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The cosmic ray radial and latitudinal intensity gradients in the inner and outer heliosphere 1996-2001.3

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Abstract. The spatial intensity gradients of 150-380 MeV/n galactic cosmic ray He and 30-60 MeV/n H and He are studied over the 1996-2001.3 time period using data from the Goddard MED experiment on IMP 8, the COSPIN/KET telescope on Ulysses and the CRS experiment on Voyagers 1 and 2. This combination provides information on the radial intensity gradients in the inner solar system over the solar minimum period of cycle 22 as well as latitudinal gradients since Ulysses has just completed its slow latitudinal scan to 80º S. With the onset of significant solar activity, the intensity gradients of 30-60 MeV/n H and He become very small as their Compton Getting factor approaches – 0 at low energies. However the radial intensity gradient, G_r, of galactic cosmic ray (GCR) He, shows relatively small variation over the period 1996-2000.5 at a mean radial distance of 3 AU, consistent with the values predicted by Fujii and McDonald (1997) over the complete 1974-1996 period using the IMP/Pioneer/Voyager data and a radial dependence of the form $G_0 r^\alpha$. After 2000.5 the heliolatitude of Ulysses begins to change at a more rapid rate and can be used to determine the latitudinal gradient over the slow latitudinal scan. Comparisons of the modulation levels at 1AU and at Ulysses with those in the distant heliosphere out to 80AU indicate much larger changes in the inner heliosphere than observed beyond ~60AU.

1 Introduction

The growing body of data from the Voyager and Ulysses missions along with that of IMP 8 at 1AU make possible synoptic studies of cosmic rays and the interplanetary medium which yield greater insight into the physical processes of particle transport in the heliosphere and of the structure, dynamics and dimensions of this vast region.

A useful focus for such studies is the long term (11 and 22 year) modulation of cosmic rays and the manner in which it changes with heliocentric distance and latitude. The energetic particles respond to variations in the interplanetary medium and to changes in the configuration of the heliosphere. Because of their higher velocity and greater mobility, they also significantly extend the range over which transport processes and heliospheric structures can be studied.

In this paper we examine the solar minimum period of cycle 22 and the onset and initial phase of cycle 23 through 2001.3 which is close to the expected time of maximum solar activity. As the Voyagers move to ever increasing heliocentric distances (V-1 is now beyond 80AU) and differences appear between the modulation at 1AU and in the distant heliosphere, the Ulysses data becomes of special importance for understanding modulation processes in the inner heliosphere.

2 Observations

The energetic particle data used in this study are from the Goddard Medium Energy Detector on IMP 8 (R. E. McGuire, P.I.), the KET telescope of the Ulysses COSPIN

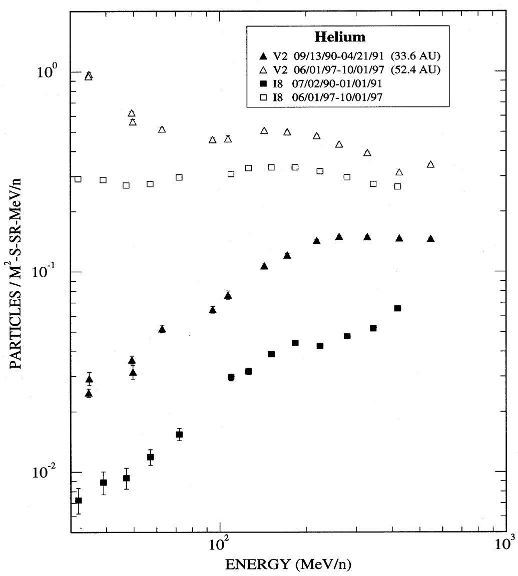

Fig. 1. V2 and IMP 8 helium energy spectra for cycle 22 solar maximum and solar minimum periods.

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experiment (R. B. McKibben, P. I. described in Simpson et al., 1992) and the Voyager Cosmic Ray Subsystem (CRS), (E. C. Stone, P. I. described in Stone et al., 1977). For these experiments, three common channels were identified which utilized multi–parameter analysis, and had comparable energy ranges: (1) 145-255 MeV/n He, (2) 34-50 MeV/n He and (3) 34-69 MeV H. The 145-255 MeV/n He nuclei are galactic cosmic rays. In the next paragraph, we discuss how the Ulysses data for this channel is normalized to the broader energy range of 150-380 MeV/n available from the IMP and Voyager experiments. Near solar minimum, the 34-50 MeV/n He are predominantly singly charged anomalous cosmic rays in the outer heliosphere. At 1AU in mid-1997 this channel consisted of ~45% anomalous cosmic ray (ACR) He^+ with the remaining 55% being of galactic origin. With increased levels of modulation there is a much more rapid decrease of the ACR component. At Voyager in 1997 the 34-69 MeV H is mainly ACR H while at 1 AU it is composed primarily of GCR H that entered the heliosphere at higher energies and has undergone significant energy losses through adiabatic deceleration processes.

