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Relative recovery of galactic and anomalous cosmic rays at 1 AU: Further evidence for modulation in the heliosheath

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[1] For solar cycle 22 the large-scale interplanetary disturbances produced by the intense solar activity of March/June 1991 had a long-term effect on the recovery of galactic cosmic rays throughout the heliosphere that persisted for almost 5 years. At 1 AU, the recovery of 13 MeV/nucleon anomalous cosmic ray oxygen (ACR O^+) is much more rapid than that of 265 MeV/nucleon galactic cosmic ray helium (GCR He), consistent with previous observations in the distant heliosphere [*McDonald et al.*, 2000] and strengthening the concept that the region of the heliosheath plays an important role in the modulation of galactic cosmic rays. A comparison of the time histories of GCR He and ACR O^+ at 1 and 44 AU observations suggest the recovery moves from the distant heliosphere inward toward 1 AU for this particular phase of the heliomagnetic cycle. There is a very low relative modulation potential, Φ, between 1 and 70 AU of 116 ± 6 MV for GCR He at solar minimum using the force field approximation. When combined with the small radial intensity gradients in the distant heliosphere, a much lower modulation potential is implied between 1 AU and the termination shock at solar minimum than had been assumed previously. There is no effect on the 13 MeV/nucleon ACR O^+ intensity as the inclination of the heliospheric neutral current sheet decreases from 32° to its minimum value of 8°. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2124 Interplanetary Physics: Heliopause and solar wind termination; 2139 Interplanetary Physics: Interplanetary shocks; 2162 Interplanetary Physics: Solar cycle variations (7536); 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections; *KEYWORDS:* anomalous cosmic rays, heliosheath, coronal mass ejections, interplanetary shocks, solar wind, galactic cosmic rays

1. Introduction

[2] The large, complex structure of the outer heliosphere is created by the interaction of the outward flowing, supersonic solar wind with the local interstellar medium (LISM). At this time our concepts of the configuration of this yet unexplored interface must be inferred from the known properties of the solar wind and of the LISM and by the observation of low-frequency radio waves and cosmic rays in the distant heliosphere by the Voyager 1 and 2 spacecraft.

[3] It is expected that when the ram pressure of the expanding solar wind drops to that of the LISM, there will be a rapid transition through the formation of a large, standing, shock wave, the termination shock. The suddenly heated and decelerated solar wind then flows out around the termination shock and makes its way to interstellar space through the extended region of the heliotail that is produced by the relative motion of the heliosphere with respect to the LISM. It is generally assumed that a separation will be maintained between the decelerated solar wind and the LISM by a boundary layer, the heliopause. The region between the termination shock and the heliopause is the heliosheath. Figure 1 is a schematic representation of these various regions and boundaries.

[4] At the termination shock the radial velocity of the solar wind will be decreased by a factor of ~2.4–4 depending on the strength of the termination shock and will continue to decrease further as $1/r^2$ (where r is the heliocentric distance) between the termination shock and the heliopause. At the same time the intensity of the transverse component of the interplanetary magnetic field jumps by the same factor and continues to increase $\propto$ r across the heliosheath. The width of the heliosheath is not well known. It is estimated to be in the range $\sim 0.3-0.5\ r_{TS}$ (where r_{TS} is the heliosheath distance to the termination shock) at the apex of the heliosphere [cf. *Holzer*, 1989; *Seuss*, 1990; *Jokipii et al.*, 1993; *Zank*, 1999].

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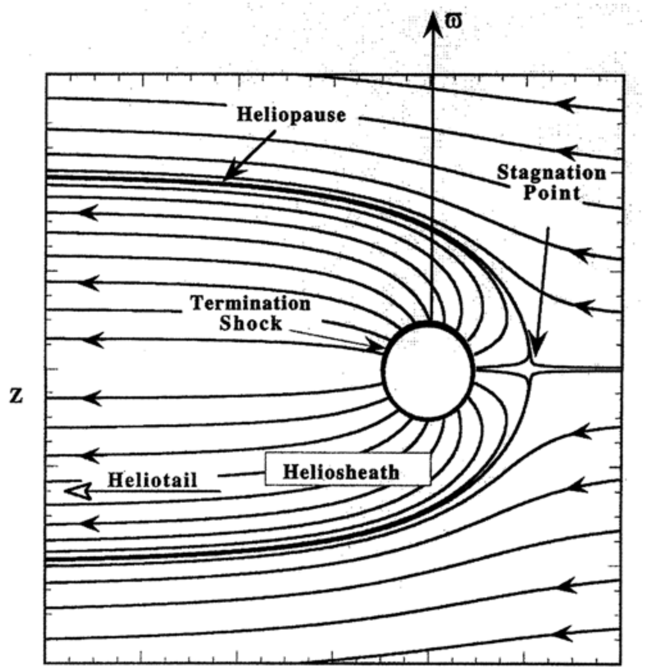

Figure 1. Simplified sketch of the heliosphere. The upward pointing arrow is directed along the spin axis of the Sun. (After *Axford and Seuss* [1994].)

[5] Comparative studies of the temporal variations of galactic and anomalous cosmic rays can determine some properties of the heliosheath. Galactic cosmic rays (GCR) entering the solar system must first traverse this region while anomalous cosmic rays (ACR) have their source region at its inner boundary. ACRs, predominantly singly charged ions, have their origin as interstellar neutrals that are ionized in the interplanetary medium, convected outward in the solar wind and accelerated at the termination shock [*Fisk et al.*, 1974; *Pesses et al.*, 1981].

