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A Probabilistic Approach to the Drag-Based Model

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Abstract. Forecasting the time of arrival of a Coronal Mass Ejection at Earth is of critical importance for our high-technology society and for any future manned exploration of the Solar System. As critical as the forecast accuracy is the knowledge of its precision, i.e. the error associated to the estimate. Here a statistical approach to the computation of the time of arrival using the Drag-Based Model is proposed through the introduction of probability distributions, rather than exact values, as input parameters, thus allowing the evaluation of the uncertainty on the forecast.

Keywords. Sun: coronal mass ejections (CMEs).

1. Introduction

Coronal Mass Ejections (CMEs) are violent phenomena of solar activity with repercussions throughout the entire heliosphere and responsible for major geomagnetic storms; therefore predicting the arrival of Interplanetary Coronal Mass Ejections (ICMEs) at 1AU starting from remote observations is one of the primary subjects of the science of space-weather forecasting. Several forecasting methods have been proposed over the last two decades and are still under development. The Drag-Based Model of ICME propagation, a kinematical model, is rapidly revisited in Section 2, pointing out the observational quantities needed to make use of it for the purpose of forecasting. Section 3 describes the procedure to extend this model to compute the most probable ICME travel times by introducing the Probability Distribution Functions that are assumed for the input parameters. In closing, some comments about this approach to the forecasting are made in Section 4.

2. The Drag-Based Model

The Drag-Based Model (DBM) of heliospheric propagation of ICMEs is based on the hypothesis that beyond a certain distance from the Sun the ICME dynamics becomes governed solely by its interaction with the ambient solar wind, and that a hydrodynamical description may be employed. The Drag-Based Model with constant solar wind speed w and drag parameter γ is considered here, referring the reader to the papers from Cargill (2004) and Vršnak *et al.* (2012) for an extensive discussion about model assumptions and details. This model provides the following expression for the evolution of the ICME heliospheric radial distance with time:

$$r(t) = \pm\frac{1}{\gamma}\ln\left[1 \pm \gamma(v_0 - w)\,t\right] + w\,t + r_0 \tag{2.1}$$

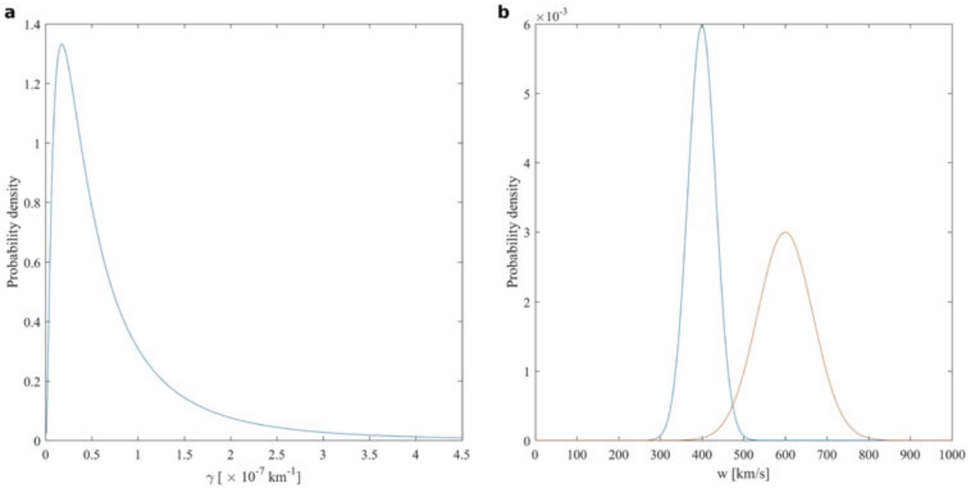

Figure 1. (a) PDF adopted for the random generation of γ in the P-DBM, modeled by a Log-Normal function with $\mu = -0.70$ and $\sigma = 1.01$. (b) PDF adopted for the random generation of w in the P-DBM, with the Slow w represented by a Gaussian PDF centered at 400km/s with $\sigma = 33$ km/s, and the Fast w represented by a Gaussian PDF centered at 600km/s with $\sigma = 66$ km/s.

