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Cosmic rays in the heliosphere over the solar minimum of cycle 22

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Abstract. The combination of Voyager 1 and 2 in the distant heliosphere and IMP 8 and Ulysses in the inner heliosphere provide cosmic ray observations over the solar minimum period of cycle 22 that extend beyond 70 AU. The cosmic ray intensity at 1 AU over the 1996-1997 time period exhibits the quasi-plateau like characteristic predicted for qA>0 epochs and the energy spectra of 20-450 MeV/n He and 20-220 MeV H are essentially identical to those observed for 1976-1977 over a similar phase of the heliomagnetic cycle, suggesting that modulation conditions at both times are very similar throughout the heliosphere. This similarity makes it possible to combine the Pioneer 10 data from 1977 with that of Voyager 1 and 2 from 1997 to obtain a more detailed measure of the distribution of cosmic rays in the heliosphere from 1 to > 70 AU near the ecliptic plane (λ<35˚). It is found that beyond ~12 AU the radial intensity gradients are very small; less than 0.33% AU for 265 MeV/n He. Such a small intensity gradient indicates that the intensity levels observed at V-1 for 7-18 MeV/n ACR 0^+ and 265 MeV/n He are close to those expected at the termination shock at the V-1 heliolatitude of 34ºN. Furthermore the measured 1997 intensities of the GCR He and ACR 0^+ at 70 AU are significantly less (x 5 smaller for ACR 0^+) than those observed at the 1987 solar minimum at 42 AU. For the ACR component such changes appear to be qualitatively consistent with Jokipii's diffusive shock drift acceleration model. For GCR He the difference may be further evidence for modulation in the region of the heliosheath combined with gradient and curvature drift effects over the two different phases of the heliomagnetic cyle.

1 Introduction

The Voyager and Pioneer 10 observations now span 1.3 heliomagnetic cycles and extend beyond 80 AU. The extensive studies of the temporal and spatial variations of galactic and anomalous cosmic rays from the data provided by these missions along with that from IMP 8 and Ulysses in the inner heliosphere have revealed a cosmic ray modulation process that is more complex than had been previously expected. While the basic physical properties that govern the transport of energetic particles are well understood, there remain vast regions of our solar system that are unexplored and whose physical configurations and transport properties are not well known. Since energetic particles respond to changes in the interplanetary medium and to the configuration of the heliosphere, their temporal and spatial variations provide insight into the structure and dynamics of the distant heliosphere. An appropriate baseline for these studies is at solar minimum when the heliosphere is in a quasi-stationary state, and the cosmic ray intensity is at its highest level. This is an excellent time to study the residual modulation and relate it to the source spectra deduced for various components and to compare with the data from past solar minimum periods including epochs of the same and of opposite polarity of the solar magnetic field. In this paper we examine the spatial variation of 150-380 MeV/n galactic cosmic ray He (GCR He) and 8-18 MeV/n anomalous cosmic ray oxygen (ACR O^+) over the solar minimum period of cycle 22 (~1996–1998.25 at 1 AU) out to heliocentric distances of 70 AU and compare these observations with the previous solar minimum periods of cycle 20 and 21.

2 Observations

The time history of the GCR 265 MeV/n He intensity (26 day Avg.) for Voyagers 1 and 2 (V1, V2) and IMP 8 are shown (Fig. 1) for 1996 – 1999.0 along with the corresponding Ulysses COSPIN/KET GCR He data when that spacecraft is at a heliolatitude < 20º and at a radial distance of 5.0 – 5.2 AU. These data exhibit the quasi-plateau feature over solar minimum expected for a qA > 0 epoch when the Sun's magnetic field in the northern hemisphere is outward directed and the drift imposed flow of positive ions is from high latitudes downward and out

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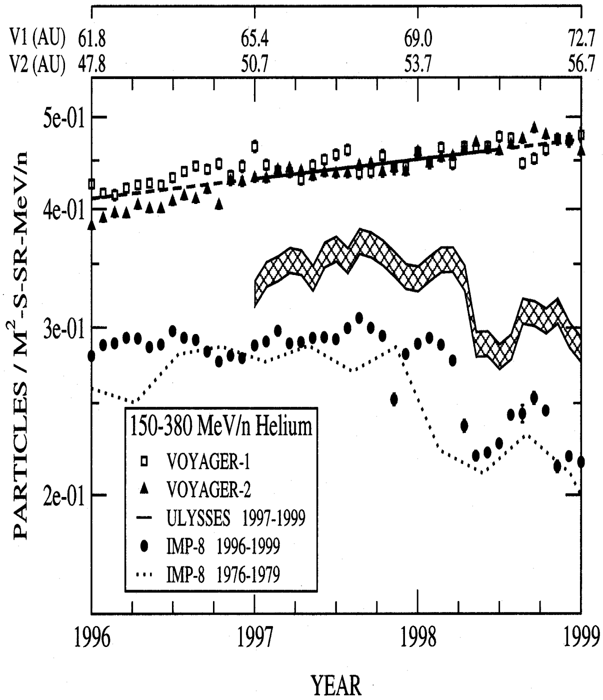

