Radial intensity gradients of galactic cosmic rays in the heliosphere at solar maximum: 1D no-shock simulation

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Resumen

El presente trabajo estudia la distribución espacial de los rayos cósmicos galácticos en la heliosfera durante el máximo solar de los ciclos 21, 22 y 23, usando un modelo en una dimensión y sin choque de la ecuación de transporte de la radiación cósmica. Investigamos los gradientes radiales de intensidad desde 1 UA hasta la heliósfera distante e interpretamos las observaciones de los satélites IMP8, Viajeros 1 y 2, Pionero 10 y del experimento BESS. En nuestro modelo consideramos tres de los procesos físicos que afectan a la radiación cósmica: la difusión, la convección y la pérdida adiabática de energía. Nuestro análisis indica que la pérdida adiabática de energía juega un importante papel en la distribución radial de los rayos cósmicos en la heliosfera interna, mientras en la región exterior la difusión y la convección resultan ser los procesos dominantes.

Palabras clave: Modulación de los rayos cósmicos, ecuación de transporte, gradientes.

Abstract

We study the spatial distribution of galactic cosmic rays in the heliosphere at solar maximum of cycles 21, 22 and 23, using a one-dimensional no-shock model of the cosmic ray transport equation. We investigate the radial intensity gradients from 1 AU to the distant heliosphere and interpret the data from IMP8, Voyagers 1 and 2, Pioneer 10 and balloon experiment BESS. We consider three physical processes that affect cosmic radiation: diffusion, convection and adiabatic energy loss. Our analysis indicates that adiabatic energy may play an important role in the radial distribution of galactic cosmic rays in the inner heliosphere. In the outer region diffusion and convection are the dominant processes.

Key words: Cosmic ray modulation, transport equation, gradients.

Introduction

Over the last 30 years several space missions have been exploring the outer heliosphere, most of them close to the ecliptic plane. Pioneers 10 and 11, Voyagers 1 and 2 were launched to investigate the outer regions of the heliosphere. They have established, together with IMP missions at 1 AU, a unique network for observing spatial and temporal cosmic-ray variations. The Voyagers are moving toward the nose of the heliosphere; Voyager 1 is at a heliolatitude of 34ºN and Voyager 2 is at 24ºS.

Many studies have used the cosmic-ray data from those missions. Some of them have analyzed the relation between cosmic-ray variations and solar activity cycle. In the present work we study the galactic cosmic ray (GCR) gradient during the last three solar maximum periods. We cover a broad range of heliospheric distances, from 1 AU to 80 AU. In a previous study, McDonald *et al.* (2003) described the radial profiles in terms 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 argued that the changes in the interplanetary medium producing the modulation from solar minimum to solar maximum occurs in the outer region, and it is related to the formation of global merged interaction regions. In this work we use a more realistic model that includes adiabatic energy loss, and compare our results with those obtained by McDonald *et al.* (2003).

A one-dimensional no-shock model does not include latitudinal transport or drift and shock effects. However, at solar maximum, the solar wind speed is much nearer to a uniform 400 km/s at all latitudes and the interplanetary magnetic field is more irregular than at solar minimum (McComas *et al.*, 2003). Therefore the particle drift is very small, 3 to 10 times smaller than at solar minimum condition (see for instance Caballero-Lopez *et al.*, 2004b); and the latitudinal gradient should be also small, as observed between the ecliptic plane (by Pioneer 10) and 34ºN (by Voyager 1) (McDonald, 1998).

According to Caballero-Lopez *et al.* (2004a), to first order, gradients are not changed by the presence of the termination shock, because they are proportional to CV / k, and both V and k jump with the same factor across the shock. In Fig. 6 from Caballero-Lopez *et al.* (2004a) we can see that for the no-drift case, shock and no-shock solutions have a simillar radial intensity profiles. These reasons justify the use of a one-dimensional no-shock model as a good approximation for the galactic cosmic ray modulation at solar maximum considering the heliosphere as spherically symmetric.

Data and model

We use 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 Myers *et al.*, 2003). The time intervals for our analysis are the last three solar maximum periods in 1981 (cycle 21), 1990 (cycle 22) and 2001 (cycle 23). The observations cover the radial distances from 1 AU to 80 AU. For the radial gradients we analyze the GCR H in the energy range of 130-220 MeV (mean energy of 175 MeV) and GCR He of 150-380 MeV/n (mean energy of 265 MeV/n).

