JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. A1, PAGES 1–8, JANUARY 1, 2000

2000-15

The relative recovery of galactic and anomalous cosmic rays in the distant heliosphere: Evidence for modulation in the heliosheath

F. B. McDonald
Institute for Physical Science and Technology, University of Maryland, College Park

B. Heikkila and N. Lal
NASA Goddard Space Flight Center, Greenbelt, Maryland

E. C. Stone
California Institute of Technology, Pasadena

Abstract. At Voyager 1 (46 AU, 33°N) the recovery of anomalous cosmic rays (ACR) is found to be very different from that of galactic cosmic rays (GCR) following the passage of the large interplanetary disturbances produced by the intensive solar activity of March/June 1991. If the modulation boundary for the GCR were at the termination shock, where anomalous cosmic rays are believed to originate, it would be expected that the intensity of the higher-energy galactic cosmic rays would recover more rapidly than the relatively low energy anomalous component. On the contrary, we find that the time constant for the recovery of 265 MeV/nucleon GCR He is approximately twice as large as that of 43 MeV/nucleon ACR He^+ and 13 MeV/nucleon O^+. A regression plot of the ACR versus GCR intensity indicates a broad plateau in the ACR intensity over a period of several years while the GCR continues to increase. These differences in the relative recovery of the ACR and GCR strongly suggest that the combined interplanetary disturbances in the form of a global merged interaction region (GMIR) produced by the March/June 1991 solar activity remain an effective modulation agent for GCR after passing beyond the termination shock and into the region of the heliosheath. Some 0.37 years after the passage of the leading portion of the GMIR by Voyager 1, there is a large anisotropy in the ACR He^+. One possible interpretation of this anisotropy is that it is produced by the initial flow of the ACR back into the heliosphere at the time that the leading portion of the interplanetary disturbance moves beyond the termination shock. If this interpretation is correct, then the inferred transit time between Voyager 1 and the termination shock of the GMIR along with an estimate of its velocity at 40 AU based on similar features in the Voyager 1 and Pioneer 11 energetic particle data give a value of the heliocentric distance to the termination shock of 88.5 ± 7 AU at ~33°N in early 1992.

1. Introduction

Our heliosphere is a giant structure carved out of the local interstellar medium by the outward flowing supersonic solar wind. At distances of the order of 100 AU the pressure of the interstellar medium forces the solar wind to undergo an abrupt transition through the formation of a large standing shock, the termination shock. The hot decelerated solar wind then flows around the termination shock and out along the heliotail while maintaining a separation from the local interstellar medium by another boundary, the heliopause (Figure 1) [cf. *Holzer*, 1989].

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 (ACR) component. 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 [*Fisk et al*., 1974; *Pesses et al*., 1981].

Paper number 1999JA900372.
0148-0227/00/1999JA900372$09.00

As ACR and GCR travel in from the termination shock, their intensity decreases with decreasing heliocentric distance. The study of the temporal and spatial variations of these particles in the outer heliosphere at distances now extending beyond 70 AU by experiments on the Pioneer and Voyager spacecraft have greatly increased our understanding of these modulation processes and of the structure and dynamics of this vast, previously unexplored, region. These studies confirmed the existence of a 22 year modulation cycle associated with the heliomagnetic cycle and established that the size of the heliosphere must be of the order of 60–100 AU [cf. *McDonald*, 1998; *Webber and Lockwood*, 1998]. It was found that the very large decrease in cosmic ray intensity from solar minimum to solar maximum occurred in a series of discrete steps produced by a new phenomena, global merged interaction regions

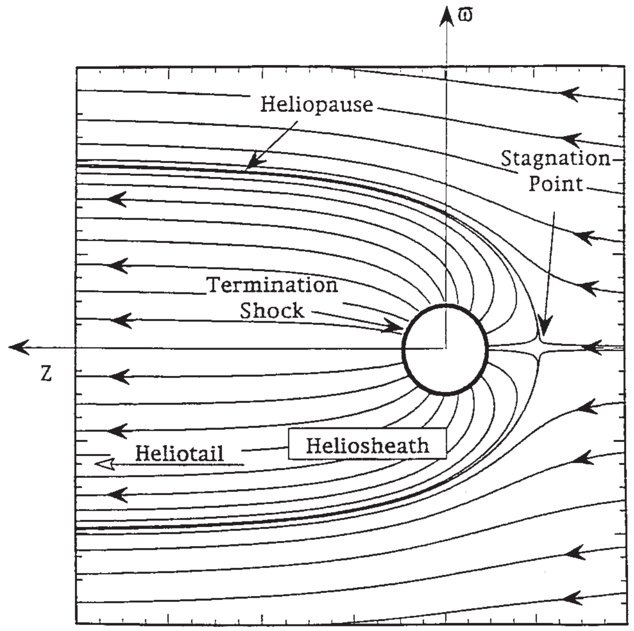

Figure 1. The heliospheric configuration resulting from the interaction between a subsonic interstellar wind and the outflowing supersonic wind [after *Axford and Seuss*, 1994].