To take advantage of the higher statistical accuracy available from the IMP and Voyager 150-380 MeV/n He data, it is desirable to normalize the Ulysses 145-255 MeV/n He to this broader channel. This is possible because the He spectra at GCR energies does not evolve significantly between 1AU and the location of V-2 at solar maximum (34AU in 1991.0) or at solar minimum (52.4AU in 1997.6) (Fig. 1). This can be examined quantitatively by comparing the ratio of $\dfrac{J(145-255\ \text{MeV/n He})}{J(150-380\ \text{MeV/n He})}$ at the two locations for a given period. At solar maximum (V-2 at 34AU):

$$\frac{J_{IMP\ 8}(145-255\ \text{MeV / n})}{J_{IMP\ 8}(150-380\ \text{MeV / n})} = 0.88\pm.01$$

$$\frac{J_{V\text{-}2}(145-255\ \text{MeV / n})}{J_{V\text{-}2}(150-380\ \text{MeV / n})} = 0.93\pm.01$$

and at solar minimum (V-2 at 52.4AU):

$$\frac{J_{IMP\ 8}(145-255\ \text{MeV / n})}{J_{IMP\ 8}(150-380\ \text{MeV / n})} = 0.92\pm.01$$

$$\frac{J_{V\text{-}2}(145-255\ \text{MeV / n})}{J_{V\text{-}2}(150-380\ \text{MeV / n})} = 0.90\pm.01$$

from which we suggest an appropriate normalization is

$$J_{Ulysses}(150-380\text{MeV / n}) = \frac{J_{IMP8}(150-380\text{MeV / n})}{J_{IMP8}(145-255\text{MeV / n})} \times J_{Ulysses}(145-255\text{MeV / n})$$

With the much smaller extrapolation in radial distance from IMP 8 to Ulysses, it is felt that this normalization procedure does not introduce significant error.

The range of heliocentric distances and latitudes covered by Ulysses, V-1 and V-2 over the period of study is shown in Fig. 2 (log-scaled distance, linear-scaled latitude).

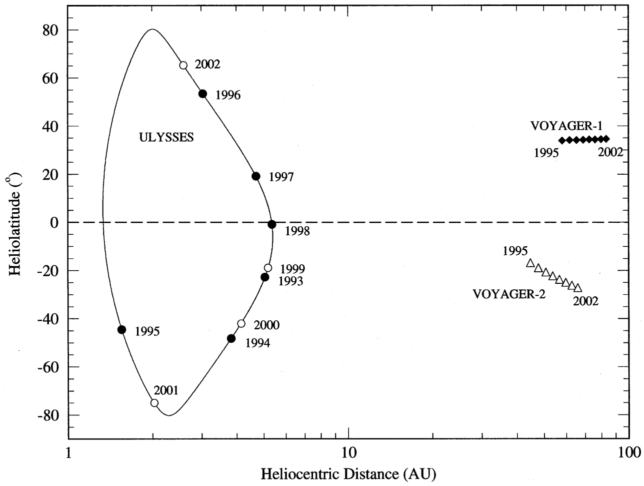

Fig. 2. Two dimensional projection in heliolatitude and radial distance for the Ulysses, Voyager 1 and Voyager 2 trajectories for 1995-2001.

Time histories (26 day averages) of the intensities of the three components from 1995 to 2001.3 are shown in Fig. 3. The corresponding IMP 8 data for 1975-1981.3 is shown as a dashed line but shifted by 20 years, consistent with the reversal of the sun's magnetic polarity in 1970 and 1990 and with the times of maximum cosmic ray intensity in 1977 and 1997 over the solar minima of cycles 20 and 22. From the comparison of these data sets it can be concluded:

