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Study of the Radial and Latitudinal Intensity Gradients of Galactic and Anomalous Cosmic Rays

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Abstract

In previous studies we have reported measurement of radial intensity gradients near the ecliptic for galactic cosmic ray helium (180-450 MeV/n) , hydrogen (130-225 MeV), and anomalous cosmic ray helium (10-20 MeV/n, 30-57 MeV/n) from Pioneer 10/ 11, Voyager 1/2, and IMP 7/8, over the period 1972-1996. We extended these studies to analyse radial and latitudinal gradients simultaneously for galactic He, H, and anomalous He , assuming the latitudinal gradients which are constant in heliolatitude over the range 0~33°. For the radial dependence of intensity gradient a functional form $dJ/Jdr=G_0r^{\alpha}$ was adopted. It was found that both G_0 and α varied in a cyclical manner over the solar cycle, but with strong evidence of effects that extended over the 22 year heliomagnetic cycle. The latitudinal gradients was negative for the negative period of 1984 to 1988 with the negative largest value in 1986-1987, and are small positive or zero for the positive period of 1991-1995, consistent qualitatively with the expected drift effects.

1 Introduction:

Cosmic ray data now available from the Pioneers 10 and 11, and Voyager 1 and 2 Deep Space missions and IMPs 6, 7 and 8 at 1 AU, span a period of more than two solar cycles and extend to heliocentric distances beyond 65 AU. In a series of papers we have reported the radial intensity gradients near the ecliptic for galactic cosmic ray helium (180-450 MeV/n), hydrogens (130-225 MeV), and anomalous cosmic ray helium (10-20 MeV/n, 30-57 MeV/n) over the period of 1972-1996 (Fujii & McDonald, 1995,1997a, 1997b). In these studies we measured the gradients, assuming the radial dependence with a functional form of $dJ/Jdr=G_0r^{\alpha}$ (G_0 and α are constant, and r is heliocentric radial distance), and investigated the spacial and temporal variation of the gradients with available yearly average data sets. It was found that both G_0 and α varied in a cyclical manner over the solar cycle, but there was also evidence of effects that extended over the 22 heliomagnetic cycle. In the present study we extended these analyses to measure the radial and latitudinal intensity gradients simultaneously.

2 Data:

The data used in this study are from IMP 6,7 and 8 at 1 AU, and Voyager 1 and 2, and Pioneer 10 and 11 deep space missions out to the heliocentric radial distance ~65 AU in the heliosphere. Pioneer 10 and Voyager 2 were near the ecliptic prior to 1993, while Voyager 1 was at a heliolatitude 30° to 35°N after 1985. We analysed radial and latitudinal gradients for the intensities of two galactic cosmic ray ion species, 180-450 MeV/n He and 130-225 MeV H, and of anomalous cosmic rays, 10-20 and 30-57 MeV/n He.

The 180-450 MeV/n He data from Voyager 2 are from a different analysis mode which is unaffected by anomalous hydrogen than that previously used and are different by some 5% higher from those used in our earlier measurement. The 10-20 MeV/n anomalous He data from Voyager 1/2 are also calculated using energy interval as close as possible to those of IMP 8 and Pioneer 10. The anomalous He^+ data have been corrected for the presence of galactic helium, using the Webber local interstellar He spectrum (Webber et al., 1987) and a one dimensional modulation model. These anomalous cosmic ray data are not available during periods close to solar maximum when the correction for GCR He becomes appreciably larger than the He+ intensity.

There is, as is known, a systematic time-delay between the observations at 1 AU and those by the deep space missions. This delay is produced by the outward propagation of interplanetary disturbances with approximately the solar wind velocity (Fillius & Axford, 1985, McDonald et al., 1981). In the following section, the Pioneer and Voyager data were all time-shifted back to the 1 AU baseline by an amount Δt_c that corresponds to the solar wind transit time between 1 AU and the location of the spacecraft assuming a nominal solar wind speed of 400 km/s.

3 Analysis and Discussion:

The spacial intensity gradients are a function of time and location in the heliosphere. In our previous papers we assumed the gradients to be dependent on heliocentric radial distance r with a functional form of $g_r(=dJ/Jdr)=G_0 r^{\alpha}$ as first suggested by the analysis of Cummings & Stone (1988), and investigated temporal and radial variation of the gradients near the ecliptic plane under the assumption of spherical symmetry. We extended these analysis to investigate radial and latitudinal gradients simultaneously for two galactic cosmic ray ion species, 180-450 MeV/n He and 120-225 MeV H, and anomalous cosmic rays, 10-20 and 30-57 MeV/n He, assuming the latitudinal gradients, G_{λ}, constant to the heliolatitude. For set of intensities,

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

where J_i is the intensity at the heliocentric radial distance r_i and in the heilolatitude λ_i (McDonald et al.,1997). In 1974 to 1982 when we have no real off ecliptic observations we determined G_0 and α numerically with data from sets of spacecraft near the ecliptic plane, IMP7/8, Pioneer 11 and 10 (1974-1978), and IMP 8, Voyager 2 and Pioneer 10 (1979-1982). In 1983 to 1995 we determined G_0, α and G_{λ} with data from IMP 8, Voyager 1/2 and Pioneer 10. The values of G_0, α and G_{λ} are determined numerically on a yearly basis and are shown for galactic He and H, and for anomalous He in Fig.1 and Fig.2 respectively.

