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A comparative study of the cosmic ray recovery process in the inner and outer heliosphere

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Abstract. The cosmic ray recovery of galactic and anomalous cosmic rays for cycle 22 over the 1991-1997 time period is strongly affected by the intense solar activity of March/June 1991. This results in a recovery that differ from that of cycle 20 and both in turn differs significantly from the cycle 21 recovery (1981-1987) in a qA<0 epoch. For cycle 22 it is found that the recovery time constants for 265 MeV/n GCR He are the same at 1 and 44 AU (τ = 1.9 years) which is much longer than the 0.95 year time constant measured at these distances for ACR 0^+. This has previously been interpreted as evidence for cosmic ray modulation in the heliosheath. There is no evidence for similar effects in cycle 21 following the large outburst of solar activity in mid 1982. What is most puzzling about the cycle 22 recovery is that the net increase in 150-380 MeV/n He between 1990 and 1997 is the same at 1 AU and at 44 AU. However, for ACR 0^+ the net increase at 44 AU is appreciably larger than at 1 AU. This analysis suggests that after 1993.2 (i.e., following the passage of the global merged interaction region produced by the March/June activity) the continuing recovery of galactic cosmic rays proceed from the outer into the inner heliosphere. Again, this is different from the 1982 – 1987 recovery which appeared to be strongly controlled by changes in the inclination of the heliospheric neutral current sheet (HNCS).

1 Introduction

Following solar maximum there is a decrease in solar activity, high-speed solar wind streams and their associated co-rotating interaction regions appear and cosmic rays start their recovery toward solar minimum conditions. This paper will be concerned with three aspects of the recovery period.

(i) The comparison of the recovery of cosmic rays over successive solar activity cycles.

(ii) The relative recovery of galactic cosmic rays and anomalous cosmic rays in the inner and in the outer heliosphere over cycle 22.

(iii) A comparative study of the cosmic ray recovery process at 1 AU and in the distant heliosphere.

For all three objectives we use the cosmic ray data from a subset of the spacecraft that make up the heliospheric network–Pioneer 10 (P-10), Voyagers 1 and 2 (V1, V2), IMP 8, SAMPEX and Wind. These observations now span the complete recovery and solar minimum periods of cycle 21 and 22 out to heliospheric distances beyond 70 AU.

2 Observations

(i) Our study of the recovery over successive solar cycles focuses on the role of drifts in qA<0 (1980-1990) and qA>0 (1990-2000) epochs. For cycle 21 (qA<0) previous studies (Lockwood and Webber, 1990; Lopate and Simpson, 1990; Cummings and Stone 1999; McDonald et al., 1993) have shown that changes in the cosmic ray intensity appears to be controlled by changes in the inclination, $\alpha_{c.s.}$, of the heliospheric neutral current sheet. The ACR and GCR components (Fig. 1) simultaneously reach a relatively sharp maximum at 1 AU. This feature is convected out in the ecliptic plane to V-2 (23 AU) at the solar wind velocity. At P-10 (42 AU) there is a plateau region of ~ 1.5 years in the 150-380 MeV/n He data. The ACR 8-16 MeV/n O^+ time history is not as sharply peaked at P-10 or at V-2 as observed at 1 AU, suggesting that the effects of changes in $\alpha_{c.s}$ near solar minimum (i.e. when $\alpha_{c.s}$ is small) in qA<0 epochs diminish with increasing heliocentric distance. The cycle 22 recovery is discussed in the next two sections.

(ii) The recovery of cycle 22 at 1 AU and at the Voyagers is a reasonably smooth exponential (Fig. 2, 3) following the passage of the GMIRs produced by the March/June 1991 periods of intense solar activity. The ACR O^+ intensity maintains a flat plateau over a 4.5 year period providing strong evidence that changes in the inclination of $\alpha_{c.s}$ at 1 AU (from 1993.75-1998.25) and in the outer heliosphere, do

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not play a significant role in the modulation process for qA>0 epochs.

