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The Relative Recovery of Galactic and Anomalous Cosmic Rays: Evidence for Modulation in the Heliosheath

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Abstract

Following the passage of the large interplanetary disturbances produced by the intensive solar activity of March/June 1991, the recovery of anomalous cosmic rays (ACR) at Voyager 1 (46AU, 3° N) is found to be very different from that of galactic cosmic rays (GCR). Contrary to what is expected, the time constant of the recovery of 265 MeV/n GCR He is approximately twice as large as that of 43 MeV/n ACR He^+ and 13 MeV/n O^+. These differences in the relative recovery of the ACR and GCR strongly suggest that the combined interplanetary disturbances produced by the March/June 1991 solar activity remain an effective modulation agent for galactic cosmic rays after it had passed beyond the termination shock and into the region of the heliosheath.

1 Introduction:

Galactic cosmic rays (GCR) entering the solar system must traverse the region between the heliopause and the termination shock, the heliosheath, before encountering the supersonic solar wind. This termination shock is the source region of a well-defined energetic particle population, the anomalous cosmic ray component (ACR). These predominantly singly charged, low velocity, high rigidity ions have their origin as interstellar neutrals which have been ionized in interplanetary space, convected outward by the solar wind and accelerated at the termination shock according to the currently accepted paradigm.

Pioneer and Voyager studies have shown that the very large decrease in cosmic ray intensity from solar minima to solar maximum occurred in a series of discrete steps produced by global merged interaction regions (GMIRs) [Burlaga et al., 1993; McDonald and Burlaga, 1997]. These long-lived, large scale, quasispherical disturbances form beyond some 10-20 AU through the coalescence of high-speed solar wind streams and multiple interplanetary shocks. The question then arises does the extended region of the heliosheath play a role in the transport of galactic cosmic rays and does the effect of GMIRs extend beyond the termination shock into this region. The relative response of galactic and anomalous cosmic rays provides a unique diagnostic tool for exploring the role of the heliosheath in the modulation process.

In March and June 1991 there occurred 2 of the most intense periods of solar activity over the past 30 years with essentially all of the March 1991 activity occurring at southern latitudes centered around ~25°S, while in June all of the large events occurred in the northern hemisphere of the sun with the resulting GMIR being a combination of the March/June activity. In this paper we compare the relative recovery of ACR He^+ and O^+ with that of GCR He.

2 Observations and Analysis:

The data used in this study is primarily from the High Energy Telescope II (HET II) of the Voyager 1 cosmic ray experiment (Stone et al. 1977). This double-ended telescope cycles between a number of different analysis modes, 3 of which respond to He nuclei stopping in the detector with an incident energy of 30-56 MeV/n. The viewing direction of one end of the telescope (A) is pointed predominantly radially inward while the other end (B) looks 180° away in the opposite direction toward the outer heliosphere.

The 3 analysis modes are independent with one for the A end and separate high and low gain modes for the B end.

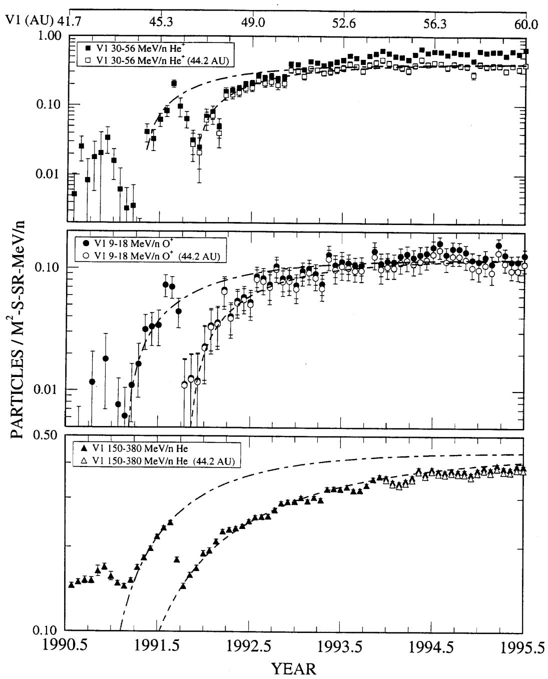

Figure 1: Time histories of 30-56 MeV/n He$^+$ (corrected for GCR He), 8-18 MeV/n O$^+$ and 150-380 MeV/n GCR He.

