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Radial and latitudinal intensity gradients of galactic and anomalous cosmic rays in the outer heliosphere

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Abstract. Radial and latitudinal intensity gradients are studied in detail for galactic cosmic ray helium (145-255 MeV/n), hydrogen (130-225 MeV), and anomalous cosmic ray helium (27-42 MeV/n, 10-16 MeV/n) during solar activity minima of positive solar polarity period (qA>0). For the radial dependence of intensity gradient, a functional form $dJ/Jdr = G_0 r^a$ was assumed for radial distance *r*, and the dependence was studied extensively, using the combined data of 1977/1978 and 1996/1997 from Pioneer 10/ 11, Voyager 1/2, Ulysses and IMP 8. It was shown that the adopted functional form for the gradients describes well the observed gradients at the extended radial distance beyond ~60 AU, and that the measured gradients are smaller than those in 1987(qA<0) at *r*>~5 AU, being qualitatively in accord with the predictions of the effects produced by particle drifts in the interplanetary magnetic field.

1 Introduction

The cosmic ray data from the deep space missions Pioneer 10/11 and Voyager 1/2, and IMP 8 at 1 AU are now available for more than two solar cycles and to heliocentric distance beyond 70 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 studying cosmic ray transport, the radial and latitudinal intensity gradients provide insight into the physical processes of cosmic ray transport in the heliosphere, and in a series of papers we have studied radial and latitudinal intensity gradients near the ecliptic plane for galactic 180-450 MeV/n He, 130-220 MeV H and anomalous 30-57 MeV/n He^+ and 10-20 MeV/n He^+ from 1974 to 1996 (Fujii and McDonald, 1997, 1999). In these studies, to investigate the spatial and temporal variation of the gradients we assumed the radial gradients to be dependent on heliocentric radial distance *r* with a functional form of $g_r = dJ/Jdr = G_0 r^a$ as first suggested by the analysis of Cummings & Stone (1988), and the latitudinal gradients G_λ constant in heliolatitude, where G_0, *a* and G_λ are constant at any particular time. We determined numerically the values of these parameter on a yearly basis. It was found that the radial intensity gradients decrease with increasing heliocentric distance except for galactic hydrogen during the solar activity maxima, and that the gradients vary in relation with the solar activity. It was also shown that in the outer hemisphere the gradients for positive solar polarity period (1970s, 1990s) are smaller than those for negative solar polarity period (1980s). These results as well as the observed negative latitudinal gradients during the solar activity minimum in the 1980s are qualitatively consistent with the expected drift effects in the large-scale interplanetary magnetic field (Jokipii and Thomas, 1981; Kota and Jokipii, 1983; Potgieter and Moraal, 1985).

In these study, however, the radial dependence of the observed gradients for 1993-1996 were different from those obtained over previous solar minima (Fujii and McDonald, 1997) This may reflect the difficulty to measure the small values of g_r in the outer heliosphere by four spacecraft, three of which, Pioneer and Voyagers are beyond ~50 AU (McDonald *et al.*, 1998, 1999). In the present paper we used the combined data observed in the solar activity minima of 1977/1978 and 1996/1997 and study in more detail, focusing on the spatial dependence of gradients in the outer hemisphere.

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2 Data

The data used in this study are mainly from IMP 8 Goddard Medium Energy Detector (R. McGuire, Principal Investigator), the Ulysses COSPIN/KET (H. Kunow, P.I.), the Voyagers 1 and 2 CRs (E.C. Stone, P.I.) and Pioneer 10 C.R.T. (F.B. McDonald, P.I.). McDonald *et al.* (1998) showed that there is remarkable agreement between the 1977/1978 and 1996/1997 spectra over the complete range of the IMP 8 MED extending from 20 to 327 MeV H and 20 to 450 MeV/n for He, as shown in Fig.1. In the present paper data are composed of those for selected periods in 1977/1978 and 1996/1997 to measure in detail the gradients during solar activity minima of positive solar polarity period, assuming that the modulation are similar over those periods throught the heliosphere, and the intensity gradients are measured for four species, galactic 145-255 MeV/n He, 130-225 MeV H and anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+. The anomalous He data have been corrected for the presence of galactic helium, using the interstellar He spectrum newly proposed by Lukasiak (2000) which is about 10% lower than that used previously. The energy bins used in the present measurement are different slightly from those in the previous analysis. This is because of availability of data. Table 1 and 2 summarize data used in the present analysis.