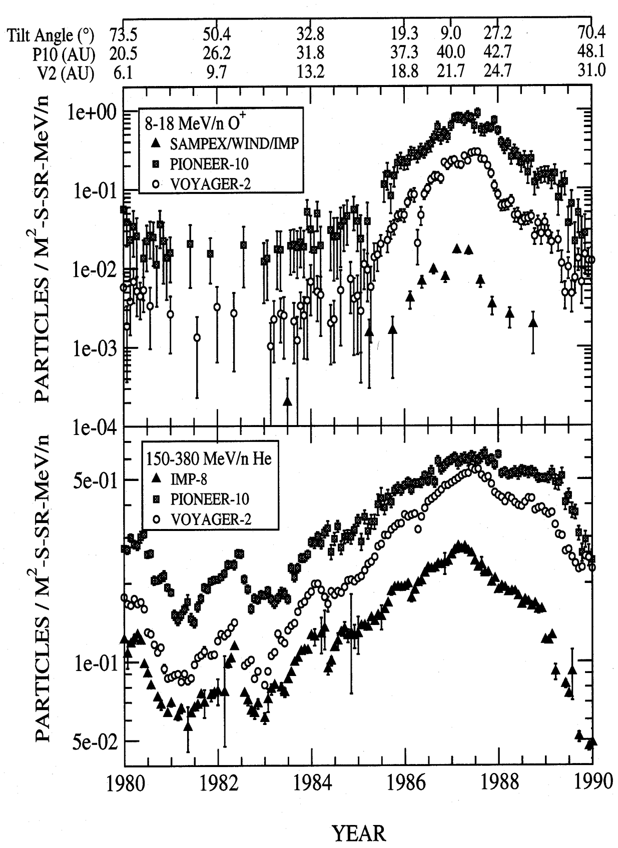

Fig. 1 Time histories of GCR He (26 Day AVG) and ACR He at 1 AU and at V-2 and P-10 over the 1980 – 1990 qA<0 epoch.

The intensity of GCR He at 1 AU and at V-1 continues to increase (until 1996.25 at 1 AU) with a recovery that is more gradual than that of ACR O^+. To intercompare the various sets of data from cycle 22, it is useful to determine the recovery time constants for ACR O^+ and GCR He at 1 AU and at the location of the two Voyagers. The procedure used here follows that developed by Webber et al. (1986) and assumes that the rate of increase is proportional to the intensity difference between the observer and the modulation boundary

$$\frac{dj(t)}{dt} = \frac{J_0 - J(t)}{\tau}$$

where J_0 is the solar minimum intensity, τ is the recovery time constant and $t = 0$ marks the onset of the 1 AU recovery at 1992.6. Then:

$$J(t) = J_0 - (J_0 - J_{\Theta\mathrm{MAX}})e^{-t/\tau} \qquad (1)$$

Fitting the 1 AU data from 1992 – 1998.0 gives the set of values of τ listed in Table 1 along with those from V-1 and V-2 . For this calculation the V-1 and V-2 intensities have been corrected back to a constant heliocentric distance of 44 and 34 AU.

Table 1. Recovery Time Constants τ_{rec} 1992-1998

	τ(1 AU)	τ(V-2) 34 AU	τ(V-1) 44 AU
150-380 MeV/n He	1.93 years	1.90 years	1.75 years
120-230 MeV H	4.0	4.2	4.2
8-18 MeV/n O^+	1.0	.93	1.0

There is a distinct difference in the relative recovery of ACR O^+ compared with GCR H and He both at 1 AU and in the outer heliosphere. As listed in Table I the recovery constant for ACR O^+ is 0.93-1.0 years while that of 265 MeV/n GCR He is 1.75-1.93 years and for 175 MeV GCR H is 4.0-4.2 years. It would be expected that the intensity of the higher energy ACR He would recover more rapidly than the much lower energy ACR O^+. The ACR O^+ approaches its plateau value near mid-1993 while GCR H and He continue to increase until late 1996 at 1 AU. As was argued previously for the observations in the outer heliosphere (McDonald et al. 2000) the most plausible explanation for this slower recovery of GCR H and He is that the global merged interaction region (GMIR) generated by the March/June 1991 activity remains an effective, but steadily diminishing, modulation agent for a period of some 3 years or longer as it passes through the termination shock and into the region of the heliosheath.