RELATIVE RECOVERY OF GCR AND ACR: The 3 panels of Figure 1 give the time history of 30-56 MeV/n He$^+$ (i.e., with the GCR He contributions removed), 8-18 MeV/n ACR 0$^+$ and 150-380 MeV/n GCR He. Also shown is the time history of these components corrected to a constant heliocentric distance of 44.2 AU. The onset of the pre-GMIR recovery period is clearly evident at 1991.2 as is the arrival of the GMIR near 1991.71. Beginning in early 1993 there appears to be a difference in the recovery of galactic and anomalous cosmic rays. For O$^+$ and He$^+$ the long term recovery rate over this period is zero or very small while GCR He shows a steady increase. This difference can be examined by plotting the intensity of 150-380 MeV/n He versus that of 30-56 MeV/n He$^+$ and 9-18 MeV/n O$^+$ over the 1991.8-1996.0 time period (Figure 2). The second Arrow (1993.1) marks the time of essentially full recovery of the ACR He$^+$ and O$^+$ intensity while the GCR He continues its recovery.

RECOVERY TIME CONSTANTS: The ACR and GCR recovery following the passage of the GMIR is distinctly exponential in character (Fig. 1). In separate on-going studies (McDonald et al. 1997) it has been found that the post GMIR data can be represented by a function of the form

$$(1) \quad J(t,r_1) = J_0(r_1) - (J_0 - J_{solar\ \max})\exp\left(-\frac{t-t_1}{t}\right)$$

where J_0 is the intensity at r_1 after full recovery, $J(r_1)_{solar\ max}$ and t_1 are the intensity and time at the onset of recovery and τ_{rec} is the recovery time constant. The fit of this function to the GCR and ACR data for the post GMIR recovery (dashed line Fig. 1a,b,c gives values of τ_{rec} = 1.75, 0.95 and 1.0 years for 265 MeV/n He, 43 MeV/n He$^+$ and 13 MeV/n O$^+$. If the modulation boundary coincided with the termination shock then it is expected that the value of τ_{rec} for GCR He would be substantially smaller than that of ACR He$^+$.

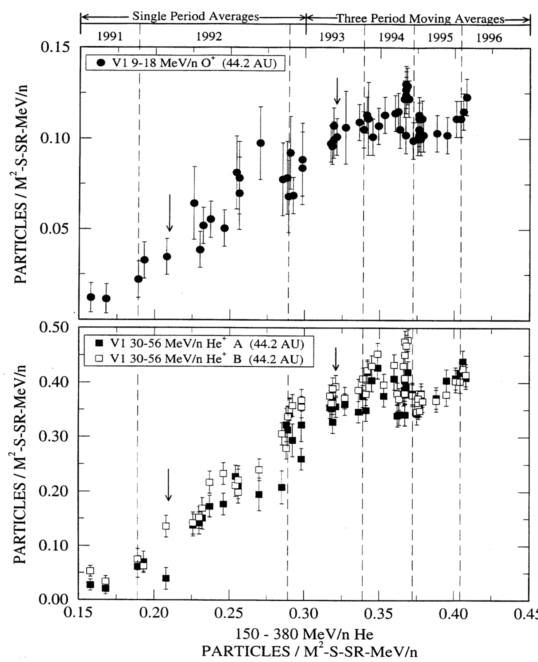

Fig. 2: Regression plots of 9-18 MeV/n O$^+$ and 30-56 MeV He$^+$ for 1991.8-1996.0

As noted previously the cosmic ray recovery at V-1 had started some 5 months before the arrival of the GMIR. This data along with Equation 1 can be used to estimate the pre-GMIR values of τ_{rec} for ACR and GCR, giving τ = 0.95, 0.95, and 0.65 years for the GCR and ACR He$^+$ and O$^+$ (Table I). It is assumed that if the 1991 GMIR had not occurred the

