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# The Cosmic Ray Radial and Latitudinal Intensity Gradients in the Inner and Outer Heliosphere over the Cycle 22 Solar Minimum

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**Abstract**

The spatial intensity gradients of galactic and anomalous cosmic ray helium are studied over the 1993.0-1998.0 time period using data from cosmic ray experiments on IMP 8, Ulysses, Voyagers 1 and 2 and Pioneer 10. The present study differs from those presented previously in that a different analysis mode has been selected for the Voyager 2 measurement of 180-450 MeV/n He that eliminates a recently discovered problem with contamination from anomalous cosmic ray hydrogen in the V-2 He data over the cycle 22 recovery and solar minimum periods. With this data set a remarkable ordering of the radial gradients for the galactic component is found over 2 complete solar cycles and 3 successive solar minima. The latitudinal gradients for the cycle 22 solar minimum period are zero or small and positive in the inner and outer heliosphere in contrast to the much larger negative latitudinal gradients observed in the outer heliosphere in 1987 over the cycle 21 solar minimum. The changes in the intensity gradients over the 3 solar minimum periods require that at those times drift effects play an important role in the transport of cosmic rays in the heliosphere and provide further evidence for the existence of a 22-year solar modulation cycle.

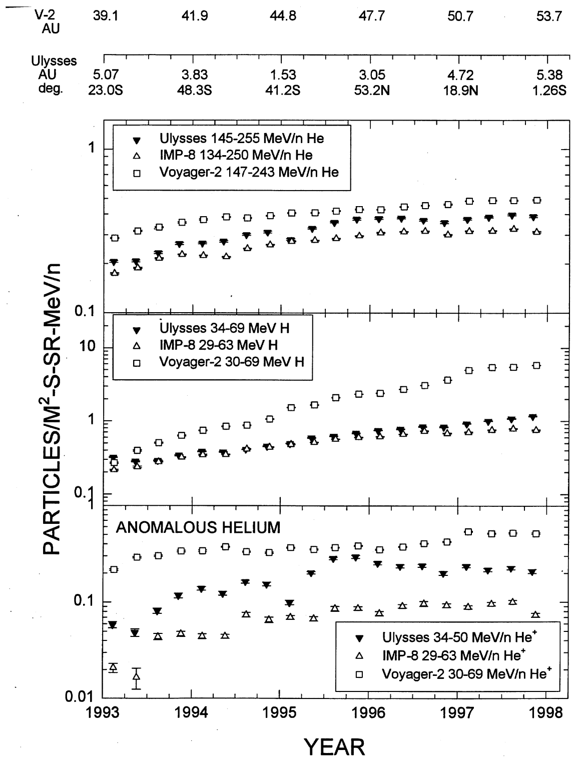
## 1 Introduction:

The observations of galactic and anomalous cosmic rays from the energetic particle experiments on the 4 Pioneer and Voyager spacecraft along with those of IMP 8 at 1 AU now cover a period of some 26 years and extend beyond 70 AU. Beginning in 1991 the Ulysses Mission, with its unique orbit over the solar poles, provides new latitudinal surveys as well as cosmic ray data at intermediate heliocentric distances. The cosmic ray radial and latitudinal intensity gradients are a convenient means of organizing this voluminous data set to give insight into the physical processes and temporal changes that are controlling the particle spatial distributions.

## 2 Observations:

The cosmic ray data used in this study are from the IMP 8 Goddard Medium Energy Experiment (R. McGuire, Principal Investigator), the Ulysses COSPIN/KET, (H. Kunow, P.I.), the Voyagers 1 and 2 CRS (E. C. Stone, P.I.) and the Pioneer 10 C.R.T. (F. McDonald, P.I.). For the five experiments, three common channels were identified which utilized multiparameter analysis, had comparable energy ranges, and accurate identification of particle species: (1) 145-255 MeV/nucleon He, (2) 34-50 MeV/nucleon He, and (3) 34-69 MeV H. The 145-255 MeV/nucleon He nuclei are galactic cosmic rays of moderate rigidity ($\overline{R}$ = 1.3 GV). The 34-50 MeV/nucleon He are a mixture of anomalous and galactic cosmic rays. The designation $He^+$ indicates that this component has been corrected for the contributions from galactic cosmic rays in the 34-50

MeV/n interval (McDonald et al. 1997) while $He^{++}$ refers to the galactic component. From late 1996-1997.0 Ulysses is within 20° of the ecliptic plane at a heliocentric distance of some 5 AU.



