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THE DRAG BASED MODEL APPLICATION

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Introduction

The drag-based model (DBM) is an analytical model appropriate for forecasting of coronal mass ejections (CMEs) trajectories in interplanetary space and allows a prediction of their arrival times and impact speeds at any point in the heliosphere ("target"). The model is based on the assumption that beyond a distance of about 20 solar radii from the Sun, the dominant force acting on CMEs is the "aerodynamic" drag force.

In the previously used form of analytical DBM (Vršnak, 2001; Cargill, 2004; Owens et al., 2004; Vršnak et al., 2007; Borgazzi et al., 2009; Lara et al., 2009; Vršnak et al., 2010; Vršnak et al., 2013), the input parameters of the model are chosen on statistical basis, considering average and unperturbed conditions in the interplanetary space and common CME properties which are not necessarily appropriate for the CME under study (Žic et al., 2015). Therefore, the further development leads to the extension of DBM which provides the DBM usage in perturbed and time dependent surrounding environment without constraint on the distances above 20 solar radii. The CME acceleration, caused by the MHD "drag" is:

$$R''(t) = -\gamma(R)\left[R'(t)-w(R)\right]\left|R'(t)-w(R)\right|.$$

where the "drag parameter" γ is defined by:

$$\gamma(R)=\gamma_\infty \frac{w_\infty}{w(R)}.$$

The large distance limit is γ_∞ and $\Gamma = \gamma_\infty \times 10^7$ km.

The instantaneous acceleration and speed of the ejection are denoted by $R''(t)$ and $R'(t)$, whereas $w(R)$ represents the ambient solar wind speed and the large distance limit is w_∞. The solar wind speed perturbation is defined in following form:

$$w(R)=\begin{cases} w_0(R)+w_p(R), R_1<R<R_2 \\ w_0(R), otherwise \end{cases}$$

where w_p is perturbed (valid between distances R_1 and R_2) and w_0 is unperturbed solar-wind speed term defined from Leblanc, Dulk, Bougeret density model (Leblanc et al., 1998).

Extended DBM

A modified and extended version of DBM is suitable for various applications, starting from automatic least-square fitting on initially detected CME kinematic data suitable for a real-time space-weather forecasting system, and ending with an embedding of the DBM into various numerical simulations of the interplanetary ambient conditions (solar wind speed, density, CME–CME interactions, etc.). For example, the DBM could be embedded into numerical codes of ENLIL, EUHFORIA, and similar advanced numerical models.

The least-square fitting

The least-square fitting (LSF) is based on a process of determining values of unknown DBM parameters. Successive variation of DBM parameters leads to minimal quadratic deviation between observational and DBM-calculated speeds and the best suited DBM parameters for CME propagation prediction.

The "goodness" of fit is represented by several statistical quantities:

- the standard deviation σ (or the rms),
- the coefficient of variation c_v
- the coefficient of determination, $\Re^2$: as $\Re^2 \to 1$, fit gets better (Motulsky et al., 1987).

Example of LSF is shown on Figure 1 where the observational dataset is described in Temmer et al. (2011).

