SH.4.2.02

Radial Diffusion Coefficients of Galactic and Anomalous Cosmic Rays in the Heliosphere.

Z. Fujii[1,2], and Frank B. McDonald[2]

[1]*Solar-Terrestrial Environment Laboratory, Nagoya University, Chikusa-ku, Nagoya, 464-8601, Japan*

[2]*Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA*

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 gradients. In a separate paper at this conference, Fujii and McDonald (1999) have shown that the measured radial intensity gradients are well described with a functional form of $dJ/Jdr= G_0r^{\alpha}$, and have determined G_0 and α for selected galactic and anomalous cosmic rays. Using these values of g_r, we obtained first order estimates of the particle diffusion coefficient over period from 1974 to 1997 out to heliocentric distance of ~ 60 AU.

1 Introduction:

The cosmic ray data from the deep space missions of Pioneer 10/11 and Voyager 1/2, and IMPs 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.

In a series of papers we have measured radial intensity gradients near the ecliptic plane for galactic 180-450 MeV/n He, 130-220 MeV H, and anomalous 30-57 MeV/n and 10-20 MeV/n from 1974 to 1996 (Fujii & McDonald, 1997a, 1999). It was found that the observed gradients are well described to 50 AU, using a radial dependence of the form $g_r=G_0r^{\alpha}$ (r is the heliocentric distance in AU). With these values of G_0 and α it is possible to estimate the gradients at a given location near the ecliptic plane as a function of time. In the present paper we obtain a first order estimate of the diffusion coefficients from these gradients using a one-dimensional modulation model as a first order estimate from observations, and are intended as a guide for more complete models of the modulation process. These estimate are an update and extension of our previous paper (Fujii & McDonald, 1997b).

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):

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

$U=4\pi J/c\beta$ is the particle density, J and β are the particle flux and the velocity relative to the velocity of light c, γ is the spectras slope of dJ/dT, T is kinetic energy/nuc. of the particle and M_0 is particle rest mass. When the particle streaming is negligible, i.e., $S_r \approx 0$ (expected for T>150 MeV),

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

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

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

where the tilde denotes characteristic value of the various quantities.

The Compton-Getting factors, C, are derived from the spectra fitted to the measured H and He spectra (Fujii and McDonald, 1995) using the local interstellar H and He spectra (Webber et al., 1987a,b; Reinecke et al., 1993) and a one-dimensional modulation model. The annual averages of C as observed at the mid-point of the energy interval on P-10, V-2 and IMP 8 (Fig. 1) show a small increase with increasing heliocentric distance superposed on a larger solar cycle dependence.

The radial diffusion coefficient are calculated by Eq.(2), using the annual averages of g_r at the ecliptic (Fujii & McDonald, 1999), C and V_{SW} from P-10, V-2 and IMP 8 for galactic 315 MeV/n He and 175 MeV H, and for anomalous 45 MeV/n and 15 MeV/n He. The radial diffusion coefficient thus obtained are shown both as a function of time (Fig.2) and of the heliocentric distance (Fig.3 and 4). The values of K_{rr} for 315 MeV/n He reflect an inverted and somewhat amplified version of the g_r data. There is a marked increase with increasing heliocentric distance with secondary maxima and minima associated with the time of minimum and maximum solar activity in cycles 20, 21 and 22. The radial dependence of K_{rr} for 175 MeV H is less than that of the He component, and the solar cycle variation is not as well defined. The values of K_{rr} for the anomalous 45 MeV/n and 15 MeV/n He are about one order smaller than those for 315 MeV/n He in the outer heliosphere.

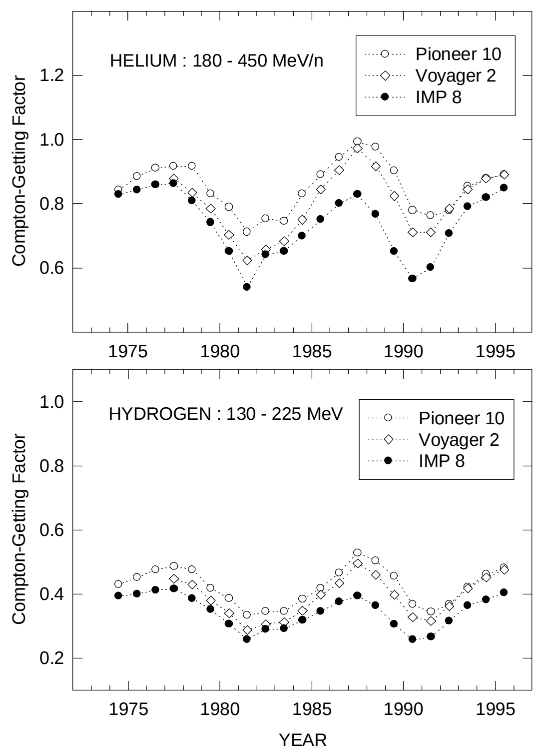

Fig.1 Comptonn-Getting factor calculated from spectra for galactic He and H.