[6] Previously, *Fujii and McDonald* [1995] studied the step decreases of galactic cosmic ray ions and electrons and ACR He and O^+ occurring over the 1978–1982 period. In the transition period of the 11-year modulation cycle of cycle 21 from solar minimum to solar maximum they found no difference in the relative behavior of these different components.

[7] However, the recovery of cosmic rays from solar maximum to solar minimum may be more dependent on changes in the distant heliosphere and thus offer a better possibility for observing differences in the relative modulation of galactic and anomalous cosmic rays. *McDonald et al.* [2000] in fact found that following the passage at Voyager 1 of the strong global merged interaction region (GMIR) associated with the March/June 1991 periods of intense solar activity, there was a marked difference in the recovery rates of 8–18 MeV/nucleon ACR O^+ and 30–56 MeV/nucleon ACR He^+ from that of 150–380 MeV/nucleon GCR He.

[8] Contrary to expectations, the recovery time constant for the two ACR components was ~1.0 year but was 1.75 years for the GCR He. The ACR He^+ and O^+ intensity reached a plateau level in early 1993 while the GCR He continued to increase over the next several years. These differences were interpreted as evidence that this GMIR remained an effective barrier to galactic cosmic rays as it traversed the region of the heliosheath while the ACR O^+ and He^+, with their source region at the termination shock began a more rapid recovery toward solar minimum conditions.

[9] With the launch of the 1 AU Sampex (1992) and Wind (1994) missions, data became available from a new generation of energetic particle experiments with much larger geometric factors for low energy ACR ions while maintaining excellent charge resolution [*Klecker et al.*, 1993; *Von Rosenvinge et al.*, 1995; *Reames*, 1999]. The data from these experiments combined with the GCR data from IMP-8 make possible greatly improved studies of the relative temporal variations of the ACR and GCR component in the inner heliosphere.

[10] In this paper we examine the 1 AU recovery for cycle 22 of 8–18 MeV/nucleon ACR O^+ relative to that of GCR H(180 MeV) and He(265 MeV/nucleon). The 1 AU studies have the advantage that unlike the measurements in the distant heliosphere, no corrections are necessary for the outward motion of the spacecraft. The time history of the ACR O^+ provides a sensitive method of examining the dependence of the cosmic ray intensity on the tilt angle (α_{cs}) of the heliospheric neutral current sheet (HNCS) over the recovery period of cycle 22. The 1 AU studies also make possible a comparative study of the recovery process in the inner and outer heliosphere. The recovery rates of the ACR and GCR components at 1 AU are found to be remarkably similar to those measured at Voyager 1 (V-1) (44 AU). The net increase in GCR He intensity from solar maximum to solar minimum is found to be the same at 1 AU and at 44 AU which is very different from what is observed for ACR O^+. The GCR data indicate that after 1992.0 the recovery process is occurring earlier at 44 AU than at 1 AU which is opposite from the behavior observed for the 1983–1987 cycle 22 recovery [*Fillius and Axford*, 1985; *McDonald et al.*, 1990].

2. Observations

[11] The ACR O^+ data at 1 AU presented here are from the SAMPEX HILT and Wind EPACT LEMT experiments. The GCR H and He data are from the Medium Energy Detector (MED) of the Goddard Cosmic Ray Experiment on IMP 8.

[12] The HILT experiment (Heavy Ion Large Telescope) [*Klecker et al.*, 1993] on the SAMPEX mission consists of a large area ion drift chamber, 2 position sensitive proportional counters, an array of 16 solid-state detectors and a CS-I scintillation detector. This provides a triple dE/dx measurement in combination with a determination of the residual energy of ions over the charge range He–Fe. For oxygen the energy interval is 8.2–42 MeV/nucleon and the geometric factor is 60 cm^2 sr. The SAMPEX spacecraft is in a relatively low (510 × 675 km) and highly inclined (82°), Earth orbit. The ACR O^+ data was collected during the polar passes at the time of solar quiet periods. Quiet time periods were selected by requiring that the flux of 5 MeV/nucleon He measured by HILT be <2 particles/m^2 sr s MeV/nucleon. Data from HILT on a continuous basis were not available after 1996.0.

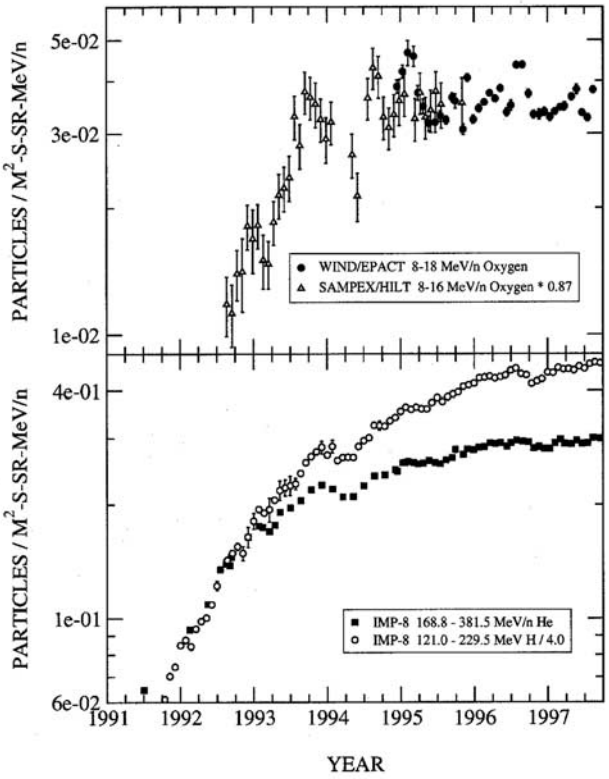

Figure 2. Time histories (26 day average) of GCR H and He from IMP 8 and 8–16 MeV/nucleon O^+ from SAMPEX and 8–18 MeV/nucleon O^+ from the Wind Mission for 1991–1997.75. Strict selection criteria (see text) have been applied to eliminate contamination from solar energetic particles.