(GMIRs) [*Burlaga et al*., 1993; *McDonald and Burlaga*, 1997]. GMIRs are long-lived, large-scale, quasi-spherical disturbances that form beyond some 10–20 AU through the coalescence of high-speed solar wind streams and multiple interplanetary shocks originating from coronal mass ejections. In preliminary studies the modulations of both GCR and ACR at the time of the step decreases have appeared to be similar [*Fujii and McDonald*, 1995], although differences could be obscured by the passage of multiple GMIRs over this period.

The questions then arise, Does the extended region of the heliosheath play a role in the transport of GCR and Does the effect of GMIRs extend beyond the termination shock into this region? The relative response of GCR and ACR provides a unique diagnostic tool for exploring the role of the heliosheath in the modulation process. As a first step, we explore in this paper the effects of a single, relatively isolated, GMIR on the two components.

In March and June 1991, there occurred two of the most intense periods of solar activity over the past 30 years. The June period produced the largest Forbush decrease ever observed at 1 AU, and the effects of the subsequent GMIR in the outer heliosphere were well documented out to 50 AU [*Van Allen and Fillius*, 1992; *Webber and Lockwood*, 1993; *Decker and Krimigis*, 1993; *McDonald et al*., 1994]. These solar events had several special features: the flare locations were asymmetric 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; these outbursts occurred in relative isolation after moderate activity around May 1990 and were followed by a sparse series of events in early 1994; of special importance is that the cosmic ray recovery toward solar minimum conditions had begun at both 1 and 51 AU, some 5 months before the arrival of the GMIR.

At 1991.71, there began a rapid reduction in the intensity of GCR and ACR at Voyager 1 (46.1 AU, 33°N) in association with a strong enhancement in the magnitude of the interplanetary magnetic field and in the flux of solar/interplanetary protons with energies as high as 60 MeV (Figure 2). These observations mark the arrival of the effects of the June 1991 solar activity at Voyager 1, some 100 days after their occurrence at the Sun. The time constant of the ensuing exponential recovery is almost twice as large for GCR He as that for ACR 43 MeV/nucleon He^+ and 13 MeV/nucleon O^+, contrary to theoretical expectations. A simple regression analysis between GCR 150–380 MeV/nucleon He and the two ACR components confirms that beginning in early 1993, there is an ~2 year period over which the GCRs continue to recover, but there is essentially no long-term change in the high rigidity ACRs. Soon after the onset of the recovery, there is a divergence of the 30–56 MeV/nucleon He^+ intensity in two of the telescopes with opposite viewing directions, indicating a significant anisotropy in the ACR He^+. The disparate behavior in the recovery of the GCR and ACR suggests that the heliosheath may play an important role in the modulation process and that the effects of this GMIR could persist for several years after its passage beyond the termination shock. An empirical model of the cosmic ray recovery is used to obtain a profile of the effects of the GMIR on both the ACR and GCR, which is consistent with the continuing role of the GMIR in the heliosheath. However, the acceleration of ACR at the termination shock

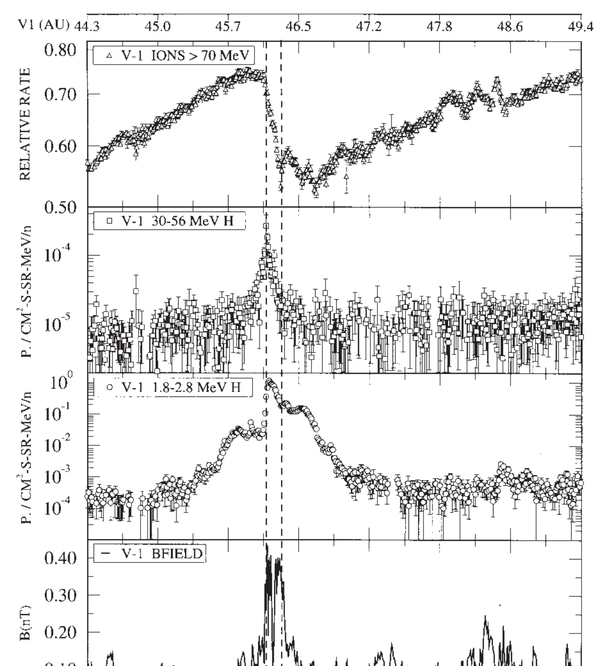

Figure 2. Time history at Voyager 1 (24 hour average) of the integral counting rate of galactic cosmic rays (GCR) with energies >70, 30–56, and 1.8–2.8 MeV H and the magnitude of the interplanetary magnetic field [*Burlaga and Ness*, 1998]. The first dashed line marks the arrival of the global merged interaction region (GMIR) at Voyager 1, and the second is the beginning of the initial recovery, which is interpreted as the passage of the leading portion of the GMIR past Voyager 1. The increase in the >70 MeV rate at 1992.19 is associated with the end of the high anisotropy period.