3 Discussion:

These data provide the first systematic estimate of K_{rr} over extended periods of time and to heliocentric distances beyond 60 AU. In a previous study Reinecke et al. (1993) fitted the detailed He, H, He^+ and O^+ energy spectra for the 1977 and 1987 solar minima with data from the same experiments as used in the present study. Reinecke et al. used a 2-dimensional no-drift modulation model and found that two sets of diffusion coefficients were necessary to fit the different solar minima. In Fig.5 the values of K_{rr} reported here are shown in comparison with those by Reinecke et al. for galactic 315 MeV/n He and 175 MeV H, and for anomalous 15 MeV/n He in 1987 when observations extend beyond 40 AU. There is a significant difference in K_{rr} between two studies. The present study is confined to the ecliptic plane and assumes spherical symmetry where there were large negative latitudinal gradients for the galactic He and H as well as the anomalous He (Fujii & McDonald, 1999). These negative latitudinal gradients require model such as that used by Reinecke et al. at two dimension. The values of K_{rr} reported here for galactic H are, however, larger than those of Reinecke et al. beyond ~60 AU, and may reflect the particle of anomalous hydrogen in the P-10 data.

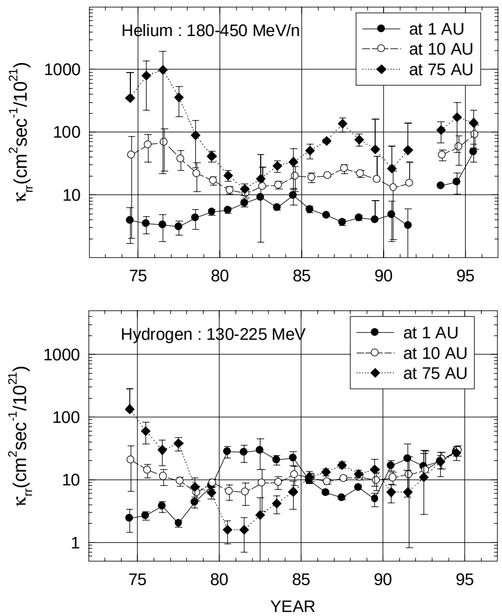

Fig.2 Annual values of K_{rr} for galactic He and H at different heliocentric distance from $g_r = G_0 r^{\alpha}$.

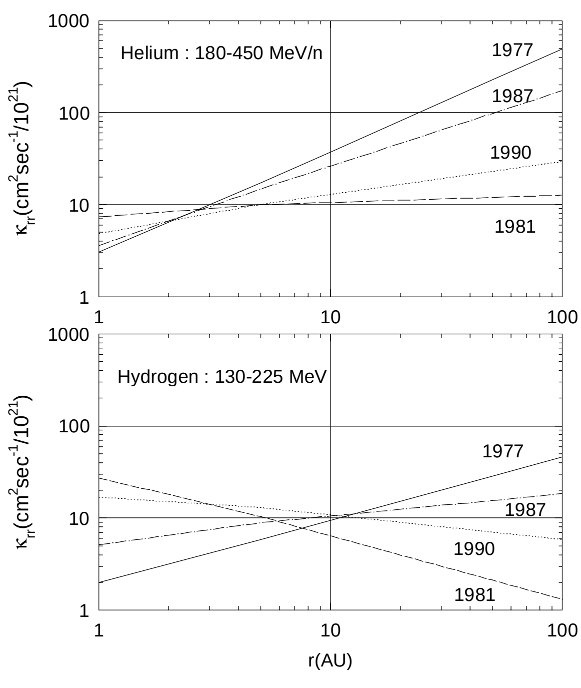

Fig.3 Values of K_{rr} for galactic He and H in 1977, 1987, 1981, 1nd 1990 solar minima and solar maxima as a function of heliocentric distance.

