Galactic Cosmic Ray Modulation in the Heliosphere at Solar Maximum

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Abstract: The spatial distribution of galactic cosmic rays in the heliosphere at solar maximum of Cicles 21, 22 and 23 are studied, using a one dimensional model of the cosmic ray transport equation. We investigated the radial intensity gradients from 1 AU to the distant heliosphere and interpreted the data from IMP8, Voyagers 1 and 2, Pioneer 10 and balloon experiment BESS. In our model we considered three of the physical processes that affect the cosmic radiation: diffusion, convection and adiabatic energy loss. Our analysis indicates that adiabatic energy loss plays an important role in the radial distribution of galactic cosmic ray in the inner heliosphere, while in the outer region the diffusion and convection are the relevant processes.

Introduction

Over the last 30 years some space missions have been exploring the heliosphere. Most of then closed to the ecliptic plane. Pioneers 10 and 11, Voyager 1 and 2 were launched to investigate the outer region of the heliosphere. They have set, together with IMP missions at 1 AU, the unique network for observing spatial and temporal cosmic ray variations. Voyagers are moving toward the nose of the heliosphere, Voyager 1 is at the heliolititude of 34°N and Voyager 2 is at 24°S.

Many studies have been done using the cosmic ray data from those missions. Some of then have analyzed the relation between cosmic ray variations and solar activity cycle. In the present work we study the galactic cosmic ray gradient during the last three solar maximum periods. We cover a broad range of heliospheric distances, from 1 AU to 80 AU. In the previous work [6] was described the radial profiles in term of a simple model that took into account diffusion and convection. Those authors found a transition region between 10 and 20 AU where a sharp change in the gradient takes place. They argue that the changes in the interplanetary medium producing the modulation from solar minimum to solar maximum occurs in the outer region, related to the formation of the global merged interaction regions. In this work we use a more realistic model that includes the adiabatic anergy loss, and compare our results with those obtained in [6].

Data analysis

In this study we have used the data from the IMP 8 Goddard Medium Energy Detector (R.E. McGuire, P.I.), Pioneer 10 Cosmic Ray Telescope (F.B. McDonald, P.I.), the Voyager Cosmic Ray Subsystem (E.C. Stone, P.I.) and the high-altitude balloon experiment BESS (data from [7]). The time interval for our analysis is the last three solar maximum periods in 1981 (cycle 21) , 1990 (cycle 22) and 2001 (cycle 23). The observations covered the radial distances from 1 AU to 80 AU. For the radial gradients we analyze the galactic cosmic ray (GCR) H in the energy range of 130–220 MeV and GCR He of 150–380 MeV/n.

In [5] and [6] the authors concluded that latitudinal intensity gradients are small between the ecliptic plane and the position of the two Voyager spacecraft. For this reason we will not take into account the latitudinal gradients, and will concentrate in the radial intensity gradients during solar maximum epochs.

The aim of the present study is to compute the gra-

dients using a more realistic model that includes the adiabatic energy loss. This model is a one dimensional model, discribed in [1].

Model

The gradients are studied with the numerical solution of the cosmic ray transport equation ([8]). For the omnidirectional part of the cosmic ray distribution function, $f(\vec{r}, p, t)$, in one dimensional approximation, $f(r, p)$, this equation takes the form,

$$V\frac{\partial f}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\kappa\frac{\partial f}{\partial r})$$
$$-\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 V)\frac{\partial f}{\partial \ln p} = 0, \quad (1)$$

where V is the solar wind velocity, p is the particle momentum, and κ is the diffusion coefficient. The radial solar wind velocity is 400 km/s at solar maximum ([4]). At $r = r_b$ we impose the local instellar spectra (LIS) for H and He given in [9]. This boundary is a parameter that we change in order to fit the observations. Diffusion coefficient κ in one dimensional case is a function of r as follow:

$$\kappa(r) = \begin{cases} \kappa_0 r^a, & r \leq r_t \\ \kappa_0\left(\frac{r}{r_t}\right)^b r_t^a, & r > r_t \end{cases} \quad (2)$$

