Radial Intensity Gradients and Diffusion Coefficients of Cosmic Rays in the Outer Heliosphere at Solar Maximum

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Abstract

The IMP-8, Voyager and Pioneer cosmic ray observations now cover the solar maximum of cycles 21, 22, and 23 and out to a heliocentric distance of 88 AU. In an accompanying paper we showed that the radial dependences of intensities J are different in the inner and outer heliosphere with a transition over the radial distance of 10 to 15 AU, and that those intensity gradients are well described as $dJ/Jdr= G_0/r$ where r is heliocentric radial distance and G_0 is constant with a different value in the inner and outer heliosphere. Using the obtained gradients and a simple one-dimensional modulation model we determined the diffusion coefficients as a function of radial distance and rigidity in the outer heliosphere at solar maximum. It is found that the diffusion coefficient, K, depends on radial distance r as $r^{\sim 1.2}$ and on rigidity R as $\beta R^{\sim 1.0}$ respectively in the outer heliosphere beyond 10 AU, where β is particle velocity over light velocity. K is determined on the assumption that K is a separable function of r and R.

1. Introduction

Cosmic ray data from the deep space missions Pioneer 10/11 and Voyager 1/2 and IMP 8 at 1 AU made it possible to study the transport of cosmic rays in the heliosphere. In a series of papers we have studied intensity gradients and diffusion coefficients in the heliosphere (Fujii and McDonald, 1997, 2001a,b). By 2002 these data cover the three solar maxima of cycles 21, 22 and 23. In an accompanying paper (McDonald et al., in this Conference) we made detailed analysis of radial intensity profile and gradients over the extended heliocentric radial location beyond 80 AU during the solar activity maximum. Using the combined data set of solar maxima it was shown that the radial dependence of intensities J are different in the inner and outer heliosphere with a transition over the radial distance of 10 to 15 AU. Those intensity gradients are well described as $dJ/Jdr= G_0/r$, where r is heliocentric radial distance and G_0 is constant with a different value in the inner and outer heliosphere. Based on this

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finding we reinvestigated the radial intensity gradients and the diffusion coefficients in the outer heliosphere with the combined data set of galactic helium, hydrogen and anomalous cosmic ray He during the solar activity maximum.

2. Data

The data in this study are from IMP 8 Goddard Medium Energy Detector (R. McGuire, Principal Investigator), the Voyager 1 and 2 CRs (E.C. Stone, P.I.) and Pioneer 10 C.R.T. (F.B. McDonald, P.I.). We used 91-day average spectra data of each spacecraft during the maximum modulation period of cycles 21, 22 and 23 listed in Table 1. Table 2 shows the mean energies of energy intervals of 7 energy bins for He, 5 energy bins for H and 5 energy bins for anomalous He. Data of He for cycle 22 maximum were normalized to those for cycle 21 and 23 by a simple procedure introduced by McDonald et al. (in this Conference). The anomalous He data have been corrected for the presence of galactic helium, using the local interstellar He spectrum newly proposed by Webber (2001) and a simple one-dimensional modulation model. These data cover the rigidity from 500 MV to 2000 MV and β from 0.15 to 0.75, where β is particle velocity over light velocity. In the analysis we neglected slight differences of energy intervals among 4 spacecraft.

Table 1. Selected period of combined data set.

	Cycle 21	Cycle 22	Cycle 23
IMP 8	Apr. 2 - Jul. 2, '81	Jun. 6 - Aug.23, '90	Sep.30 - Dec.30, '00
V-2	Apr. 2 - Jul. 2, '81	Oct. 1 - Dec.31, '90	Apr. 2 - Jul. 2, '01
V-1	Apr. 2 - Jul.28, '81	Oct. 1 - Dec.30, '90	Apr. 2 - Jul. 2, '01
P-10	Feb.22 - Jul.28, '81	Nov. 9, '90-Jan.27, '91	

3. Gradients and diffusion coefficients in the outer heliosphere

Based on the finding that the radial dependence of intensitity J is approximated well with $J = J_0 r^n$ (McDonald et al., in this Conference), we determined the radial dependences of intensities in the outer heliosphere (r>10 AU) by fitting at 7 energy intervals of He and 5 energy intervals of H for the combined data set of cycles 21, 22 and 23 listed in Table 1 and 2, to calculate the intensity gradients, $g_r = G_0/r$. Using these gradients, the diffusion coefficients, K, are calculated by the relation, $K = CV/g_r$, of the force-field approximation of one-dimensional modulation model where C and V are Compton-Getting factor and the solar wind velocity respectively (McDonald et al., 1992). The Compton-Getting factors are derived from the spectra obtained by fitting, using the local interstellar He and H spectra (Webber et

Table 2. Mean energies of spectrum data for four spacecraft (MeV/n).