McDonald (1998) and McDonald *et al.* (2003) found that latitudinal intensity gradients are small between the ecliptic plane and the position of the two Voyager spacecraft. Therefore, in this first study (using a 1D model) we will not take into account the latitudinal gradients, but concentrate on the radial intensity gradients during solar maximum epochs.

The gradients are studied with the numerical solution of the cosmic ray transport equation, originally derived by Parker (1965). For the omnidirectional part of the cosmic-ray distribution function, $f(\vec{r}, p, t)$, in the one-dimensional approximation, $f(r, p)$, and for the steady-state case, this equation takes the form (see Caballero-Lopez and Moraal, 2004),

$$V\frac{\partial f}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 k\frac{\partial f}{\partial r}\right] - \frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 V)\frac{\partial f}{\partial \ln p} = 0, \qquad (1)$$

where V is the solar wind velocity, p is the particle momentum, and k is the diffusion coefficient. The radial solar wind velocity is 400 km/s at solar maximum (McComas *et al.*, 2003) and it is fairly independent of heliolatitude. At $r = r_b$ we impose the local instellar spectra (LIS) for H and He given in Webber and Lockwood (2001). This boundary (called the heliopause) is a parameter that we change in order to fit the observations. The diffusion coefficient k in the one-dimensional case is a function of r as follows:

$$k(r) = \begin{cases} k_0\left[\frac{r}{r_e}\right]^a, & r \le r_t \\ k_0\left[\frac{r}{r_t}\right]^b\left[\frac{r_t}{r_e}\right]^a, & r > r_t \end{cases} \qquad (2)$$

where r_t is the position of the transition region, $r_e = 1$ AU, k_0, a and b are the other parameters that we change to obtain a good fit to the observations. The measured cosmic-ray intensity, j_T, with respect to kinetic energy per nucleon, T, is related to the omnidirectional distribution function f through $j_T = p^2 f$. Taking into account this relationship, we calculate the radial intensity gradient between two points (at r_1 and r_2) inside the modulation region, by:

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

Parameter variation

Following Caballero-Lopez *et al.* (2004a), we first used a radially independent value of the diffusion coefficient k ($a = b = 0$ in equation 2). In Fig. 1 we present the energy spectra of GCR H (panel A) and GCR He (panel D) for the last solar maximum. In these two panels we observe that the spectra reach the adiabatic limit at low energies ($j_T \propto T$), and this can only be explain with a model that considers energy loss (last term of equation 1). The radial intensity profile for the last three solar maxima (from 1 to 80 AU) are shown in panel B (175 MeV H) and E (265 MeV/n He). Although, it is difficult to fit all the observations with a one-dimensional model, we obtained a resonable fit with a boundary at 120 AU and a radially independent value of the diffusion coefficient $k_0 = 2.4 \times 10^{22}\, \beta P$ (GV) cm^2/s. This means that in principle one can reproduce the observed intensities without any transition region where the modulation conditions change.

According to expression (3) we calculated the radial intensity gradients for this fit. We present them in panel C (175 MeV H) and F (265 MeV/n He). Also we added the diffusion mean free path, λ ($\equiv 3k / v$), and the gradients obtained by McDonald *et al.* (2003) in order to compare those calculations with our results. McDonald *et al.* (2003) assumed that $j_T \propto r^\beta$, and from this they calculated the radial gradient. 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 for GCR 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. As one can see from panels C and F, the gradients calculated from the numerical solution of the one-dimensional transport equation are of the same order of magnitude than those of McDonald *et al.* (2003), which obtained using an empirical model for the GCR modulation. However, the