Fig. 1. The He data is from the following sources: V-1, V-2 CRS exp., E.C. Stone, P.I.; Ulysses, Cospin KET, H. Kunow, P.I.; IMP 8, GSFC MED, R. McGuire, P.I.

along the heliospheric neutral current sheet (HNCS). The lower dashed line is the IMP 8 data from 1976 – 1979.0, shifted by 20 years to line-up the approximate times of the 1970 and 1990 changes in the polarity of the Sun's magnetic field.

The 1 AU data for the two periods indicate that the GCR He intensity is nearly the same over the 1976.5 – 1977.5 and 1996.5 – 1997.5 time periods with the ratio of the fluxes over these periods being $\dfrac{J(1976.5-1977.5)}{J(1996.5-1997.5)} = 0.986 \pm .003$. For the Climax Neutron monitor the ratio for the two periods is 1.001. The 1 AU ACR and GCR He energy spectra are also very similar (Fig. 4). These comparisons of the cosmic ray data for the two periods suggest that from a modulation perspective the state of the heliosphere was essentially the same over both these qA>0 solar minima, making it possible to compare the 1977 Pioneer data near 13 AU with that of V-1 in 1998 at 70 AU to better define the GCR spatial distribution.

To check the relative calibration of the P-10 and V-1 measurements, the GCR He spectra are compared (Fig. 2a) at a time when the two spacecraft are separated by 2 AU in radial distance and 34º in heliolatitude with the ratio for 265 MeV/n He being $\dfrac{J(\mathrm{P}-10)}{J(\mathrm{V}-1)} = 0.95 \pm .03$. This ratio is taken as an upper limit of the relative accuracy of the V-1 and P-10 measurement and on the latitudinal gradient, $G_\lambda < 0.25\%/°$. The 1977 P-10 GCR He spectra is very similar to that of V-1 at 70 AU in 1998 (Fig. 2b) and a value of the non-local radial gradient $G_r = 0.1 \pm 0.1\%/\mathrm{AU}$ is obtained at an average heliocentric distance, $\bar{r} = 42\,\mathrm{AU}$. In the outer heliosphere from 1997-1999.0 the GCR He intensities (Fig. 1) are essentially identical, and give a value of $G_r = 0.13 \pm 0.2\%/\mathrm{AU}$ between 52 and 67 AU. A value of 5%/AU is obtained for 265 MeV/n He between 1 and 5 AU using the 1997 IMP 8 and Ulysses data. The 1996 V-1, V-2 and P-10 data gives a value of $G_\lambda = 0.2 \pm 0.15\%/°$ at $\bar{r} = 63\,\mathrm{AU}$.

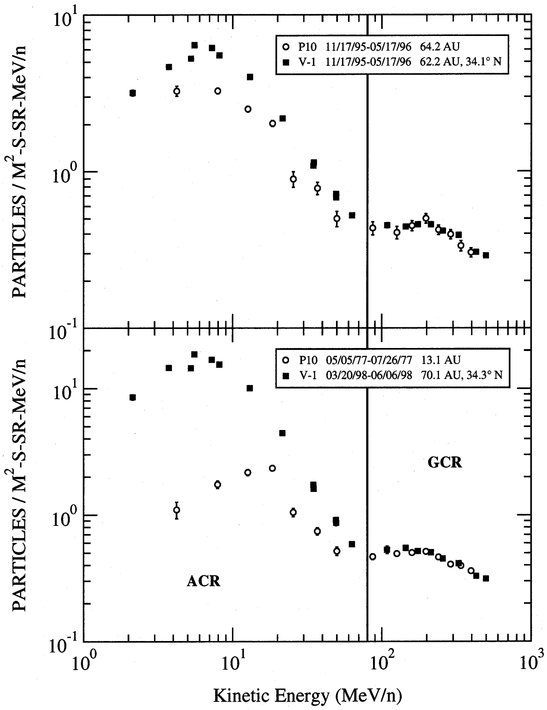

Fig. 2. P-10 data from CRT, F. B. McDonald, P.I.