3.1 Radial Gradients: The annual values of G_0 and α obtained for galactic He and H display fairly consistent cyclic changes over most of solar cycle 21 and 22. There are, however, some scatter of the values obtained for 1993-1995 from their cyclic variation in 1974-1992. These results were examined and

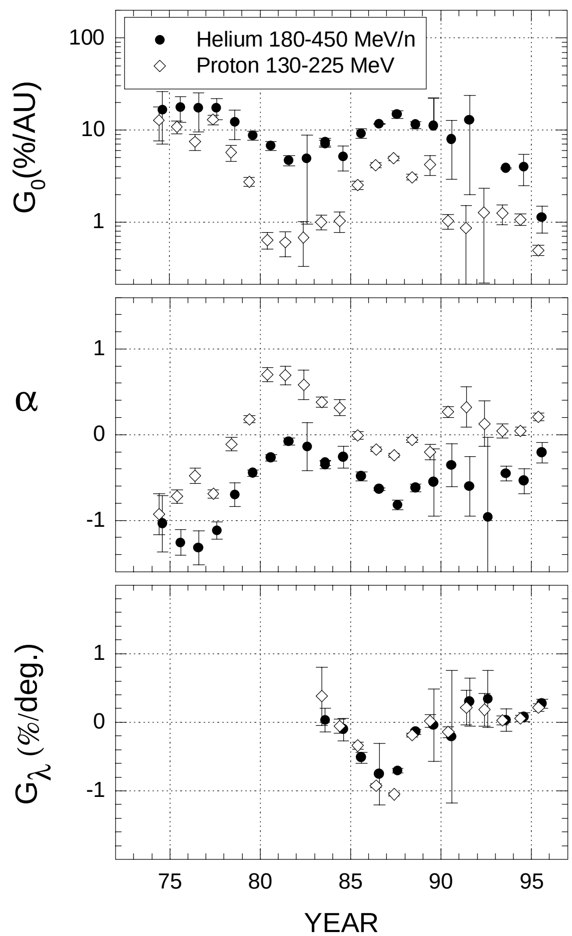

Fig.1 Annual values of G_0, α and G_{λ} for galactic 180-450 MeV/n He and 130-225 MeV H.

discussed in our previous papers (Fujii and McDonald, 1997a) in relation with fitting of g_r with IMP at 1 AU, and Pioneer and Voyager both beyond 40 AU.

With the measured parameters it is possible to estimate the gradients at a certain location. To examine drift effects, radial gradients near the ecliptic plane are calculated for the periods of successive solar minima when the effects of solar activity is at its lowest level and when the influence of drifts should be most prominent, and are shown for galactic He and H, and anomalous He in Fig.3 and 4. 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 measurement defined by $(r_2-r_1)^{-1}G_0(r_2^{\alpha+1}-r_1^{\alpha+1})(\alpha+1)^{-1}=G_0(r*)^{\alpha}$. These figures shows that the adopted functional form for the gradient describes the observed gradients well. The gradients estimated for nagative solar polarity period (1987) are smaller than those for positive solar polarity periods (1976/1977, 1995) at the extended radial location of r>~10 AU where the measurement were made, which are qulitatively consistent with the expected drift effects in the large-scale interplanetary magnetic field (Jokipii and Thomas, 1981).