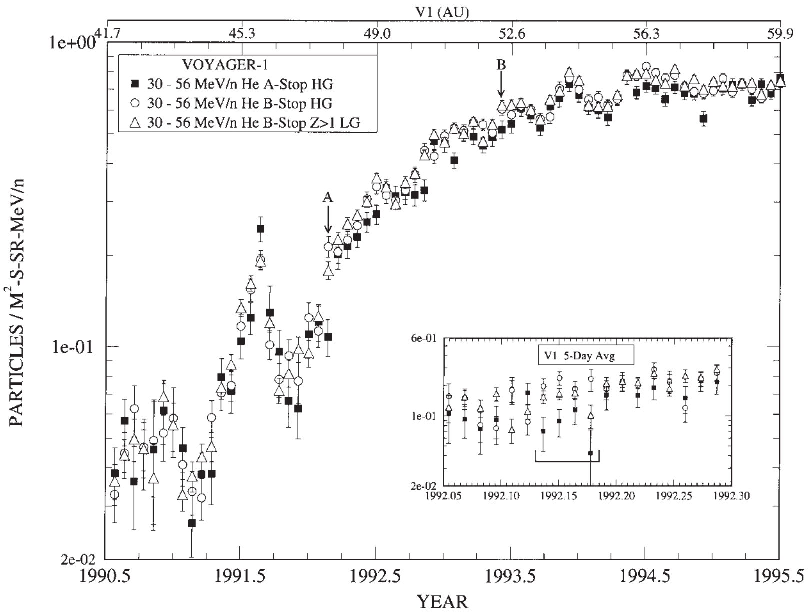

Figure 3. Time history (26 day averages of 30–56 MeV/nucleon He for three different analysis modes of the cosmic ray subsystem High Energy Telescope II (HET II) telescope. For A stopping particles the telescope look direction is essentially radially inward, while B stopping is 180° in the opposite direction. No corrections for GCR He or radial gradients have been applied to this data. The first arrow marks the period of high anisotropy, and the second is at the beginning of the quasi-plateau period. The smaller anisotropy at 1991.68 may reflect the sweeping effect of the GMIR. The insert is a plot of 5 day averages of the three intensities from 1992.0 to 1992.3. The 20 day interval used for the high anisotropy period is marked by a bracket.

and the transport of cosmic rays in the unexplored distant regions of our heliosphere may be different from our expectations and could lead to other explanations for these observations.

2. Observations and Analysis

The data used in this study are 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, three of which respond to He nuclei, stopping in the detector with an incident energy of 30–56 MeV n^{-1}. 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 three analysis modes are independent with one for the A end and separate high and low gain modes for the B end.

The onset of the pre-GMIR recovery period is clearly evident at 1991.2 as is the arrival of the GMIR near 1991.71 in coincidence with a sharp spike in the strength of the interplanetary magnetic field and in the intensity of 30–56 MeV protons of solar/interplanetary origin (Figure 2) as had been shown previously [*McDonald et al.*, 1994]. Unlike the Pioneer 10 and 11 and Voyager 2 observations [*Van Allen and Fillius*, 1992; *Webber and Lockwood*, 1993; *McDonald et al.*, 1994] the Voyager 1 GCR and ACR intensities at 33°N do not appear to be affected by the March 1991 activity, which was predominantly in the Southern Hemisphere. However, the combined effect of this activity was to reduce the Pioneer 10, Voyager 1, and Voyager 2 GCR to the same intensity level after the passage of the June 1991 related disturbances [*McDonald et al.*, 1994].

2.1. Anisotropy Observations

The time history of 30–56 MeV/nucleon He for the three different analysis modes are shown for the 1990.5–1995.5 time period (41.7–59.9 AU) in Figure 3. On 1992.14, there is a sudden divergence between the intensity of inward flowing 30–56 MeV/nucleon 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 given by the relation

$$\delta = \frac{J(\mathrm{B}) - J(\mathrm{A})}{J(\mathrm{B}) + J(\mathrm{A})}.$$

Where $J(\mathrm{A})$ and $J(\mathrm{B})$ is the flux of 30–56 MeV/nucleon He from the A and B ends of the HET II Telescope. The values obtained for the 20 day period centered on 1992.16 are $\delta = 0.46 \pm 0.1$ and 0.31 ± 0.09 for the high and low gain data, giving a mean value of 0.38 ± 0.09. During the continuing recovery from 1992.3 to 1992.6, $\delta = 0.08 \pm 0.02$. With only two telescopes it is not possible to define accurately the direction of the anisitropy except that it is consistent with the flow of He^+ back into the heliosphere from the direction of the termination shock.

2.2. Relative Recovery of GCR and ACR

Figures 4a, 4b, and 4c give the time history of 30–56 MeV/nucleon He^+ (i.e., with the GCR He contributions removed), 9–18 MeV/nucleon ACR O^+, and 150–380 MeV/nucleon GCR He. Also shown in Figures 4a–4c is the time history of these components corrected to a constant heliocentric distance of 44.2 AU using the measured radial intensity gradients from