To compare with the data from previous cycles in greater detail, the time history of ACR O^+ and GCR He is shown for 1972–1999.0 using data from IMP, Wind, and Sampex spacecraft at 1 AU and a combination of P-10 and V-2 in the outer heliosphere (Fig. 3). As Cummings and Stone (1999) and McDonald et al. (1998) had noted previously, the cycle 21 solar minimum intensity of ACR O^+ at 42 AU is ~ 5x larger than in 1998 at 70 AU. For GCR He the cycle 21 intensity is ~36% greater. At 1 AU the ACR O^+ intensity is slightly lower (~40%) in 1987 than in 1997. Webber and Lockwood (1997) and McDonald et al. (1998) found that this relative reduction in GCR and ACR intensities at 1 AU between qA< 0 and qA>0 solar minimum periods was a function of ßR (ß is the particle velocity relative to c and R is its rigidity) below ~ 1 GV for a given species. However this situation is reversed at neutron monitor energies leading to a crossover in the relative response over successive solar minima Reinicke and Potgieter (1990).

Further intercomparisons of these solar minimum data sets is provided by the detailed He spectra (Fig. 4). These illustrate the equivalence at 1 AU of the cycle 20 and 22 solar minimum, the small gradients in qA>0 cycles between 13 and 70 AU and the higher intensity levels in 1987 at 42 AU compared to V-1 at 70 AU in 1998. Also shown are the local interstellar He spectra derived by Webber and by Lukasiak (private communications, 2000) using the BESS and AMS high energy He measurements. Also shown is an extrapolation of the 1987 spectra to the termination shock (at an assumed location of 90 AU) using a spatial dependence of $g_r = \frac{1}{J}\frac{dJ}{dr} = G_0 r^{\alpha}$ with $G_0 = 28\%/\mathrm{AU}$ and $\alpha = -1.15$.

The ACR He data (Figs. 2 and 4) illustrate the complexities of ACR modulation at low values of ßR. Nevertheless the ACR He display the same relative behavior as the GCR He in the comparison between cycle 21 and 22 down to ACR He^{+} energies of 25 MeV/n.

3 Discussion

The 1 AU ACR O^{+} time histories (Fig. 3) graphically illustrates the expected behavior of cosmic rays in the region inside the termination shock over a 22 year heliomagnetic cycle when drift effects are important [Jokipii and Thomas, 1981][Kóta and Jokipii, 1983]. The peaked response over 1987 (Fig. 3) shows the dominant effect of changes in the tilt angle for qA<0 while the flat plateau region, extending from 1993.7 to 1998.0 clearly establishes that changes in the tilt angle of the heliospheric neutral current sheet does not play a role in the modulation process in qA>0 epochs at tilt angles < 30º. Cummings and Stone (1999) reached a similar conclusion for ACR O in the outer heliosphere. The slower recovery of GCR He has been ascribed to the continuing modulation effectiveness of the global merged interaction region, produced by the March/June 1991 periods of very high solar activity as it traversed the region of the heliosheath (McDonald et al. 2000).

The very low values of G_r in the outer heliosphere should have been anticipated. Small gradients over qA>0 solar minima were clearly predicted when drift effects are important (Kóta and Jokipii,1983) . For 1977 Fujii and McDonald (1997) using a radial dependence of the form $\frac{1}{J}\frac{dJ}{dr} = G_0 r^{\alpha}$ and obtained values of $\alpha = -1.12$ and $G_0 =$ 0.17% AU. These predict $g_r = 0.26\%\,\mathrm{AU}$ at 41.5 AU and 0.17% at 60 AU compared to the observed upper limits of 0.2% AU and 0.33%/AU at these heliocentric distances. The 1996 $G_{\lambda} = 0.02 \pm .15\%/°\,\mathrm{AU}$ at 63 AU would appear to be small at a time when drift effects are expected to be large.

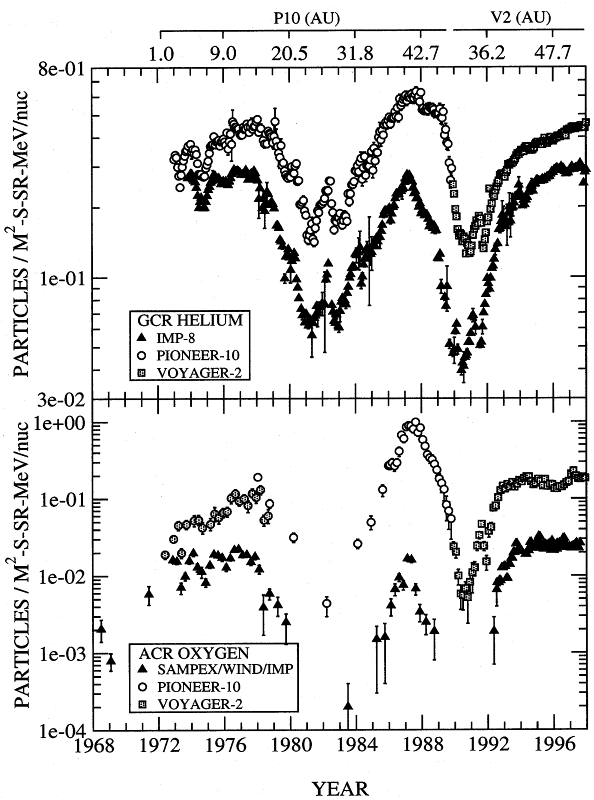

Fig. 3 The 1 AU data for GCR He is from the IMP 8 MED, and the ACR O is from IMP-8 (R. Mewaldt) SAMPEX HILT (B. Klecker) and WIND EPACT-LEMT (D. Reames) The outer heliosphere GCR He and ACR O intensities are from the P-10 CRT and V-2 CRS.

