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Grad-Shafranov reconstruction of a magnetic cloud: Effects of the magnetic-field topology on the galactic cosmic-ray intensity

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Summary. — The passage of the interplanetary counterpart of a coronal mass ejection was observed at L1 between 2016 August 2 at 14:00 UT and August 3 at 03:00 UT. The transit of shock, sheath and magnetic cloud (MC) regions are identified and the MC configuration is studied through the Grad-Shafranov reconstruction technique. A classical Forbush decrease (FD) in the galactic cosmic ray (GCR) intensity was observed by the particle detector (PD) aboard the European Space Agency LISA Pathfinder (LPF) mission on 2016 August 2. The PD allowed to monitor the GCR intensity at energies above 70 MeV n^{-1} with a statistical uncertainty of 1% on one-hour binned data. The observed fractional decrease of the GCR intensity around the dip of the event is investigated through a full-orbit particle propagation in the MC and related to the reconstructed magnetic field topology.

1. – Introduction

Drops in the galactic cosmic ray (GCR) count rate with sudden onset and gradual recovery, observed in presence of solar wind transients and interplanetary shocks, are called Forbush decreases (FDs). The most intense FDs are associated with the transit of the interplanetary coronal mass ejections (ICMEs) [1-3]. In general FDs associated with ICMEs present a two-step profile: the first step is a GCR intensity drop caused by the passage of the shock/sheat region, while the second step is associated with ICME ejecta, that in some cases can be described as a magnetic cloud (MC). A MC is a closed plasma structure with magnetic field lines helically wrapped around a central axis. The signature of a MC passage in solar wind plasma and interplanetary magnetic field *in situ* mesurements is detected by a smooth rotating magnetic field associated with low proton temperature and plasma-beta parameter [4].

In this work a MC associated with an ICME is studied in detail and its Grad-Shafranov (GS) reconstruction is provided, sect. **2**˙2. Then, a full-orbit test particle simulation

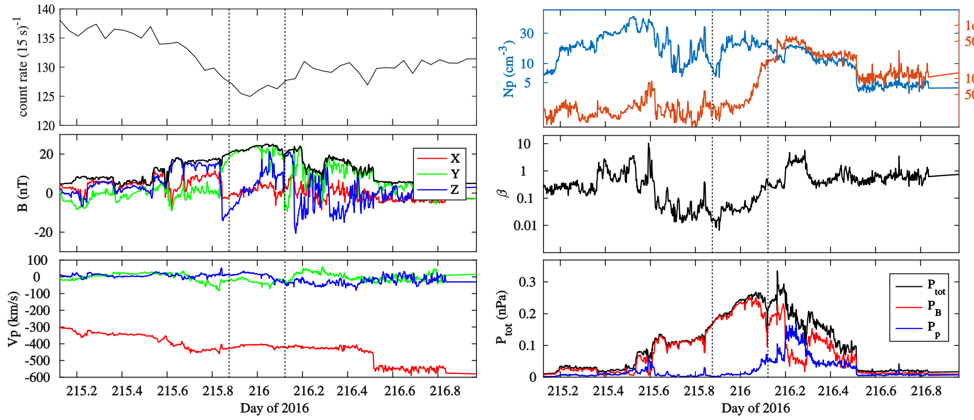

Fig. 1. – L1 *in situ* data from LPF PD (first panel) and Wind magnetic field and plasma observations for the 2016 August 2 event (other panels). The MC transit time is represented by vertical dashed lines.

(TPS) is presented to investigate the particle spatial distribution in response to the MC configuration, sect. **2**˙3, in order to explain an FD observed by LPF, sect. **2**˙1.

2. – ICME passage at L1 on 2016 August 2

2˙1. *LPF PD Observations.* – LISA Pathfinder (LPF) was a mission for the technological test of instruments to be placed on LISA, the first interferometer for gravitational waves in space [5,6]. The LPF spacecraft (S/C) orbited around the L1 Lagrangian point for one and half year. The mission hosted on board a particle detector (PD) [7] meant for the monitoring of the integral proton and helium nucleus fluxes above 70 MeV n^{-1} with statistical uncertainty at percent level on hourly-averaged data. During the LPF flight, from December 2015 through July 2017, the most intense FD was observed between 2016 August 2 and 2016 August 3 [8,9], shown in the left top panel of fig. 1.

2˙2. *GS Reconstruction of the MC.* – The GS reconstruction represents an advanced and unique data analysis technique that allows to recover the spatial topology of a MC using *in situ* interplanetary plasma data from a single S/C [10]. This technique is based on the GS equation in cartesian coordinates, which describes a 2D plasma structure in magnetohydrostatic equilibrium by assuming the z axis invariance: $\partial/\partial z \approx 0$. The deHoffmann-Teller (HT) frame of reference [11] comoving with the structure with velocity $\boldsymbol{V}_{HT}$ is determined. The application of the Hu and Sonnerup [12] method to the MC data allows to estimate a residue which quantifies the deviation of the structure from the GS equilibrium hypotesis. For the FD dated 2016 August 2, the MC passage started on 2016 August 2 at 21:00 UT and ended on 2016 August 3 at 2:55 UT [13], as apparent in fig. 1 from solar wind plasma and magnetic field paramenters. Using solar wind plasma and magnetic field measurements from the Wind S/C, the HT analysis gives an excellent constant $\boldsymbol{V}_{HT} = (-413.69, -27.94, 11.64)$ km s^{-1}, with a correlation coefficient among the measured electric field and $-\boldsymbol{V}_{HT} \times \boldsymbol{B}$ greater than 0.998. The GS reconstruction result is illustrated in fig. 2 (left panel). In order to compare Wind and LPF positions with respect to the MC configuration, their path projections are shown in the same panel.