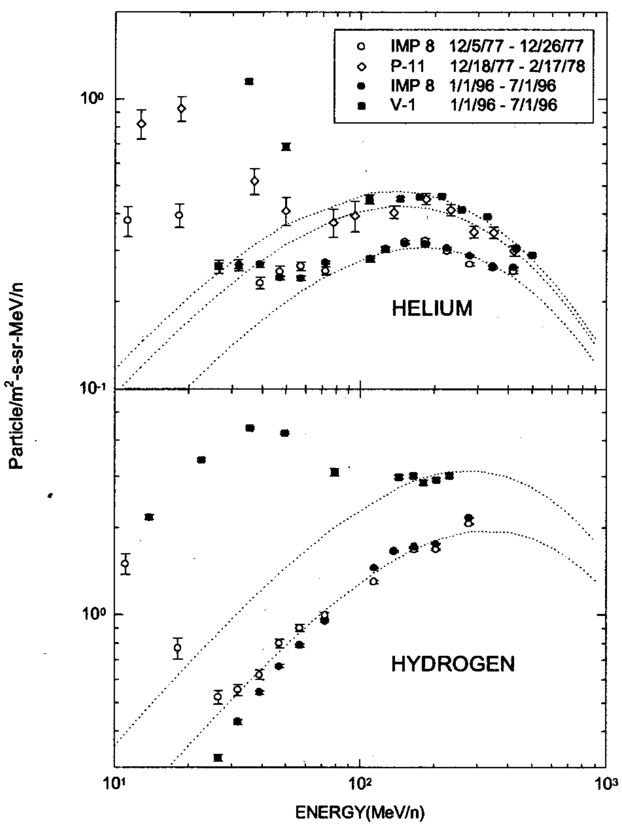

Fig.1 He and H energy spectra observed by IMP 8 Pioneer 11 and Voyager 1 for 1977/1978 and 1996 solar minimum periods of qA>0.

2 Analysis and discussion

The spatial intensity gradients are a function of time and location in the heliosphere. To study temporal and radial variation of these gradients we assumed the radial gradients to be dependent on heliocentric radial distance r with a functional form of $g_r(=dJ/Jdr)=G_0r^a$, and the latitudinal gardients G_λ to be constant in heliolatitude, where G_0, a and G_λ are constant at any particular time. For combination of intensities under the assumption of spherical symmetry,

$$\ln\left(\frac{J_2}{J_1}\right)=G_0\frac{r_2^{a+1}-r_1^{a+1}}{a+1}+G_\lambda(\lambda_2-\lambda_1)\ , \qquad (1)$$

Table 1 Summary of combined data set for galactic 145-255 MeV/n He, 130-225 MeV H, Spacecraft, period, average radial distance and heliolatitude.

He 145-255 MeV/n, H 130-225 MeV					
1977/78	IMP 8	12/5/77 - 12/26/77	1 AU	0°
	P-11	12/18/77 - 2/17/78	6.3 AU	8.3°
	V-2	12/1/77 - 4/1/78	1.7 AU	4.7°
	P-10	1/1/78 - 4/1/78	15.1 AU	3.0°
1997	IMP 8	6/1/97 - 10/1/97	1 AU	0°
	V-2	6/1/97 - 10/1/97	52 AU	-19°
	V-1	6/1/96 - 10/1/97	67 AU	34°
	Uly.	1/1/97 - 12/31/97	5.1 AU	9.8°

Table 2 Summary of combined data for anomalous 27-42 MeV/n He^+, and 10-16 MeV/n He^+, Spacecraft, period, average radial distance and heliolatitude.

He^+ 27-42 MeV/n, He^+ 10-16 MeV/n				
1977/78	IMP 8	12/5/77 - 12/26/77	1 AU	0°
	P-11	12/18/77 - 2/17/78	6.3 AU	8.3°
	V-2	12/1/77 - 4/1/78	1.7 AU	4.7°
	P-10	1/1/78 - 4/1/78	15.1 AU	3.0°
1996	IMP 8	1/1/96 - 7/1/96	1 AU	0°
	V-2	1/1/96 - 7/1/96	48 AU	-19°
	V-1	1/1/96 - 7/1/96	62 AU	34°
	P-10	1/1/96 - 7/1/96	64 AU	3.0°

where J_i is the intensity at the heliocentric radial distance r_i and in the heilolatitude λ_i (Fujii and McDonald,1999). The values of G_0, a and G_λ are determined by fitting of all combinations of intensities. The obtained values of parameters for four species are summarized in Table 3.