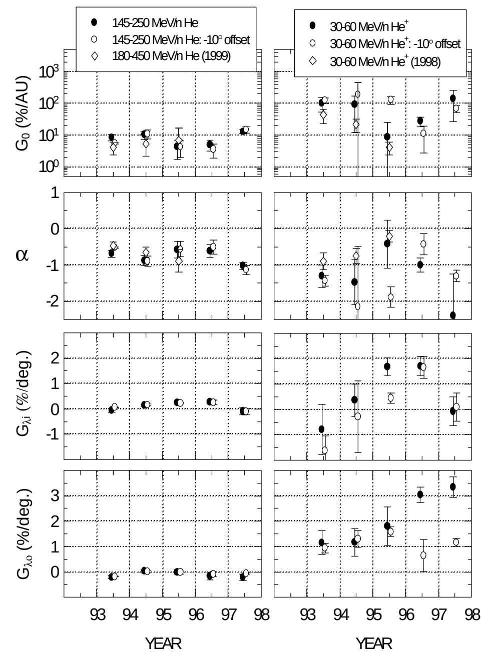




**Figure 1: Time histories (91 Day Averages) of 200 MeV/n He, 50 MeV H and 44 MeV/n He**

**Figure 2: Annual averages of $G_0$, α, $G_{l_0}$ and $G_{l_i}$. The values of $G_0$ and α with the ◊ symbol used data from IMP 8, V-1, 2 and P-10 while all the other parameters used Ulysses, IMP-8 and V1.2**

The time histories (91 day averages) of galactic and anomalous He and low energy H for the 3 spacecraft are shown in Figure 1 for 1993.0-1998.0. What is surprising is how close the high latitude (>75°, 2 AU) Ulysses $He^{++}$ and $He^{+}$ intensities in 1995.75 are to those of V-2 (−18°, 47AU). However as Ulysses moves out to 5 AU and returns to the ecliptic plane there is a steady divergence between the data sets, showing the presence of significant positive latitudinal gradients in the inner heliosphere. The 50 MeV H component is dominated by the presence of anomalous H at V-2 and beyond but has very small latitudinal and radial gradients in the inner heliosphere.

ANALYSIS

In the following analysis the differential radial gradient is taken to be of the form, $\frac{1}{J}\frac{dJ}{dr} = G_0 r^a$ (Cummings et al. 1990a, Fujii and McDonald, 1997) where $G_0$ and α vary with time and particle species and energy. The latitudinal gradients, $G_\lambda$, are assumed to be constant with λ and are determined separately for the inner (<5AU) heliosphere, $G_{l_i}$, and for the outer heliosphere, $G_{l_0}$. For any 2 pair of spacecraft at heliocentric distances $r_1$ and $r_2$, latitudes $\lambda_1$ and $\lambda_2$: $\ell n \frac{J_2(r_2,t)}{J_1(r_1,t)} = \frac{G_0(r_2^{a+1} - r_1^{a+1})}{a+1} + G_{l_i}\Delta l_{i_{1,2}} + G_{l_0}\Delta l_{i_{0_{1,2}}}$ where $J$ is the particle intensity at time $t$ for a particular particle species and energy interval. $G_0$, α, $G_{\lambda i}$ and $G_{\lambda 0}$ can be determined from the simultaneous solution of equation 1 involving different pairs of spacecraft over the 1993-1995 time period (Fig. 2). Also shown in Figure 2 is an updated analysis of the 180-450 MeV/n He channel involving IMP 8, V2, and P-10. (Pioneer 10 data is not available after 1996.5 and the subsequent analysis is based on the data from 4 spacecraft.) These values of $G_0$, and α for 180-450 MeV/n He over this period differ from those published previously (Fujii and McDonald, 1997) in that high gain data used in the earlier studies from the V-2 CRS has been used for the GCR $He^{++}$ analysis. Unlike the low gain data, this analysis mode is not affected by the presence of anomalous hydrogen. Only after ~1993 does this result in a significant change in the values of $G_0$ and α from those previously published. There is excellent agreement between the 180-450 MeV/n $G_0$ and α values and the 145-255 MeV/n channel using the Ulysses KET data.

The Ulysses investigators [Simpson et al., 1996; Huber et al. 1996] found that the cosmic ray data from the Ulysses fast-latitude scan were best ordered with a $-10°$ offset in heliolatitude. At this time it is not clear whether this is a persistent feature of the solar magnetic field so the $G_0$ , α, and $G_\lambda$ in Figure 2 have been calculated with and without a $-10°$ offset in λ. This offset has essentially no effect on the galactic cosmic ray He analysis but does result in some sporadic differences in the 4 parameters for anomalous $He^+$ .