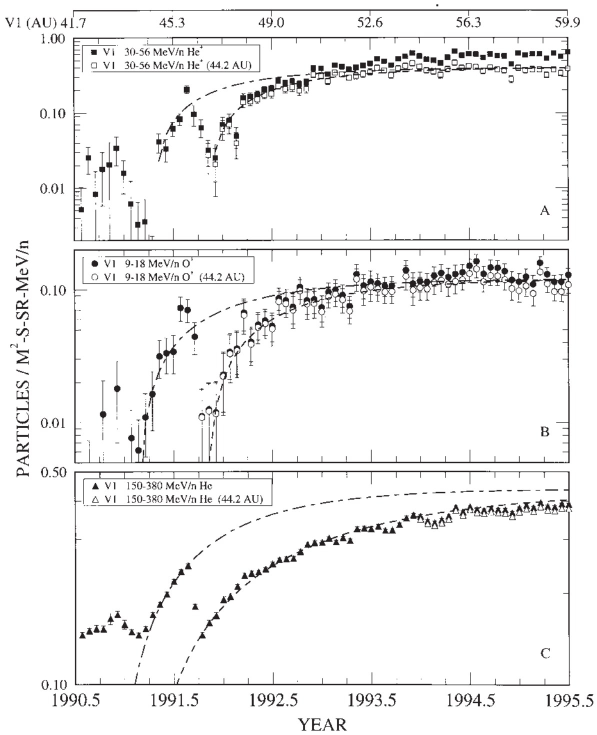

Figure 4. Time histories (26 day averages) of 30–56 MeV/nucleon He^+ (corrected for GCR He), 8–18 MeV/nucleon O^+, and 150–380 MeV/nucleon GCR He. The open symbols in each plot represent the same fluxes corrected to a constant heliocentric distance of 44.2 AU. The lower dashed lines in Figures 4a, 4b, and 4c are the fit of (1) for the post-GMIR data. The upper dashed lines are the fit of the same equation to the pre-GMIR intensities. The $\tau_{recovery}$ values derived from these analyses are given in Table 1.

similar experiments on Voyager 1 and 2 and Pioneer 10 [*Cummings and Stone*, 1997; *Webber and Lockwood*, 1997; *McDonald et al.*, 1998]. Beginning in early 1993 (Figure 4), 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 the period 1993–1996 is zero or very small, but there are shorter-term temporal changes while GCR He shows a steady increase.

This difference can be examined by plotting the intensity of 150–380 MeV/nucleon He versus that of 30–56 MeV/nucleon He^+ and 9–18 MeV/nucleon O^+ over the 1991.8–1996.0 time period (Figure 5). Arrow A, at 1992.14, marks the appearance of the strong anisotropy discussed previously. Arrow B, at 1993.1, marks the time of essentially full recovery of the ACR He^+ and O^+ intensity while the GCR He continues its recovery. There are smaller-scale features in the period between the 2 arrows that are somewhat different for ACR He for the two viewing directions of the telescope.

2.3. Recovery Time Constants

In Figure 4 the ACR and GCR recovery following the passage of the GMIR is distinctly exponential in character. In separate ongoing studies [*McDonald et al.*, 1995] it has been found that the post-GMIR data can be represented by a function of the form

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

where J_0 is the intensity at r_1 after full recovery, $J(r_1)_{\text{solar max}}$ 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 is shown as a dashed line in Figures 4a, 4b, and 4c with values of τ_{rec} = 0.95, 1.0, and 1.75 years for 43 MeV/nucleon He^+, 13 MeV/nucleon O^+, and 265 MeV/nucleon He. These recovery rates are well defined and accurately characterize the post-GMIR recovery period. 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 for ACR He^+. That the opposite relation is observed will be shown to be a strong indicator that the modulation region may extend well into the heliosheath.

As noted previously the cosmic ray recovery at Voyager 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 He. The fits to this partial recovery (using the same values of J_0 as for the post-GMIR analysis) (Figure 4) give τ = 0.95, 0.95, and 0.65 years for the GCR and the ACR He^+ and O^+ (Table 1).

It is assumed that if the 1991 GMIR had not occurred, the

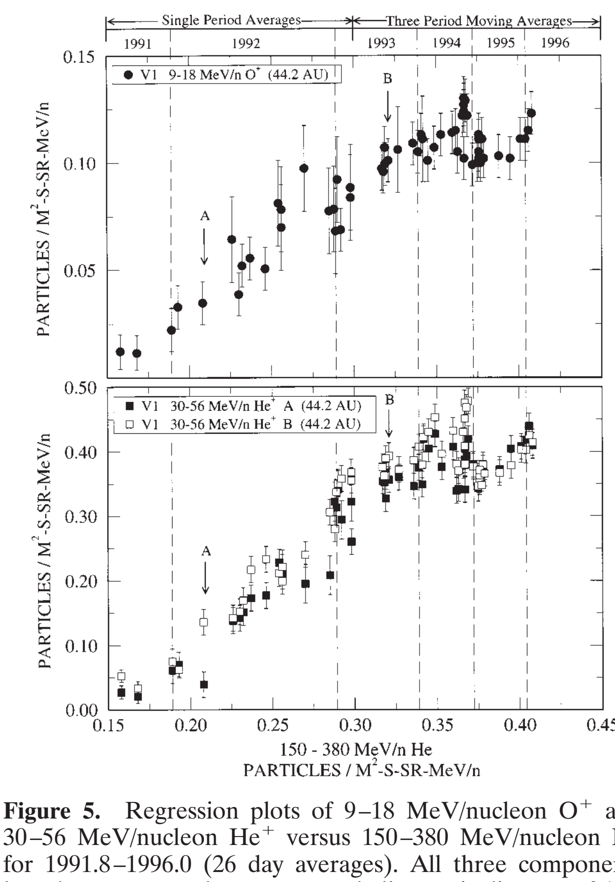

Figure 5. Regression plots of 9–18 MeV/nucleon O^+ and 30–56 MeV/nucleon He^+ versus 150–380 MeV/nucleon He for 1991.8–1996.0 (26 day averages). All three components have been corrected to a constant heliocentric distance of 44.2 AU. After 1993 the data have been summed over three period moving averages to reduce the statistical fluctuations. Arrow A marks the time of the abrupt change in the He^+ anistropy and intensity (Figure 2), and arrow B is the time when the He^+ intensity has returned to its "nominal level."

recovery would be that shown by the upper dashed line in Figures 4a–4c. 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 6) give an estimate of the GMIR-imposed cosmic ray decrease. The arrows from Figure 5 are also shown for the same times in Figure 6. Because of the short time interval available for determining $\tau_{\rm rec}$ for the pre-GMIR period, the time histories shown in Figure 6 become increasingly uncertain over the time periods after 1994.5.

