res. Lett.*, 25, 3019

Cargill, P. J. 2004, *Sol. Phys.*, 221, 135

Cargill, P. J., Chen, J., Spicer, D. S., & Zalesak, S. T. *J. Geophys. Res.*, 101, 4855

Gonzalez-Esparza, J. A., Lara, A., & Perez-Tijerina, E. 2003, *J. Geophys. Res.*, 108, 1039

Gosling, J. T. 1990, in Physics of Magnetic Flux Ropes, *Geophys. Monogr.* Ser. vol. 58, eds. Russell, C. T., Priest, E. R., Lrr, L. C., AGU, Washington, D.C., 343

Gopalswamy, N., Lara, A., Yashiro, S., Kaiser, M. L., & Howard, R. A. 2001 *J. Geophys. Res.*, 106, 29207

Leblanc, Y., Dulk, G. A., & Bougeret, J.-L. 1998, *Solar Phys.*, 183, 165

Lindsay, G. M., Luhmann, J. G., Russell, C. T., and Gosling, J. T. 1999, *J. Geophys. Res.*, 104, 12515

Manoharan, P. K. 2006, *Solar Phys.*, 235, 345

Schwenn, R., dal Lago, A., Huttunen, E., & Gonzalez, W. D. 2005, *Annales Geophysicae*, 23, 1033

Vršnak, B., Ruždjak, D., Sudar, D., & Gopalswamy, N. 2004a, *A&A*, 423, 717

Vršnak, B., Magdalenić, J., & Zlobec, P. 2004b, *A&A*, 413, 753

Vršnak, B. & Žic, T. 2007, *A&A*, 472, 937

Vršnak, B., Vrbanec, D., & Čalogović, J. 2008, *A&A*, in press

Webb, D. F., Forbes, T. G., Aurass, H., *et al.* 1994, *Solar Phys.* 153, 73

Yashiro, S., Gopalswamy, N., Michalek, G., *et al.* 2004, *J. Geophys. Res.*, 109, 7105

Discussion

SPANGLER: I am surprised your drag coefficients were so close to unity. I would have expected that for an obstacle (the CME) moving through an MHD medium, there would be enhanced drag due to radiation of Alfven waves. This effect was responsible for the accelerated orbital decay of the echo-satellite in 1960.

VRSNAK: In fact, the "aerodynamic" drag in the corona and IP space is almost entirely due to the emission of MHD waves since the viscosity is negligible. Numerical simulations by Cargill *et al.* 1995, and later Cargill 2004 show that in the corona and IP space $c_d \approx 1$ except in the case e.g. when CME is of very low density.

IBADOV: If you are not taking into account gravity why CME mass is important for the drag coefficient?

VRSNAK: In principle the drag acceleration depends on the density of the body. Here we used the mass of CME since mass is a measurable quantity (for the density we have to assume the line-of-sight length).

GOPALSWAMY: Your drag essentially is proportional to inverse of CME size scale. Is this correct?

VRSNAK: Yes, that 's right.

SCHMIEDER: If slow and not many CME are accelerated they could loose their identity in the Solar Wind and will be not geoeffective.

VRSNAK: Depends what you mean by the phrase "their identity": they will move with solar wind so we will not detect them in the flow velocity observation. Yet, their magnetic structure will be preserved (that is why slow CMEs can be also geoffective) except in the case of an efficient reconnection which may also "wash-out" their "magnetic identity".

FAINSHTEIN: The force for CME drag must depend on the CME velocity and size. I think that your plot of the acceleration of CME vs mass of CME is a result of this. What do you think about this idea? I assume that CMEs of small size have small masses, and CMEs of large sizes have large masses, on average.

VRSNAK: Basically yes, since CME densities probably do not differ very much, i.e. the mass is primarily determined by the volume.