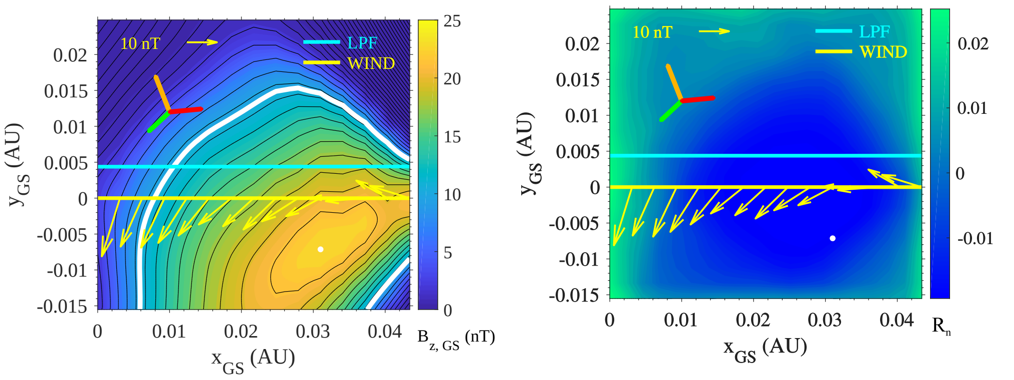

Fig. 2. – Left panel: GS reconstruction, the colour plot represents the $B_{z,GS}$ intensity respect to the GS frame of reference, the black solid lines are isopotential lines. Horizontal lines are the projections of LPF (cyan) and Wind (yellow) paths through the MC and in the top left corner is reported a projection of the GSE frame of reference (x_{GSE} in red, y_{GSE} in green and z_{GSE} in yellow). Right panel: fractional particle spatial distribution R_n (see text).

2'3. *Full-Orbit TPS*. – The investigation of the role of the magnetic field in the GCR flux variation during the MC transit is carried out with a full-orbit TPS. The basic idea is to inject an isotropic particle flux at the boundaries of the MC and to get the particle spatial distribution due to the magnetic field configuration, at the end of the particle propagation. The particles injected in the TPS are protons and the only force acting on them is the Lorentz force due to the presence of the magnetic field. At the beginning particle positions and angles of incidence are randomly selected along the boundaries of the simulation space, outside the MC field. Particle energies are extracted from the differential proton flux estimated on 2016 August 2 at 21:00 UT, *i.e.* the beginning of the MC passage at L1. The parametrization of the energy spectrum is done using the function in eq. (1), which is well representative of the GCR observation trend in the inner heliosphere for the energy interval of interest [14], ranging from 70 MeV to 100 GeV in the TPS:

$$F(E) = A(E+b)^{-\alpha}E^{\beta} \qquad \text{particles (m}^2\text{ sr s GeV n}^{-1})^{-1} \tag{1}$$

where $A = 18000$, $b = 1.034$, $\alpha = 3.66$ and $\beta = 0.869$. The integration of the test particle trajectories is then based on the Lorentz force only and the system is assumed to be collisionless. In response to the magnetic structure, each particle could be rejected, bended or could go through the field, depending on its initial position, energy and angle of incidence. Finally the simulation space is divided in cells and the number of trajectories crossing them is computed. In order to obtain a fractional variation of test particle distribution in space, the ratio between the particle number n_{cell} counted in each cell and the total particle number N involved in the simulation is computed: $R_n = n_{cell}/N$. The particle spatial distribution due to the presence of the 2016 August 2 MC, retrieved with the GS reconstruction, is shown in fig. 2 (right panel). The R_n value computed along the LPF path through the MC is displayed in fig. 3.

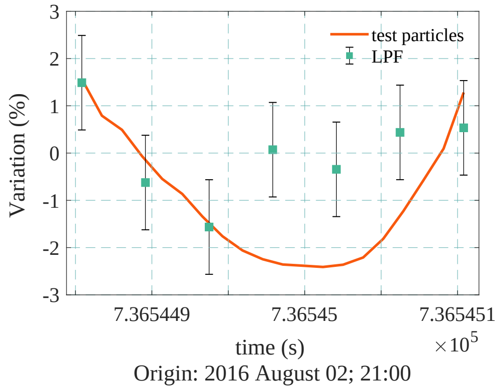

Fig. 3. – GCR flux variation (normalized to the mean value over the Bartels rotation number 2496) measured by LPF during the MC passage (squares) and percentage variation R_n obtained by TPS (line).

3. – Conclusions

The particle variation along the LPF path is obtained through a TPS in the frame of reference comoving with the MC. This variation is found to be consistent with the FD time profile observed by LPF, fig. 3. Further investigations are needed as the upgrade of the TPS method (*e.g.,* including the shock/sheat effect, the spatial diffusion, etc.) as well as its application to other ICME events, to better understand the details of the physical processes involved in the generation of FDs.

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