The GCR and ACR recoveries at Voyager 2 (35.5 AU, 12°S) are remarkably similar to those of Voyager 1 after 1991.8 except that there are no measurable anisotropies at Voyager 2. A regression plot of the Voyager 2 13 MeV/nucleon O^+ and 43 MeV/nucleon He^+ versus 265 MeV/nucleon He^{++} would be essentially identical to that for the Voyager 1 data shown in Figure 5. The recovery of the lower-energy ACR He (4–20 MeV n^{-1}) and of 30–56 MeV/nucleon ACR H at Voyager 1 and Voyager 2 does not appear to follow the same pattern. However, because of their relatively low intensity levels, it is not possible to isolate these ACR components from the GCR over the 1990–1993 time period, so they have not been included in the present study.

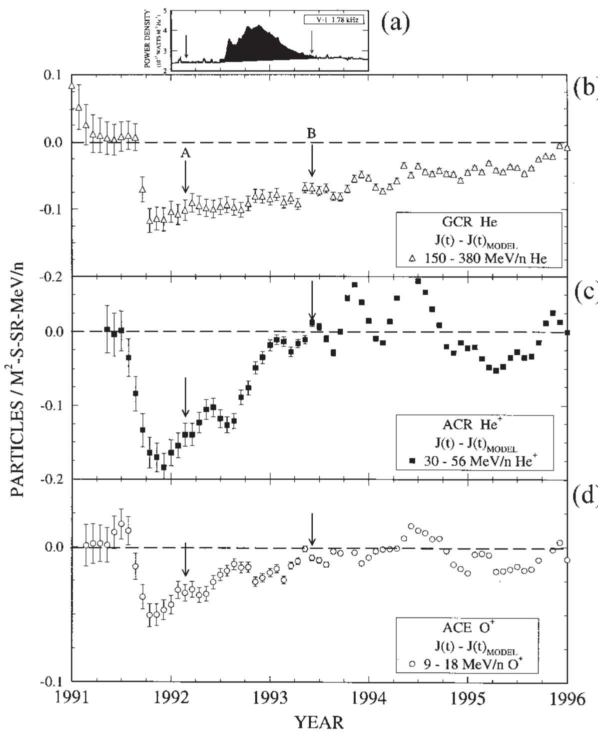

Figure 6. The estimated decrease in the GCR He^+ and ACR He^+ and O^+ due to the passage of the 1991 GMIR. This decrease was obtained by subtracting the extrapolated recovery curve of the pre-GMIR period (Figures 4a, 4b, and 4c) from the actual gradient-corrected data. The two arrows marks the same time as those in Figures 3 and 5. Three period moving averages have been used to reduce statistical fluctuations. The data shown in Figure 6a are the Voyager 1 plasma were [*Gurnett et al.*, 1993; *Gurnett and Kurth*, 1996] of the 1.78 K Hz spectral power density plotted on the same timescale as the cosmic ray data.

3. Discussion

At the termination shock the flow of the solar wind becomes subsonic with the velocity decreasing by a factor of ~4, while the interplanetary magnetic field will be increased by essentially the same factor, and there is a strong increase in the solar wind temperature. Thus a thinner but still coherent GMIR propagates out into the heliosheath with an enhanced and possibly more turbulent magnetic field. As the leading portion of the GMIR crosses the termination shock, the ACR ions should begin to flow back into the heliosphere. The subsequent behavior of the GCR depends on whether or not the GMIR is an effective modulating agent in the heliosheath.

3.1. Calculated and Observed Recovery Time Constants

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 $n)^{-1}$) 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. The value of $\bar{t}_p$ can be regarded as a measure of the time for this entire volume to return to an equilibrium state. O'Gallagher obtained an approximate expression for $\bar{t}_p$ given by

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

where V is the solar wind velocity, κ is the particle diffusion coefficient, and r_{TS} is the distance to the termination shock. Since the termination shock is assumed to be the ACR source and ACR modulation boundary, it will be used in the calculations to contrast the behavior of the ACR and GCR. Here κ is assumed to be independent of r out to the termination shock but is a function of rigidity R and the particle velocity β relative to the velocity of light, c, such that $\kappa(\beta, R)$ scales as $\beta\ R\ \kappa_0$. The value κ (375 MeV/nucleon He^{++}) at 40 AU over the 1992–1993 time period [*Fujii and McDonald*, 1997b] is 4.8×10^{22} $cm^2\ s^{-1}$ based on measurements of the radial intensity gradients. R_{TS} is taken to be 100 AU and $V = 450$ km based on the Voyager 2 solar wind data.