- When Ulysses is below moderate heliolatitudes of ~30º (i.e. 1997.0-1999.0) there is an excellent correspondence between changes in the cosmic ray intensity at 1AU and near 5AU. Over this period the radial gradient of 265 MeV/n GCR He appears to be almost constant.
- With the onset of moderate solar activity in 1998.75, the radial gradients of low energy H and He (lower 2 panels, Fig. 3) become very small between IMP 8 and Ulysses.
- In 1997.7 the percentage of modulation (18%) for GCR He between 1 and 5AU was the same as that between 5AU and 68AU. The radial intensity gradient at this time are on the order of 5%/AU at 3AU, 0.3%/AU between 5 and 68AU, and <0.25% AU between 53 and 68AU.
- The total modulation and its time history (over the first three years of the cycle) is very similar at 1AU for both cycle 21 and 23 and for the IMP 8 and Ulysses observations.
- The GCR He intensity at 1AU and at Ulysses has decreased by a factor of ~4.6 (Fig. 3, top panel) from solar minimum to 2001.3. At 64AU the decrease is 36% and at 81AU is 17%.
- From 1998.25 to 2001.3 there are reasonably well-defined step decreases at 1AU and at Ulysses with a very similar pattern at the two locations in the inner heliosphere.

This pattern, but with greatly reduced amplitude, is convected out to the locations of V-1 and V-2 at the solar wind velocity. The effects are clearest comparing the GCR He data in the inner heliosphere with the V-1 and V-2 ACR 30-56 MeV/n He (top and middle panel, Fig. 3).

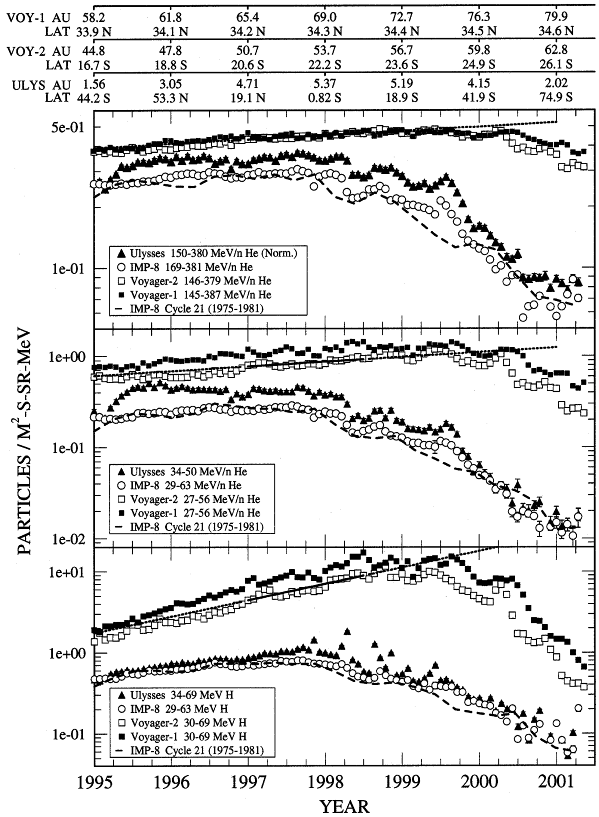

Fig. 3. Time histories (26 day AVG) of 150-380 MeV/n GCR He, 34-50 MeV/n He and 30-69 MeV H from the IMP 8 MED (R. E. McGuire, P.I.), Ulysses COSPIN KET (H. Kunow, P.I.) and the Voyager 1 and 2 CRS (E. C. Stone, P.I.) experiments. Periods with significant solar energetic particle contributions have been eliminated although there may be some residual in the low energy H in the inner heliosphere

It is of interest to examine the variations of the radial intensity gradients, g_r in the inner heliosphere. Fujii and McDonald (1997) found that the radial variations of g_r could be represented by $g_r = \frac{1dJ}{Jdr} = G_0 r^{\alpha}$ (where r is the heliocentric distance in AU and G_0 and α are constants for a given species over a specific time period). They used the Pioneer 10, 11 and Voyagers 1, 2, IMP 8 and Ulysses data to compute annual values of G_0 and α for 1974-1999.0. Such a representation makes it possible to estimate the value of g_r at any heliocentric distance within the termination shock. The annual values of g_r for 3AU over the 25-year period for GCR He are plotted in the top panel of Fig. 4. Also shown are the non-local gradients, $G_r = \frac{1}{r-1} \ell n \frac{J_u}{J_{IMP}}$ between IMP8 and Ulysses. There is one data point at 1993.1 and then G_r is measured for each 26 day period from 1996-2001.0, with excellent agreement between g_r and G_r. In 1998 as Ulysses moves more rapidly toward higher latitudes, there is an increase in the apparent G_r. As discussed below this is most likely due to a small positive latitudinal gradient, G_λ.

What is very unexpected is the relative constancy of g_r over the period time span 1974-2000 and the confirmation of this near constancy from the Ulysses data.

