Forbush decreases caused by expanding ICMEs: analytical model and observation

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Forbush decreases caused by Interplanetary Coronal Mass Ejections (ICMEs)

REMOTE OBSERVATION

SOHO/LASCO C2 image

Temmer & Nitta (2015)

VISUALISATION

IN SITU MEASUREMENTS

Richardson & Cane (2011)

Dumbovic et al (2012)
Two-step Forbush decreases caused by ICMEs

1st step:
- shock/sheath region
- highly turbulent
- strong B
- fast decrease,
  prolonged recovery

2nd step:
- CME ejecta
  (magnetic cloud, flux rope)
  smooth & strong B
  fluctuations very low

Symmetric-like decrease,
  timespan limited to the ejecta

Dumbovic et al (2012)
**The analytical model - assumptions**

- **magnetic ejecta (ICME, magnetic cloud, flux rope)**
  - a closed magnetic structure: no direct magnetic connection between the inside and the outside
  => particles can enter into the ejecta via perpendicular diffusion and/or drift (simplicity reasons -> only diffusion)
  - **initially empty**

- **magnetic ejecta (ICME, magnetic cloud, flux rope)**
  - cylindrical form
  - **moves with constant velocity**
  - **does not vary in shape or size**

*Based on Cane et al (1995)*
Building the analytical model

For the particle density, we have:

\[
\frac{\partial U}{\partial t} = \frac{1}{r} \left( \frac{\partial}{\partial r} \left( rD_\perp \frac{\partial}{\partial r} \right) \right),
\]

- radial diffusion
- \( D \) does not change throughout ejecta

Initial & boundary conditions:

\[
U(r, t) = \begin{cases} 
0, & 0 < r < a, \ t = 0 \\
U_0, & r = a, \ t \geq 0 
\end{cases}
\]

- initially empty
- Density outside constant

Exact analytical solution:

\[
U(r, t) = U_0 \left( 1 - \frac{2}{a} \sum_{n=1}^{\infty} \frac{J_0(\lambda_n r)}{\lambda_n J_1(\lambda_n a)} e^{-D \lambda_n^2 t} \right),
\]

oscillatory   rapidly decreasing

We neglect terms with \( n > 1 \) and renormalize according to initial & boundary conditions to get the solution:

\[
U(r, t) = U_0 \left( 1 - J_0(\alpha_1 \frac{r}{a}) e^{-D\left(\frac{\alpha_1}{a}\right)^2 t} \right).
\]
The analytical model - results

Forbush decrease depends on:

- Radius of ICME \[f = f(a,t,D)\] \textit{Blanco et al (2013)}
- Diffusion (transit) time \[\textit{Blanco et al (2013)}\]
- Diffusion coefficient: \[?\] \textit{e.g. Dumbovic et al (2012)}

\[U(r,t) = U_0 \left(1 - J_0(\alpha_1 \frac{r}{a})e^{-D(\frac{\alpha_1}{a})^2t}\right).\]

\[f = f(a,t,D)\]
- a = radius of ICME
- t = diffusion (transit) time
- D = diffusion coefficient

What is a typical diffusion coefficient in magnetic cloud and compared to normal solar wind??
The analytical model - results

Typical values:
- Transit time: 72 hours
- MC radius: 0.05 AU
- Forbush decrease: 6-7%
- Diffusion coefficient: $10^{18} \text{ cm}^2/\text{s}$

$10^{14} \text{ m}^2/\text{s}$
**Typical:**
\[ a = 0.05 \text{ AU} \]
\[ TT = 72 \text{h} \]

**Max:**
\[ a = 0.02 \text{ AU} \]
\[ TT = 96 \text{h} \]

**Min:**
\[ a = 0.2 \text{ AU} \]
\[ TT = 12 \text{h} \]

Forbush decrease "typical" range of amplitudes cca 1-15%

**Estimation based on theoretical consideration**

<table>
<thead>
<tr>
<th>Amplitude (A_max)</th>
<th>Time (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<tr>
<td>-7</td>
<td>1</td>
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<tr>
<td>-14</td>
<td>2</td>
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<td>-21</td>
<td>3</td>
</tr>
<tr>
<td>-28</td>
<td>4</td>
</tr>
</tbody>
</table>