The values of $\bar{t}_p$ and $\tau_{\rm rec}$ are given in Table 1 for the three components; $\bar{t}_p$ provides an estimate for the relative ACR and GCR recovery times and should be of the same order as the recovery times $\tau_{\rm rec}$ measured directly from the He^+, O^+, and He time histories (Equation (1) and Figure 2). This is indeed the case for ACR He^+ and O^+, while the observed $\tau_{\rm rec}$ for GCR He is 7 times larger than its calculated value of $\bar{t}_p$. Furthermore this value of $\tau_{\rm rec}$ is 1.75 years for GCR He, while

Table 1. Observed and Calculated Times

	κ (50 AU), $cm^2\ s^{-1}$	$\tau_{\rm rec}$, years (Pre GMIR)	$\tau_{\rm rec}$, years (Post GMIR)	$\bar{t}_p$, years
150–380 MeV/nucleon He	4.8×10^{22}	0.95	1.75	0.24
30–56 MeV/nucleon He^+	1.7×10^{22}	0.95	0.95	0.6
9–18 MeV/nucleon O^+	2.1×10^{22}	0.65	1.0	0.5

GMIR, global merged interaction region.

values of τ_{rec} of 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. *Webber and Lockwood* [1993] also noted the smooth recovery of ions >70 MeV long after the GMIR should have passed beyond the termination shock.

It has generally been assumed, but not established, that significant solar modulation did not occur beyond the termination shock. However, in a study of the radial intensity gradients of ions >70 MeV, *Webber and Lockwood* [1987] found that over the period from 1977 to 1983, when this integral rate at 1 AU decreased by a factor of 3, the radial gradient of these ions did not change and was independent of heliocentric distance out to 30 AU. *Webber and Lockwood* [1987] interpreted these observations as evidence for a modulation barrier between 55 and 90 AU, the region where the heliosheath was thought to be located at that time. *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 observations. *Jokipii et al*. [1993], in a more detailed simulation that 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 that include both the effects of low- and high-energy particles. Studies of the radial intensity gradients of 180–450 MeV/nucleon He and 140–220 MeV H [*Fujii and McDonald*, 1997a], which included the same time period as was covered by Webber and Lockwood, found very significant changes in GCR radial intensity gradients with heliocentric distance and with solar activity that gave estimates of diffusion coefficients in the outer heliosphere [*Fujii and McDonald* 1997b], which appeared to eliminate the need for a "modulation barrier" in the region of the heliosheath on the basis of radial gradient studies.

3.2. Scattering Mean Free Paths Derived From Anisotropy Data

Early in the recovery phase following the passage of the GMIR, there is a period of some 20 days when the intensity of 30–56 MeV/nucleon 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 $\delta = 0.38 \pm .09$. From 1992.3 to 1992.6, there is a smaller anisotropy of $0.08 \pm .022$.

Marshall and Stone [1977], using the theoretical studies of *Jokipii and Parker* [1970], obtained an expression for δ of the form

$$\boldsymbol{\delta} = \boldsymbol{\delta}_{\rm conv} + \boldsymbol{\delta}_{\rm diff} = \frac{3}{\beta c}\left(VC - \kappa\,\frac{\nabla J}{J}\right) = \frac{3}{\beta c}\,(VC - \kappa G_r), \quad (3)$$

where J is the particle intensity, G_r is the radial intensity gradient, and C is the Compton getting factor. For the period 92.3–92.6, C is 0.66 for 43 MeV/nucleon He^+, and V is estimated to be 600 km s^{-1}, leading to a convective anisotropy of 0.014.

Writing $\kappa = \beta c\lambda/3$, where λ is the scattering mean free path, allows the diffusion anisotropy to be expressed as

$$\begin{aligned} \delta_{\rm diff} &= \lambda G_r = \boldsymbol{\delta} - \boldsymbol{\delta}_{\rm conv} = -0.38 - 0.014 = -0.39 \pm 0.1 \\ \delta_{\rm diff} &= \lambda G_r = \boldsymbol{\delta} - \boldsymbol{\delta}_{\rm conv} = -0.08 - 0.014 = -0.094 \pm 0.25 \end{aligned} \quad (4)$$

for 1992.18 and 1992.45, respectively. It is not possible to determine G_r for the 1992.18 period, but using both the Voyager 1 and Voyager 2 data, a value of $3.6 \pm 0.5°$ deg^{-1} AU^{-1} is obtained for the second interval, leading to a scattering mean free path of 2.6 ± 0.8 AU, which is an estimate of λ_r in the outer heliosphere under nonequilibrium conditions. This is of the same order as the value of 1 AU obtained by *Cummings and Stone* [1997] on the basis of studies of the energy spectra of ACR using Voyager 1 and Voyager 2 data during 1995–1996. It is a factor of 4.6 larger than the value obtained from the gradient studies of *Fujii and McDonald* [1997b], which was used to calculate $\bar{t}_p$ for 30–56 MeV/nucleon He^+ in Table 1. These were averaged over a more extended time period.

