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 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
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):
  \[ n_0(R) = \frac{k_2}{R^2} + \frac{k_4}{R^4} + \frac{k_6}{R^6} \quad \text{for } R > 1.8 \]
  \[ k_2 = 3.3 \times 10^5 \, \text{cm}^{-3}, k_4 = 4.1 \times 10^6 \, \text{cm}^{-3}, k_6 = 8.0 \times 10^7 \, \text{cm}^{-3} \]
Solar wind perturbation

- stationary and isotropic
- density flux conservation
- unperturbed solar-wind speed becomes:

\[ w_0(R) = \gamma_\infty \left( 1 + \frac{k_4/k_2}{R^2} + \frac{k_6/k_2}{R^4} \right)^{-1} \]

- 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:

\[ \gamma(R) = \frac{\gamma_\infty}{w(R)} \]
\[ n(R) = \frac{k_2}{R^2} \frac{1}{w(R)} \]

**INPUT:**
\[ w(R), w_\infty, \gamma_\infty \]

**Cone geometry**: \( A \propto R^2 \)

**Constants**:
\[ w_\infty = \lim_{R \to \infty} w_0(R) \]
\[ \gamma_\infty = \Gamma \times 10^{-7} \text{ km}^{-1} \]
\[ \gamma_\infty = \lim_{R \to \infty} \gamma(R) \]
Parameter $\gamma$, SW density and speed
Options of ICME cone-geometry

a) ICME direction to the observer

b) 

c)
DBM with constant $w$ and self-similar CME geometry

- solar-wind speed $w$:
  - isotropic and constant
  $\rightarrow$ 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

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CME take-off date:
CME take-off time (UTC):
\( y \) - 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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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:  
$\nu_0$ - speed of CME at $R_0$:  
$\lambda$ - CME's angular half-width:  
$\varphi_{CME}$ - central meridian distance of source region:  
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

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
$y = 0.2 \times 10^{-7} \text{ km}^{-1}$, $w = 450 \text{ km/s}$,
$R_0 = 20 \, r_{\text{Sun}}$, $V_0 = 1000 \text{ km/s}$, $\lambda = 30^\circ$, $\varphi_{\text{CME}} = 0^\circ$
$R_{\text{target}} = 1 \text{ AU}$, $\varphi_{\text{target}} = 0^\circ$

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)

CCMC Contact: Leila Mays (M.Leila.Mays@nasa.gov)
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,
- $\lambda = 30^\circ$, $\varphi_{CME} = 0^\circ$
- $R_{target} = 1$ AU, $\varphi_{target} = 0^\circ$
Calculated in 13.48 seconds.

- LEFT: Cross-section of CME propagation in ecliptic plane
- RIGHT: Propagation of ' + CME' point in geometry plot
Example of DBM + ENLIL model
(http://oh.geof.unizg.hr/~tomislav/DBM-ENLIL/)

- LEFT: Cross-section of CME propagation in ecliptic plane. The CME take-off time: February the 10th, 2009 at 06:13 UT.
- RIGHT: Propagation of '+ CME' point in geometry plot

\[ w(R), \gamma(R) \rightarrow \text{CME-edge flattening} \]
- 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
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 \(\rightarrow\) minimal deviation between observed \(v_i\) and DBM-calculated speeds \(v(R_i)\):
  \[
  \sigma(\Gamma, w_\infty, R_0, v_0) = \sqrt{\frac{1}{(N+1)} \sum_{i=0}^{N} [v_i - v(R_i)]^2}
  \]
  \(\rightarrow \sigma_{\text{min}} \rightarrow\)
  \(\rightarrow\) the best \((\Gamma, w_\infty, R_0, v_0)\)
- for real-time space-weather forecasting (successive fitting as ICME propagates)

\[\sigma_{\text{min}} = 29.87 \text{ km/s}, \quad c_{v,\text{min}} = 7.50\% , \quad r^2 = 0.67\]
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