[13] The other set of ACR O^+ data are from the Low Energy Matrix Telescope (LEMT) of the EPACT (Energetic Particle Acceleration, Composition and Transport experiment) on the Wind spacecraft. LEMT [*Von Rosenvinge et al.*, 1995; *Reames*, 1999] consists of three individual telescopes each with a 16-element array of 17 μm thick ΔE silicon detectors, a large position-sensing detector 1 mm thick to measure the residual energy and an anticoincidence element. LEMT covers the charge range H-U. The energy interval for oxygen is 3.3–20 MeV/nucleon and the total geometric factor for the three telescopes is 51 cm^2 sr. The Wind spacecraft has occupied several different ~1 AU locations, all beyond the effective confines of the Earth's magnetosphere. Quiet times were defined as 8-hour periods when the 2.1–2.4 MeV H intensity was <100/m^2 sr s MeV and 2–4 MeV/nucleon He < 0.3/m^2 s sr MeV/nucleon. The geometric factors for the HILT and LEMT telescopes are more than an order of magnitude larger than those flown previously.

[14] The 168–380 MeV/nucleon He and 140–220 MeV/nucleon H data are from the IMP 8 MED (Medium Energy Detector) telescope of the Goddard Cosmic Ray Experiment (R. McGuire, P.I.). This is a dE/dX versus E telescope using a thin and thick CsI scintillator partially surrounded by a plastic anticoincidence counter with a third dE/dX detector at the back of the thick E detector that permits triple dE/dX analysis for penetrating particles thus providing the extended energy range for H and He ions. The Geometric factor for penetrating particles is 5.1 cm^2 sr. The IMP 8 spacecraft is in an earth-centered elliptical orbit that ranges between 27 and 42 Earth radii. Quiet time is defined as 24–29 MeV H intensity < 2/m^2 sr s MeV. The 30–56 MeV/nucleon He data available from the IMP 8 MED was not used in this study because of the difficulty in separating the GCR and ACR components in this energy range during the early stages of the recovery period.

1. For the recovery from solar maximum at 1 AU, the time history of the 8–18 MeV/nucleon O^+ and GCR H and He from 1992.0 to 1997.75 are shown in Figure 2 (26 day averages). Beginning in early 1992 the ACR O^+ intensity increases at a rapid rate, reaching its peak value at 1993.7 with an *e*-folding time, τ, of $\simeq$0.9 years (Figure 2). This is followed by a transient decrease of ~35%, probably as a result of the appearance of a series of high-speed solar wind streams and several moderate sized solar events. Following the recovery from this transient modulation event, the ACR O^+ intensity, on the average, remains at a quasi-plateau level through 1997.75. The recovery of the GCR H and He (Figure 2) is more gradual, approaching their plateau levels in 1996.5, some 2.7 years later than the 13 MeV/nucleon ACR O.

These different recovery rates can be examined more closely using a regression analysis of pairs of the three components. The log-log plot of 175 MeV GCR H versus 275 MeV/nucleon GCR He (Figure 3a) shows a simple straight-line fit for these two data sets over the period

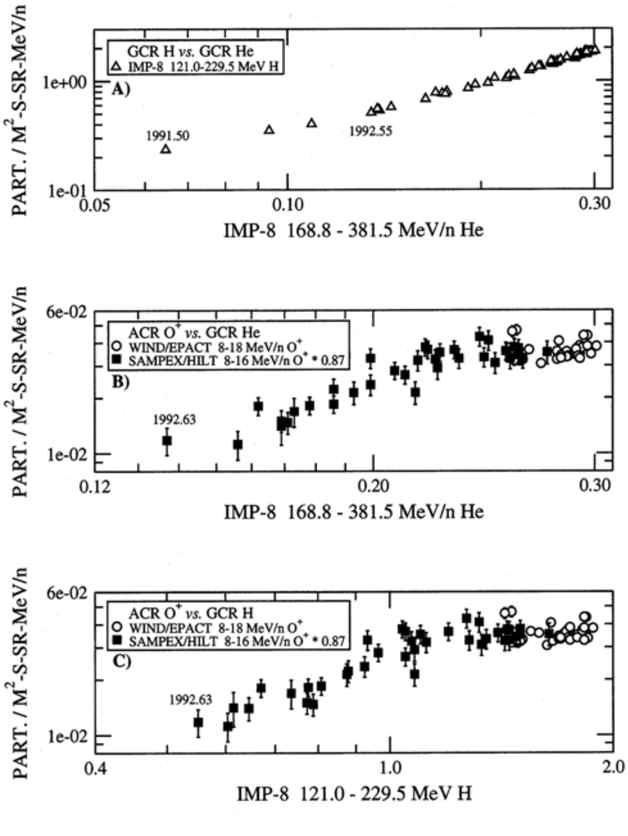

Figure 3. Regression plots of three pairs of cosmic ray components from the time history data shown in Figure 2.