The ~20 day period of large anisotropy starting at 1992.14 is highly unusual and difficult to interpret. The relation $\delta_{\rm diff} = G_r\lambda = 0.39 \pm 0.1$ requires unrealistically large values of G_r or λ on the basis of the observation just before and after the passage of the GMIR. It cannot be established whether this anisotropy is a consequence of local conditions or whether it represents the influx of ACR He from the termination shock. It is interesting to note that the width of the high anisotropy period (~20 days) is of the same order as the half width of the large magnetic enhancement at Voyager 1 (22 days) centered about 1991.75. The passage of such an enhanced interplanetary magnetic field may lead to an increase in the ACR He intensity at the termination shock and hence to a substantially larger value of G_r. At the end of this large anisotropy event there, is a short-term increase in the intensity of ions >70 MeV (Figure 2) that is associated with a small disturbance in the interplanetary magnetic field.

3.3. Distance to the Termination Shock

One possible interpretation of this anisotropy is that it marks the initial flow of the ACR back into the heliosphere from which they have been severely depleted. The passage of the leading portion of the GMIR past Voyager 1 would appear to be associated with the first minimum in the 150–380 MeV/nucleon intensity at 1991.76 (Figure 2) (rather than at 1991.71, its time of arrival as defined by the initial energetic particle decrease) or by the passage of the large magnetic field enhancements beyond Voyager 1 at 1991.77. Using an average of these later two times gives an elapsed time of 0.375 years for the GMIR to reach the termination shock and for the associated increase in the shock-accelerated ACRs to diffuse back to Voyager 1. If the diffusion mean free path and the average speed $\bar{V}$ of the GMIR between 46.1 AU and the termination shock are known, then it is possible to determine r_{TS}. In particular, the total elapsed time is equal to $t_{\rm GMIR} + t_{\rm diff}$, where $t_{\rm GMIR} = \Delta r/\bar{V}$ and $t_{\rm diff} = 3(\Delta r)^2/\beta c\lambda$ (Δr is the mean distance from Voyager 1 to the termination shock during this period).

There are no measurements of the solar wind velocity available from the Voyager 1 experiments. However, Pioneer 11 and Voyager 1 are separated by only 17° in heliolatitude and 23° in heliolongitude, and the arrival time of the GMIR is well defined in the energetic particle data available from both spacecraft. The transit time of the GMIR between the two spacecraft is $\Delta t = 26.2 \pm 2$ days, giving $\bar{V}$ (40 AU) = 811 ± 66 km s^{-1}. Note that this latter method eliminates the need for defining t_0 among the six large June 1991 events. *Le Roux and Fichtner* [1999] have estimated that there will be a further deceleration of some 20% between 40 and 100 AU, leading to an estimate of $\bar{V}$ (70 AU) = 730 km s^{-1}.

Using this $\bar{V}$ and $\lambda = 1.8 \pm 0.4$ AU derived above from the anisotropy, it can be shown that $\Delta r = 38 \pm 5$ AU yields a total elapsed time of 0.375 years. The mean location of Voyager 1 during this time was 47 AU, yielding a shock location of 88.5 ± 7 AU. There could be additional, even larger errors if our interpretation of the relation between the onset of recovery and the features of the GMIR are incorrect.

This distance is in excellent agreement with the value of 85 AU obtained by *Stone et al*. [1996] on the basis of the radial distribution of anomalous O^+ for the 1993–1994 time period from experiments on Pioneer 10, Voyager 1, and Voyager 2 combined with an appropriate transport model.

Van Allen and Randall [1997], using Pioneer 10 and 11 observations of the intensity of galactic cosmic ray ions >80 MeV in the heliosphere near the heliographic equator, noted the significant effect of the great 1991 Forbush decrease on the recovery period of cycle 22 and the very low value of the radial intensity gradient in 1996. They concluded that at this time the modulation boundary of the heliosphere is far beyond 65 AU. *Lockwood and Webber* [1995] using the measurements of the integral intensity of ions >70 MeV from Voyager 2 and Pioneer 10, determined the local radial gradient between the two spacecraft. Then, using a summation technique to extrapolate these intensities out to the modulation boundary along with new estimates of the GCR interstellar intensity, they found that for the 7 years from 1983 to 1990 the inferred location of the modulation boundary remained constant at 83 ± 5 AU, again in good agreement with the value of 85 AU obtained both by *Stone et al*. [1996] and this work.

Le Roux and Fichtner [1999] modeled the spherical evolution of GMIRs and their local global effects on the modulation of GCRs and ACRs. They found that the decay of GMIRs is particularly fast during their interaction with the termination shock and in the regions beyond, which do not appear to be in agreement with the observations presented here.

The 2–3 kHz radio emission observed by the Voyager 1 and Voyager 2 plasma wave (PWS) experiment [cf. *Gurnett and Kurth*, 1996] were interpreted to imply a distance of 70–120 AU to the termination shock. This detection starting ~1992.5 of 2–3 kHz radio emission (Figure 6) by the Voyager 1 and Voyager 2 PWS experiment was one of the most spectacular after effects of the March/June 1991 solar activity. It has been reasonably established that such events are produced following unusual periods of intense solar activity. The most probable explanation for the emission is that it represents the interaction of the GMIR with the higher-density plasma in the vicinity of the heliopause [*Gurnett and Kurth*, 1996]. The relation of this emission to the continuing recovery of the GCR is shown in Figure 6. There do not appear to be any features in the recovery period related to the kHz emission.

