A simple model of Forbush decreases caused by sheathless magnetic clouds

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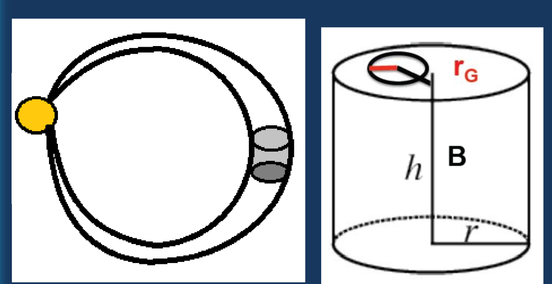
INTRODUCTION

Forbush decreases (FDs) are short term depressions in the galactic cosmic ray (CR) flux observed at Earth and in the interplanetary space, caused by interplanetary counterparts of coronal mass ejections (ICMEs). In a general case, when ICME drives a shock, a two-step FD is observed, the first decrease caused by the shock-sheath region, whereas the second decrease is caused by the ejecta (ICME). These two regions have different characteristics and presumably modulate cosmic rays in different ways. The ejecta-modulation can be studied separately in ICMEs which do not drive shocks/sheaths.

We study ejecta- modulated FDs for a special subset of ejecta that have a smooth rotation in an enhanced magnetic field, low proton temperatures and low plasma beta parameter – *MAGNETIC CLOUDS* (MCs). The magnetic structure of the MC is presumably that of a flux rope, where it's local magnetic configuration can be modeled using a cylindrical geometry. In order to model FD we assume a simple cylindrical structure of the MC.

MODEL



The MC is represented by a cylinder consisting of a uniform magnetic field B. We consider 2D circular region (MC cross-sectional area) in polar coordinates.

$$N = \int n \mathrm{d}s, \qquad n(E) = \int g(E) f(E) \mathrm{d}E$$

The number of particles within the surface element ds is N, and n is particle density, a function of particle energy, E

$$g(E,\theta,r) = g(\xi) = \begin{cases} 1, & \xi \le R \\ 0, & elsewhere \end{cases}$$

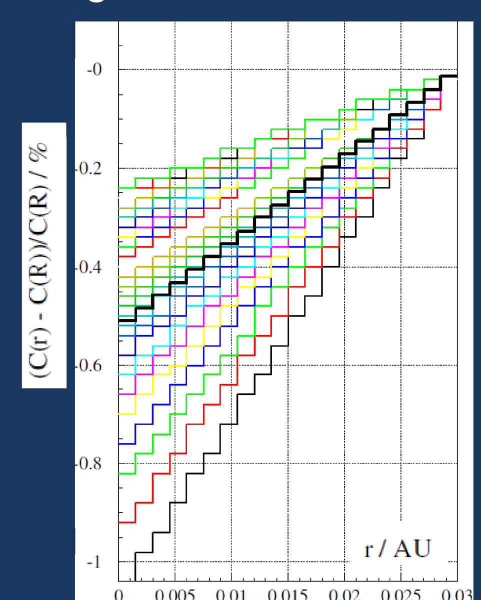
A particle that gyrates along its guiding center field line at a distance r will stay in the flux rope if $\xi = r + r_G < R$, where r_G is Larmor radius of the particle. This condition defines the weight function, g.

$$f(E) = J(T,\phi) = J_{\mathrm{LIS}}(T+\phi)\frac{T(T+2E_0)}{(T+\phi)(T+\phi+2E_0)}$$

Outside the MC energy distribution of particles is given by a force field approximation of the galactic cosmic ray spectrum , J (e.g. Usoskin, 2011)

$$A(r)_{\mathrm{FD}}(\%) = \frac{n_0 - n(r)}{n_0},$$

For a given energy the magnitude of the FD can be calculated, where n_0 is the particle density when magnetic field is not present and n(r) is the particle density in the presence of a magnetic field. We can derive the number of particles modulated/excluded by the occurrence of the MC assuming it corresponds to the number of confined particles in our model, when magnetic field is "switched on".



The weighted sum (black) of series of modeled FDs (colored) at different energies using a force field approx. gives an estimation of FD which can be compared to observation. (Heber et al., 2015)

Calculations are done numerically, using a grid:
$\Delta R = 0.005$ AU and $\Delta\Theta = 0.0002$
0.2 - 20 GeV, $\Delta E = 0.1$ GeV

SUMMARY & OUTLOOK

This simple model predicts that the number of CRs will decrease towards the center of the MC, the profile and its amplitude depend on the magnetic field strength and spatial extent of the MC, and qualitatively describes observations. However, the model tends to underestimate the amplitudes. Since the shape of the FD strongly depends on the trajectory of the spacecraft through the MC, we don't expect a match between the model and observations. Future improvements should include the analysis on a larger sample as well as using more realistic magnetic field in the modeling.