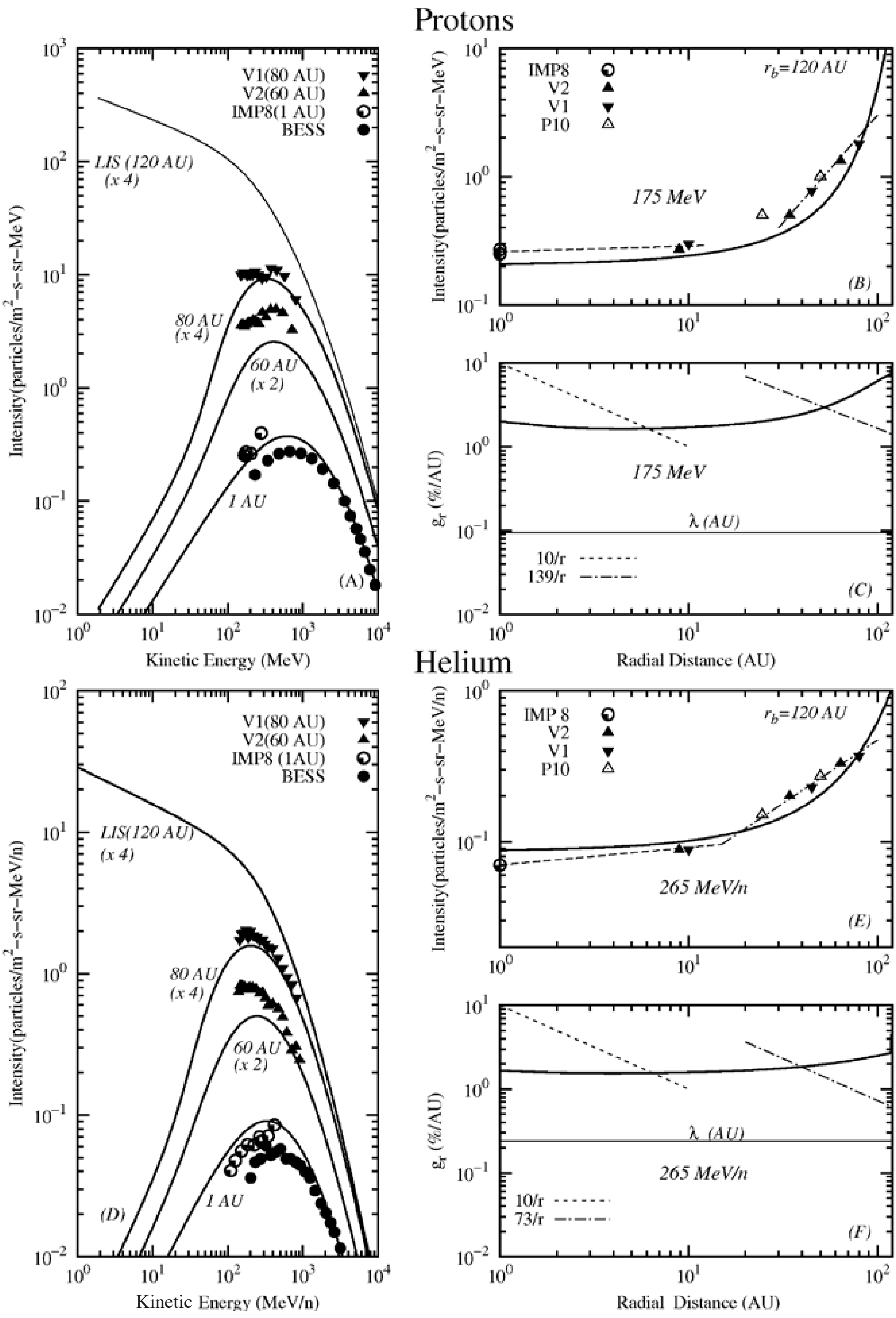

Fig. 1. 1D no-shock simulation of GCR modulation with a heliopause at 120 AU and radially independent diffusion coefficient (k = 2.4 x 10^{22} βP (GV) cm²/s in equation 2). Spectra for H (A) and He (D) in 2000, radial profile for 175 MeV H (B) and 265 MeV/n He (E) during the last three solar maxima, and radial gradient for H (C) and He (F). Intensities in panels A and D are multiplied by factors of 2 to enhance visibility. Solid lines show the results from our model, dash and dash-dot lines are from McDonald et al. (2003). The jump in the dashed and dash-dot lines in panels (C) and (E) is due to the parameterization used by McDonald *et al*.

