

Cosmic Ray Modulation studied with HelMod Monte Carlo tool and comparison with Ulysses Fast Scan Data during consecutive Solar Minima

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Abstract: The Cosmic Rays propagation was studied in details using the HelMod - 2-D Monte Carlo code, that includes a general description of the diffusion tensor, and polar magnetic-field. The Numerical Approach used in this work is based on a set of Stochastic Differential Equations fully equivalent to the well know Parker Equation for the transport of Cosmic Rays. In our approach the Diffusion tensor in the frame of the magnetic field turbulence does not depends explicitly by Solar Latitude but varies with time using a diffusion parameter obtained by Neutron Monitors. The parameters of the Model were tuned using data during the solar Cycle 23 and Ulysses latitudinal Fast Scan in 1995. The actual parametrization is able to well reproduce the observed latitudinal gradient of protons and the southward shift of the minimum of latitudinal intensity. The description of the model is also available online at website www.helmod.org. The model was then applied on Pamela/Ulysses proton intensity from 2006 up to 2009. The model during this 4-year continuous period agree well with both PAMELA (at 1 AU) and Ulysses data (at various solar distance and solar latitude). The agreement improves when considering the ratio between this data. Studies done also with particles with different charge (e.g. electrons) allow us to explain the presence (or not) of protons and electrons latitudinal gradients observed by Ulysses during the Latitudinal Fast Scan in 1995 and 2007.

Keywords: heliosphere, cosmic ray, solar modulation.

1 Introduction

Galactic Cosmic rays (GCR) entering into the heliosphere experience a diffusive process before reaching the inner regions (e.g. Earth orbit). This diffusion is mainly due to small scale irregularities of the interplanetary magnetic field (IMF), generated from the Sun, that permeates and defines the Heliosphere itself. During their propagation, GCR are also convected by the expanding solar wind, they experience a magnetic drift due to the large scale structure of IMF, and finally they undergo an adiabatic energy loss. The global effect is the cosmic rays flux reduction for energy below 10~20 GeV, the so-called *solar modulation*, depending on the solar activity, particle charge and interplanetary magnetic field (IMF) polarity. Ulysses spacecraft extend the GCR observations outside the ecliptic (i.e. the plane where the Earth orbit lies) up to $\pm 80^\circ$ (see e.g. [1, 2]). In this work we present the results obtained by the HelMod Monte Carlo code (presented in section 2) along the Ulysses orbit during the period 2006 to 2009 and compare the results at Earth location. The obtained results were then used to explore the computed latitudinal gradient during this period and we compared our results with those one obtained during the previous Solar Minimum.

2 Model Description

The GCR diffusion process into the heliosphere medium with adiabatic energy loss, and the outward convection of solar particles, were studied in details by Parker in 1965 [3]. He proposed a transport equation that describes the time

evolution of particle distribution into the space (e.g. see ref. [4]):

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x_i} \left(K_{ij}^S \frac{\partial U}{\partial x_j} \right) - \frac{\partial}{\partial x_i} [(V_{sw,i} + v_{d,i})U] + \frac{1}{3} \frac{\partial V_{sw,i}}{\partial x_i} \frac{\partial}{\partial T} (\alpha_{rel} TU) \quad (1)$$

where U is the number density of Galactic Particles per unit of particle kinetic energy T , at the time t . $V_{sw,i}$ is the solar wind velocity along the axis x_i [5], K_{ij}^S is the symmetric part of diffusion tensor [3], v_d is the drift velocity that takes into account the drift of the particles due to the large scale structure of the magnetic field [6, 7, 8] and finally $\alpha_{rel} = \frac{T+2m_r c^2}{T+m_r c^2}$. The last term of eq. (1) is the adiabatic energy loss [3, 9].

This equation can be solved numerically using the HelMod Code (see www.helmod.org [10]). HelMod Code is based on a Monte Carlo technique to integrate Parker's equation, in a bi-dimensional (radius and co-latitude) approximation, from the boundary of an effective heliosphere (in the present model located at 100 AU) down to the Earth position.

The magnetic drift is included into the model as a convective term expressed through the drift velocity. This is split in regular drift (radial drift v_{D_r} and latitudinal drift v_{D_θ}) and neutral sheet drift ($v_{D_{NS}}$), as described in Ref. [7], and is scaled using the tilt angle [11] (α_t) of the neutral sheet as described in Ref. [12].

