Intensity Gradient of Galactic Cosmic Ray in the Heliosphere at Solar Maximum

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***Abstract*. The spatial distribution of galactic cosmic ray in the heliosphere at solar maximum of Cicles 21, 22 and 23 are studied, using a two dimensional model of the cosmic ray transport equation. We investigated the radial and latitudinal intensity gradients from 1 AU to the distant heliosphere and diferents heliografic latitudes, and interpreted the data from IMP 8, Voyager 1 and 2, Pioneer 10, Ulysses and balloon experiment BESS. In our model we considered four of the physical processes that affect the cosmic radiation: diffusion, convection, adiabatic energy loss and drifts. 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. The latitudinal gradients are small.**

***Keywords*: galactic cosmic rays, gradients, heliosphere.**

I. INTRODUCTION

Over the last 30 years some space missions have been exploring the heliosphere. Most of then closed to the ecliptic plane. Pioneer 10 and 11, Voyager 1 and 2 were launched to investigate the outer region of the heliosphere. They have set, together with IMP mission at 1 AU, the unique network for observing spatial and temporal cosmic ray variations. Voyager 1 and Voyager 2 crossed the termination shock and entered the heliosheath on 16 December 2004 and 30 August 2007, respectively. Voyager 1 is at heliolatitude of $\sim 34°$N and Voyager 2 is at $\sim 27°$S.

Many studies heve 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. [1] 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 our previous study ([2]) we used a one dimensional model and obtained a different radial gradient in the inner heliosphere, where the addiabatic energy loss are more important. In this work we use a more realistic model that also includes latitudinal diffusion and drifts. We compare our results with those obtained in [1] and [2].

Althought our model do not include the effects of the solar wind termination shock, according to [3], to first order, gradients are not changed by the presence of the termination shock, because they are proportional to $\frac{CV}{\kappa}$ (C is the Compton–Getting factor, V is the solar wind velocity and κ is the radial difussion coefficient), and both V and κ jump with the same factor across the shock.

In [1] and [4] the authors concluded that latitudinal intensity gradients are small between the ecliptic plane and the position of the two Voyager spacecrafts. In this work we calculate the latitudinal gradients and confirm that they are small in the ecuatorial region of the heliosphere at solar maximum.

II. 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 [5]). 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. We analyze the gradient of galactic cosmic ray (GCR) H in the energy range of 130-220 MeV and GCR He of 150-380 MeV/n.

The gradients are studies with the numerical solution of the cosmic ray transport equation ([6]). For the omnidirectional part of the cosmic ray distribution function, $f(\vec{r}, p, t)$:

$$\frac{\partial f}{\partial t} + \mathbf{V} \cdot \nabla f - (\kappa \cdot \nabla f) - \left(\frac{1}{3}\right) (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} = Q \quad (1)$$

In two dimensional approximation, ($f(r, p, \theta)$, where r is the radial distance, θ is the polar angle and p is the particle momentum), if there are no particles sources

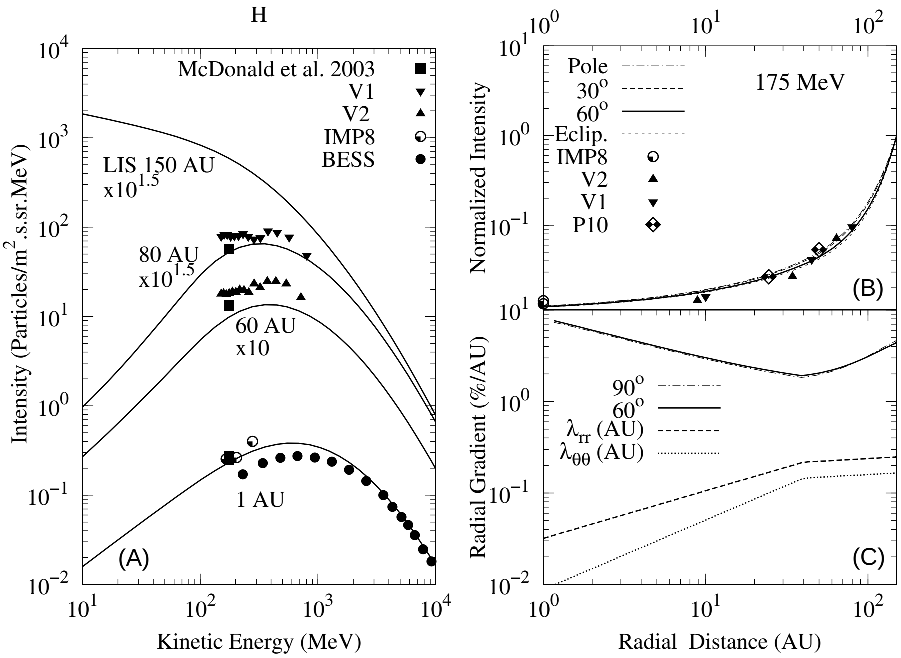

Fig. 1: Intensity spectrum (panel A), radial intensity profile (panel B) and gradient (panel C) for H. The lines are the results from a two dimensional model described in the text. Data in panel B are from [1].

