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A Study of Galactic Cosmic Ray Modulation Using Numerically Determined Transport Parameters

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Numerical simulations of test particle trajectories in a model Heliospheric Magnetic Field (HMF) allow calculations of local transport coefficients. The HMF model is based on spacecraft data at different heliospheric locations. The numerically estimated transport coefficients are used as input parameters on a numerical solution of the GCR transport equation for the case when qA>0. The solutions obtained with this set of parameters reproduce well the observed cosmic ray radial profiles up to at least 20AU on the ecliptic plane.

1. Introduction

In any attempt to solve the GCR transport equation it is necessary to have an appropriate knowledge of the parameters of **K,** the diffusion tensor, that contains elements describing diffusion along the field and perpendicular to it as well as the effects of drifts caused by the gradient ,curvature and the neutral sheet of the HMF. The form and magnitude of the drift effects are reasonably understood [1], however there are still efforts to try to understand parallel and perpendicular diffusion as these are closely related to the solar wind turbulence whose comprehension represents a major task [see, e.g. 2,3].

Here we take an alternative approach that does not make any special assumption nor relies in any theory regarding the form or structure of the turbulence. To solve the GCR transport equation we use parallel and perpendicular diffusion coefficients obtained with a numerical model to follow test particle trajectories. The model makes use of high time resolution spacecraft HMF measurements at different locations in the ecliptic plane of the heliosphere ranging from 1 to 20AU [see 4, and references therein]. In principle, all the local fluctuations are automatically incorporated in these simulations and their effects will be sensed as the test particles propagate in the so called *layer model* of the HMF.

2. Model and Parameters

Steenkamp [5] developed a solution of the GCR transport equation:

$$\frac{\partial f}{\partial t} + \mathbf{V}\cdot\nabla f - \nabla(\mathbf{K}\cdot\nabla f) - (1/3)(\nabla\cdot\mathbf{V})\,\partial f/\partial \ln p = Q \qquad (1)$$

where p is particle momentum **V** is the solar wind velocity and **K** is the diffusion tensor containing all the terms already mentioned. This solution has been applied to several aspects of the cosmic ray intensities, with the aim to reproduce the observations of different spacecrafts from the inner to the outer heliosphere [see, e.g., 6, 7].

As indicated by Ulyses observations we have used a solar wind velocity of 400km/s in the ecliptic regions, increasing between latitudes 10° and 30° to 800 km/s and constant in higher latitudes [8]. The heliospheric boundary was set at 90 AU. We have solved equation (1) only for proton species and for the case qA>0, at the heliosphere boundary we impose the proton spectrum of [9], it is shown in Figure 2. The HMF used is a modified Parker spiral field as given by [7].

Based on the test particle simulation diffusion coefficients obtained with the layer model from 1 to 20 AU we set:

$K_{rr}= [4.67\, \beta\, P\, (GV)\, f(r)\, g(\theta)]\;\; 6x10^{20} cm^2/s$

Where β is particle speed in terms of the speed of light,

$f(r)=r$ for $r<30\ AU$ and 1 for $r>30AU$; $g(\theta)=1+3\cos(\theta)$

$K_{rr}= K_{\theta\theta}$ throughout. The resulting mean free paths $\lambda= 3K/v$ are given in terms of the parallel and perpendicular coefficients by $\lambda_{rr} = \lambda_{\|} \cos^2 \psi + \lambda_{\perp} \sin^2 \psi$, and $\lambda_{\theta\theta} = \lambda_{\perp}$. The most notorious facts are the growth of λ_{rr} with radial distance and the "inverse" dependence of λ_{rr} as compared with $\lambda_{\theta\theta}$ as determined by the test particle numerical experiments. These functional forms have not been tried in the past with the present solution of equation (1).

Gradient and curvature drifts are described in the standard manner by the asymmetric coefficient $K_T =\beta P/(3\mathbf{B})$ of the diffusion tensor. The drift velocity is $\mathbf{v}_d =(\beta P/3)\nabla x \mathbf{B}/B^2$. The wavy neutral sheet has a tilt angle of 10° The solution is started with the initial condition that the LIS pervades the entire heliosphere and it is stepped forward in time until it reaches steady state.

3. Results and Discussion

The solid triangles and squares in Figure 1 represent the observations, the solid line shows the proton intensity spectra as obtained from the solution of equation (1) at the Earth´s orbit, using the set of parameters presented in Section 2 of this paper; the dashed line corresponds to the LIS as given by [9]. Proton spectrum observations correspond to the balloon-borne BESS experiment on july 1997 [10], and to the IMP8 spacecraft observations from 20 April 1997 to 23 March 1998, a period around the minimum of cycle 22, when qA>0. The BESS data serve as a good reference since they have higher accuracy and cover a wide energy range providing excellent information about the rigidity dependence of the modulation. The solution fits well the observations from 10^2 to 10^4 MeV, showing that the set of transport parameters used in the solution is capable to reproduce features of the modulation process and thus validating the layer model of the HMF used in the test particle numerical experiments as a realistic representation of the turbulence found by GCR as they propagate into the Heliosphere.