He	IMP-8	109.4	151.7	183.7	224.3	278.5	344.3	418.5
	V-2	108.0	143.7	172.8	218.6	259.1	324.2	420.0
	V-1	108.6	144.6	174.4	213.3	256.6	327.2	478.7
	P-10		141.1	175.9	224.7	256.6	313.2	396.3
H	IMP-8	137.8	166.3		203.8	278.3		
	V-2	142.3	162.8	182.5	200.9	227.0		
	V-1	143.9	164.9	181.3	204.1	231.3		
	P-10	139.4	155.9	177.9	207.6	243.3		
ACR He	V-2	13.1	21.7	34.7	49.3	62.9		
	V-1	13.1	21.7	34.7	49.3	63.1		

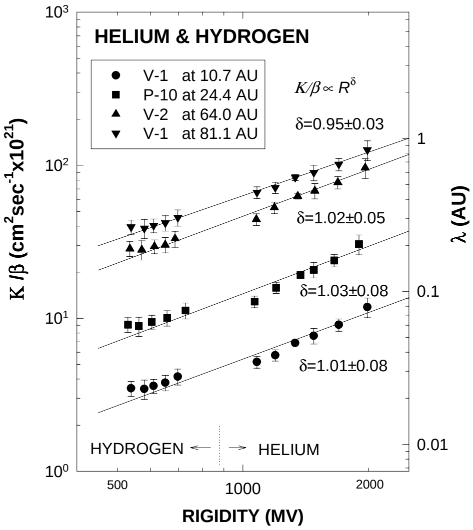
al., 1987; Webber, 2001) and a simple one-dimensional modulation model. We use an average solar wind velocity of 400 km/s.

The diffusion coefficients thus obtained for the 7 energy intervals of He and 5 energy intervals of H are shown to depend on r as r^{γ} with $\gamma = \sim 1.2$ within the accuracy of errors through the heliosphere from 10 AU to 80 AU. Then, the rigidity dependence of the diffusion coefficients is investigated in the observed rigidity range of He and H. Those diffusion coefficients are divided by β and are plotted as a function of rigidity R in Figure 1. In the Figure the corresponding mean free path λ are also shown as $\lambda = 3K/\beta c$. Figure 1 shows that K/β (and λ) has a rigidity dependence of R^{δ} with $\delta =\sim 1.0$ within the accuracy of errors over R from 500 MV to 2000 MV and β from 0.5 to 0.7.

Anomalous He corrected for the presence of galactic helium are clearly observed during the solar activity maximum of cycle 23 by two spacecraft, Voyager 1 at 81 AU and Voyager 2 at 64 AU. By the same procedure for galactic He and H we determined the radial dependences of anomalous cosmic ray He intensity with $J = J_0 r^n$ and calculated the intensity gradients $r = G_0/r$ to derive the diffusion coefficients by $K = CV/g_r$. The Compton-Getting factors are calculated from the spectra interpolated by the Spline-interpolation (e.g., Press et al., 1992). The diffusion coefficients obtained at 81 AU and 64 AU are divided by β and the K/β (and λ) are plotted as a function of rigidity in Figure 2 in comparison with those of the galactic He and H. It may be said that the diffusion coefficients for anomalous He agree well with those of the galactic He and H, although some deviation exists with those at 64 AU.

Based on these results, then we assumed that K/β (and λ) is a separable function of r with r^{γ} and R with R^{γ}, and we determined K by fitting those for the galactic He and H, and anomalous He as,

$$K = (0.31 \pm 0.07)\beta(R/1GV)^{0.95\pm0.03}(r/1AU)^{1.21\pm0.05} \times 10^{21} \quad cm^2 sec^{-1} \tag{1}$$



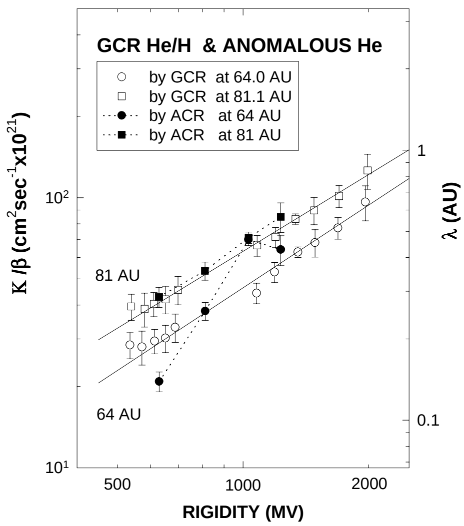


Fig. 1. K/β for He and H plotted as a function of rigidity R. The corresponding mean free path λ is also shown as $\lambda = 3K/\beta c$.

Fig. 2. K/β for the anomalous He plotted as a function of rigidity R in comparison with those of the galactic He and H.

for β from 0.15 to 0.7, R from 500 MV to 2000 MV, and r from 10 AU to 80 AU.

4. References

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