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Access of cosmic rays to an ICME from external field lines

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Interplanetary coronal mass ejections (ICMEs) cause decreases, so-called Forbush decreases, in the cosmic ray (CR) intensities. FDs are seen as up to 25% decreases in neutron monitor counts at Earth, lasting up to over a week. An ICME is thought to cause a FD through two mechanisms: by enhancing diffusion in the ICME shock wave sheath; and by preventing the CRs from penetrating the magnetic fluxrope embedded in the ICME. CR propagation during a FD is usually modelled as enhanced diffusion either within the whole ICME or within the embedded fluxrope. However, a question that is so far unanswered is how the CRs can reach the isolated fluxrope fieldlines from the open, external interplanetary fieldlines. We study the propagation of CRs from external field into a fluxrope by employing full-orbit particle simulations with scattering. The interface between the internal and external field lines is modelled analytically. We find that the CRs can access the fluxrope rapidly through x-point region, where the external magnetic field partially cancels the magnetic field of the fluxrope. The access is rapid compared to diffusive radial propagation of CRs within the rope. We find that CR propagation within the fluxrope can be modelled using diffusion models, without need to separately model the access to the isolated field lines, provided that the bounds of the diffusion area are taken as that of the isolated fieldlines instead of the region with smoothly rotating magnetic field. Thus, to evaluate the role of a fluxrope in FDs, the extent of the region where the rope magnetic fields are not connected to the external field must be analysed.

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1. Introduction

Cosmic ray (CR) propagation in the heliosphere is guided by the interplanetary magnetic field, which is typically of Parker spiral shape. During solar eruptions, magnetic clouds that form the core of the interplanetary coronal mass ejections (ICMEs) propagate through the interplanetary medium, and their magnetic structure and enhanced turbulence affect the propagation of both the Solar Energetic Particles (SEPs) and the cosmic rays that have their origin outside of the heliosphere.

In this study, we investigate how the magnetic clouds affect the propagation of CRs. The effect is often seen in Earth-based neutron monitors as a intensity decrease of up to 25%, the so-called Forbush Decrease (FD) [1]. The decrease can take up to over a week, typically with decay lasting for hours, after which recovery for up to over a week. The slow component often is accompanied with a faster, one-day symmetric decay-recovery component. The faster component is attributed to the magnetic fluxrope-like structure that presents a barrier for the CRs that would have to propagate across the mean field direction to reach the axis of the fluxrope [2, 3].

2. Models

The flux rope in our study is modelled using the force-free Gold-Hoyle model[4] which in (r, ϕ, Z), is

$$\mathbf{B}_{\rm GH} = \frac{B_a\, b\, r}{b^2 r^2 + 1}\,\hat{\mathbf{e}}_\phi + \frac{B_a}{b^2 r^2 + 1}\,\hat{\mathbf{e}}_{\mathbf{Z}}, \tag{1}$$

where B_a gives the axial field, and b parametrises the azimuthal winding of the field around the axis. We limit he flux rope with a modulating function

$$f(s) = 2\,s^3 - 3\,s^2 + 1 \tag{2}$$

which goes from 1 to 0 as the variable s goes from 0 to 1, and has a vanishing derivative at 0 and 1, and define the flux rope field as

$$\mathbf{B}_r = \begin{cases} \mathbf{B}_{\rm GH}(r) & r < r_b \\ f\left(\frac{r-r_b}{t_b}\right)\mathbf{B}_{\rm GH} & r_b \le r < r_b + t_b \\ 0 & r \ge r_b + t_b, \end{cases} \tag{3}$$

where r_b is the rope radius r_b and t_b the thickness of a sheath region around the flux rope. This modulation ensures that the extent of the flux rope is finite, as implied by observations[5]

The magnetic fluxrope is embedded in an external magnetic field, which we take as constant B_0. Thus, the total magnetic field in our simulations will be

$$\mathbf{B} = \mathbf{B}_{\rm r} + \mathbf{B}_0. \tag{4}$$

We simulate the CR propagation using full-orbit test particle simulation code[6]. The CRs are scattered with velocity isotropisation events as a Poisson process characterised by scattering time $\tau_{\rm sc} = \lambda_{\rm sc}/v$. The parallel scattering mean free path $\lambda_{\rm sc}$ is kept constant in the simulations, likewise the velocity v is constant.

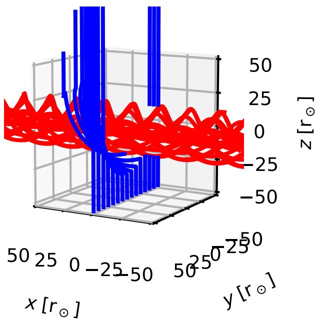

Figure 1: 3D projection of the flux rope magnetic field, with $r_b = 32\,\mathrm{r}_\odot$, $t_b = 1\,\mathrm{r}_\odot$ and $B_a = 5B_0$. The red curves show the fieldlines that are isolated from the open field (blue curves).

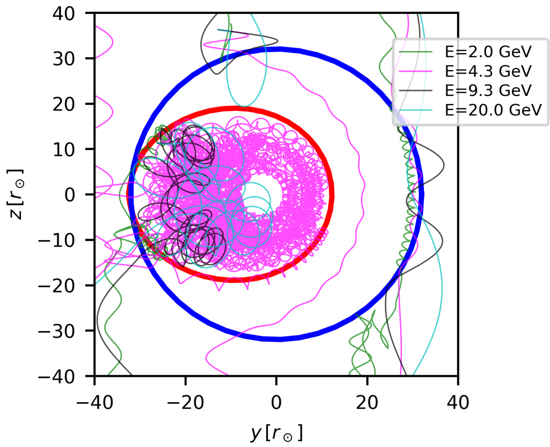

Figure 2: A sample of particle paths in the field configuration shown in Figure 1. The fluxrope radius $r_b = 32\mathrm{r}_\odot$ is shown by the blue circle, and the isolated field region with the red dashed oval. The parallel scattering mean free path is 1 AU.

In addition to the full-orbit simulations, we solve the CR propagation by solving numerically a 1D radial diffusion equation for density $n(r,t)$

$$\frac{\partial n(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\,\kappa_{\mathrm{radial}}(r)\frac{\partial n}{\partial r}. \quad (5)$$

where the diffusion coefficient is given as [7, 8]

$$\kappa_{\mathrm{radial}} = \frac{r_L^2}{3\tau_{\mathrm{sc}}}. \quad (6)$$

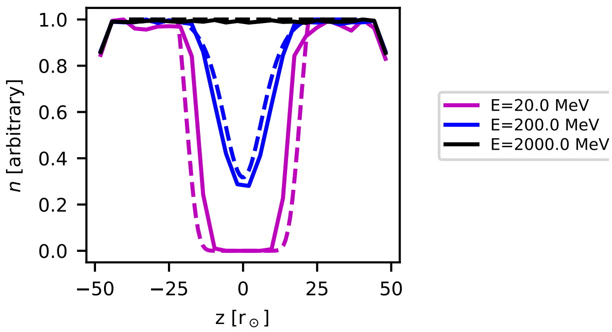

Figure 3: Density of 200 MeV protons across a fluxrope obtained from the full-orbit simulations (solid curves) and the radial diffusion solution (dashed curves) 3 days after injection.

3. Results

4. Discussion and Conclusions

References

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