Proceedings of ICRC 2001: 3674 © Copernicus Gesellschaft 2001

ICRC 2001

Radial diffusion coefficients in the outer heliosphere

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Abstract. When cosmic ray streaming in the heliosphere is negligible, the basic transport equation gives a simple approximation for the diffusion coefficient of cosmic ray particles, $K=CV_{SW}/g_r$, where C is the Compton-Getting factor, V_{SW} is the solar wind velocity and g_r is the radial intensity gradient. In a separate paper at this Conference, Fujii and McDonald have studied extensively the spatial dependence of intensity gradients during the solar activity minima of qA>0, using the combined data of 1977/1978 +1996/1997. It was shown that the measured radial intensity gradients near to the ecliptic plane are well described with a functional form of $dJ/Jdr=G_0r^a$, and the values of parameters G_0 and a were determined for galactic 145-255 MeV/n He, 130-225 MeV H and anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+. Using these values of g_r, we made first order estimates of the particle diffusion coefficients out to heliocentric distance of ~ 70 AU.

1 Introduction

The cosmic ray data from the deep space missions of Pioneer 10/11 and Voyager 1/2, and IMP 8 at 1 AU are now available for more than two solar cycles and beyond 65 AU. The Ulysses mission launched in 1991 extend these observations to high heliolatitudes in the inner heliosphere. These extensive data sets made it possible to study in more detail the transport of cosmic rays in the heliosphere.

Using data from these observations we have measured radial intensity gradients for galactic and anomalous cosmic rays near the ecliptic plane from 1974 to 1997 (Fujii & McDonald, 1997, 1999a; McDonald *et al.*, 1999). It was found that the observed gradients are well described to ~60 AU with a radial dependence of the form $g_r=G_0r^a$ (r is the heliocentric distance in AU). Using these obtained values of G_0 and a it is possible to estimate the gradients at a given location near to the ecliptic plane as a function of time.

With these gradients and a one-demensional modulation model we further calculated the diffusion coefficients and the distance to the modulation boundary as a guide for more complete models of the modulation process (Fujii and McDonald, 1999b, 2001). The distance was found to be 65 AU to 110 AU, varying inversely proportional to solar activity with the smallest value around solar maximum and the largest around solar minimum up to the end of the 1980s. However, in the 1990s errors of the estimated values were so large that the distances were not significant. In an accompanying paper at this Conference we studied the spatial dependence of gradients in more detail with the combined data 1977/1978 and 1996/1997 in the solar activity minima of qA>0, focusing on the spatial dependence of gradients in the outer heliosphere. In the present paper we make first order estimate of the diffusion coefficients from these gradients. These estimates are an update and extension of our previous papers (Fujii and McDonald, 1999b, 2001).

2 K_{rr} Determined from Radial Intensity Gradients

The radial flux or streaming, S_r, in a spherically symmetric system in the frame of the observer at rest with respect to the sun is given by (Gleeson and Axford, 1968):

$$S_r=CV_{SW}U-K_{rr}\frac{\partial U}{\partial r},$$
$$C=1-\frac{1}{3}\frac{\partial}{\partial T}(\alpha TU)=\frac{1}{3}(2-\alpha\gamma)\ (CG\text{-}factor), \qquad (1)$$
$$\alpha=\frac{T+2M_0c^2}{T+M_0c^2},\ V_{SW}=Solar\ Wind\ Velocity$$

$U=4\pi J/c\beta$ is the particle density, J and β are the particle flux and the velocity relative to the velocity of light c, γ is the spectra slope of dJ/dT, and T is kinetic energy/nuc. of the

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particle. When the particle streaming is negligible, i.e., $S_r \approx 0$ (expected for T>150 MeV),

$$\frac{1}{J}\frac{\partial J}{\partial r}=\frac{CV_{SW}}{K_{rr}} \quad or \quad K_{rr}(R,r,t)=\frac{CV_{SW}}{G_0 r^{\alpha}} \qquad (2)$$

Fisk and Axford (1969) have shown that this approximate relation is valid under conditions such that

$$\left|\frac{\tilde{C}}{2}(\tilde{C}-1)(\frac{\tilde{V}_{SW}\tilde{r}}{\tilde{K}_{rr}})\right|=\tilde{r}\left|\frac{\tilde{C}-1}{2}\right|\tilde{G}_r \ll 1 \qquad (3)$$

where the tilde denotes characteristic value of the various quantities.