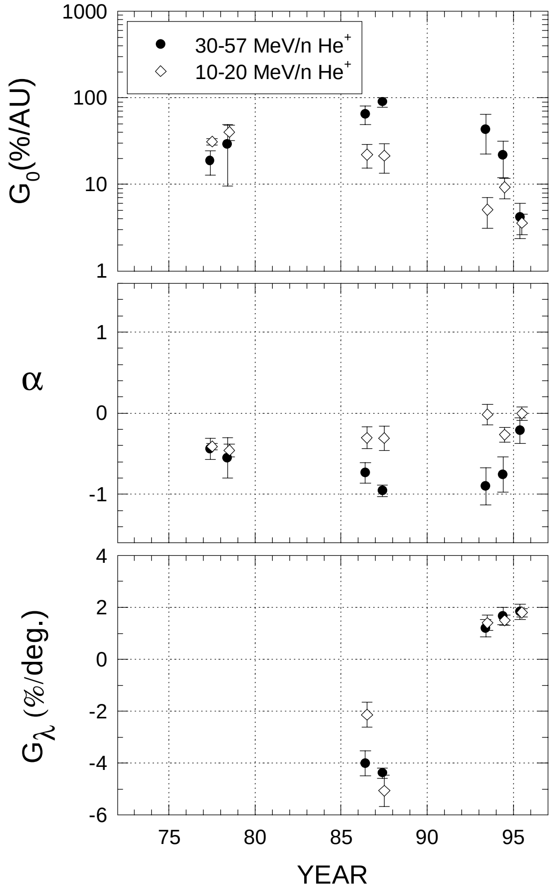

Fig.2 Annual values of G_0, α and G_λ for anomalous 10-20 and 30-57 MeV/n.

3.2 Latitudinal Gradients: The measured values of latitudinal gradients, G_λ, are negative for the negative period of 1984 to 1988 with the largest negative value of -~1%/° for galactic He and H in 1986-1987, the activity minimum period. The values are small positive or zero for the positive period of 1991-1995 time as was reported by McDonald et al. (1997, 1998) and Webber & Lockwood (1997). The latitudinal gradients obtained for 10-20 MeV/n and 30-57 MeV/n anomalous He are -4~-5%/° in 1987 and 1~2%/° in 1993-1995, which are in accord with those for the 10 MeV/n anomalous oxygen obtained by Cummings et al. (1995) and for He+ obtained by McDonald et al. (1998). These obtained latitudinal gradients for galactic He and H are also consistent with with the expected drift effects.

Acknowledgment

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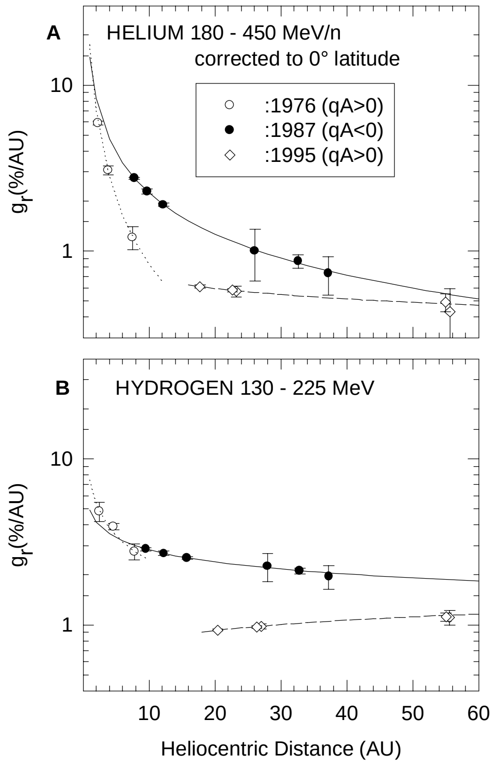

Fig.3 Estimated and observed non-local radial gradients for galactic 180-450 MeV/n He and 130-225 MeV H.

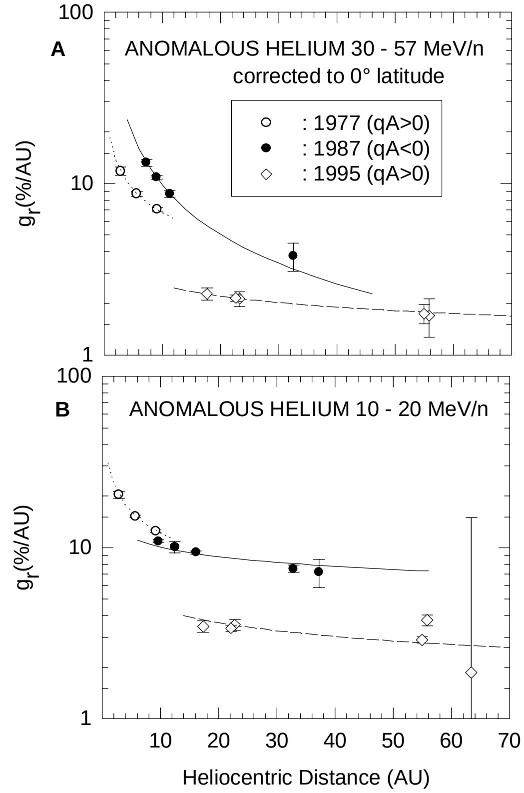

Fig.4 Estimated and observed non-local radial gradients for anomalous 30-57 and 10-20 MeV/n He.

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