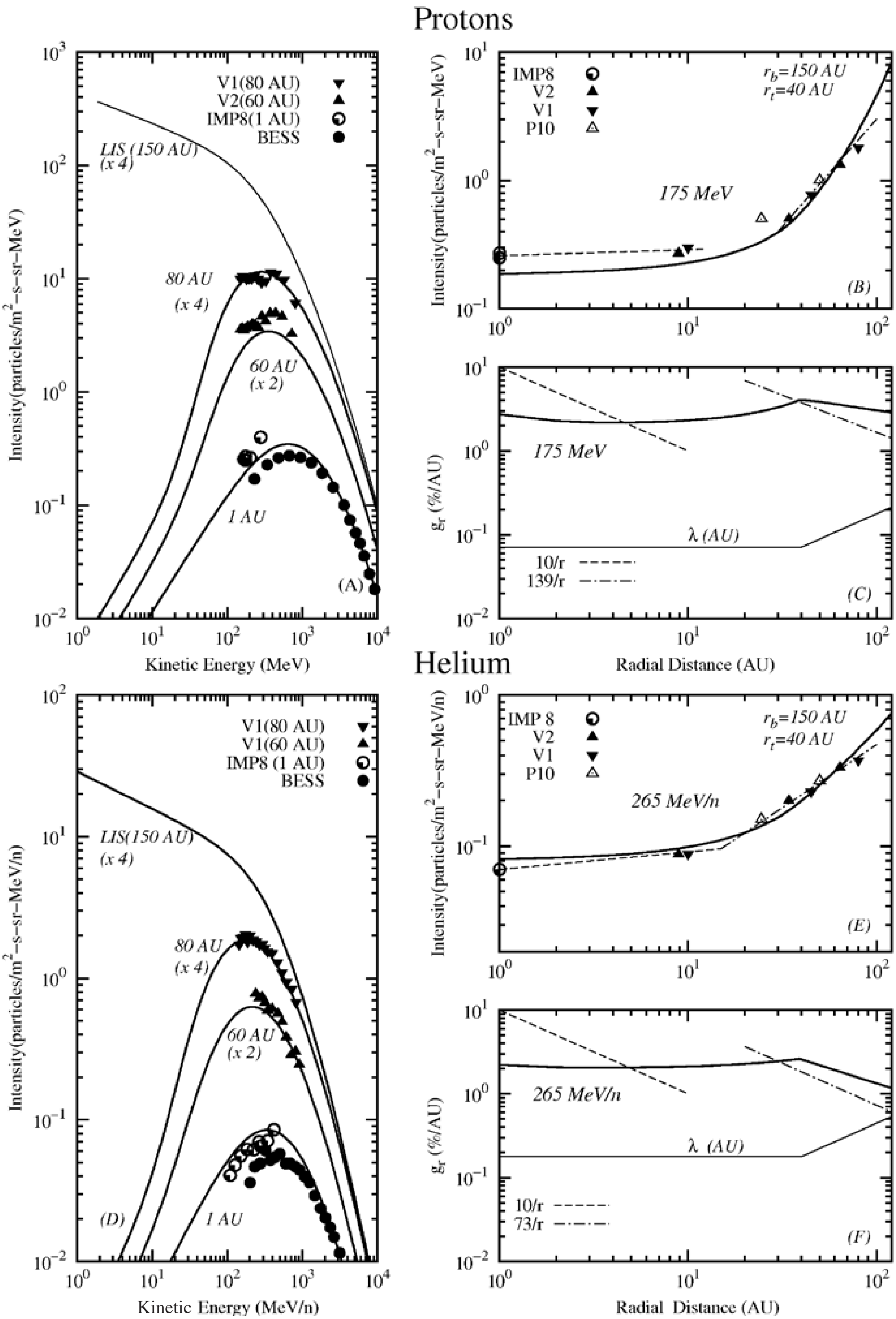

Fig. 2. Same as in Fig. 1, but $k_0 = 1.8 \times 10^{22}\ \beta P$ (GV) cm²/s, $r_t = 40$ AU, $a = 1$, $b = 0$ in expression (2) and $r_b = 150$ AU.

radial dependence is different. In our model we take into account the energy change and that produces smaller gradient in the inner heliosphere.

The next step is to introduce a transition region. We used $a = 0$ and $b = 1$ in equation (2) because we want see if we can explain the observations with the simplest diffusion coefficient. In McDonald *et al*. (2003), the authors pointed out that there must be some transition region (between 10 and 20 AU) where the modulation changes, producing different radial gradients. With our model we have tried to find where this region should be in order to explain the observations. In this respect we have modified the position of the transition region, varying r_t from 20 to 40 AU, and the boundary (r_b) from 120 to 180 AU. Although, we do not show all the results, we do present the most significant one in Fig. 2.

Discussion

The intensity gradients in Figs. 1C and 1E present a different radial dependence in the outer heliosphere than those in Fig. 2C and 2E. (That is not a surprise because we chose the same radial dependence of the diffusion coefficient in the inner region, and a different one beyond the position of the transition region). If one compares them with the gradients found by McDonald *et al*. (2003), one sees that the main difference appears in the inner heliosphere. This is due to the role of the adiabatic energy losses that are more important close to the Sun, once the particles have traveled through most of the modulation region.