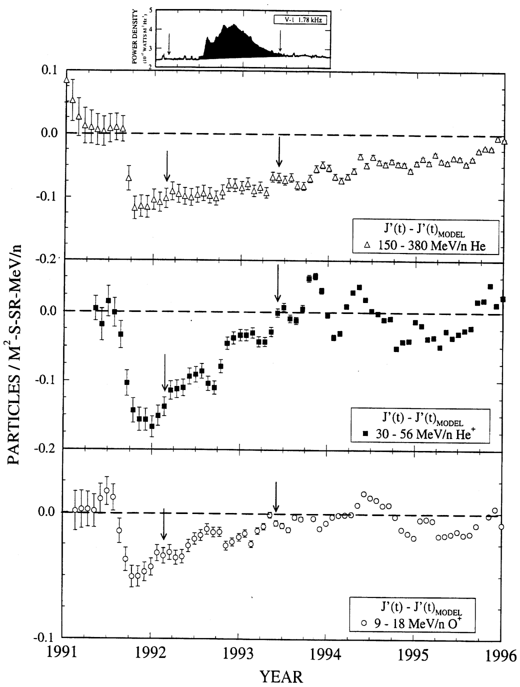

Fig. 3: The estimated decrease in the GCR He^{++} and ACR He$^+$ and O$^+$ due to the passage of the 1991

recovery would be that shown by the upper dashed line in each of the 3 panels of Figure 4. The effect of the GMIR can then be determined by subtracting the actual post-GMIR intensity from the pre-GMIR extrapolated value. The resulting profiles (Figure 3) give an estimate of the GMIR-imposed cosmic ray decrease.

ANISOTROPY OBSERVATIONS: The time history of 30-56 MeV/n He for the 3 different analysis modes are shown for the 1990.5-1995.5 time period (41.7-59.9 AU) in Figure 4. On 1992.14 there is a sudden divergence between the intensity of inward flowing 30-56 MeV/n He (B-end) over that of outward flowing He (A-end) that is maintained for some 20 days. After that time there are smaller anisotropies that persist through most of 1992 and for several brief periods over the next several years. The magnitude of the anisotropy, δ, is estimated by the relation $\delta = \dfrac{J(B) - J(A)}{J(B) + J(A)}$. The values obtained for the 20 day period centered on 1992.16 give a mean value of 0.38 ± .09. During the continuing recovery from 1992.3 to 1992.6, $\delta = 0.08 \pm .02$.

3 Discussion:

As the GMIR moves through the heliosphere toward the termination shock it greatly reduces the intensity of the ACR and of the medium energy (<500 MeV/n) GCR components. Theoretical studies of the cosmic ray hysteresis effect (O'Gallagher, 1975, Chih and Lee, 1986) have estimated the average propagation time $\bar{t}_p$ for a particle to travel from the modulation boundary to 1 AU, as a function of κ the particle diffusion coefficient, $r_{t.s.}$ the distance to the termination shock and V the solar wind speed.

The values of $\overline{t_d}$ and τ_{rec} are given in Table I for the 3 components. Assuming that the ten $\overline{t_d}$ provides an estimate for the relative ACR and GCR recovery times and should be of the same order as the recovery times τ_{rec} measured directly from the He$^+$, O$^+$ and He^{++} time histories (Eq. 1, Figure 1). This is indeed the case for ACR He$^+$, and O$^+$ while the observed τ_{rec} for GCR He^{++} is 7 times larger than its calculated value of $\overline{t_d}$. Furthermore this value of τ_{rec} is 1.75 years for GCR He^{++} while values of τ_{rec} = 0.95 and 1.0 years are measured for He$^+$ and O$^+$. The most plausible explanation for the much longer recovery time for GCR He^{++} is that the GMIR remains an effective modulator for a significant time after its passage beyond the termination shock.

