The 8th Community Coordinated Modeling Center Workshop

THE DRAG-BASED MODEL

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General classification of space-weather models

- The DBM: a „tool“ for prediction of ICMEs propagation in the heliosphere → primary task for space-weather forecasting
- modeling and forecasting can be divided:
  - a) purely empirical/statistical methods
  - b) kinematical-empirical methods
  - b/c) analytical (M)HD-based models (DBM)
  - c) numerical MHD-based models
The DBM hypothesis

- The DBM hypothesis at large heliocentric distances:
  - the Lorentz force ceases in upper corona
  - ICME dynamics is solely governed by interaction with solar wind (ambient) ← observational facts:
    - fast CME → decelerate
    - slow CME → accelerate
  - collisionless environment:
    - low viscosity
    - low resistivity → dissipative processes are negligible
  - momentum and energy are transferred by magnetosonic waves

\[ v \rightarrow w \]
The DBM equations in general form

- At heliocentric distances beyond $R \geq 15 \, r_s$:

- net acceleration (drag is dominant): $a = a_L + a_g + a_d$

- equation of motion in quadratic form (Cargill, 2004):
  $$ R''(t) = -\gamma(R) [R'(t) - w(R)] |R'(t) - w(R)| $$

- parameter $\gamma$:
  $$ \gamma \propto C_d \frac{A \rho_{SW}}{M} $$
  - for $R \gg 1r_s = M = M_i + M_v = \text{const.}$

- LDB density expression (Leblanc et al., 1998):
  $$ n_0(R) = \frac{k_2}{R^2} + \frac{k_4}{R^4} + \frac{k_6}{R^6} \quad \text{for} \quad R > 1.8 $$
  $$ k_2 = 3.3 \times 10^5 \, \text{cm}^{-3}, \quad k_4 = 4.1 \times 10^6 \, \text{cm}^{-3}, \quad k_6 = 8.0 \times 10^7 \, \text{cm}^{-3} $$
Solar wind perturbation

- stationary and isotropic
- density flux conservation
- unperturbed solar-wind speed becomes:
  \[ w_0(R) = w_\infty \left( 1 + \frac{k_4}{k_2} \frac{k_6}{k_2} \right)^{-1} \]

- total solar-wind speed with perturbation term \( w_p(R) \):
  \[ w(R) = \begin{cases} 
  w_0(R) + w_p(R), & R_1 < R < R_2 \\
  w_0(R), & \text{otherwise} 
  \end{cases} \]

- leads to:
  \[ \gamma(R) = \gamma_\infty \frac{w_\infty}{w(R)}; \quad n(R) = \frac{k_2}{R^2} \frac{w_\infty}{w(R)} \]

INPUT:
- \( w(R), w_\infty, \gamma_\infty \)

+ "Cone geometry": \( A \propto R^2 \)

\[ w_\infty = \lim_{R \to \infty} w_0(R) \]

\[ \gamma_\infty = \Gamma \times 10^{-7} \text{ km}^{-1} \]

\[ \gamma_\infty = \lim_{R \to \infty} \gamma(R) \]
Parameter $\gamma$, SW density and speed
Options of ICME cone-geometry
DBM with constant $w$ and self-similar CME geometry

- solar-wind speed $w$:
  - isotropic and constant
  - parameter $\gamma$ is constant as well
- „self-similar“ CME expansion:
  - the initial cone-shape of CME is preserved during its interplanetary propagation
- for a given set of input parameters the model provides the ICME Sun-“target” transit time, the arrival time, and the impact speed
Basic $w=\text{const.}$ & SS-expansion

(http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

CME take-off date:
CME take-off time (UTC):
$\gamma$ - constant drag parameter:
$w$ - constant solar wind speed:
$R_0$ - starting radial distance of CME:
$v_0$ - speed of CME at $R_0$:
Select target from the list:

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04/12/2016  T. Žic, et al. - The DBM
Advanced $w=\text{const.}$ & SS-expansion

(http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

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<th>Basic DBM</th>
<th>Advanced DBM</th>
<th>Documentation</th>
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- **CME take-off date:** Apr 8 2018
- **CME take-off time (UTC):** 15 h 10 min
- **$\gamma$ - constant drag parameter:** $0.2 \times 10^{-7} \text{ km}^{-1}$
- **$w$ - constant solar wind speed:** 450 km/s
- **$R_0$ - starting radial distance of CME:** 20 $R_{\text{Sun}}$
- **$\nu_0$ - speed of CME at $R_0$:** 1000 km/s
- **$\lambda$ - CME’s angular half-width:** 30 deg
- **$\varphi_{\text{CME}}$ - central meridian distance of source region:** 0 deg

Select target from the list:

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Results $w=\text{const.}$ & SS-expansion