The best fit to the observations probably obtained with $r_t = 40$ AU, the boundary at $r_b = 150$ AU, and $k_0 = 1.8 \times 10^{22}\ \beta P$ (GV) cm^2/s (Fig. 2). This value of r_b for the heliopause is more realistic than 120 AU (see Gurnett *et al*., 2003).

In our study, from the numerical solution of equation (1), we found different radial gradients than McDonald *et al*. (2003) in particular in the inner heliosphere. In this region we obtained an average radial gradient of ≈3%/AU for GCR H and ≈2.2%/AU for GCR He (shown in Figs. 2C and 2F). Our model naturally reproduces the smaller gradients in the inner heliosphere due to the fact that it includes the adiabatic energy loss, which is more significant in the inner part of the heliosphere (Caballero-Lopez and Moral, 2004).

In the outer region the modulation is essentialy driven by diffusion and convection, and in this case our results for the radial gradients are of the same order of magnitude as those in McDonald *et al*. (2003). However, some differences are clear. Beyond 40 AU the gradients calculated from our model do not follow the $1/r$ dependence, even when $k \propto r$. The reason for that lies in the adiabatic term that modifies the form of the gradient derived from the Force Field model ($g_r = CV/k$), used in McDonald *et al*. (2003).

Conclusions

We analyzed the galactic cosmic ray modulation at solar maximum conditions using a one-dimensional no-shock model that includes diffusion, convection and adiabatic energy loss. With this model we can conclude:

1.- The observed radial intensity profiles can be reasonably well explained with a radially independent diffusion coefficient, however, we get the best fit to the observations with a transition region at about 40 AU and the heliopause at 150 AU [$k = 1.8 \times 10^{22}\ \beta P$(GV) cm^2/s, for r<40 AU; and $k = 1.8 \times 10^{22}\ \beta P$(GV) ($r$/40) cm^2/s, for r>40 AU].

2.- In the inner heliosphere, r< 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.

This is a first step in our study of the galactic cosmic ray gradients at solar maximum. The next step will include a two-dimensional shock model.

Bibliography

Caballero–Lopez, R. A. and H. Moraal, 2004. Limitations of the force-field equation to describe cosmic ray modulation, *J. Geophys. Res., 109, A01101*, doi:10.1029/2003JA010098

Caballero–Lopez, R. A., H. Moraal and F. B. McDonald, 2004a. Galactic cosmic ray modulation: effects of the solar wind termination shock and the heliosheath, *J. Geophys. Res., 109, A05105*, doi:10.1029/2003JA010358

Caballero-Lopez, R. A., H. Moraal, K. G. McCracken and F. B. McDonald, 2004b. The heliospheric magnetic field from 850 to 2000 AD inferred from ^{10}Be records, *J. Geophys. Res., 109, A12, 12102*, doi:10.1029/2004JA010633

Gurnett, D. A., W. S. Kurth and E. C. Stone, 2003. The return of the heliospheric 2–3 KHz radio emission during solar cycle 23, *Geophys. Res. Lett., 30, 23*, doi:10.1029/2003GL018514

McComas, D. J., H. A. Elliott, N. A. Schwadron, *et al.*, 2003. The three-dimensional solar wind around solar maximum, *Geophys. Res. Lett., 30, 10*, 1517–1522

McDonald, F. B., 1998. Cosmic ray modulation in the heliosphere. A phenomenological study. *Space Sci. Rev., 83*, 33–50

McDonald, F. B., Z. Fujii, B. Heikkila and N. Lal, 2003. The radial distribution of cosmic rays in the heliosphere at solar maximum, *Adv. Space Res., 32, 4*, 633–638

Myers, Z. D., E. S. Seo, K. Abe, *et al.*, 2003. Cosmic ray ^{3}He and ^{4}He spectra from BESS 98, *Proc. 28 ICRC, 4*, 1805–1808

Parker, E. N., 1965, The passage of energetic particles through interplanetary space. *Planet. Space Sci., 13*, 9–13

Webber, W. R. and J. A. Lockwood, 2001. Voyager and Pioneer spacecraft measurements of cosmic ray intensities in the outer heliosphere: toward a new paradigm for understanding the global modulation process 1. Minimum solar modulation (1987 and 1997). *J. Geophys. Res., 106*, 29,323–29,331

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