inside the heliosphere, $Q = 0$, this equation takes the form,

$$-\kappa_{rr}\frac{\partial^2 f}{\partial r^2} - \frac{\kappa_{\theta\theta}}{r^2}\frac{\partial^2 f}{\partial \theta^2} + \left[-\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\kappa_{rr}) + V + v_{dr}\right]\frac{\partial f}{\partial r} + \left[-\frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}(\sin\theta\,\kappa_{\theta\theta}) + \frac{v_{d\theta}}{r}\right]\frac{\partial f}{\partial \theta} - \frac{2V}{3r}\frac{\partial f}{\partial \ln p} = 0 \quad (2)$$

In (2), κ_{rr} and $\kappa_{\theta\theta}$ are the radial and latitudinal diffusion coefficients, respectively. v_{dr} and $v_{d\theta}$ are the radial and latitudinal components of the particle drift velocity, respectively. The solar wind velocity V is 400 km/s at solar maximum ([7]). At $r = r_b$ we impose the local interstellar spectra (LIS) for H and He given in [8]. This boundary is a parameter that we change in order to fit the observations. κ_{rr} and $\kappa_{\theta\theta}$ have the general form:

$$\kappa_o f_1(r) f_2(\theta) \times \beta P, \quad (3)$$

where$P$ is the particle rigidity in GV. $f_1(r)$ and $f_2(\theta)$ are dimensionless functions of the form,

$$f_1(r) = \begin{cases} \left(\frac{r}{r_e}\right)^a, & r \le r_t \\ \left(\frac{r}{r_t}\right)^b \left(\frac{r_t}{r_e}\right)^a, & r > r_t \end{cases} \quad (4)$$

where r_t (the position of the transition region), $r_e = 1$ AU. And,

$$f_2(\theta) = 1 + c\cos(\theta). \quad (5)$$

κ_o (in cm^2/s), a, b and c 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:

$$g_r = \frac{\ln(J_{T_2}/J_{T_1})}{r_2 - r_1}. \quad (6)$$

Consequently, we compute the latitudinal gradient between two positions (at r, θ_1 and r, θ_2) with the following expression:

$$g_\theta = \frac{\ln(J_{T_2}/J_{T_1})}{\theta_2 - \theta_1}. \quad (7)$$

III. Results and discussion

Using our numerical model we made a parameter variation. The best fit to the observations is obtained with the following set of parameters: $r_t = 40$ AU, the boundary at $r_b = 150$ AU; 1) for κ_{rr}: $\kappa_o = 4.8 \times 10^{21}$cm^2/s, $a = 0.52$, $b = 0.1$, and $c = 0.25$, and 2) for $\kappa_{\theta\theta}$: $\kappa_o = 1.3 \times 10^{21}$cm^2/s, $a = 0.76$, $b = 0.1$, and $c = 0.7$. With these parameters κ_{rr} is 1.25 larger over the Pole than in the ecliptic plane and $\kappa_{\theta\theta}$ is 1.7 times larger. This value of r_b for the heliopause is more realistic (see [9]). In Figure 1 we present the energy spectrum (panel A), radial profile (panel B) and radial gradient (panel C) for H (in Figure 2 we show the results for He in the same format as in