Table 1. Cycle 22 Recovery Time Constants for GCR He, H, and ACR O^+

	τ(1 AU), years	τ (V-2, 34 AU), years	τ (V-1, 44 AU), years	R, MV	βR, MV
150–380 MeV/nucleon He	1.93	1.90	1.75	1508	920
120–230 MeV H	4.0	4.2	4.2	600	312
8–18 MeV/nucleon O^+	1.0	0.93	1.0	2510	414

1992.25–1998.0. Such a response with possible moderate charges in slope is what would be expected physically if both components had traversed the same modulation regions. The plots of ACR O^+ versus GCR He and H (Figures 3b and 3c) show a different behavior consistent with the time histories of Figure 2. The more rapid recovery of the ACR is followed by a plateau region as the galactic cosmic rays continue to increase over the next 2.7 years.

2. For the 1 AU recovery time constants, in the analysis of the Voyager 1 recovery time constants [*McDonald et al.*, 2000], a simple model was used which assumes that the rate of increase is proportional to the intensity difference between the observer and the solar minimum intensity at that location.

$$\frac{dJ(t)}{dt} = \frac{J_0 - J(t)}{\tau}, \tag{1}$$

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 1991.6, and $J_{\Theta\mathrm{MAX}}$ is the minimum intensity recorded over the time of solar maximum. Then

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

This is identical to the procedure used by *Webber et al.* [1986] to determine the time constants for the recovery of Forbush decreases.

Fitting the 1 AU data from 1992 to 1998.0 gives the set of values of τ listed in Table 1 along with those from V-1 (44 AU) and V-2 (34 AU) [*McDonald et al.*, 2000], where R is the particle rigidity and β is its velocity relative to the velocity of light. These recovery time constants reflect the recovery from solar maximum starting in mid-1990 as well as the long-term effects associated with the GMIR produced by the March/June 1991 solar activity.

For this calculation, the V-1 and V-2 intensities have been corrected back to a fixed heliocentric distance of 44 and 34 AU. Choosing the value of $J_{\Theta\mathrm{MAX}}$ as the minimum values over the 1990 solar maximum was necessary because the IMP 8 MED was saturated by the large March/June solar energetic particle events and no GCR He measurements were available until after mid-July 1991. Furthermore the large transient Forbush decreases observed at this time by neutron monitors were not representative of the long-term modulation although the GMIR produced by the combined March/June activity appears to be the controlling factor in the recovery phase of cycle 22. $J_{\Theta\mathrm{MAX}}$ for GCR He at Voyager 1 and 2 in late 1990 and early 1991 is very similar to the minimum intensity immediately following the passage of the interplanetary disturbances produced by the March/June solar events.

3. Relation of the 1 AU GCR H, GCR He and ACR O^+ intensity to the inclination, α_{cs}, of the heliospheric neutral current sheet (HNCS): When gradient and curvature drifts are an important part of particle transport in the heliosphere, the inclination of the HNCS should play a role in the modulation process [*Jokipii and Thomas*, 1981; *Kóta and Jokippi*, 1983; *Potgieter and Moraal*, 1985]. A plot of the 1AU GCR and ACR intensities as a function of α_{cs} is shown in Figure 4. For values of α_{cs} between ~8° and ~32°, the ACR O^+ intensity is essentially constant, reflecting the plateau-like time history of ACR O^+ from late 1993 to 1997.75 (Figure 2). A least squares fit to the O^+ data over this period is consistent with no variation of the O^+ intensity with changes in α_{cs}. The discontinuous change in the apparent response of ACR O^+ for values of $\alpha_{cs} > \sim 35°$ is probably related to other changes in the modulation conditions. The small increase in GCR He as $\alpha_{C.S}$ approaches its solar minimum value of ~8° must also be due to other factors since it is not observed for ACR O^+. The difference in the two data sets for values of $\alpha_{C.S}$ between 30 and 48° is due to a small transient decrease in α_{cs} from 40° to 24° in 1992.4 which has no effect on the GCR recovery (Figure 2). The ACR O^+ intensity is below the level

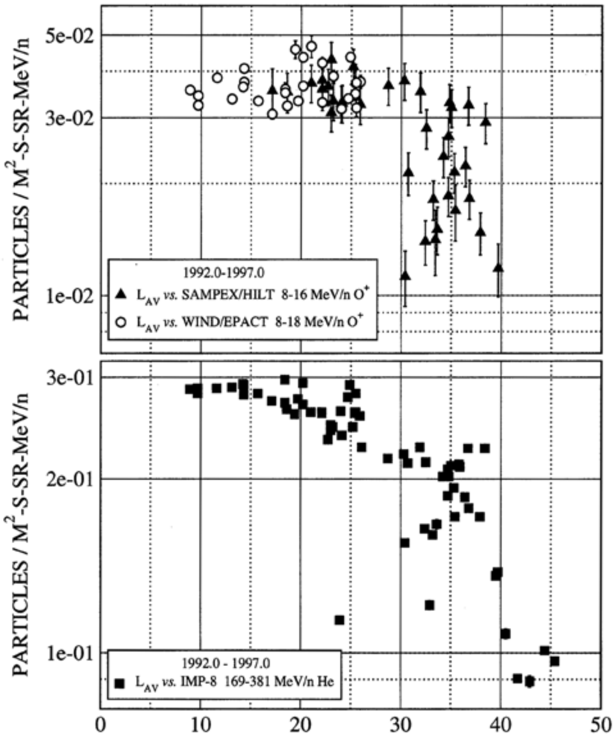

Figure 4. Plot of ACR O^+ and GCR He versus the tilt angle α_{cs} of the heliospheric neutral current sheet. The values of α_{cs} are from the Wilcox Observatory using the radial line of sight method. L_{avg} is the average of the Northern and Southern Hemisphere values.

of detectability at this time. Overall we see no evidence for any dependence of the recovery at 1 AU on current sheet inclination in this phase of the heliomagnetic cycle.

