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Galactic cosmic ray modulation in the heliosphere based on muon telescopes and ion chambers data. Analysis of interplanetary magnetic field deviations.

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We study the galactic cosmic ray modulation in the heliosphere based on muon telescopes and ion chambers data. We analyze the modulation parameters of galactic cosmic ray transport in the heliosphere retrieved from GCR anisotropy for solar cycles 18-23 and parts of 17 and 24, covering the period 1937-2018. We find that the ratio α of mean free paths normal and parallel to mean interplanetary magnetic field B is polarity dependent at Earth orbit with higher values for periods around solar minima for positive polarity (A>0) than for negative (A<0). Timeline of ratio α for more than 7 decades, exhibits a slight ~11-year and dominant ~22-year variation and has a strongly polarity-dependent character with the considerable enhancement in the minimum epoch of solar activity for A>0 magnetic polarity. Results are confronted with current modulation theories. We examine the timeline of variance of the interplanetary magnetic field magnitude and components and their contribution in the solar cycle and solar magnetic polarity dependence of cosmic ray modulation.

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1. Introduction

The transport of galactic cosmic ray (GCR) particles in the heliosphere is controlled by the expanding solar wind and frozen-in interplanetary magnetic field (IMF). The global modulation of GCR in the heliosphere is governed by four most important processes: convection, diffusion, particle drifts (due to gradient and curvature of the IMF, and on the heliospheric current sheet (HCS)), and adiabatic cooling. Despite the recent significant progress in our understanding of the GCR modulation by the solar wind, e.g. [1], up to now still there remain some difficulties and insufficient knowledge of the spatial, rigidity and especially the temporal dependence of the diffusion coefficients. However, for selecting an appropriate set of modulation parameters used in theoretical modelling (especially diffusion coefficients, etc.), one criterion remains the most important (if it is possible), that is to estimate them from the experimental data. We analyze long-period variations of the radial and azimuthal components of the GCR anisotropy for the period of 1937-2018 recorded by muon telescopes (MT) and ion chambers (IC) data. Observations of GCR anisotropy by MT and IC can be successfully used to derive various characteristic parameters of GCR modulation by the solar wind. The main purpose of this paper is to estimate the temporal variation of the parameter α, denoting the ratio of mean free paths normal and parallel to the mean IMF B, and the standard deviation of the IMF components over solar cycles.

2. Experimental Data

GCR solar diurnal anisotropy observed at Earth is a consequence of an equilibrium state between inward diffusion of GCR and outward radial convection by the solar wind. The convection-diffusion mechanism of GCR diurnal variation were proposed by [2-4].

Here we present the timeline of α using yearly solar diurnal variations recorded by Forbush [5] shielded IC at Cheltenham for 1937-1977, MT data at Nagoya for 1971-2017, for details please see in [6-7] and vertical MT Hobart (Australia) for 2007-2018, location 43.0S, 147.3E, 65 m, median primary rigidity of response Rm=54.6 GV, [8].

Additionally we analyse the daily data of the IMF magnitude and components in GSE, standard deviations delta B and the ratio B/deltaB.

3. Data analysis

Ahluwalia and Dorman [9] derived the following relations for Ar, $A\varphi$ assuming flat HCS:

$$(Ar^p + Ar^n)/2 = 3/v\ (CV - KrrGr) \qquad (1),$$

$$(A\varphi^p + A\varphi^n) = (1-\alpha)\ \lambda_{\parallel} Grsin2\psi \qquad (2),$$

$$Krr = K_{\parallel} cos^2\psi + K_{\perp} sin^2\psi$$

$$\lambda_{\parallel} Gr = -Ar + \frac{3CV}{v} + A\varphi Tan\psi$$

the superscripts p/n apply to positive and negative B polarities, Gr is GCR radial density gradient directed away from the Sun, Krr is radial diffusion coefficient, $\lambda_{\parallel}$ is the free path parallel to B, V is solar wind velocity, v (~ c) is GCR velocity, ψ is IMF spiral angle, its yearly value fluctuates around 45°, $C \approx 1.5$ is Compton-Getting coefficient.