(iii) A comparative study of the cosmic ray recovery process at 1 AU and in the distant heliosphere for cycle 22.

There are two ways to consider the relative recovery between 1 AU and the Voyagers in the outer heliosphere. Since the recovery time constants are very close for GCR He (1.9 years) and ACR O^+ (1 year) at 1 and 44 AU, it should be possible to superimpose each pair of time histories by shifting the 1 AU data in time and magnitude (Fig. 3c, 4c). The resulting displacements are a measure of the relative recovery time and modulation between 1 AU and 44 AU (for V-1). The GCR He time displacement is –0.43 years and the relative modulation is 1.4. For ACR O^+ the relative time displacement is –.93 ± .04 years and the relative modulation is 4.0.

It is important to note that these time displacements refer to the relative recovery between 1 AU and 44 AU. The values of τ_{rec} given in Table I are a measure of the exponential recovery at the particular locations. The difference for GCR He between $\tau_{rec} = 1.9$ years at 1 AU and 1.75 years at 44 AU and the displacement Δt of 0.4 years between 1 AU and 44 AU, simply reflects the fact that the GCR recovery is occurring beyond the location of V-1. The ACR Δt of 0.89 years is closer to τ_{rec} as might be expected. It is also important to note that for both the ACR and GCR components this recovery appears to be moving from the outer heliosphere inward toward 1 AU.

O'Gallagher (1975) and Chih and Lee (1986) have estimated the average propagation time, $\bar{t}_p$, for a particle to travel from a modulation boundary (which they assumed to be the termination shock at a radial distance of $r_{T.S.}$ to 1 AU to be $\bar{t}_p = \frac{r^2}{6K_{rr}}$ if $V \ll \frac{6K_{rr}}{r_{T.S.}}$ where V is the solar wind velocity, K_{rr} is the particle diffusion coefficient and is assumed to be of the form $K_{rr} = \beta\, R\, K_0\,(r,t)$, where R is the particle rigidity and β is its velocity relative to the velocity of light.

Assuming that $\bar{t}_p$ can also be regarded as an approximate measure of the time to reach equilibrium between two different heliocentric locations, then for the 1 and 44 AU observations, the ratio of

$$\frac{t_p(\text{ACR O}^+)}{t_p(\text{GCR He})} = \frac{K_{rr}(\text{GCR He})}{K_{rr}(\text{ACR O}^+)} = \frac{\beta\,\text{R}(265\,\text{MeV/n He})}{\beta\text{R}(13\,\text{MeV/n O}^+)}$$

$$= \frac{0.92\text{GV}}{0.41\text{GV}} = 2.24$$

This can be compared to the Δt time displacement correction applied to the 1 AU data in Fig. 2c and 3c giving the observed ratio of

$$\frac{\Delta t(\text{ACR O}^+)}{\Delta t(\text{GCR He})} = \frac{0.93}{0.43} = 2.2$$

While this close agreement between the observed and predicted values may be, in part, fortuitous, it is also an indication that inside the termination shock, particle transport conforms reasonably well to the behavior expected from standard diffusion theory with the proper choice of diffusion coefficients.