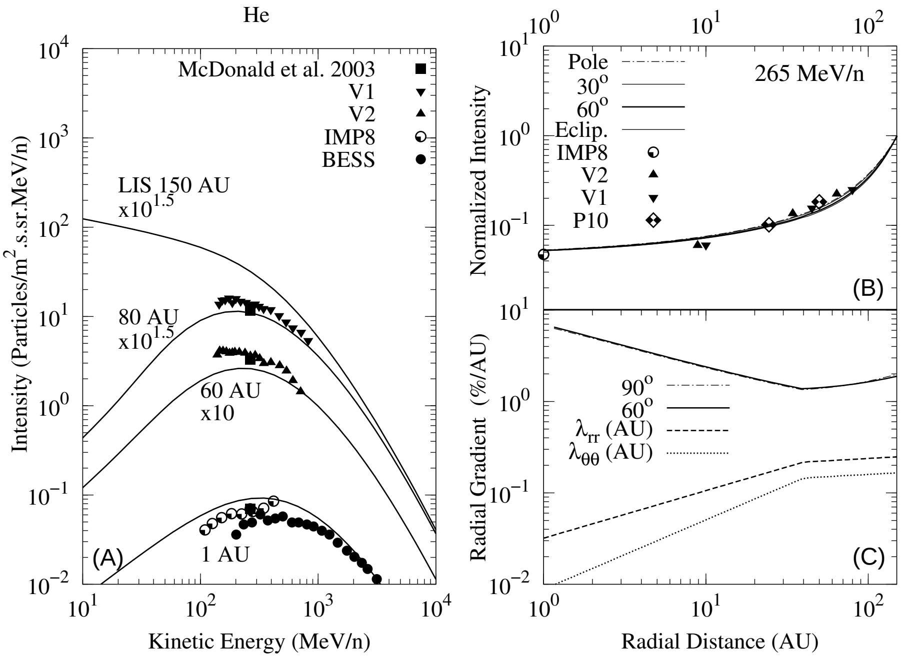

Fig. 2: Same as in Figure 1, but for He.

Figure 1).

[1] assumed that $j \propto r^{\beta}$, and from this they calculated the radial gradient ($g_r = (1/j)\partial j/\partial r$). In that analysis 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 radial intensity gradient for H is $139/r$ %/AU and $73/r$ %/AU for He. In our previous study ([2]), in the inner heliosphere we obtained an average radial gradient of $\approx$ 3 %/AU for H and $\approx$ 2.2 %/AU for He.

In the present work, from the numerical solution of equation (2) the radial gradients are: $7.9/r^{0.43}$ %/AU for H and $6.8/r^{0.46}$ %/AU for He in the inner heliosphere ($r <$ 40 AU), and $0.09r^{0.77}$ %/AU for H and $0.42r^{0.3}$ %/AU for He in the outer heliosphere ($r >$ 40 AU). They are shown in panel C of Figures 1 and 2. These gradients do not follow the relation $\frac{CV}{\kappa}$ because our model considers the addiabatic energy loss, that affects the force–field expression for gradient.

The fit to the observations in this work is much better than in [2] in both regions (see panel B of Figures 1 and 2), and that explains the differences in the radial gradient. From both panels B we see that from 80 AU to the heliopause at 150 AU still have a lot of modulation for 175 MeV H and 265 MeV/n He. Therefore, the radial gradient in this region should be larger than the predicted by [1]. However, there is the possibility that the LIS from [8] is too large at those energies and in this case the gradient will be smaller. This scenario has to be tested in the future with a model that include the solar widn termination shock.

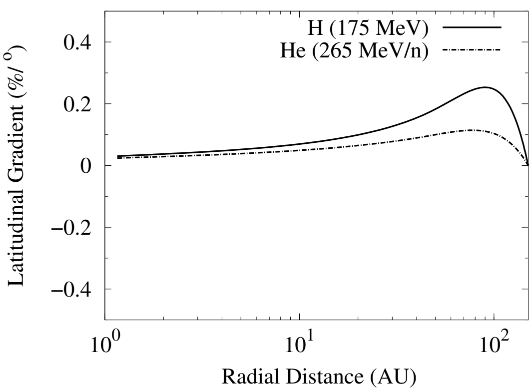

Fig. 3: Latitudinal gradient as a function of radial distance between ecliptic plane ($\theta = 90^o$) and Voyager location ($\theta = 60^o$).

An interesting result of this work is the small latitudinal gradient. As we can see from panel B of Figures 1 and 2, all radial profiles are of the same magnitude for all heliolatitudes. In Figure 3 we show the latitudinal gradient between ecliptic plane ($\theta = 90^o$) and the Voyager position ($\approx \theta = 60^o$). For 175 MeV H the latitudinal gradient is less than < 0.3 %/^{o} and for 265 MeV/n He is less than < 0.1 %/^{o}. These results confirm the obervations in the outer heliosphere made by Pioneer 10 and Voyagers ([4]).

IV. Conclusions

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

1) The observed radial profiles can be explained with a transition region at about 40 AU and the heliopause at 150 AU. In this case diffusion mean–free paths κ_{rr} and $\kappa_{\theta\theta}$ increase with radial distance and are larger over the polar region.
2) In the inner region, < 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 diffusion and convection terms. But we still have to investigate the effects of the LIS and the solar wind termination shock on the radial gradient in this region. It seems that the LIS values from [8] are too high in the MeV energy range.
4) Latitudinal gradients are small between ecliptic plane and 30^o above and below this plane. This confirms the very small (≈ 0) latitudinal gradient between Pioneer 10 and Voyager spacecrafts.

V. Acknowledgements

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