In a coordinate system with one axis parallel to the average magnetic field and the other two perpendicular to this the symmetric part of the diffusion tensor K_{ij}^S is (see e.g. Refs. [13, 14]):

$$K_{ij}^S = \begin{bmatrix} K_{\parallel} & 0 & 0 \\ 0 & K_{\perp,r} & 0 \\ 0 & 0 & K_{\perp,\vartheta} \end{bmatrix} \quad (2)$$

with K_{\parallel} the diffusion coefficient describing the diffusion parallel to the average magnetic field; $K_{\perp,r}$ and $K_{\perp,\vartheta}$ are the diffusion coefficient describing the diffusion perpendicular to the average magnetic field in the radial and polar directions respectively. For this work K_{\parallel} is the one proposed by Strass et al. [15] that follows from previous study on data taken at the Earth orbit [16, 17, 18]:

$$K_{\parallel} = \frac{\beta}{3} K_0 \frac{P}{1GV} \left(1 + \frac{r}{1 \text{ AU}} \right); \quad (3)$$

where K_0 is the diffusion parameter, described in Section 2.1 of [19], that depends on solar activity and IMF polarity (as described in Ref. [14]), β is the particle speed in unit of light speed, $P = pc/|Z|e$ is the particle rigidity expressed in GV and r is the heliocentric distance from the Sun in unit of Astronomical Unit (AU). As remarked in Ref. [14], in this description K_{\parallel} has no latitudinal dependence and a radial dependence $\propto r$, nevertheless the frame transformation between the field aligned to spherical heliocentric frame (see e.g. Ref. [20]) introduces a polar angle dependence. In Ref. [14] we shown how this is sufficient to explain the latitudinal gradient observed by Ulysses during the latitudinal *fast scan* in 1995 (see e.g. [1, 2]).

A complete description of the model and the used parameters can be found in Refs. [19, 14]. Further information and results can be found in the dedicated website (www.helmod.org). Through the website is also possible to obtain the computed proton spectra at Earth orbit every month since 1990.

3 Modulation outside the ecliptic plane

Several high precision experiments (e.g. BESS [21], AMS-01 [22] and PAMELA [23]) allow us to know in details the modulated proton spectra at Earth orbit for different condition of Solar activity. Outside the ecliptic plane only the Ulysses spacecraft gave us information on the heliocentric latitudinal distribution of GCR up to $\pm 80^\circ$ of solar latitude at a solar distance from ~ 1 up to ~ 5 AU. Proton observation carried out by Ulysses spacecraft during his first *fast scan*, from September 1994 up to August 1995 corresponding to an IMF with $A > 0$, show (a) a nearly symmetric latitudinal gradient with the minimum near ecliptic plane, (b) a southward shift of the minimum and (c) the intensity in the north polar region at 80° exceeds the south polar intensity [1, 2]. In Refs. [19, 14] we had shown how the HelMod code, using the parametrization treated in the previous section, was able to reproduce both the time variation during the last solar cycle 23 as well the latitudinal distribution of galactic Proton.

The observations performed during the third Ulysses *fast scan*, from May to December 2007 corresponding to an IMF with $A < 0$, found an almost zero latitudinal gradient in Proton intensity (see, e.g. Ref. [24, 25]). In Refs. [24] it was estimated that the latitudinal gradient of 2.5 GV protons (~ 1.7 GeV) is consistent with zero, while

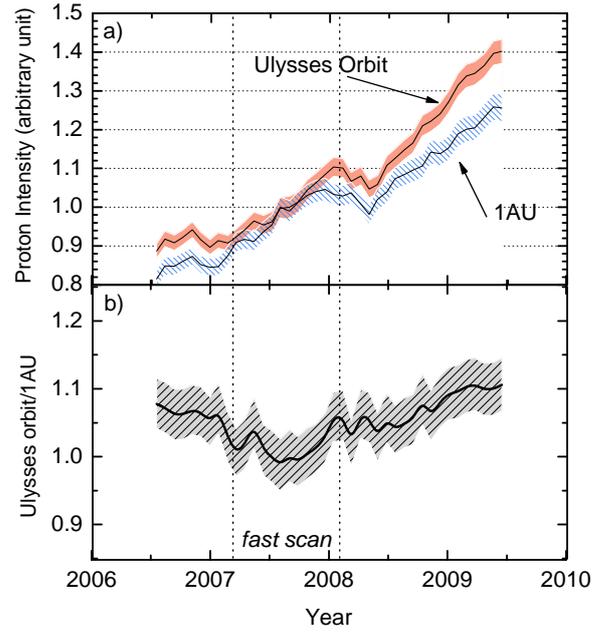


Figure 1: Panel (a): Comparison of HelMod proton intensities at rigidity ~ 1.7 GV along Ulysses orbit (red) with that at Earth orbit (blue); the proton intensities are normalized to the value corresponding to the closest approach of Ulysses spacecraft to Earth orbit. Panel (b): Proton intensity along Ulysses orbit divided with those at Earth as computed by HelMod. For both plot the shadow represents the statistical and systematic.

Ref. [25] finds that for 1.6–1.8 GV Protons (~ 1 GeV) the latitudinal gradient during the same period is $(-0.024 \pm 0.005)\%/degree$. The same study on electron leads to the opposite conclusion: Ref. [26] concludes that, during the $A > 0$ *fast scan*, electron intensity do not show any evidence of latitudinal dependence, at least up to 2.5 GV.

In Fig. 1a we show the ~ 1.7 GV Proton intensities computed with HelMod Code along the Ulysses orbit (red) and at Earth Orbit (blue) in function of time during the 3rd Ulysses *fast scan*. The data are normalized to the intensity measured when the spacecraft passed through the ecliptic plane, i.e. at a closer distance to the Earth. The HelMod solution was evaluated in the rigidity range 1.67–1.98 GV with a frequency of one simulation every 27 day, i.e. a Carrington Rotation. The blue and red shadow represents the uncertainties of our model, accounting both statistical and systematic errors as widely explained in Refs. [19, 14].