Table I. Observed and Calculated Times

	κ(50 AU) cm^2 - s	τ_{rec} (years) pre GMIR	τ_{rec} (years) post GMIR	$\bar{t}_d$ (years)
150 – 380 MeV/n He	4.8 x 10^{22}	0.95	1.75	0.24
30 – 56 MeV/n He$^+$	1.7 x 10^{22}	0.95	0.95	0.6
9 – 18 MeV/n O$^+$	2.1 x 10^{22}	0.65	1.0	0.5

SCATTERING MEAN FREE PATHS DERIVED FROM ANISOTROPY DATA: Following the passage of the GMIR there is a period of some 20 days when the intensity of 30-56 MeV/n He observed in the B-telescope is a factor of 2.25 greater than that of the A-telescope leading to a mean anisotropy of 0.38 ± 0.9 (Fig. 4).

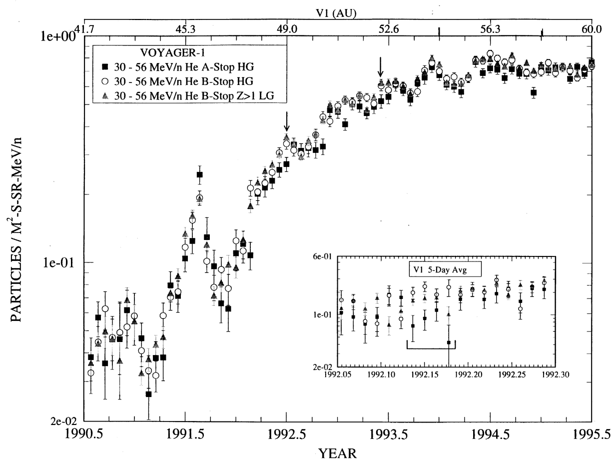

Fig. 4: Time history (26 day AVG) of 30-56 MeV/n He for 3 different analysis modes of the CRS HETI telescope.

From 1992.3 – 1992.6 there is a smaller anisotropy of 0.08 ± .022. Marshall and Stone (1977), using the theoretical studies of Jokipii and Parker (1970), obtained an expression for δ of the form:

$$(2)\quad \vec{d} = \vec{d}_{corr.} + \vec{d}_{diff.} = \frac{3}{b\,c}\left(VC - \vec{K}\,\frac{\vec{\nabla}J}{J}\right) = \frac{3}{b\,c}\left(VC - \kappa G_r\right) = \frac{3Vc}{b\,c} - lG_r$$

J is the particle intensity, G_r is the radial intensity gradient, C is the Compton-getting factor and $k = \frac{b\,c\,l}{3}$ where λ is the scattering mean free path. C = 0.66 for 43 MeV/n He^+, V is estimated to be 600 km/s, leading to a convective anisotropy of 0.014. (a) $\vec{d}_{diff} = \lambda G_r = -0.38 - .014 = -0.39 \pm .09$ (b) $\vec{d}_{diff} = \lambda\, G_r = -.08 - .014 = -.094 \pm .025$ for 1992.18 and 1992.45 respectively.

It is not possible to determine G_r for the 1992.18 period but using both the V1 and V-2 data a value of 3.6 ± 1%/AU is obtained for the 2nd interval, leading to a scattering mean free path of 2.6 AU. This is essentially an estimate of λ_r in the outer heliosphere conditions and is in reasonable agreement with the value of 1 AU obtained by Cummings and Stone (1997) based on studies of the energy spectra of ACR using V-1 and V-2 data during 1995-1996..

In a study of the radial intensity gradients of ions > 70 MeV Webber and Lockwood (1987) found over the period from 1977-1983 when this integral rate at 1 AU decreased by a factor of 3, the radial gradient of these ions did not change and interpreted these observations as evidence for a modulation barrier between 55-90 AU. Potgieter and le Roux (1989) and Quenby et al. (1990) showed that properly chosen diffusion coefficients for the region of the heliosheath would provide the required radial gradients and level of modulation that were consistent with the observation. Jokipii et al. in a more detailed simulation which included drifts, found that the radial gradients changed abruptly at the termination shock, with the nature of the change being a strong function of particle energy making it difficult to interpret integral gradients which include both the effects of low and high energy particles.

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