where r_t (the position of the transition region), κ_o, a and b are the other parameters that we change to obtained a good fit to the observations. The mesuared cosmic ray intensity, j_T, with respect to kinetic energy per nucleon, T, is related to the omnidirectional distribution function f through $j_T = p^2 f$. Take into account this relationship, we calculate the radial intensity gradient between two points (at r_1 and r_2) inside the modulation region, by:

$$g_r = \frac{\ln(j_{T1}/J_{T2})}{r_2 - r_1}. \quad (3)$$

Results and discussion

Using our numerical model we made a parameter variation. Following [2], first we used a constant value of the diffusion coefficient κ. In figure 1 we present the energy spectra for H (panel A) and for He (panel B) for the last solar maximum. Although, it is difficult to fit all the observations with a one dimensional model, we obtained a resonable fitting with a boundary at 120 AU and $\kappa = 2.4 \times 10^{22}\beta P(\text{GV})$ cm^2/s. This means that in principle one can reproduce the observed intensities without any transition region where the modulation conditions change. In this figure we observe that the spectra reach the adiabatic limit at low energies ($j_T \propto T$), and that is only possible with a model that considers the energy loss.

The next steep is to introduce a transition region. In order to compare our results with the results in [6], we used $b = 1$ in (2). We took $a = 0$ because we want the see if we can explain the observations with the simplest diffusion coefficient. In this case the best fit is obtained with $r_t = 40$ AU, the boundary at $r_b = 150$ AU and $\kappa_0 = 1.8 \times 10^{22}\beta P(\text{GV})$ cm^2/s. This value of r_b for the heliopause is more realistic (see [3]). In figure 2A and 2B we show the radial intensity profiles observed by those missions over tha last three solar maxima. In the inner heliosphere (< 20 AU) the gradient for H is smaller than in the outer region. Dash lines in figure 2A and 2A are from [6]. Those authors assumed that $j \propto r^{\beta}$, and from this calculated the radial gradient ($g_r = (1/j)\partial j/\partial r$). In that analysis ([6]), they considered a transition region from 10 to 20 AU, that separates the inner from the outer intensity gradients. In the inner heliosphere they obtained a similar gradient from H and He, ($10/r$ %/AU), while in the outer heliosphere the intensity gradient for H is $139/r$ %/AU and $73/r$ %/AU for He.

In our study, from the numerical solution of (1), we found different radial gradients, in particularly in the inner heliosphere. In this region we obtained an average radial gradient of ≈ 3 %/AU for H and ≈ 2.2 %/AU for He (shown in figure 2C and 2D). Our model naturally reproduces the small gradient due to the fact that it includes the adiabatic energy loss, that are more significant in the inner part of the heliosphere ([1]).

In the outer region the modulation is essentially driven by diffusion and convection, and in this case our results for the radial gradients are of the same order of those in [6]. However, some differences are clear. Belong 40 AU the gradients calculated from our model do not follow the $1/r$ dependence,
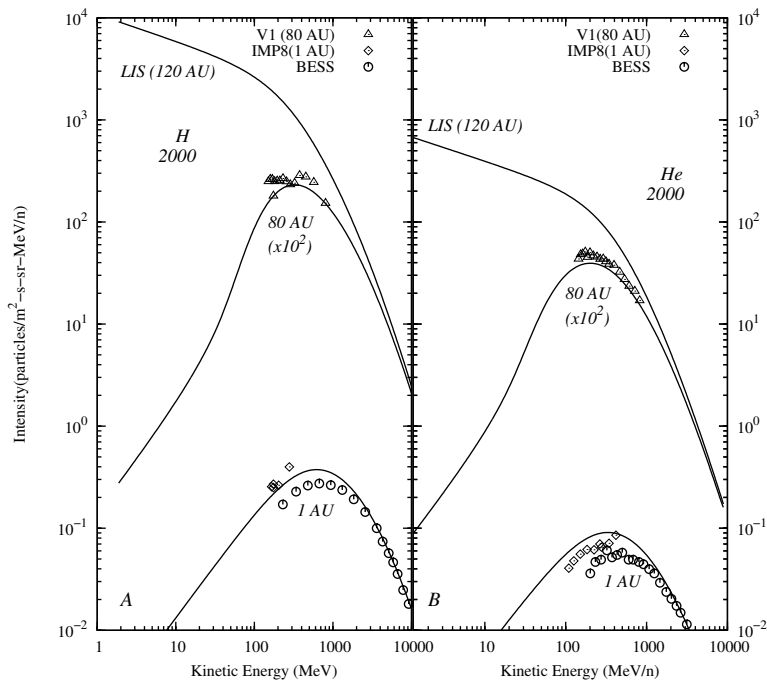
Figure 1: Intensity spectra for H (panel A) and He (panel B) for 2000. The lines are the results from a one dimensional model described in the text.