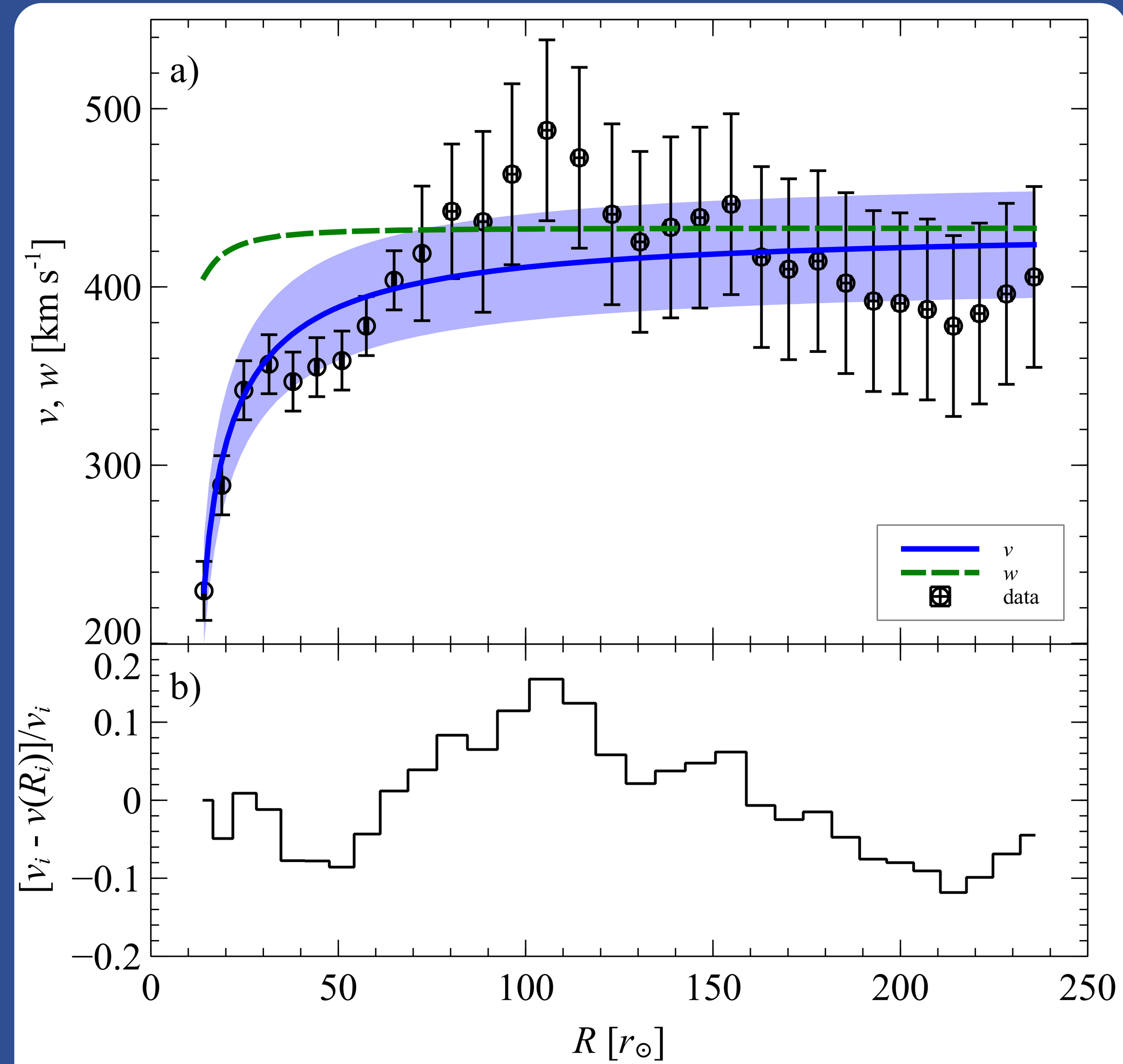

Fig. 1. LSF application on the dataset extracted from Event 1of the paper by Temmer et al. (2011) which started on 2008 June 1 at ~21 UT. The standard deviation of the observed dataset is σ_o = 42.81 km/s.
The LSF determined the DBM parameters:

- Γ = 2.84 , w_∞ = 433.04 km/s, v_0 = 229.50 km/s, R_0 = 14.17 r_{Sun},
- σ_{min} = 29.87 km/s, $c_{v,min}$ = 7.50%, $\Re^2$ = 0.67.

The fitted standard deviation σ_{min} is smaller than the observed σ_o.

(a) The LSF estimated kinematic $v(R)$ curve is presented by solid blue line with error shown as the blue shaded area. The observed CME speed values are black circles (with error bars), and numerically calculated solar wind speed w is plotted by dashed green line. The blue shaded area is the "average" error of the fit, spanning values from $v(R) - \sigma_{min}$ to $v(R) + \sigma_{min}$.
(b) The relative residuals between observational v_i and DBM-calculated $v(R_i)$ speeds of CME.

