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

VISUALISATION

ICME Sheath

Shock

Richardson & Cane (2011)

Temmer & Nitta (2015)

IN SITU MEASUREMENTS

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
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

Equation for the particle density:

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

- 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:

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

oscillatory
rapidly decreasing

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

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

Forbush decrease depends on:

- Radius of ICME  \( \text{Blanco et al} (2013) \)
- Diffusion (transit) time  \( \text{Blanco et al} (2013) \)
- Diffusion coefficient:
  - depends on the strength of B  \( \text{e.g. Dumbovic et al} (2012) \)
  - but how?

What is a typical diffusion coefficient in magnetic cloud and compared to normal solar wind??

\[
U(r, t) = U_0 \left( 1 - J_0(\frac{r}{a}) e^{-D(\frac{a_1}{a})^2 t} \right).
\]

\( f = f(a, t, D) \)

- \( a \) = radius of ICME
- \( t \) = diffusion (transit) time
- \( D \) = diffusion coefficient
Typical values:
Transit time 72 hours
MC radius 0.05 AU
Forbush decrease 6-7%

Diffusion coefficient $10^{18}$ cm$^2$/s
($10^{14}$ m$^2$/s)

The analytical model - results
**Forbush decrease**
"typical" range of amplitudes cca 1-15%

**Estimation based on theoretical consideration**

Typical:
- $a = 0.05$ AU
- $TT = 72$ h

Min:
- $a = 0.2$ AU
- $TT = 12$ h

Estimation based on theoretical consideration

Estimation based on observational consideration

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

Estimated range for the diffusion coefficient:
- $D_{\text{min}} = 7 \times 10^{16} \text{ cm}^2/\text{s}$
- $D_{\text{max}} = 2.4 \times 10^{20} \text{ cm}^2/\text{s}$

Estimated range for the diffusion coefficient based on the empirical distribution of $t/a^2$ for MCs derived from Richardson & Cane (2010) list:
- $D_{\text{min}} = 7 \times 10^{17} \text{ cm}^2/\text{s}$
- $D_{\text{max}} = 1.2 \times 10^{20} \text{ cm}^2/\text{s}$
Forbush decrease amplitude vs transit time

\[ y = -0.05x + 8.27 \]
\[ R^2 = 0.06 \]

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

Forbush decrease measurements on Earth (R~10GV) shifted to satellite values (R=0GV) using empirical formula from Cane (2000)
The model vs observation: spacecraft measurements

Measurements from Helios I and II

Blanco et al (2013a)
Possible model changes...

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

Diffusion is still too fast!!

=> Additional mechanism

Blanco et al (2013) trend

model
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??

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

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

At 0.3 AU
U (CME) = 117
U (SW) = 78
FD = 10%

At 1 AU
U (CME) = 6.5
U (SW) = 7
FD = 44%

30 % decrease due to expansion

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

Typical transit time 60 h

At 1 AU
a = 0.05 AU
D = \(10^{18}\) cm\(^2\)/s
FD = 10%

90 % increase due to diffusion

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

Expansion vs diffusion – a very rough estimate

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

a = 0.05 \text{ AU}

TT = 72 + 24 \text{ h}
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!