even when $\kappa \propto r$. The reason for that yields also in the adiabatic term that modifies the form of the gradient derived from the force field model ($g_r = CV/\kappa$), used in [6].

Conclusions

We analyzed the galactic cosmic ray modulation at solar maximum using a one dimensional model that includes diffusion, convection and adiabatic energy loss. With this model we can conclude:

1. The observed radial profiles can be explained wiht a constant value of the diffusion coeffcient, however, we get the best fit with a transition region at about 40 AU and the heliopause at 150 AU.

2. In the inner heliosphere, < 40 AU, the adiabatic energy loss is more important, and the radial intensity gradients are determined by this physical process.

3. In the outer heliosphere the radial intensity gradient can be explained mainly by diffuion and convection terms.

Acknowledgements

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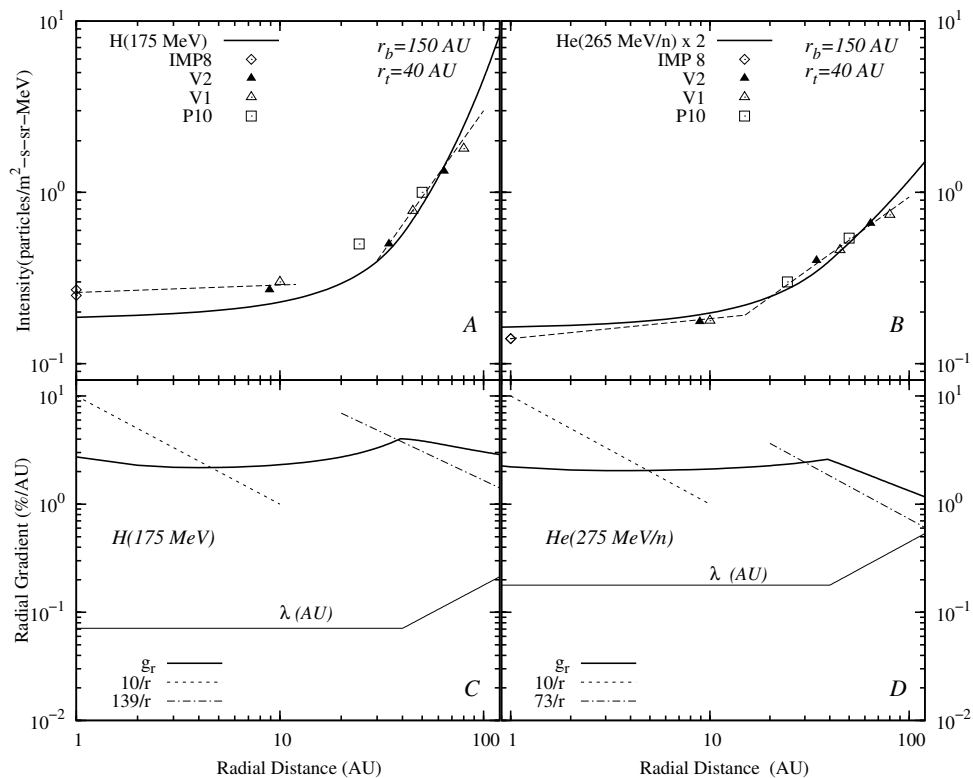
Figure 2: Radial intensity profiles (panel A for H and panel B for He) and radial gradient (panel C for H and panel D for He). Full lines are from a one dimensional model with a transition region at 40 AU and heliopause at 150 AU. Dash and dot lines are from [6].

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