Where r_0 is the CME initial radial distance from the Sun, and v_0 the initial radial speed. Such equation can be used to perform a forecasting of the ICME travel time to 1AU, provided that initial conditions r_0 and v_0, and the values for the solar wind speed w and the drag parameter γ are given from observations. While initial position and speed can be measured from coronagraphic images in time sequence (see Shi *et al.* 2012), the evaluation of the drag parameter relies on the knowledge of quantities far from being measurable with sufficient accuracy through coronagraphic images. Also, it is not immediate how to realistically make a choice of a unique, precise value for the solar wind speed accompanying the ICME from Sun to Earth.

3. The Probabilistic-Drag-Based Model

As discussed, the DBM needs four quantities for a travel time computation, namely (r_0, v_0, w, γ), and the last two are, in general, unknown. Following the method proposed by Vršnak *et al.* (2012), an evaluation of the drag parameter, through numerical inversion of the DBM equations for each event of the CME lists compiled by Schwenn *et al.* (2005), has been performed. A Log-Normal distribution, shown in Figure 1a, provides a good fit to the resulting distribution, capturing its properties in just two parameters. With regard to the choice of the solar wind speed, the common understanding is that there exist two different regimes: the so-called Slow solar wind (speed below 500 km/s), and the Fast solar wind, originated from the coronal holes. Therefore we adopt the two different Gaussian PDFs shown in Figure 1b, and choose the Fast w PDF in those cases where there is a prominent coronal hole in the center on the disk at the CME onset time, and the Slow w PDF otherwise. To complete, measurement errors on initial position and speed are generally described by Gaussian PDFs derived from the tracking algorithm of the CME leading edge in coronagraphic images (Shi *et al.* 2012).

The Probabilistic Drag-Based Model (P-DBM), performs an evaluation of the time of arrival of an ICME at a chosen distance from the Sun by generating N initial conditions sets (r_0, v_0, w, γ), each entry of which is randomly chosen from the relative PDF, and then

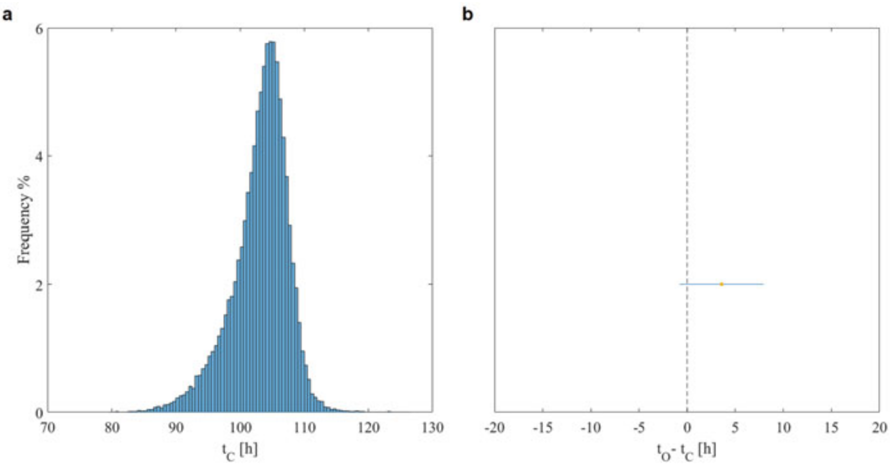

Figure 2. (a) Distribution of the transit times t_C calculated through the P-DBM generating $N = 50.000$ initial conditions. Mean value $< t_C >= 103.1$h and root mean square $\sigma = 4.4$h of this distribution are compared with the actual arrival time $t_O = 106.7$h in panel (b).

numerically computing via Eqn. (2.1) the transit time at 1 AU. This process produces in short computational times a distribution of values associated to the computed travel time t_C, which can be used to estimate relevant quantities statistically, in particular an error on the estimate of the travel time. Figure 2 shows the result from the application of the P-DBM to the CME occurred on 2008-12-12 08:37 UT and reaching the Earth about 113 hours later (see Shi *et al.* 2012). A graphical comparison of the P-DBM predicted travel time with the observed arrival time t_O is also shown.

4. Conclusions

This work proposed an approach to the evaluation of the forecast accuracy by evolving a previously well-established forecasting method based on a kinematical model. The error on the estimate evaluated in this way relies on general features obtained from a statistical analysis of a sample of CMEs, and takes into account our missing knowledge about ICME morphology, details of its dynamics and the precise values of the solar wind speed. Given that the lack of information about the onset parameters and characteristics of the ICME dynamics is a general issue for each forecasting model, the choice of putting together probabilistic and kinematical aspects certainly deserves further investigations, since it requires low computational facilities and certainly contributes to the important topic of the development of CME arrival prediction tools.

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