Yearly α values are obtained as follows from (2):

$$\alpha = 1 - (A\varphi^p + A\varphi^n)/(\lambda_{\parallel} Grsin2\psi) \qquad (3)$$

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4. Results

We analyzed the modulation parameters of galactic cosmic ray transport in the heliosphere retrieved from GCR anisotropy for solar cycles 18-23 and parts of 17 and 24, covering the period 1937-2018. Fig. 1 presents the timeline of parameter α for IC Cheltenham for 1937-1977, MT Nagoya for 1971-2017, details please see in [6-7] and MT Hobart for 2007-2018 [8].

We found that the ratio α of mean free paths normal and parallel to mean IMF B is polarity dependent at Earth orbit with higher values for periods around solar minima for positive polarity (A>0) than for negative (A<0). Timeline of modulation parameter α for more than 7 decades, exhibits a slight ~11-year and dominant ~22-year variation and has a strongly polarity dependent character with the considerable enhancement in the minimum epoch of solar activity for A>0 IMF magnetic polarity.

Here we did not include contributions from drift-related symmetric (normal to HCS) gradient ($G_{\theta s}$). Simone et al. [10] state its value measured for low energy protons by Ulysses and PAMELA is smaller than expected from theories but signs are correct; supporting earlier Simpson et al. [11] inference that latitude gradients measured by Ulysses are small. Minnie et al. [12] argue that particle drifts may be suppressed by turbulence in background B. Engelbrecht et al. [13] further discuss reduction of drift coefficients in the presence of turbulence.

Figure 2 presents the time variations of the standard deviations delta B of daily interplanetary magnetic field components for 1995-2022, following the solar cycle dependence.

Figure 3 displays ratios B/deltaBx, B/deltaBy and B/deltaBz of daily interplanetary magnetic field components for 1995-2022. Values of B/deltaBz are much higher in comparison to Bx and By components and exhibit solar cycle pattern. The timeline of the ratio B/deltaBy exhibits some tendency of ~22-year variation with some enhancement in the minimum epoch of solar activity for A>0 IMF magnetic polarity.

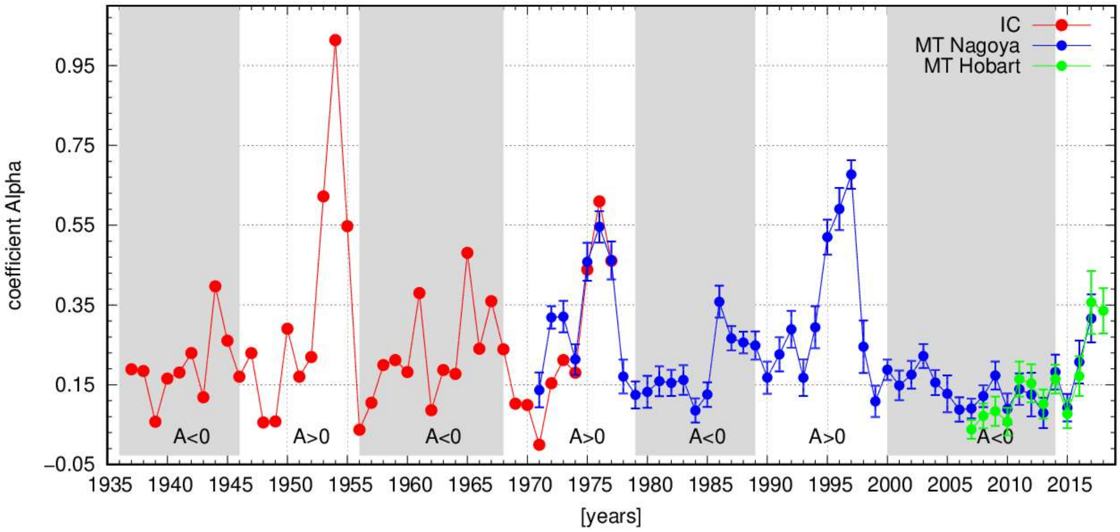

Figure 1: Yearly α for IC Cheltenham, MT Nagoya and MT Hobart data for 1937-2018, for solar cycles 18–23 and parts of 17 and 24.