In a separate paper at this Conference, Fujii and McDonald have studied extensively the spatial dependence of intensity gradients during the solar activity minima of qA>0, using the combined data of 1977/1978 +1996/1997. For the radial dependence of gradients a functional form of g_r(= dJ/Jdr)=$G_0 r^a$ was assumed, and the values of parameters G_0 and a were determined for galactic 145-255 MeV/n He, 130-225 MeV H and anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+. With these values of parameters it is possible to calculate the gradients near the ecliptic at the extended radial distance as shown in Fig.1. In the Figure the estimated radial intensity gradients are shown in comparison with those for 1987 during the solar activity minimum, and for 1981 and 1990 during solar activity maxima by Fujii and McDonald (1999a).

Using these gradients the radial diffusion coefficients are calculated by Eq.(2) for the galactic the galactic and

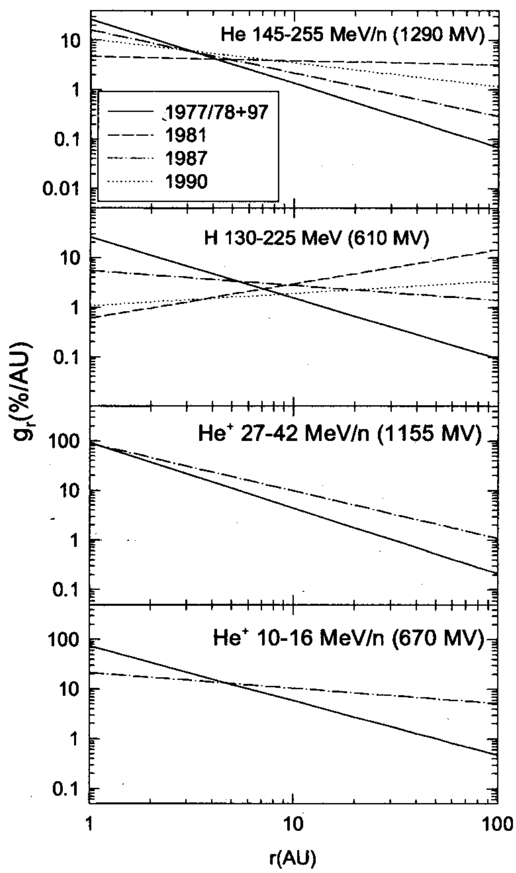

Fig.1 Radial gradients calculated with the obtained values of parameters G_0 and a as a function of radial distance r for galactic 145-255 MeV/n He, 130-225 MeV H and anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+. The estimated gradients are also shown for 1987 during the solar activity minimum, and for 1981 and 1990 during solar activity maxima by Fujii and McDonald (1999a).