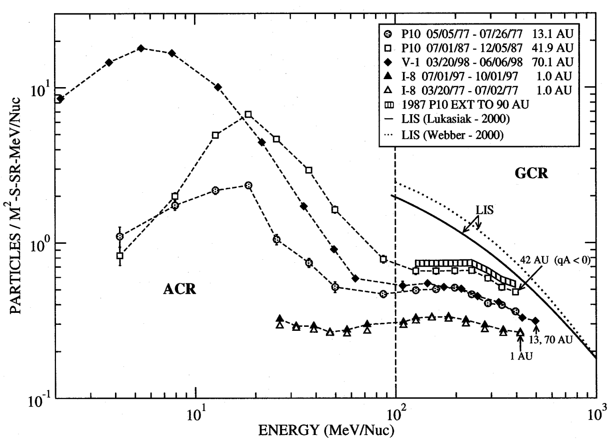

Fig. 4. The ▥▥▥▥ is the extrapolation of the 1987 GCR He flux from 42 AU to 90 AU–the assumed location of the termination shock using gradient parameters derived from I-8, V-2 and P-10 peak He intensities of 1987.

Such a small value of G_{λ} suggest that simple spherically symmetric models might give some insight about the particle diffusion coefficient, K_{rr} , in these distant regions. At these heliocentric distances $K_{\perp} \sin^2 \psi \gg K_{\parallel} \cos^2 \psi$ where ψ is the spiral angle of the interplanetary magnetic field and $K_{rr} \approx K_{\perp} \approx \frac{CV}{G_r}$ using the force-field approximation where C is the Compton-Getting factor (0.8 for GCR He) and V is the solar wind velocity (450km/s) and $G_r < 0.33\%$ / AU so $K_{rr} = K_{\perp} > 2.0 \times 10^{23}\ \mathrm{cm}^2 - \mathrm{s}^{-1}$ for GCR He and $\lambda = \frac{3K_{rr}}{\beta C} > 3.6$ AU. These lower limits on K_{rr} and λ are larger than those generally calculated for this region (c.f. le Roux et al. 1999), but are very similar to the value of λ = 2.0 ± 0.4 deduced for 1.5 GV ACRs in 1998 (Cummings and Stone, 1999b).

In the inner heliosphere G_r for 265 MeV/n He is large, 5%/AU. In 1997 ~0.5 of the modulation between 1 and 70 AU near the ecliptic plane occurs between 1 and 5 AU. The gradients of ACR O show a similar radial dependence with large gradients inside 10 AU and essentially zero gradient beyond (Cummings and Stone, 1999a).

The differences between the 1997 and 1987 intensities in the outer heliosphere (Figs. 3, 4) establishes that cosmic rays enter the region inside the termination shock most readily via the HNCS at solar minimum in qA<0 epochs with this path becoming more difficult at lower values of ßR in the inner heliosphere. For ACR O, Cummings and Stone (1999a) concluded that the difference between 1987 and 1997 was qualitatively consistent with Jokipii's (1986) model of diffusive shock drift acceleration with ions gaining energy as they drift along the shock front. For qA<0 the drift direction is from the pole to the equator with the maximum energy at the helioequator. For qA>0 the maximum energy is attained at the pole.

For galactic cosmic rays the extrapolation of the 1987 data to the termination shock (Fig. 4) is consistent with significant residual modulation in the heliosheath. The 1997 data would imply even larger modulation in the heliosheath when qA>0.

Suess and Nerney (1993) have argued that because of reconnection effects between the interplanetary magnetic field in the heliosheath and the magnetic field in the local interstellar medium near the nose of the heliopause, galactic cosmic rays will have direct access across the heliopause to field lines connected to equatorial regions of the inner solar system. Conversely, they suggest that because polar heliospheric magnetic field lines never approach the heliopause, polar regions are accessible to GCRs only through magnetically transverse diffusion across the flanks of the heliotail. Jokipii (2001, private communication) has argued that because of the effects of field-line meandering at the Sun, the difference between ease of particle entry into the heliosphere at the equatorial and at the polar regions will not be significant. The resolution of this matter requires 2D modulation models with drifts, heliosheath effects and proper account of turbulence over the solar poles.

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