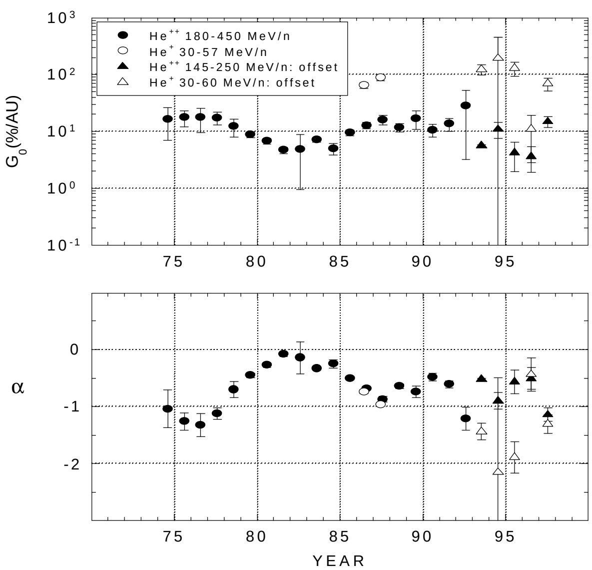



**Figure 3: Annual values of $G_0$ and α for galactic cosmic ray He for 1974.0-1992.0 using data from IMP-8, V-2 and P-10. The 1993.0-1998.0 $G_0$ and α values were based on IMP-8, Ulysses, V-1, V-2 and P-10. For 45 MeV/n anom $He^+$, $G_0$ and α are also shown for those times when meaningful measurements of $He^+$ can be made at 1 AU.**

The value of $G_{l_0}$ (Figure 2) over the solar minimum period of cycle 22 are consistent with a zero latitudinal gradient for galactic cosmic ray helium in the outer heliosphere in agreement with similar results obtained by Webber and Lockwood (1997) for 1996 and McDonald et al. (1998). The small positive value of $G_{\lambda i}$ for $He^{++}$ is consistent with the value of 0.19 ± .04%/° obtained by McDonald et al. (1998). The values of $G_{l_i}$ and $G_{l_0}$ for anomalous He are positive and appreciably higher than those of 200 MeV/n $He^{++}$ and when calculated with the 10° offset are consistent with previous measurements. (Webber and Lockwood, 1997; McDonald et al., 1997: McKibben et al. 1996).

The annual values of α and $G_0$ (Figure 3) for the 1974-1998.0 period (using the Ulysses based data from 1993.0-1998.0) spanning 2 complete solar cycles and 3 solar minima show a well defined cyclic pattern. α has its maximum negative value at solar minimum and it decreases more rapidly with heliocentric distance in qA>0 cycles than in qA<0 cycles. Of special note is the fact that the α and $G_0$ values for 1997 and 1977 are in reasonable agreement despite the very large changes in spacecraft locations over that time. The value of α for $He^+$ tend to be somewhat more negative than for $He^{++}$ while the values of $G_0$ are almost an order of magnitude larger. The absence of α and $G_0$ values for $He^+$ over periods of enhanced solar activity is due to the large relative correction at 1 AU for the contribution of galactic cosmic rays to the 30-60 MeV/n He interval.

## 3 Discussion:

The representation of the intensity gradients by equation 1 have produced a remarkable ordering of the radial intensity gradients over 2 solar cycles and 3 successive solar minima. At the time of these solar minima the 200 MeV/n $He^{++}$ spatial gradients become very small with increasing heliocentric distance. However at all radial distances the 1987 values of $g_r$ are larger than in 1977 and 1997. For example over the 40-60 AU interval these values differ by a factor of ~3. These smaller values of $g_r$ in 1997 and 1977 occur in qA>0 epochs (1970-1980, 1990–~2000) when cosmic ray ions are drifting in over the solar poles and leave via the heliospheric neutral current sheet–in broad agreement with the predictions of drift theory. [Jokipii and Thomas, 1981; K  ta and Jokipii, 1983; Potgieter and Moraal, 1985].

In cycle 21, $G_\lambda$ for all components in the outer heliosphere reached their peak negative value when the particle intensities are at a maximum and in coincidence with the minima inclination of the current sheet at V-1 (31.3°N, 32 AU). [Cummings et al. 1990; McDonald, 1992]. The peak values of $G_\lambda$ at that time are of the same order as the radial gradients indicating the large asymmetry in the cosmic ray distribution that must exist at that time between the ecliptic plane and the polar regions. The 1994-1998 values of $G_\lambda$ in the outer heliosphere are zero or positive and much smaller in magnitude than in 1987 just as the cycle 22 radial gradients over solar minimum are smaller than those observed in 1987. The values of $G_\lambda$ in the inner heliosphere are positive and somewhat larger than those at larger radial distances. The difference in magnitude of the spatial gradients over the 2 successive solar minimum periods suggest that polar turbulence as suggested by Jokipii and K  ta (1989) is an important factor in explaining these observations.

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