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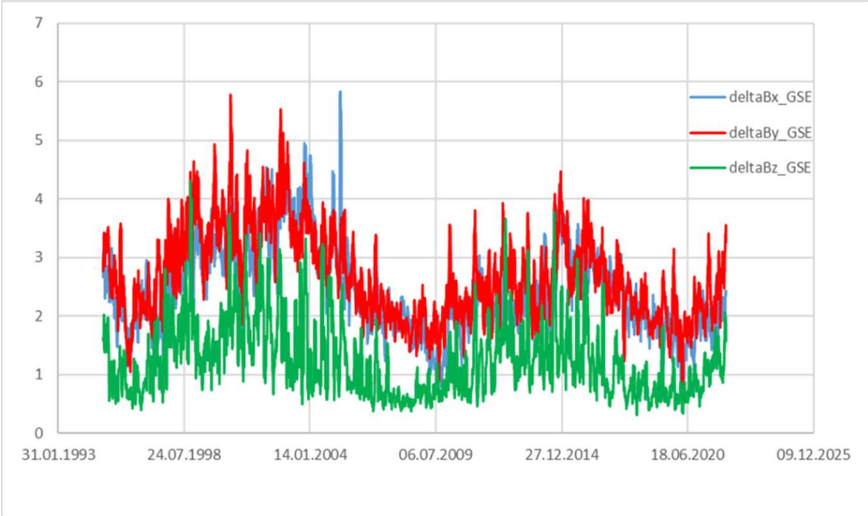

Figure 2: Standard deviation delta B of daily interplanetary magnetic field components for 1995-2022

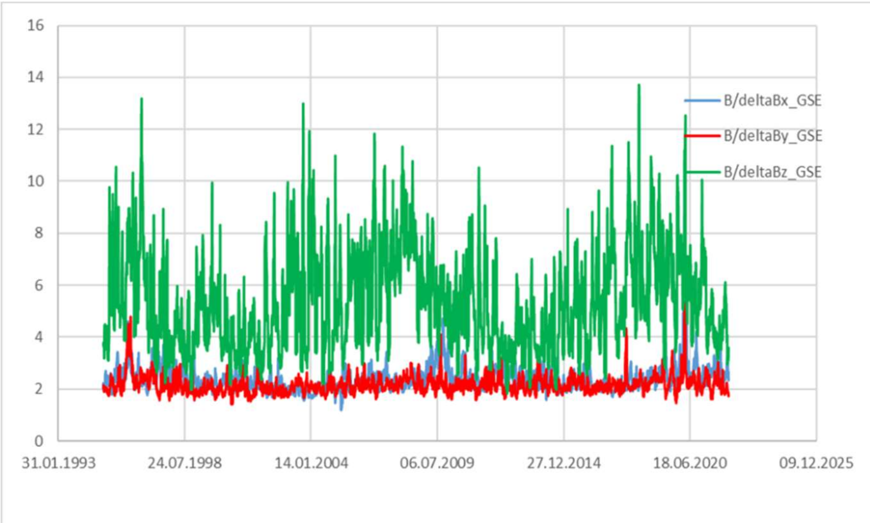

Figure 3: Ratio B/deltaB of daily interplanetary magnetic field components for 1995-2022

An alternative interpretation (see Kota et al. [14] and references therein) explain the difference between the GCR anisotripies in A<0 and A>0 solar minima as a result of drift effects. Drift effects increase with increasing rigidity, the Larmour radius of a 50 GV cosmic-ray ion in a 5 nT field is around 0.20 AU that well above the coherenece length of the random magnetic fluctuations (which are in the range of ~0.01 AU). These authors considered particle trajetories in the global IMF with random fluctuations superimposed and found that these trajectories inthersect the flattish HCS during A<0 solar minima multiple times, but barely interacted with the HCS during A>0 minima when positively charged ions drifted from high latitudes toward the equatorial regions. This difference could explain the disparity of anisotropies between even and odd solar minima.

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