REFERENCES

Usoskin et al. (2011), JGR, 116, 2104
Heber et al. (2015), submitted to CEAB

ACKNOWLEDGMENT

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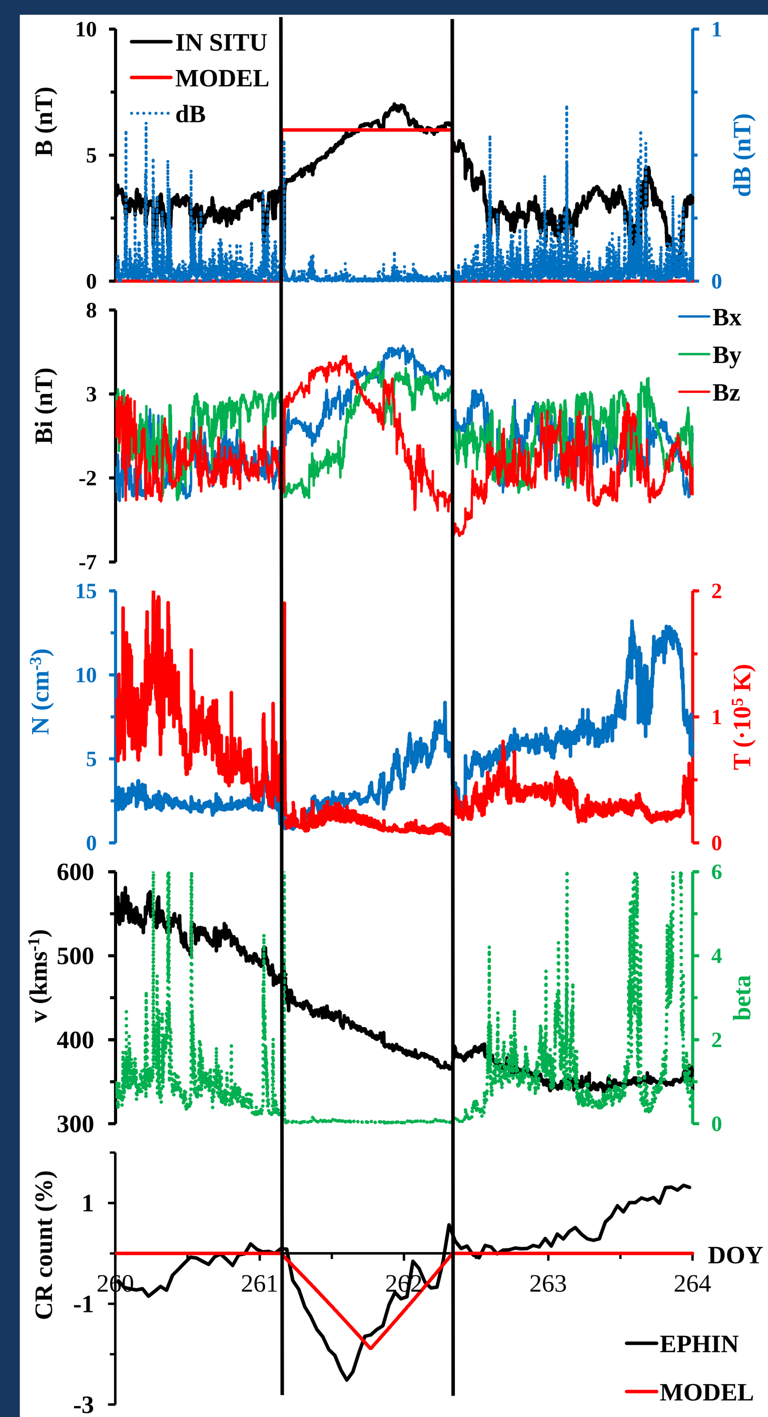
ANALYSIS & RESULTS

EVENT 1
17.9.2008.



EVENT 1 – MODEL INPUT:

start - end doy: 261.15 – 262.35
Duration: 28.8 h
R=0.172 AU
(MC expansion included)
B=6 nT

EVENT 1 – MODEL OUTPUT:

Tmin = the time of the FD minimum
Tmin(obs) doy: 261.6
Tmin(model) doy: 261.77
$\Delta T = 4$ h

Amin = FD minimum amplitude
Amin(obs) = 2.5%
Amin(model) = 1.9%
ΔAmin = 0.6%

IN SITU MEASUREMENTS

MCs were identified using in situ measurements of solar wind plasma density, temperature, speed, and plasma beta parameter (SWE/WIND) as well as magnetic field components, strength, and fluctuations (MAG/ACE). Solid black lines mark the beginning and the end of the MC in analyzed events (event 1 and 2).

COSMIC RAY MEASUREMETS

FDs are identified using EPHIN/SOHO measurements of CR count, normalized to the CR count at the start of the MC. The lowest panel displays the measured and modeled FD (black and red lines, respectively). Taking into account the simplicity of our model we find a reasonable agreement.

EVENT 1

The MC seems to be embedded in the fast solar wind. The start of the MC is characterized by temperature drop, as well as drop in plasma beta parameter and magnetic field fluctuations and the start of a smooth rotation in the Bz component of the magnetic field. The declining trend of the speed profile throughout the MC is indicative of its expansion. The end of MC is determined by the temperature and plasma beta increase, as well as the change in the speed profile and the end of the Bz rotation.