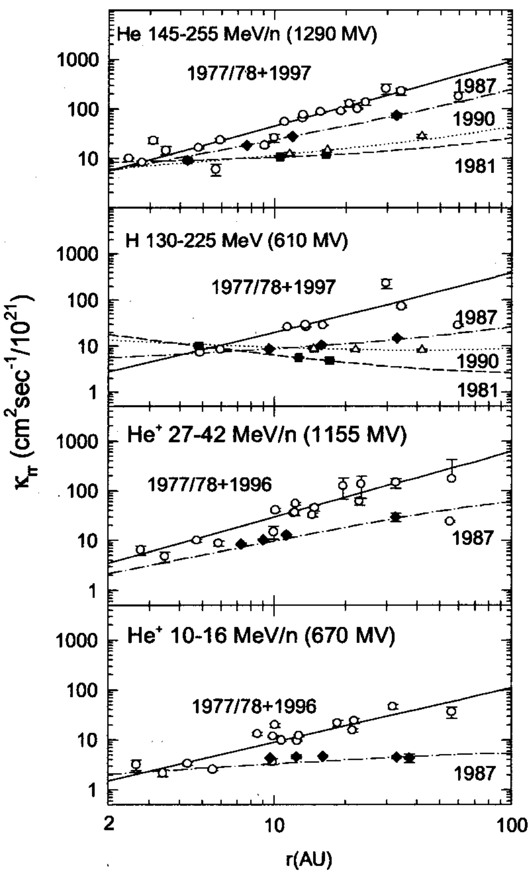

Fig.2 Diffusion coefficients K_{rr} calculated for galactic 200 MeV/n He and 175 MeV H, and for anomalous 35 MeV/n He^+ and 13 MeV/n He^+ in the 1977/1978 +1996/1997 solar activity minima, together with those for the 1987 solar minimum , the 1981 and 1990 solar maxima by Fujii and McDonald (1999b). In the Figure, K_{rr} calculated for the observed non-local gradients are plotted at the effective radial distance.

anomalous cosmic rays at the mid-point of energy interval, 200 MeV/n He, 175 MeV H, 35 MeV/n He^+ and 13 MeV/n He^+. The Compton-Getting factors are derived from the spectra fitted to the observed energy spectra, using the local interstellar He (Lukasiak, 2000), H spectra (Webber *et al.*, 1987) and anomalous He source spectra (Reinecke *et al.*, 1993), and a one-dimensional modulation model (Fujii and McDonald, 1995). We used the interstellar He spectrum newly proposed by Lukasiak (2000) which is about 10% lower than that used previously.

Fig.2 shows the diffusion coefficients K_{rr} thus obtained for galactic 200 MeV/n He and 175 MeV H, and for anomalous 35 MeV/n He^+ and 13 MeV/n He^+ in the 1977/1978 +1996/1997 solar activity minima, together with those for the 1987 solar minimum, and for the 1981 and 1990 solar maxima by Fujii and McDonald (1999b). In the Figure, K_{rr} calculated for the observed non-local gradients are plotted at the effective radial distance. The values of K_{rr} increase with increasing heliocentric distance except for galactic hydrogen during the solar activity maxima. For the galactic species in the outer heliosphere, values for K_{rr} are one to two orders of magnitude larger at the solar activity minima than at the solar activity maxima. Those for anomalous helium are about one order smaller than those for galactic helium in the outer heliosphere. It is noted here that K_{rr} for the 1977/78+1996/97 solar activity minima (qA>0) is a factor of 5 to 10 larger than those for the 1987 minimum (qA<0) in the outer heliosphere. The values of K_{rr} at distances less than several AU are not understood and may be physically unrealistic. It may be that the functional form we have chosen, $g_r = G_0 r^a$ may need to be modified for $r < 5$ AU. This is also the region where $K_{||}$ is dominant relative to $K_{\perp}$ for K_{rr}. These are the first systematic estimate of K_{rr} to heliocentric distance beyond ~70 AU, although the estimates are based on a basic one-dimensional modulation model and data which are confined mostly to the ecliptic.

3 Discussion

Fujii and McDonald (2001) have made first order estimates of the distance to the modulation boundary, using the diffusion coefficients calculated from the measured radial intensity gradients. However, in the 1990s the errors of estimated distance were so large that the distance was not significant. In the preceding section we calculated diffusion coefficients, using the gradients measured in detail over the extended radial distance. Using these diffusion coefficients we extended estimate of the distance to the modulation boundary, simulating the observed spectra by a one-dimensional cosmic ray transport equation.

The cosmic ray transport equation in the steady state (Gleeson and Axford, 1968; Fisk, 1971),