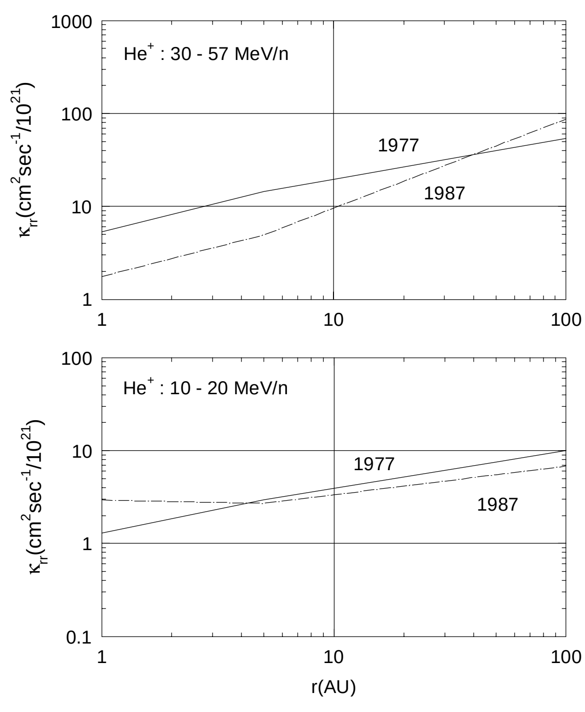

Fig.4 Values of K_{rr} for anomalous He in 1977, 1987 solar minima.

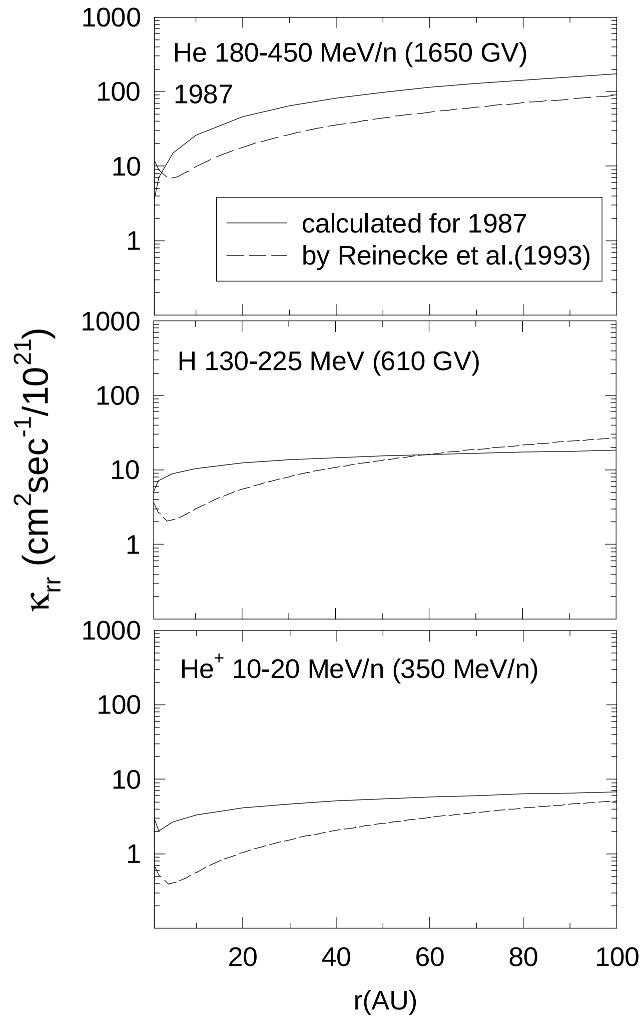

Fig.5 Values of K_{rr} in comparison with those by Reinecke et al. (1993)

References

Fisk, L.A., and Axford, W.I. 1969, J. Geophys. Res., 74, 4973

Fujii, Z., and McDonald, F.B. 1995, J. Geophys. Res., 100, 17043

Fujii, Z., and McDonald, F.B. 1997a, J. Geophys. Res., 102, 24201

Fujii, Z., and McDonald, F.B. 1997b, Proc. 25th ICRC (Durban), 2, 97

Fujii, Z., and McDonald, F.B. 1999, at this conference.

Gleeson, L.J., and Axford, W.I. 1968, Ap.J., 154, 1011

Reinecke, J.P.L., Moraal, H., and McDonald, F.B., 1993, J. Geophys. Res, 98, 9417

Webber, W.R., Golden, R.L., and Stephans, S.A. 1987a, Proc. 20th ICRC(Moscow), 1, 325

Webber, W.R., Golden, R.L., and Mewaldt, R.A. 1987b, Ap.J., 312, 178