Results are compared with those presented by Ref. [25] using KET/Ulysses and PAMELA (located at the Earth orbit) proton intensity experimental measurements. It is evident from Fig. 1a how the GCR intensity increases with time so far that the solar activity decreases. Simulations outside the ecliptic plane are then normalized for the actual solar activity using the intensity at Earth orbit (see Fig. 1b). In this way we get the spatial variation of GCR intensity in the heliosphere with radius and latitude. This technique follow from the one used by Refs. [1, 24, 25] to study the spatial variation of GCR intensity, and allows us to direct compare with experimental results. These authors normalized the Ulysses computed GCR rate with those obtained by near-

Earth satellites (like e.g. IMP-8 or PAMELA) and obtained spatial profile of GCR intensity. The ratio in Fig. 2b are normalized to be ~ 1 at the time of closest approach. Although in this analysis we do not correct our results for the KET efficiency response as done by Ref. [25], our results are in good agreement with the observed intensities. This allows us to extend the analysis outside ecliptic plane, as presented in Ref. [14] for $A > 0$ period, also to a period with opposite IMF polarity.

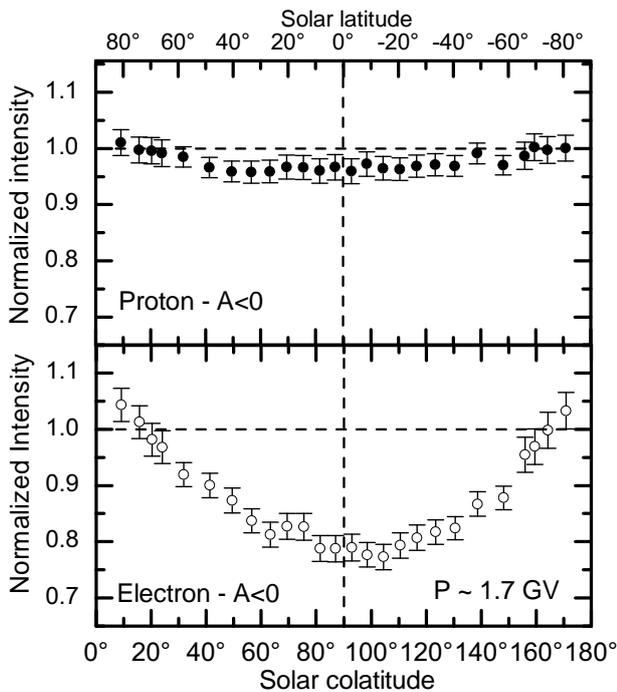


Figure 2: Latitudinal relative intensity along the Ulysses orbit, obtained at different solar co-latitude for proton and electron with particle rigidity 1.7 GV. Intensity are divided by the solution at Earth orbit at the same time, then normalized to the average values at south pole. Solutions with $A < 0$ IMF are evaluated during the Ulysses *fast scan* in 2007.

In Fig. 2 we computed the GCR intensities along the Ulysses orbit. These are then divided by the intensities computed at the same time at Earth orbit and subsequently normalized to average intensity at solar South pole. The GCR intensity was computed for both protons and electrons during the third Ulysses *fast scan* (i.e. $A < 0$ solar minimum period). From this figure we can conclude, for the studied period, that

- the model does not predict a Proton GCR latitudinal gradient,
- conversely, a gradient is found reversing the charge of the simulated particle for the same rigidity.

The presented results are in a good agreement with conclusion from Ref. [24] for the same rigidity interval. This behavior is a clear consequence of particle charge interaction with the IMF polarity. The model not including the drift effects shows a small presence of latitudinal gradient of GCR intensity, but it is not enough to reproduce Ulysses

observation in 1995. The introduction of drift effects create two opposite picture, depending on the product of particle charge (q) and IMF polarity (A): with $qA > 0$ the GCR intensity varies strongly with the latitude. On the contrary, with $qA < 0$ there is a more uniform distribution of GCR intensity. This enforces the idea that the condition $qA > 0$ enhances the entrance of GCR into the inner heliosphere passing through the poles, while the condition $qA < 0$ IMF enhances the GCR arriving from ecliptic region. This conclusion agrees with similar analysis [27, 26, 15].

4 Conclusions

In this work we present the HelMod Monte Carlo Code for the study of Solar modulation. We extend the application of the Code, that is able to reproduce the complete solar cycle 23, outside the the ecliptic region. The qualitative agreements of computed intensities with those observed by Ulysses spacecraft confirm the statement in literature that the drift mechanism has a great influence into the GCR propagation in the inner heliosphere. The model shows that, in presence of drift mechanism and for rigidities of the order of a few GV, the condition $qA > 0$ prefers the GCR penetration into the inner heliosphere from high latitude, i.e. along the polar regions. On the other side with the condition $qA < 0$ a more uniform GCR distribution with latitude is obtained.

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