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 S_r) = -\frac{\partial}{\partial T}[V_{SW}\frac{\partial}{\partial r}(\frac{1}{3}\alpha TU)], \tag{4}$$

is solved numerically for galactic He, using the interstellar He spectrum (Lukasiak, 2000) and the estimated diffusion coefficients under assumption of $K_{rr}=\beta R K(r)$. The distances to the modulation boundary r_B are determined to fit the P-10 spectral intensities of seven energy interval at $T>100$ MeV/n where the anomalous He are negligible. The obtained distances for 1981, 1987, and 1990 are 63 AU (with $X^2=31$), 140 AU ($X^2=66$) and 115 AU ($X^2=9.1$) respectively. These obtained values are consistent with those derived under the Force Field approximation (Fujii and McDonald, 2001), although the determined r_B are not significant statistically with values of X^2 for degrees of freedom of 7 except that for 1990. Fig.3 shows the observed and simulated He spectra for 1981, 1987, and 1990 at P-10, and the observed He spectrum for 1996 at P-10. It should be noted here that no solution was found for the 1996 P-10 spectrum, as the values of K_{rr} determined from the observed gradients are too large to simulate the P-10 1996 He spectrum. The value of K_{rr} were calculated from the gradients determined with $g_r=G_0 r^a$ throughout the heliosphere, and validity of this functional form should be examined further in detail, although $g_r=G_0 r^a$ may describe well the observed gradients beyond ~60 AU. Reinecke *et al.* (2000) fitted in detail the He, H, He^+ and O^+ energy spectra with the combined data of 1977/1997 from the same experiment as used in the present study. They showed that the mean free path $\lambda_{rr}(=3K_{rr}/\beta c)$ should increase with r toward ~30 AU in the inner heliosphere and decrease in the outer heliosphere, to simulate the observed spectra at distances from 1 to 66 AU. These facts may reflect lower intensities and smaller gradients of cosmic rays in the outer heliosphere for the 1996/1997 solar minimum than those for the 1987 solar minimum, as shown by Webber and Lockwood (1997) and McDonald *et al.*(1998). Further study is in progress as a guide for more complete models of the modulation process.

In summary, in a separate paper at this Conference, Fujii and McDonald have studied extensively the spatial dependence of intensity gradients during the solar activity minima of qA>0, with the combined data of 1977/1978 +1996/1997. Using these gradients and a one-dimensional modulation model we calculated the diffusion coefficients. It was shown that the values of K_{rr} determined from the observed gradients is too large to simulate the P-10 1996 He spectrum. These diffusion coefficients for the 1977/1978 +1996/1997 solar activity minima (qA>0) as well as for the 1987 solar activity minimum (qA<0) are discussed in relation with the distance to the modulation boundary.

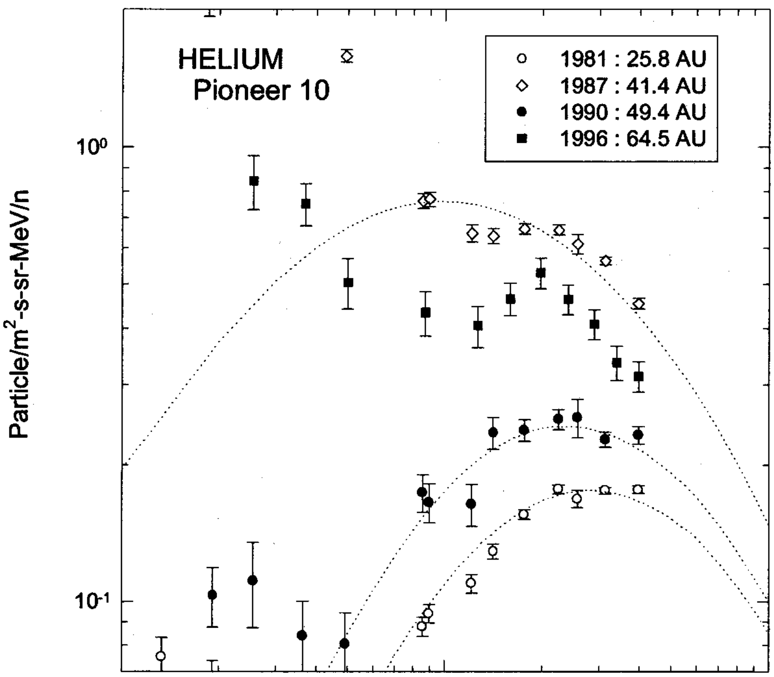

Fig.3 Observed and simulated He spectra for the 1981, 1987, and 1990 at P-10, and the observed He spectrum for 1996 at P-10.

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