Example of DBM and ENLIL integration

We have chosen a demonstration of embedding DBM to more sophisticated numerical models. In this example DBM is integrated into the WSA-ENLIL+Cone model Odstrcil et al. (2004) from the Community Coordinated Modeling Center at the NASA Goddard Space Flight Center (NASA/CCMC; Odstrcil et al. 2002; Odstrcil et al. 2004; Taktakishvili et al. 2009). For background solar wind w is used numerical ENLIL dataset calculated for date 10th of February 2009 at 6h 12min 57sec (UT). In this example the common DBM parameters are employed:

- drag parameter: Γ = 0.2
- initial CME distance: R_0 = 31 r_{Sun}
- initial CME speed: v_0 = 1000 km/s
- CME half-width: λ = 30°
- launching CME meridian distance φ = 150°

and Mars is selected as target for this example.

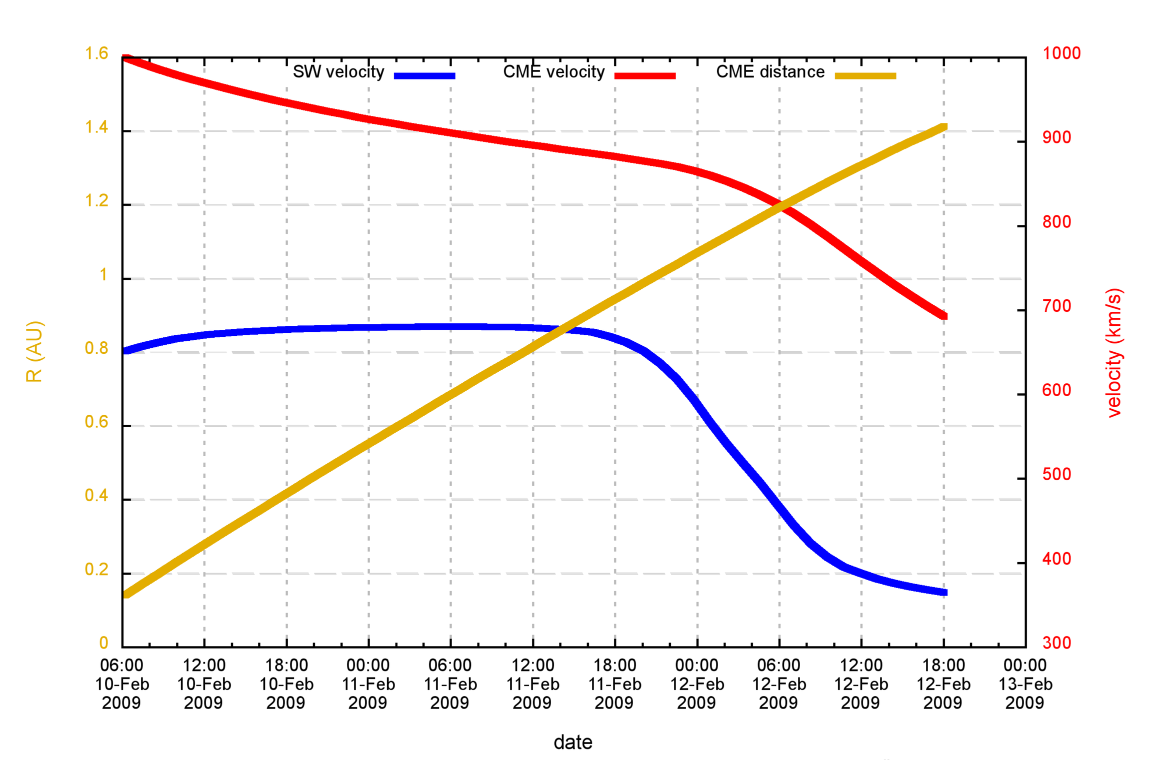

Fig. 2. CME kinematic curves of CME toward target position (Mars). Blue, red and yellow lines represent ambiental solar-wind velocity, CME velocity and CME distance, respectively (see Fig. 3.)