3. Discussion

3.1. Cosmic Ray Modulation in the Heliosheath

[15] For cycle 22 we have established a distinct difference in the relative recovery at 1 AU between ACR O^+ and GCR H and GCR He. As listed in Table 1, the recovery constant for ACR O^+ is ~1 year while that of 265 MeV/nucleon GCR He is 1.93 years and for 175 MeV GCR H is 4.0 years. The ACR O^+ approaches its plateau value near mid-1993 while GCR H and He continue to increase until ~1996.5, where they approach a plateau region. 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 activity remains an effective 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. It is also possible that the cumulative effect of GMIRs produced earlier in cycle 22 may also play a role in this process.

[16] The question of modulation in the extended region of the heliosheath has been examined by *Jokipii et al.* [1993] using both two- and three-dimensional models. It is generally assumed that the diffusion coefficient in the outer heliosphere K_{rr} is proportional to $1/B$, where B is the magnitude of the interplanetary magnitude field. Since V (the speed of the solar wind) and K_{rr} change by the same factor across the termination shock the modulation parameter, V/K_{rr}, should not change significantly near this boundary. The *Jokipii et al.* [1993] two-dimensional modeling shows significant modulation in the heliosheath over a wide range of energies for both $qA > 0$ and $qA < 0$ epochs with a complex energy dependence due in part to the effects of the acceleration of GCR that occurs at the termination shock itself. Previously, *Potgieter and Le Roux* [1989] and *Quenby et al.* [1990] examined the effects of enhanced modulation parameters in the heliosheath. It is reasonable to expect that the heliosheath will play a role in the global modulation of galactic cosmic rays. One key question is what are the effects of large transient disturbances as they traverse this region?

[17] *Le Roux and Fichtner* [1999] studied the spatial evolution of GMIRs and their effects on both GCR and ACR using a self-consistent model of the interaction of a time-varying solar wind, including pick-up ions, with cosmic rays. With this model they found that the decay of GMIRs is particularly fast during their interaction with the termination shock and in the heliosheath so "they probably cannot be interpreted as downstream modulation barriers." Le Roux and Fichtner also found no qualitative difference in the effects of a single GMIR on the recovery of the ACR and GCR components. These conclusions do not appear to be in agreement with the observations presented here.

3.2. Effect of Changes in α_{cs} on Cosmic Ray Intensity Near Solar Minimum

[18] Our observations, which show no clear evidence for dependence of cosmic ray intensities on α_{cs} during the recovery, were made at the time when the Sun's magnetic field in the northern hemisphere is outwardly directed ($qA > 0$) (1990–~2000), and the drift imposed flow of positive ions is inward over the solar poles and out along the heliospheric neutral current sheet. When the solar field reverses ($qA < 0$) (1980–1990, ~2001–2012) this flow pattern is reversed. *Jokipii and Thomas* [1981], using a two-dimensional drift dominated model showed that in $qA > 0$ epochs, changes in α_{cs} over a range of 0–30° had very little effect on the cosmic ray intensity during $qA > 0$ epochs, but the effect was much larger for the alternate solar minimum with $qA < 0$. Similar modeling by *Potgieter and Burger*