**D = 10^{18} \text{ cm}^2/\text{s}**

**Estimated range for the diffusion coefficient:**

- **D_{min} = 7 \times 10^{16} \text{ cm}^2/\text{s}**
- **D_{max} = 2.4 \times 10^{20} \text{ cm}^2/\text{s}**

**Typical D for unperturbed solar wind:**
\[ D \sim 10^{21} \text{ cm}^2/\text{s} \]

**Estimation based on observational consideration**

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**D = 10^{18} \text{ cm}^2/\text{s}**

**Estimated range for the diffusion coefficient:**

- **D_{min} = 7 \times 10^{17} \text{ cm}^2/\text{s}**
- **D_{max} = 1.2 \times 10^{20} \text{ cm}^2/\text{s}**

**Estimation based on the empirical distribution of t/a^2 for MCs derived from Richardson & Cane (2010) list**

**Max:**
\[ a = 0.02 \text{ AU} \]
\[ TT = 96 \text{h} \]

**Min:**
\[ a = 0.2 \text{ AU} \]
\[ TT = 12 \text{h} \]
Forbush decrease amplitude vs transit time

D=10^{18} \text{ cm}^2/\text{s}

a=0.05 \text{ AU}

data source: IZMIRAN database (courtesy of A. Belov)

The model vs observation: ground based measurements at Earth

Forbush decrease measurements on Earth (R\sim10GV) shifted to satellite values (R=0GV) using empirical formula from Cane (2000)
The model vs observation: spacecraft measurements

Blanco et al (2013a)

Measurements from Helios I and II
Possible model changes...

diffusion time > transit time
(diffusion of particles starts even before CME liftoff)
Curve shifted by 24 hours

A(%) vs. T T (h)

Diffusion is still too fast!!
=> Additional mechanism

model
Blanco et al (2013) trend
CMEs expand!

CME expansion observed remotely near the Sun, in IP space and in situ measurements!
Expansion vs diffusion – a very rough estimate

Could expansion be large "enough" factor to counteract diffusion??

\[ U = 6.5R^{-2.4} \]  
MC density with heliocentric distance, Bothmer & Schwenn, 1998

\[ U = 7R^{-2} \]  
Solar wind density with heliocentric distance

At 0.3 AU  
\[ U \text{ (CME)} = 117 \]  
\[ U \text{ (SW)} = 78 \]  
\[ FD = 10\% \]

At 1 AU  
\[ U \text{ (CME)} = 6.5 \]  
\[ U \text{ (SW)} = 7 \]  
\[ FD = 44\% \]

30 % decrease due to expansion

At 0.3 AU  
\[ a = 0.05 \text{ AU} \]  
\[ D = 10^{18} \text{ cm}^2/\text{s} \]  
\[ FD = 100\% \]  
(Empty MC)

At 1 AU  
\[ a = 0.05 \text{ AU} \]  
\[ D = 10^{18} \text{ cm}^2/\text{s} \]  
\[ FD = 10\% \]

90 % increase due to diffusion

Typical transit time 60 h

Typical estimation: Expansion can "slow down" the diffusion by roughly 30%

A very rough estimation: Expansion can "slow down" the diffusion by roughly 30%

\[ D = 10^{18} \text{ cm}^2/\text{s} \]
\[ a = 0.05 \text{ AU} \]
\[ TT = 72 + 24 \text{ h} \]
Expansion vs diffusion – a very rough estimate

Calculated based on relative MC (plasma) density decrease due to expansion with respect to solar wind density decrease due to expansion (empirical relation from Bothmer & Schwenn, 1998)

Calculated based on our model for the same distance/time as above

Ratio

1

. .

3
A very rough estimation:
Expansion can "slow down" the diffusion by roughly 30%
CONCLUSIONS:

diffusion-based analytical model in present form qualitatively agrees with observation, but quantitatively suffers from several drawbacks

The qualitative aspect of the model could be improved by including observable facts regarding CMEs (e.g. expansion)

Thank you for your attention!