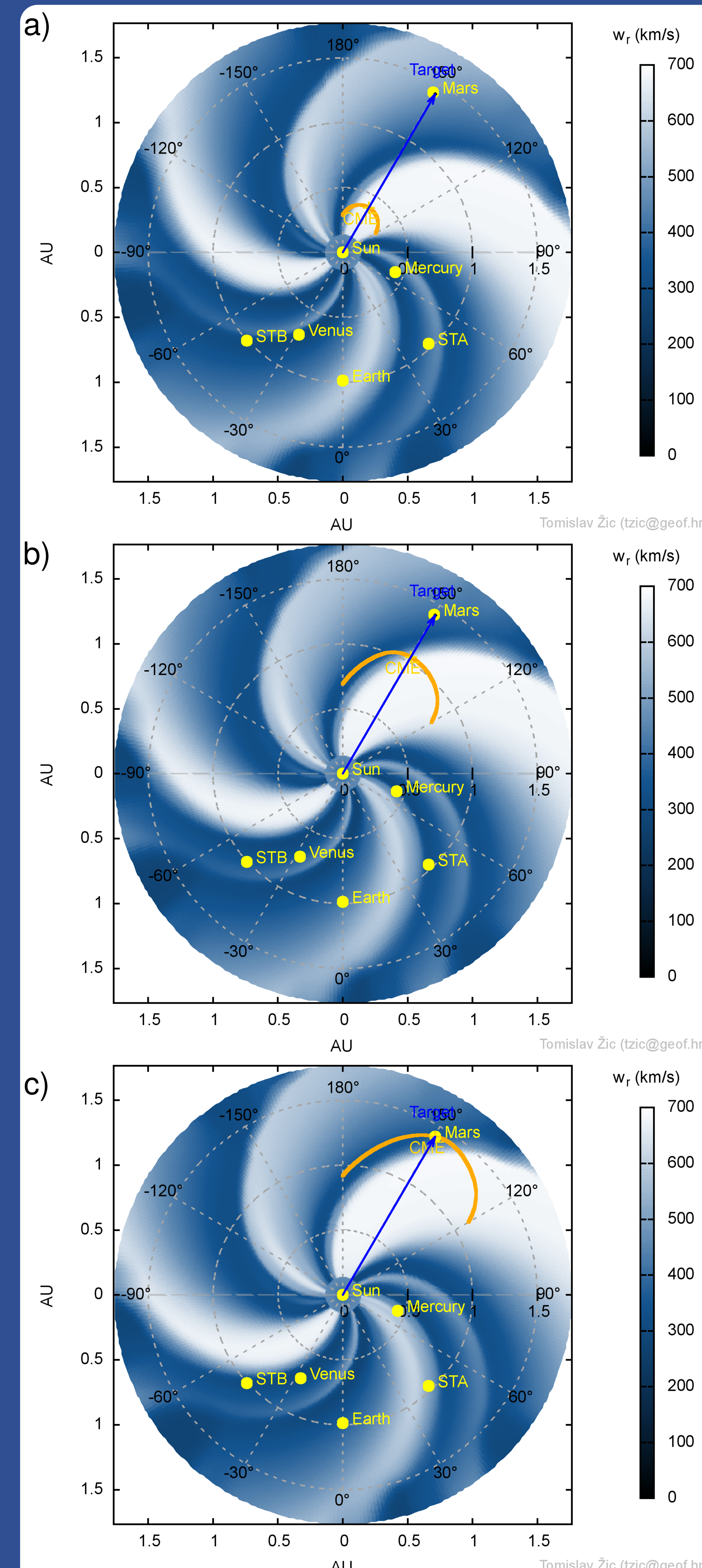

Fig. 3. Example of CME propagation in ecliptic from its initial position to Mars which represents a target. The background ENLIL solar-wind speed w_r rotates in time and is based on calculation of February the 10th, 2009 at 06:13 UT. The leading CME edge deforms as its segments travel in fast or slow environment. The kinematic curves on Fig. 2 describe the travel of CME segment presented by „+" sign on this figure.

Conclusion

The presented demonstration opens an opportunity for LSF implementation in real-time space-weather forecasting tools and alerting systems for CME impacts on Earth (or any heliospheric "target" of interest). The novel approach is based on real-time data-driven DBM-parameter optimization that iteratively improves the accuracy of CME kinematics in the heliosphere. Furthermore, the integration with other advanced numerical codes as ENLIL and EUHFORIA gives an availability for employment in practical and fast online CME prediction tools.

The current and development DBM versions are available at web-site:

http://www.geof.unizg.hr/~tzic/dbm.html

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