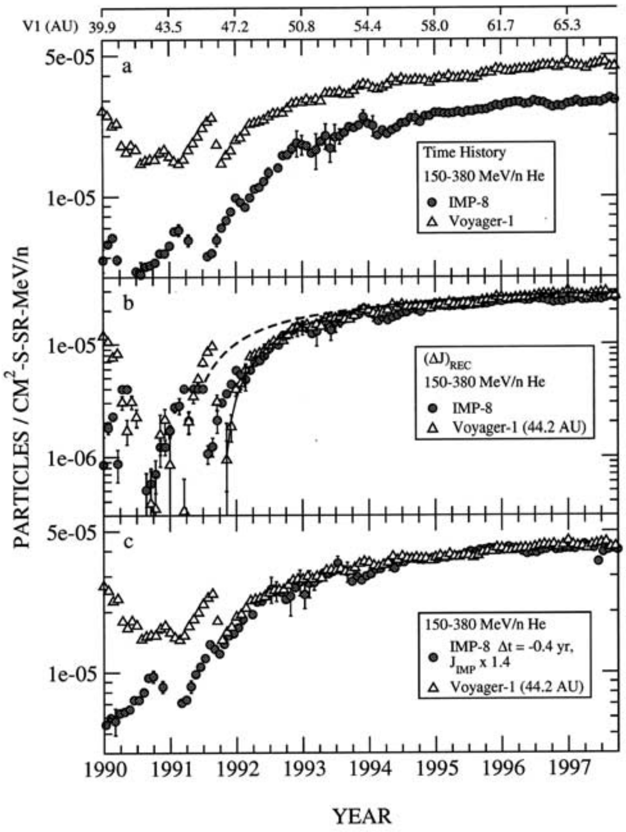

Figure 5. (a) A comparison of the time histories of 150–380 MeV/nucleon He at 1 AU and at V-1 for 1990–1997.75. The V-1 radial distance is shown at the top of the figure. (b) $\Delta J_{\rm rec} = J(t) - J_{\Theta\rm MAX}$) is the net recovery at 1 AU and at 44 AU, i.e., the difference between $J(t)$, the GCR He intensity at time t and the minimum intensity $J_{\Theta\rm MAX}$ (78 day average) over the 1990 solar maximum period. The Voyager 1 intensities have been corrected to $r = 44$ AU. The solid curve through the Voyager 1 data is a fit of equation (1) to the V-1 recovery and gives a value of $\tau = 1.75$ years. The dashed curve shows the effect of applying a convection correction to the V-1 data (assumed solar wind speed of 400 km/s). This clearly establishes that the recovery is not being convected outward with the solar wind. (c) The IMP 8 intensities have been shifted by $\Delta t = -0.4$ years and the relative modulation = $1.4 \times J_{\rm IMP\ 8}$ (t) to bring the recovery period of the two data sets into alignment. The negative value of Δt indicates that the recovery moves inward from the outer heliosphere.

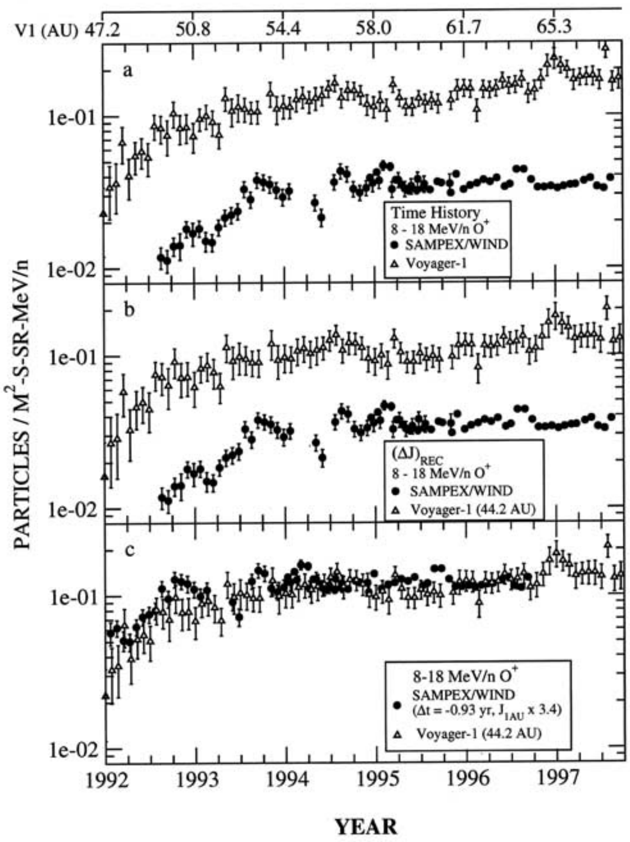

Figure 6. Same as Figure 5 except for ACR O^+.

[1990] and *Webber et al.* [1990] also found no variation of cosmic ray intensity with changes in α_{cs} for $qA > 0$ over an extended range of energies for GCR H, He and electrons.

3.3. Comparative Study of the Cosmic Ray Recovery of Cycle 22 at 1 and 46 AU

[19] The time histories of GCR He (Figure 5a) show a much larger relative increase at 1 AU than in the outer heliosphere, resulting in a dramatic decrease in the value of the nonlocal radial gradient from 2.5%/AU in 1990 to 0.3%/AU in 1997. However, the recovery time constants, τ, (Table 1) obtained by fitting these time histories using equation (1) give closely related values of τ for GCR He (1.93 and 1.75 years) and for ACR O^+ (1 year) at 1 AU and at 44 AU.

[20] 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 relatively close for GCR He at 1 and 44 AU, and for ACR O^+ (1 year) at the same radial distances, it should be possible to superimpose each pair of time histories by shifting the 1 AU data in time and magnitude with the resulting displacements being a measure of the relative recovery time and modulation between 1 AU and 44 AU (for V-1). The GCR He time displacement is -0.4 years and the relative modulation is 1.4 (Figure 5c). For ACR O^+ the relative time displacement is $-0.93 \pm .04$ years and the relative modulation is 3.4 (Figure 6c).

[21] 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 1 are a measure of the exponential recovery at the particular locations. The difference between $\tau_{\text{rec}} = 1.93$ years for He at 1 AU and 1.75 years at 44 AU and the displacement Δt of 0.4 years between 1 and 44 AU reflects the fact that the GCR recovery is occurring beyond the location of V-1. The ACR Δt of 0.93 years is closer to $\tau_{\text{rec}} = 1.0$ years at both 1 and 44 AU as might be expected with the ACR source at the termination shock. It is also important to note that from the sign of these displacements it appears that for both the ACR and GCR components this recovery is moving from the outer heliosphere inward toward 1 AU.