If cosmic ray streaming is negligible then Gleeson and Axford (1968) have shown that the radial diffusion coefficient is given by

$$K_{rr} = \frac{CV}{g_r} = \frac{CV}{G_0 r^{\alpha}}$$

where V is the solar wind velocity, V, and C is the Compton-Getting factor = ⅓ (2–αγ) where α is the spectral

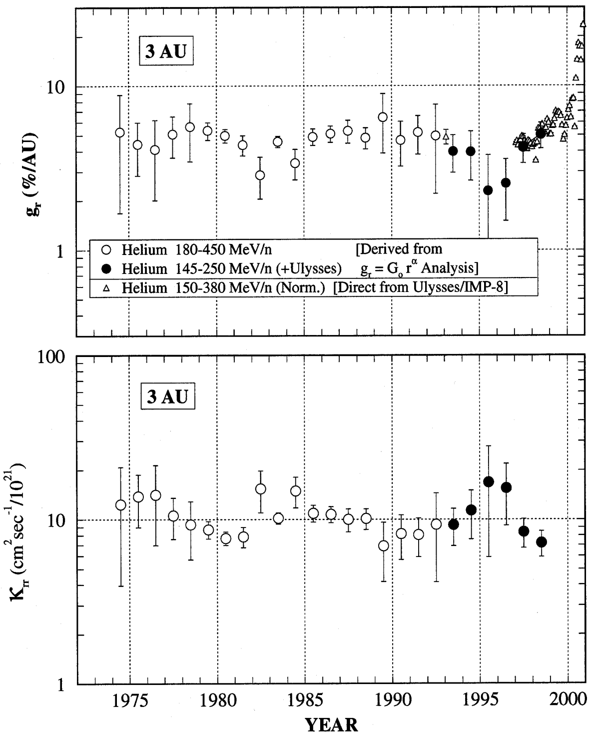

Fig. 4. Top panel: annual values of g_r at 3AU near the ecliptic plane for GCR He determined from the relation $g_r = G_0 r^{\alpha}$ based on P-10, P-11, V-1, V-2, IMP and Ulysses data. The triangular points are measurements of the non-local gradient $G_r = \frac{1}{r-1} \ell n \frac{J_u}{J_{IMP}}$. The apparent increase in G_r in 2000 is most probably due to the presence of a small, positive latitudinal gradient (~0.25%/°) as Ulysses moves to high latitudes.

slope of the differential energy spectra for the component being studied. The values of K_{rr} (lower panel, Fig. 4) appear to show slightly smaller variations over the 25 year period. Over a solar cycle V varies by ~20% and C by ~25% (Fujii and McDonald, 1997) and they are somewhat but not completely, out of phase with each other.

While the values of g_r (Fig. 4) have all been from data near the ecliptic plane, the proper analysis of the Ulysses/IMP G_r requires that

$$\ell n \frac{J_{\mathrm{IMP}}}{J_u} = G_r \Delta r + g_\lambda \Delta\lambda$$

where $\Delta\lambda$ are the differences in radial distance and latitude between IMP and Ulysses.

The apparent increase in G_r is most probably due to the movement to high latitudes by Ulysses in 2000 and preliminary analysis gives a value of 0.25%/° at 1/1/2001.

3 Discussion

While the changes in GCR He (265 MeV/n) at Ulysses and IMP 8 are very similar there is a steady decrease in the gradient of 34-50 MeV/n He in the inner heliosphere from ~9.5%/AU to ~0%/AU. as the modulation level increases. The gradient of 34-69 H was small at solar minimum and decreases rapidly toward 0 with the onset of modulation. These very small radial gradients below ~100 MeV/n are in agreement with the relation $G_r = \frac{CV}{K_{rr}}$ from the force-field approximation (see Discussion in Section 2). For H the spectral slope γ is already close to 1 at solar minimum: for 30-69 MeV/n He it approaches 1 with increasing modulation and hence C will approach zero. The gradients for both components become quite small at energies below 100 MeV. The consequences of small variation of g_r and K_{rr} for GCR He over two complete solar cycles are not completely understood at this time although they do appear consistent with GMIRs playing a large role in the modulation process from solar minimum to solar maximum. However the small modulation of GCR He in the distant heliosphere through 2001.3 and the small size of the step decreases at the Voyagers compared to those in the inner heliosphere pose difficulties for such a model.

For cycle 21 and 22 the step decreases in the outer heliosphere out to 49AU were generally of the same order or larger than those at 1AU (McDonald et al., 1993). However this same study did suggest that the net modulation from solar minimum to solar maximum for GCR He was somewhat smaller at 40AU than at 1AU. It may be possible to resolve these difficulties with a higher frequency of GMIRs for the period from solar minimum to solar maximum.

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