Table 3 Values of parameters determined for 145-255 MeV/n He, 130-225 MeV H, 27-42 MeV/n He^+ and 10-16 MeV/n He^+.

Species	a	G_0(%/AU)	G_λ(%/deg.)
He 145-255 MeV/n	-1.29±0.16	26.5±4.6	-0.70±0.35
H 130-225 MeV	-1.22±0.56	27±18	0.12±0.95
He^+ 27-42 MeV/n	-1.32±0.21	92±32	0±0.9
He^+ 10-16 MeV/n	-1.10±0.20	74±30	0±1.2

The obtained values of parameter a are around -1.1 to -1.3 for four species which are negative larger values than those in our previous measurement by IMP 8, V1/2 and P10 in 1996 (Fujii and McDonald, 1997). It should be noted that the error of a for galactic H is relatively large, compared with those for galactic and anomalous He. This may indicate that in fitting the gradients with $g_r=G_0r^a$, the spatial dependence for H is somewhat different from those for He, as McDonald *et al.* (1998) indicate that the 130-225 MeV H at V-2 in 1997 heliosphere has a significant contribution from anomalous H.

McDonald *et al.*(1998) measured the radial and latitudinal gardients for galactic and anomalous cosmic rays in 1996, using data from three spacecraft, P10, V1 and V2 in the outer heliosphere from 50 to 65 AU. The radial gradients they measured for galactic 140-380 MeV/n He, 130-225 MeV H, and anomalous 10-22 MeV/n He are 0.4±0.2, 1.0±0.2, and 3.3±0.3 %/AU respectively. Using the values of parameters in Table 3 it is possible to estimate the gradinets at a certain location. The gradients calculated for for 145-255 MeV/n He, 130-225 MeV H, and 10-16 MeV/n He^+ at 50 AU are 0.16±0.13, 0.2±0.3, and 1.0±0.7 %/AU respectively which appear to be slightly smaller than those by McDonald *et al.* McDonald et. al. also showed that for 1996.0-1996.5, G_λ are positive or zero, consistent with the present result except the obtained negative values for 145-255 MeV/n He.

Fig.2 and 3 show the gradients near the ecliptic plane calculated for galactic 145-255 MeV/n He and 130-225 MeV H, and anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+ respectively, using the values of parameters in Table 3. In the Figures the observed non-local gradients, $\ln(J_2/J_1)/(r_2-r_1)$ are also plotted at the effective radial distance r^* of measurementdefined by $G_0(r^*)^a=(r_2-r_1)^{-1}G_0(r_2^{a+1}-r_1^{a+1})(a+1)^{-1}$. These Figures demonstrate that the adopted functional form for the gradient describes the observed gradients fairly well.

To compare the radial gradients observed in solar minima of qA<0 and qA>0, the gradients are also shown for 180-450 MeV/n He, 130-225 MeV H, 30-57 MeV/n He^+ and 10-20 MeV/n He^+ in 1987 by Fujii and McDonald (1999). The gradients calculated for positive solar polarity period (1977/78+1996/97) are clearly smaller than those for negative solar polarity period (1987) at the extended radial location of r>~5 AU where the measurement were made. These results are consistent with those by Webber and Lockwood (1997) and McDonald *et al.* (1998), and are qualitatively in accord with the predictions of the effects produced by particle drifts in the interplanetary magnetic field (Jokipii and Thomas, 1981; Kota and Jokipii, 1983; Potgieter and Moraal, 1985).

In summary, the radial and latitudinal intensity gradients were studied extensively for for four species, galactic 145-255 MeV/n He, 130-225 MeV H and anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+, using the combined data of 1977/1978 and 1996/1997 during solar activity minima of positive solar polarity period (qA>0). The radial gradients are assumed to be dependent on heliocentric radial distance r with a functional form of g_r $(=dJ/Jdr)=G_0r^a$ and the latitudinal gardients G_λ to be constant in heliolatitude. The values of these parameters were determined nemrically. It was shown that the adopted functional form for the gradient describes the observed gradients well at the extended radial location beyond ~60 AU. The measured gradients are larger than those in 1987(qA<0) at r>~5 AU, and are qualitatively in accord with the predictions of the effects produced by particle drifts in the interplanetary magnetic field.