The beginning and the end of FD correspond to the beginning and the end of MC (bottom panel).

The model somewhat underestimates the amplitude of FD and we observe some deviations from the observed shape of FD. The modeled FD minimum is delayed compared to the observed FD minimum.

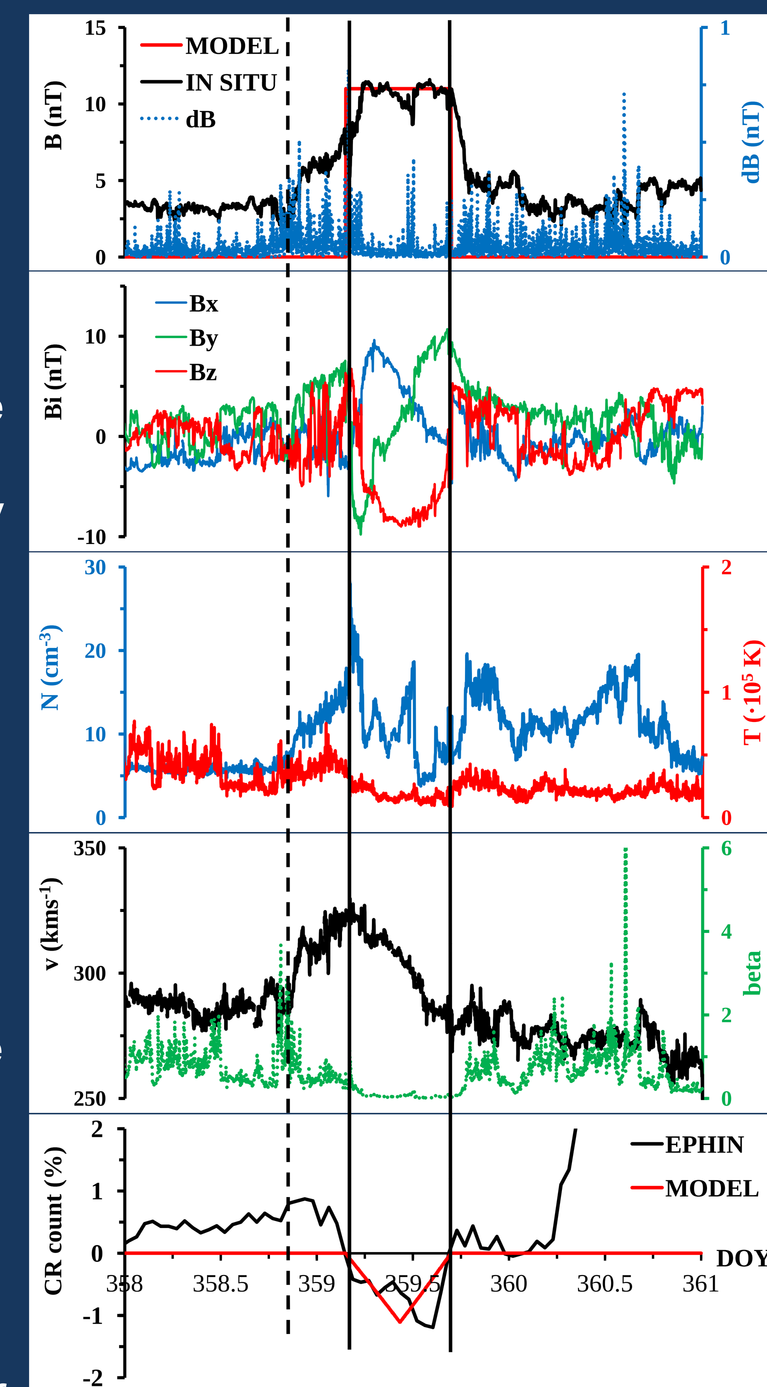
EVENT 2

This MC is faster than the upfront solar wind and seems to have formed a sheath region by increasing speed profile , small temperature and density increase, as well as increased magnetic field fluctuations (dashed black line). The beginning and the end of the MC are determined based on the low temperature and plasma beta parameter, smooth rotation in the By component of the magnetic field, as well as the declining speed profile (indicative of the MC expansion).

The FD starts somewhat earlier than the MC, within a sheath region, whereas the end of FD corresponds to the end of MC (bottom panel).

There is a good correspondence in the value of the FD amplitude between the model and observations, however, there are some deviations in the shape. The observed FD minimum is delayed compared to the modeled FD minimum.

EVENT 2
25.12.2013.



EVENT 2 – MODEL INPUT:

start - end doy: 359.15 – 359.75
Duration: 13.2 h
R=0.055 AU
(MC expansion included)
B=11 nT

EVENT 2 – MODEL OUTPUT:

Tmin = the time of the FD minimum
Tmin(obs) doy: 359.6
Tmin(model) doy: 359.43
$\Delta T = 4$ h

Amin = FD minimum amplitude
Amin(obs) = 1.2%
Amin(model) = 1.1%
ΔAmin = 0.1%