In Figure 2 we present the cosmic ray radial intensity profiles obtained from the solution of equation (1) for protons with an average kinetic energy of 175 MeV, in the range of energies used for the test particle simulations. The curves correspond to intensities at the ecliptic plane, at θ = 60° (latitude 30°), at θ = 30° (latitude 60°) and at the pole. The intensities are normalized at the boundary, set at 90 AU. Squares correspond to observations by various spacecrafts: IMP8 at 1AU, Voyager 2 at 1.8 AU, Voyager 1 at 2 AU, Pioneer 11 at 7 AU, 15°N, and Pioneer 10 at 12 AU in 1977 (qA>0). The outermost two data points are from Voyager 2 at 56 AU, 24°S and Voyager 1 at 72 AU, 34° N, in 1997. Combining data from 1977 and 1997 is justified by observations [12].

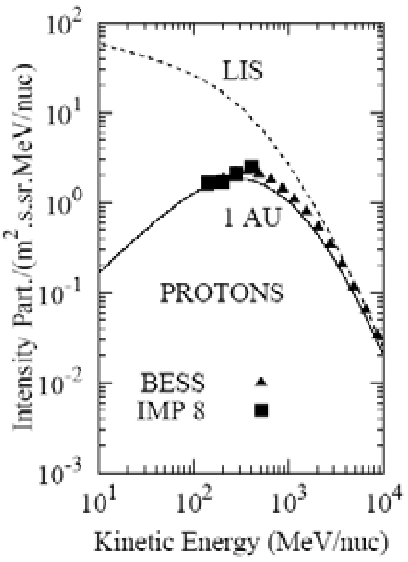

Figure 1. The proton spectrum obtained at 1AU compared with data from IMP 8 and BESS, and the Local Interstellar medium of [9] used here as a boundary condition.

The radial profile produced by the solution in the ecliptic plane fits well all the observations from 1 AU to 20 AU, the range of heliodistances covered by the test particle simulations. Voyager 1 and 2 points at 54 and 71 AU are close to the ecliptic radial profile. However, these spacecraft were 34°N and 24°S of the ecliptic plane in 1997, when these data were taken. They should therefore match with the dashed curve corresponding to polar angle 60° and not with the ecliptic plane curve. This is an indication that the latitudinal gradients produced by this solution are much higher than expected. Additionally the intensity curves predicted by the present solution in the outermost portion of the heliosphere are perhaps too steep to be considered plausible.

Nonetheless, bearing in mind that the test particle simulations were done with data of spacecraft on the ecliptic plane, with no assumptions as to the latitudinal or radial structure of the turbulence, therefore with a very localized validity, it is encouraging that these parameters can reproduce observations just in the range of heliospheric locations where the simulations were done. This is a further proof that the layer model of the HMF is able to represent adequately the local turbulence found by charged energetic particles and can be used to calculate parameters that represent the transport conditions to which GCR are subject.

The layer model of the HMF was also able to reproduce proper mean free paths in the case of several Solar Proton Events [4].

Our results are valid only when qA>0 and particles drift from the ecliptic to outer latitudes. In the case qA<0 we have not yet been able to obtain solutions that reproduce observations.

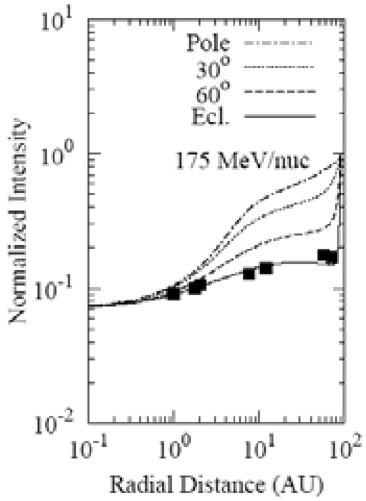

Figure 2. Radial profiles of the solutions obtained from this work. Squares up to 12 AU correspond to spacecraft measurements in the ecliptic plane. The outermost two points are data at 30° latitude (see text).

4. Summary and Conclusions

In this work we obtained solutions of the GCR transport equation based on transport parameters calculated with numerical simulations of test particles into the layer model of the HMF that makes use of high time resolution spacecraft data.

Solutions for 175 MeV protons at solar minimum conditions reproduce well the observed spectrum at 1AU and also the cosmic ray radial profiles in the ecliptic plane out to about 20 AU. The latitudinal and radial gradients in the outermost heliosphere obtained are too high to be considered plausible. In these regions assumptions were made as to the transport conditions, since there are no numerically determined transport parameters outside the ecliptic or further than 20 AU from the Sun.

The layer model of the HMF can adequately represent transport conditions in localized places of the heliosphere.

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