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Recent progress in solar modulation modeling in light of new cosmic-ray data from AMS-02

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Summary. — After entering into the heliosphere, Galactic cosmic rays (CRs) are influenced by magnetic turbulence and solar wind disturbances, which cause the so-called "solar modulation" effect. Understanding the relationship between the Sun's variability and the CR modulation effect is essential for the investigation of the physical processes of CR transport in the heliosphere, as well as for the establishment of predictive models of CR radiation in the interplanetary space. In the study of this phenomenon, the key ingredients are the knowledge of the CR interstellar spectrum and the detailed understanding of how this spectrum is modulated inside the heliosphere. For this purpose, we present a newly developed model of solar modulation where the key parameters describing the CR physics processes are constrained by the new monthly-resolved data of AMS-02. The comparison between model calculations and CR data is presented at various energies and epochs of the solar cycle. Calculations of the propagation times of CRs, their energy losses, and their trajectories through the heliosphere are also presented and discussed.

1. – Introduction

During their propagation through the interplanetary space, Galactic Cosmic Rays (GCRs) can be spatially diffused, magnetically drifted, advected and decelerated by the solar wind and its embedded magnetic field. As a result, the energy spectrum of GCRs inside the heliosphere is significantly different from their Local Interstellar Spectrum (LIS) beyond the heliopause. The modifications of the GCR intensities and energy spectra are known to vary with time, in connection with the variability of the Sun's magnetic activity. This phenomenon is referred to as *solar modulation of GCRs*, and it is observed to change periodically, following the periodical change in the numer of sunspots observed in the solar corona. Understanding the solar modulation phenomenon is an important challenge in GCR physics, either to infer their LIS's of GCRs or to investigate the dynamics of charged particles in the heliospheric plasma. Along with the Voyager-1 data beyond the heliosphere [1], the new precise data from AMS-02 [2] and

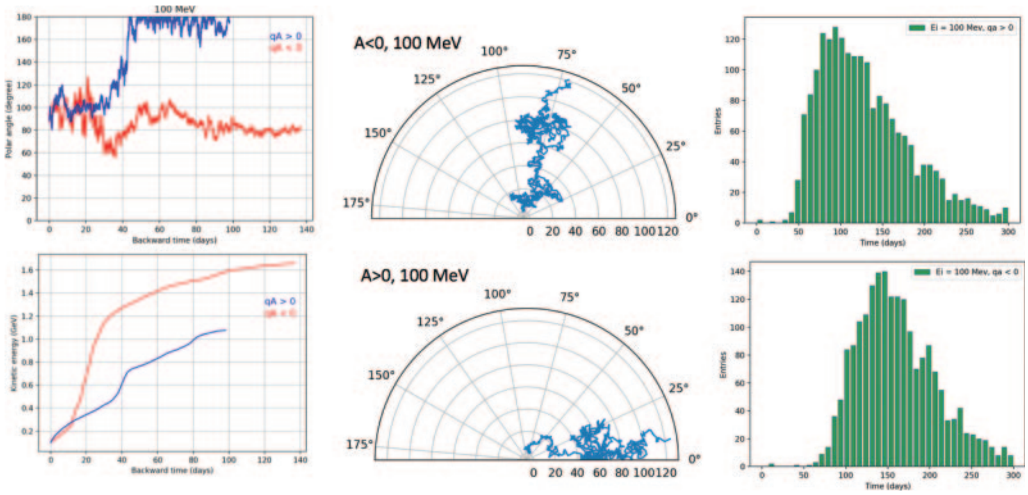

Fig. 1. – Left panel: GCR polar angle and kinetic energy evolution for different polarities in upper and lower panels, respectively. Middle panel: proton trajectories in polar plane in different polarities. Right panel: propagation time of protons inside the heliosphere.

PAMELA [3] experiments offer a unique possibility to study the time-dependent solar modulation over a significant fraction of the solar cycle.

2. – Methodology

The propagation of GCRs in the heliosphere is described by the Parker-Krymsky equation [4]

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln R}. \tag{1}$$

The equation describes the time evolution of the GCR phase space density $f(t, R)$, where $\mathbf{K}$ is the spatial diffusion tensor of GCRs, $\mathbf{V}$ is the solar wind speed, $\langle \mathbf{v}_D \rangle$ is the mean drift speed and $R = p/Z$ is the GCR particle rigidity. In the right side the diffusion, convection, drift and adiabatic energy loss terms are shown, respectively. The numerical model is also described in [5].

3. – Results

In fig. 1, we illustrate the typical trajectories of 100 MeV GCR protons in the heliosphere, simulated under epochs of negative (upper panels) and positive (lower panels) magnetic polarities. The model parameters for the two configurations are obtained by fitting the AMS-02 proton data [2] before (negative) and after (positive) the 2013 magnetic reversal. We found that, during epochs of positive polarity, the energy losses of GCRs are smaller and their propagation times are shorter, on average, in comparison with the case of negative polarity. Further investigations are being carried on, in particular, for different GCR energies and over different phases of the solar cycle.

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