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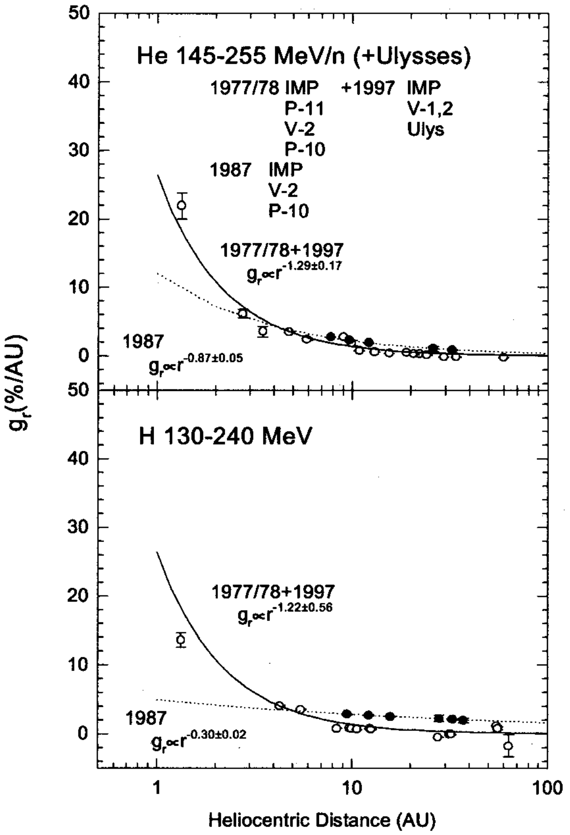

Fig.2 Gradients near the ecliptic plane calculated for galactic 145-255 MeV/n He and 130-225 MeV H in 1977/1978+1997(qA>0), using the obtained values of parameters in Table 3, and those for 180-450 MeV/n He and 130-225 MeV/n H in 1987 (qA<0). In the Figure the observed non-local gradients, $\ln(J_2/J_1)/(r_2-r_1)$ are also plotted at the effective radial distance r^* of measurement.

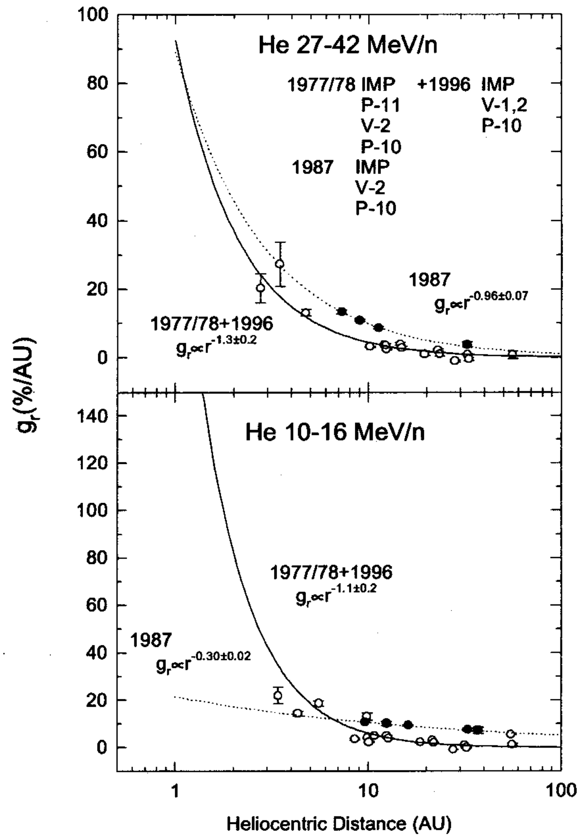

Fig.3 Gradients near the ecliptic plane calculated for anomalous 27-42 MeV/n He^+ and 10-16 MeV/n He^+ in 1977/1978+1996(qA>0), using the obtained values of parameters in Table 3, and those for 30-57 MeV/n He^+ and 10-20 MeV/n He^+ in 1987 (qA<0). In the Figure the observed non-local gradients, $\ln(J_2/J_1)/(r_2-r_1)$ are also plotted at the effective radial distance r^* of measurement.