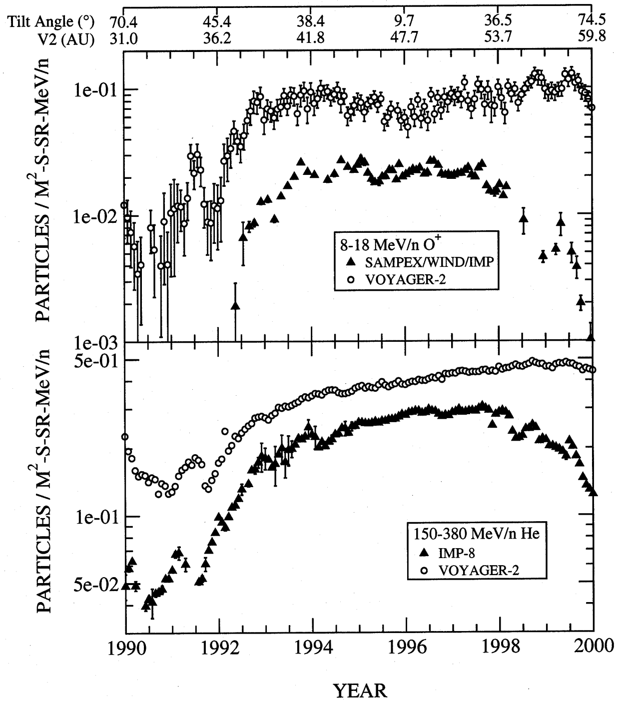

Fig. 2 Time histories of GCR He (26 Day AVG) and ACR He at 1 AU and at V-2 and P-10 over the 1990-2000 qA>0 epoch.

The second way to examine the relative recovery between 1 and 44 AU is using the quantity $\Delta J(R,t)_{rec} = J(R,t) - J_{\Theta MAX}$ (Eq. 1). This characterizes the net increase versus time of a given component, at a fixed location and above its solar maximum level. It is found that after 1992.25, $\Delta J_{rec}(R,t)$ is the same for GCR He at 1 and 44 AU (Figure 3b). (This is also true for the Pioneer 10 and V-2 ΔJ_{rec} for GCR He over the same period).

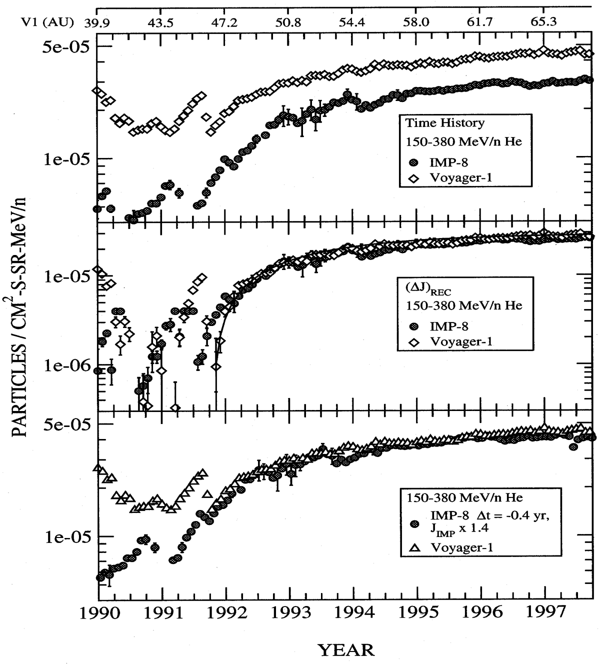

Fig. 3 **(a)** A comparison of the time histories of 150-380 MeV/n He for 1990-1997.75. The top curve through the Voyager 1 data is a fit of equation 1 to the initial V-1 recovery starting ~1991.0 and gives a value of τ = 0.95 years. **(b)** middle panel--$\Delta J_{rec} = J(t) = J_{\Theta MAX}$ is the net recovery at 1 AU and at 44 AU – i.e. the difference between J(t), the GCR He intensity at time t and the minimum intensity (78 day AVG) over the 1990 solar maximum period. The Voyager 1 intensities have been corrected to r = 44 AU. **(c)** lower panel--The IMP 8 intensities have been shifted by Δt = – 0.4 years and $J_{IMP\ 8} = 1.4 \times J_{IMP}(t)$ to bring the recovery period of the two data sets into alignment. A convection correction would shift the 1 AU data in panel a ~ 0.5 years to the right.

This result is surprising and not fully understood at this time. It may reflect the small level of modulation between 1 and 44 AU over most of this period. Using the force-field approximation the relative modulation potential, ΔΦ, between 1 and 70 AU in 1997 is 116 ± 6 MV. This use of a 1-D spherically symmetric model is partially justified by the small latitudinal gradients observed at 63 AU in 1996 (G_λ = 0.02 ± .15%/°, McDonald et al., 1998). The intensity gradients in the outer heliosphere at this time are so small—less than 0.15%/AU between 40 and 70 AU—that the relative modulation potential would be only slightly reduced at 44 AU. If the termination shock is located in the vicinity of 90 – 100 AU, then the modulation potential between 1

AU and the termination shock will be ~ $\Delta\Phi$ = 130 MV. This value is only ~ ⅓ of that obtained for 1 AU over solar minimum from using the standard LIS GCR He spectra.