[22] *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_{TS}) to 1 AU to be

$$\bar{t}_p\,(r_{TS},\,V,\,K_{rr}) = \left[\frac{\frac{r_{TS}^2}{K_{rr}}}{\frac{V^2}{K_{rr}} + \frac{36K_{rr}}{r_{TS}^2}}\right]^{1/2} \qquad (2)$$

where V is the solar wind speed, K_{rr} is the particle diffusion coefficient and is assumed to be of the form $K_{rr}\,(\beta, R, r, t) = \beta\, RK\,(r, t)$

[23] If $V \ll 6K/r$, then equation (2) reduces to

$$\bar{t}_p \approx \frac{r^2}{6K_{rr}}. \qquad (3)$$

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

$$\frac{t_p(\text{ACR O}^+)}{t_p(\text{GCR He})} = \frac{K_{rr}(\text{GCR He})}{K_{rr}(\text{ACR O}^+)} = \frac{\beta R(265\text{MeV/nucleon He})}{\beta R(13\text{MeV/nucleon O}^+)}$$
$$= \frac{0.92\text{GV}}{0.41\text{GV}} = 2.24.$$

This can be compared to the Δt time displacement correction applied to the 1 AU data in Figures 5c and 6c giving the observed ratio of

$$\frac{\Delta t(\text{ACR O}^+)}{\Delta t(\text{GCR He})} = \frac{0.93}{0.4} = 2.3\,.$$

Because of the crudeness of our assumptions, this close agreement between the observed and predicted values must be, in part, fortuitous. Nevertheless, it is also an indication that inside the termination shock, particle transport conforms reasonably well to that expected from standard diffusion theory.

[24] The second way to examine the relative recovery between 1 and 44 AU is using the quantity $\Delta J(R,t)_{\text{rec}} = J(R,t) - J_{\Theta\text{MAX}}$ (equation (1)) which is a measure of the time history of the net increase of a given component at a fixed location above its solar maximum level. It is found that after 1992.25, $\Delta J_{\text{rec}}(R,t)$ is the same for GCR He at 1 and 44 AU (Figure 5b). (This is also true for the Pioneer 10

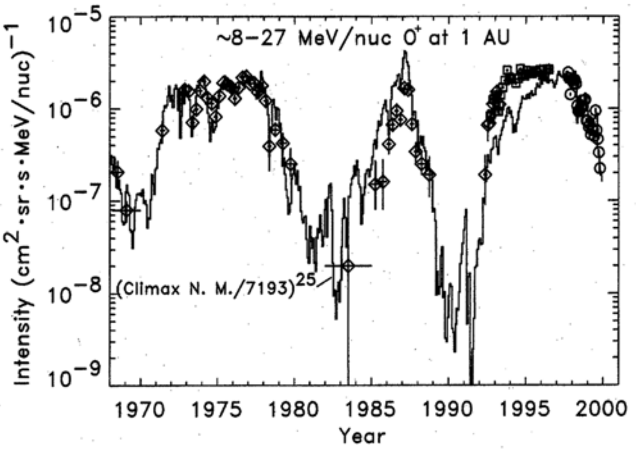

Figure 7. Quiet time intensities of $\sim$8–27 MeV/nucleon ACR O at 1 AU over the past three solar cycles (data points), compared with the Bartels rotation averaged count rate of the Climax neutron monitor scaled as indicated (histogram). Recent ACR data are from SAMPEX (squares) and from SIS on ACE (circles); earlier data (diamonds) are from OGO-5 (29, 30) and IMP 6 (7) for 1968–1971, and IMP 7 and 8 (26) for 1972–1992 [after *Leske et al.*, 2000].

and V-2 $(\Delta J)_{\mathrm{rec}}$ for GCR He over the same period.) This result merely reflects the radial distribution of GCR He at solar maximum and does not appear to have any physical significance. The dashed line in Figure 5b illustrates the effect of adding a convection correction to the V-1 data assuming a nominal solar wind velocity of 400 km/s. This shows very clearly that the recovery is not moving from the inner heliosphere rapidly outward as was observed for the $qA < 0$ recovery of cycle 21.

[25] What is surprising is the small level of modulation between 1 AU and the outer heliosphere at solar minimum. Using the force field approximation, the relative modulation potential, Φ for GCR He, between 1 and 70 AU in 1997 is 116 ± 6 MV. 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. The latitudinal gradient, G_λ at 62 AU is 0.02 ± 0.2%/deg. This small upper limit on G_λ lends some degree of credence to using a simple spherically symmetric approach to extrapolate out to the termination shock. 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 $\sim\Phi = 130$ MV. This value is only $\sim$1/3 of the 1 AU solar minimum value obtained from using the standard LIS GCR He spectra. However this procedure should be regarded with some degree of caution. The small values of the GCR He radial gradient in the outer heliosphere suggest that drift effects may be important over the solar minimum period of cycle 22 [*Jokipii and Thomas*, 1981]. Furthermore this is the regime where for a simple 1-D model, diffusion and convection are much more important than adiabatic energy losses.

[26] However, if the solar minimum value of Φ is this small, it has important ramifications on the interpretation of 1 AU cosmic ray data since adiabatic energy losses are not expected to be a significant part of the modulation process in the heliosheath. We assume, following *Jokipii et al.* [1993], that with the presence of cosmic ray modulation in the heliosheath, there will not be the large "skin effect" or increase in the intensity gradients near the termination shock such as was predicted by the model of *Potgieter* [2000]. If the estimates of the LIS GCR spectra are correct then these results would suggest there is still a large residual modulation in the heliosheath even at solar minimum after the effects of the March/June 1991 GMIR have become small.