(http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

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<th>Results</th>
<th>Kinematic plot</th>
<th>CME geometry plot</th>
<th>Documentation</th>
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**Output:**

CME arrival at target (date & time): 14.04.2016 at 18h:12min
Transit time: 50.20 h
Impact speed at target (at 1 AU): 634 km/s

**Input parameters:**

CME take-off date & time: 12.04.2016 at 16h:00min
$\gamma = 0.2 \times 10^{-7}$ km$^{-1}$, $w = 450$ km/s,
$R_0 = 20 \, r_{\text{Sun}}$, $v_0 = 1000$ km/s, $\lambda = 30^\circ$, $\varphi_{\text{CME}} = 0^\circ$
$R_{\text{target}} = 1$ AU, $\varphi_{\text{target}} = 0^\circ$

Calculated in 3.15 seconds.
Plots \( w = \text{const.} \) & SS-expansion

(http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)

● UP: Propagation of '+ CME' point in geometry plot

● LEFT: Ecliptic plane cross-section of CME propagation
Online applications of DBM with $w=\text{const.}$ & SS-expansion

Used on web pages of:

- Hvar Observatory - Forecasting the Arrival of ICMEs: [http://oh.geof.unizg.hr/DBM/dbm.php](http://oh.geof.unizg.hr/DBM/dbm.php)


  (courtesy of Leila M. Mays)

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DBM with $w(R)$ and CME leading-edge flattening

- solar-wind speed $w$:
  - is radially dependent: $w(R)$
    $\rightarrow$ parameter $\gamma$ becomes function of radial distance as well: $\gamma(R)$
- each CME leading-edge segment propagates independently
  $\rightarrow$ the initial cone-geometry flattens
Plots $w(R)$ \& CME edge flattening
(http://oh.geof.unizg.hr/~tomislav/DBM/)

Output:
- CME arrival at target (date \& time): 14.04.2016 at 18h:20min
- Transit time: 50.35 h
- Impact speed at target (at 1 AU): 633 km/s

Input parameters:
- CME take-off date \& time: 12.04.2016 at 16h:00min
- $\gamma_\infty = 0.2 \times 10^{-7}$ km$^{-1}$, $w_\infty = 450$ km/s,
- $R_0 = 20$ $r_S$, $v_0 = 1000$ km/s,
- $\lambda = 30^\circ$, $\varphi_{CME} = 0^\circ$
- $R_{\text{target}} = 1$ AU, $\varphi_{\text{target}} = 0^\circ$

Calculated in 13.48 seconds.
Example of DBM + ENLIL model
(http://oh.geof.unizg.hr/~tomislav/DBM-ENLIL/)

\[ w(R), \gamma(R) \rightarrow \text{CME-edge flattening} \]

- drag parameter: \( \Gamma = 0.2 \)
- initial CME distance: \( R_0 = 31 \, r_S \)
- initial CME speed: \( v_0 = 1000 \, \text{km/s} \)
- CME half-width: \( \lambda = 60^\circ \)
- launching CME meridian distance: \( \varphi = 150^\circ \)
- target: Mars

\begin{itemize}
  \item LEFT: Cross-section of CME propagation in ecliptic plane. The CME take-off time: February the 10th, 2009 at 06:13 UT.
  \item RIGHT: Propagation of '+' CME' point in geometry plot
\end{itemize}
Automatic Fitting

• INPUT: observed ICME dataset: \( \{ (R_0, v_0), \ldots, (R_N, v_N) \} \)

• OUTPUT: DBM parameters \((\Gamma, w_\infty, R_0, v_0)\)

• The least-square fitting (LSF):
  – successive variation of DBM parameters → minimal deviation between observed \(v_i\) and DBM-calculated speeds \(v(R_i)\):

\[
\sigma(\Gamma, w_\infty, R_0, v_0) = \sqrt{\frac{1}{N+1} \sum_{i=0}^{N} [v_i - v(R_i)]^2}
\]

→ \(\sigma_{\text{min}}\) →
  → the best \((\Gamma, w_\infty, R_0, v_0)\)

• for real-time space-weather forecasting (successive fitting as ICME propagates)

The fitted standard deviation \(\sigma_{\text{min}}\) is smaller than the observed \(\sigma_o\)!
Conclusion

- The drag-based model is useful because:
  - it is simple, fast and versatile
  - its accuracy is not worse in comparison to the other advanced models (Vršnak et al., 2014)
  - it is suited for a fast real-time space-weather forecasting (Žic et al., 2015)

- Drawbacks:
  - the magnetic field/Lorentz force is not included in the DBM
  - CME-CME interaction is problematic for calculation
  - the DBM is not basically designed for usage in a complex heliospheric environment
    (Will DBM + ENLIL provide better forecasting results?)
Thank you for your attention!
References