From Fig. 4b it can be seen that ΔJ_{rec} for ACR O^+ is much less at 1 AU than at 44 AU, which is consistent with most of the GCR He modulation occurring beyond the termination shock. Unfortunately the presence of ACR H in the Voyager data makes it difficult to carry out a similar analysis for GCR H.

The Δt corrections of Figs. 2c and 3c are opposite to that expected if the recovery was moving radially outward from the sun. If a convection correction were applied to the V-1 GCR He data in Figure 5b, then the recovery would appear to occur some 6 months earlier at 44 AU as compared to the actual recovery shown in Fig. 3a. These observations suggest that the cosmic ray recovery moves inward from the distant heliosphere. As noted previously the recovery of cycle 21, in a qA<0 epoch, was completely different.

3 Discussion

Over the 1983-1987 period it was found that all of the GCR and ACR components over an extended range of βR values showed a simultaneous peaked time-history at 1 AU that was convected out to the location of V-2 (22 AU) and Pioneer 10 (42 AU) at the solar wind velocity (McDonald et al. 1990). Lockwood et al. (1988) and Cummings and Stone (1999) found a strong correlation between changes in the cosmic ray increases and $\alpha_{c.s.}$ over the 1985-1988 time period. It would appear that the current sheet inclination plays a dominant role in the long term recovery for qA<0 epochs and is much less important for qA>0.

The recovery process in qA>0 epochs appear to be more complex. The two methods of comparing the relative recovery at 1 AU with that at 44 AU may be complimentary. The displacement technique of Fig. 3c and 4c is a measure of the time required to reach equilibrium between 1 and 44 AU. The equivalence of ΔJ_{rec} for GCR He (Fig. 3b) requires a small value of $\Delta\Phi$, a slight increase in K_{rr} between 1 and 44 AU over the recovery process and significant residual modulation in the heliosheath. The fact that ΔJ_{rec} is large for ACR O^+ may reflect the greater modulation sensitivity of this component. A full understanding will require 2D simulations that take into account drift effects inside the termination shock, modulation in the heliosheath and the effects of the strong turbulence in the region above the solar poles (Jokipii and Kóta, 1999; Balogh et al. 1995).

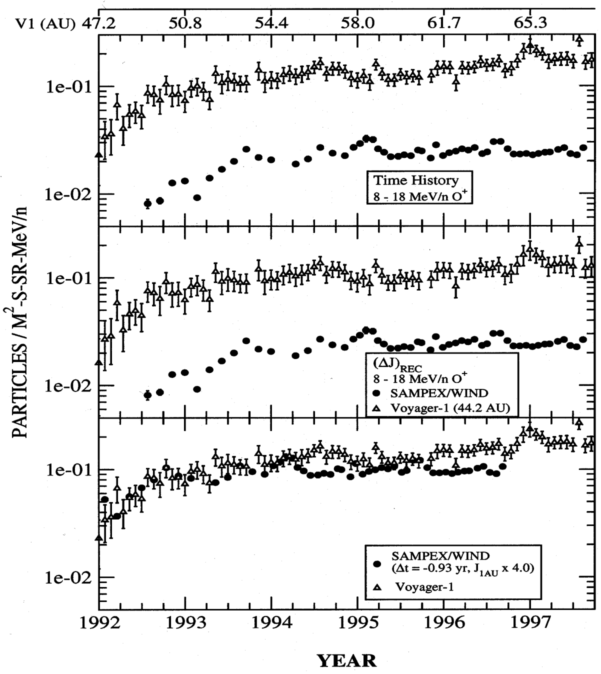

Fig. 4 Same as Fig. 3 except for oxygen The two top panels are essentially identical since $J_{\theta MAX}$ is so small.

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