[27] From Figure 6b it can be seen that $(\Delta J)_{\mathrm{rec}}$ for ACR O^+ is much less at 1 AU than at 44 AU. Unfortunately, the presence of ACR H in the Voyager data makes it difficult to carry out a similar analysis for GCR H.

[28] The Δt corrections of Figures 5c and 6c are opposite to that expected if the recovery was moving radially outward from the sun. When a convection correction is applied to the V-1 GCR He data in Figure 5b, the recovery appears to occur even earlier (by some 6 months) at 44 AU.

[29] These observations suggest that the cosmic ray recovery moves inward from the distant heliosphere. A comparison of the relative recovery of ACR O^+ and GCR He (from the Δt displacements shown in Figures 5c and 6c) and the analysis of equation (3) indicates a strong βR dependence. The recovery of cycle 22, in a $qA < 0$ epoch, was completely different. 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 et al.* [1994] found a strong correlation between changes in the cosmic ray increases and α_{cs} over the 1985–1988 time period. It would appear that the current sheet inclination plays a dominant role in the long-

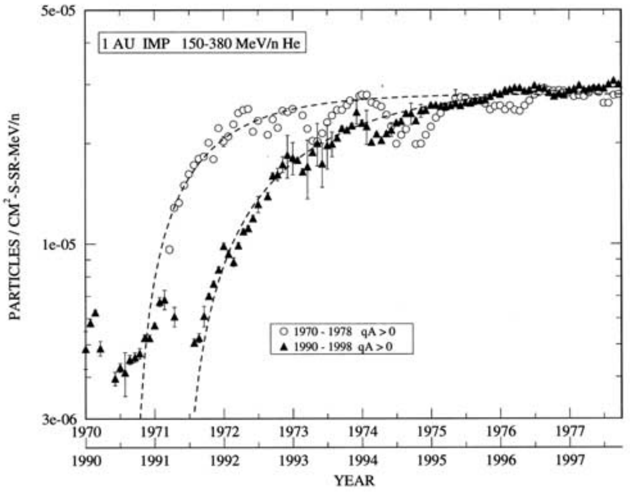

Figure 8. Comparison of time histories (1971–1977.75, 1990–1997.75) of 150–380 MeV/nucleon GCR He for similar epochs of the heliomagnetic cycle. The intensities are absolute values. The fit of equation (1) to the cycle 20 recovery (top curve) is $\tau \approx 1$ year; for the cycle 22 recovery (1990–1997), $\tau \approx 1.95$ years.

term recovery for $qA < 0$ epochs and is much less important for $qA > 0$.

3.4. How Long Did the March/June 1991 GMIR Remain an Effective Modulation Barrier?

[30] The time histories (Figure 2) and regression plots (Figure 3) show that the GCR He and H continue to increase until early 1996, several years after ACR O^+ reached its plateau level in late 1993. Previously, *Mewaldt* [1990] and *Leske et al.* [2000] found an excellent correlation between the 8–27 MeV/nucleon O^+ flux at 1 AU and the normalized counting rate of the climax neutron monitor raised to the 25th power over the 30-year period 1969–1999 except for the 1991–1996 time interval (as shown in Figure 7). This empirical comparison is consistent with the modulation effects of the 1991 GMIR persisting for some 5 years.

[31] It is instructive to compare the recovery of GCR He in cycle 22 with that of cycle 20 some 20 years earlier which also took place over a $qA > 0$ epoch. This has been done using the 1970–1980 and 1990–2000 periods and aligning the time axes at the year of the reversal of the solar magnetic field, 1970 and 1990. Although the IMP GCR He data only extends back to early 1971, the cycle 20 recovery is much more rapid than that of cycle 22 and is consistent with a recovery time constant, $\tau \approx 1$ year (Figure 8) similar to that found for ACR O^+ at 1 and 44 AU in cycle 22. The initial brief recovery at V-1 in cycle 22 before the arrival of the GMIR was also consistent with a τ of ≈ 1 year [*McDonald et al.*, 2000]. This suggests that the nominal recovery time constant within the termination shock is of the order of a year. The change in the neutron monitor counting rate from solar minimum to solar maximum of cycle 20 was the smallest yet recorded and there were no events over 1969–1970 that would have produced long-lived modulation barriers comparable to the 1991 solar activity of cycle 22.

4. Conclusions

[32] The relative recovery of galactic and anomalous cosmic rays in cycle 22 at 1 AU and at 44 AU is strong evidence that the large interplanetary disturbance produced by the March/June 1991 solar activity continued to modulate galactic cosmic rays for a period of some 4 years after they have crossed the termination shock and passed into the region of the heliosheath.

[33] The modulation process inside the termination shock is complex with drift effects being important particularly with regard to the acceleration and transport of the ACR component at the termination shock. There are also the effects of the strong turbulence above the Sun's polar region [*Jokipii and Köta*, 1989; *Balogh et al.*, 1995].

[34] The question then arises could the temporal evolution of these processes and regions inside the termination shock produce the observations reported here. The answer to this question will require detailed 2-D and 3-D simulations of the recovery process. However, it is felt that the observations of the relative recovery of GCR He and ACR O^+ at 1 AU and at 44 AU along with the comparison with the cycle 20 recovery strongly support the concept that the heliosheath plays a significant role in the modulation process and that the modulation effect of GMIRs can persist as they traverse the heliosheath.

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