4. Conclusion

The GMIR associated with the March/June 1991 solar activity dominates much of the cosmic ray recovery period of cycle 22. The observations presented here strongly suggest that this GMIR continued to have an effect on the GCR intensity several years after its passage beyond the termination shock. This GMIR was one of the largest interplanetary disturbances over the past 30 years, so its effects should be much more pronounced than those of more moderate levels of solar activity. However, it is expected that their influence will also extend into the heliosheath. As the Voyager spacecraft move even closer to the termination shock, the observed response of the GCR and ACR should become increasingly sensitive to the more normal-sized disturbances. It is also expected that the change in particle flow patterns associated with the polarity reversal of the solar magnetic field will have a major impact on the effects of the GMIR on galactic cosmic rays during the recovery phase from solar maximum to solar minimum.

Acknowledgments. Janet G. Luhmann thanks James A. Van Allen and John Quenby for their assistance in evaluating this paper.

References

Axford, W. I., and S. Seuss, Spacecraft to explore the outer heliosphere, *Eos Trans. AGU*, *75*, 587, 1994.

Burlaga, L. F., and N. F. Ness, Magnetic field strength distributions and spectra in the heliosphere and their significance for cosmic ray modulation: Voyager 1, 1980–1994, *J. Geophys. Res*., *103*, 29,719, 1998.

Burlaga, L. F., F. B. McDonald, and N. F. Ness, Cosmic ray modulation and the distant heliospheric magnetic field: Voyager 1 and 2 observations from 1986 to 1989, *J. Geophys. Res*., *98*, 1, 1993.

Chih, P. P., and M. A. Lee, A perturbation approach to cosmic ray transients in interplanetary space, *J. Geophys. Res*., *91*, 2903, 1986.

Cummings, A. C., and E. C. Stone, Rigidity dependence of the interplanetary mean free path, paper presented at 25th International Cosmic Ray Conference, Int. Union of Pure and Appl. Phys., Durban, South Africa, 1997.

Decker, R. B., and S. M. Krimigis, Two unusual shock events observed at the Voyagers, paper presented at 23rd International Cosmic Ray Conference, Int. Union of Pure and Appl. Phys. Calgary, Alberta, Canada, 1993.

Fisk, L., B. Kozlovsky, and R. Ramaty, An interpretation of the observed oxygen and nitrogen enhancement in low-energy cosmic rays, *Astrophys. J. Lett*., *190*, L35, 1974.

Fujii, Z., and F. B. McDonald, Study of the property of the step decreases in galactic and anomalous cosmic rays over solar cycle 21, *J. Geophys. Res*., *100*, 17,043, 1995.

Fujii, Z., and F. B. McDonald, Radial intensity gradients of galactic cosmic rays (1972–1995) in the heliosphere, *J. Geophys. Res*., *102*, 24,206, 1997a.

Fujii, Z., and F. B. McDonald, Radial diffusion coefficient of galactic cosmic ray hydrogen and helium in the heliosphere, paper presented at 25th International Cosmic Ray Conference, Int. Union of Pure and Appl. Phys., Durban, South Africa, 1997b.

Gurnett, D. A., and W. S. Kurth, Radio emissions from the outer heliosphere, *Space Sci. Rev*., *78*, 53, 1996.

Gurnett, D. A., W. S. Kurth, S. C. Allendorf, and R. L. Poynter, Radio emission from the heliopause triggered by an interplanetary shock, *Science*, *262*, 199, 1993.

Holzer, T. E., Interaction between the solar wind and the interstellar medium, *Annu. Rev. Astron. Astrophys*., *270*, 1999, 1989.

Jokipii, J. R., and E. N. Parker, On the convection, diffusion, and adiabatic deceleration of cosmic rays in the solar wind, *Astrophys. J*., *160*, 735, 1970.

Jokipii, J. R., J. Kóta, and E. Merényi, The gradient of galactic cosmic rays at the solar-wind termination shock, *Astrophys. J*., *405*, 782, 1993.

le Roux, J. A., and H. Fichtner, Global merged interaction regions, the heliosphere termination shock, and time-dependent cosmic ray modulation, *J. Geophys. Res*., *104*, 4709, 1999.

Lockwood, J. A., and W. R. Webber, An estimate of the location of the modulation boundary for $E > 70$ MeV galactic cosmic rays using Voyager and Pioneer spacecraft data, *Astrophys. J*., *442*, 852, 1995.

Marshall, F. E., and C. Stone, Persistent sonward flow of ~1.6 MeV protons at 1 AU, *Geophys. Res. Lett*., *4*, 57, 1977.

McDonald, F. B., Cosmic ray modulation in the heliosphere: A phenomenological study, *Space Sci Rev*., *83*, 33, 1998.

McDonald, F. B., and L. F. Burlaga, Global merged interactions regions in the outer heliosphere in *Cosmic Winds in the Heliosphere*, edited by J. R. Jokippi, C. P. Sonett, and N. S. Giampapa, pp. 389–423, Univ. of Ariz. Press, Tucson, 1997.

McDonald, F. B. A. Barnes, L. F. Burlaga, P. Gazis, J. Mihalov, and R. Selesnick, The effects of the intense solar activity of March/June 191 observed in the outer heliosphere, *J. Geophys. Res*., *99*, 14,705, 1994.

McDonald, F. B., N. Lal and R. E. McGuire, The initial cosmic ray

recovery phase of solar cycle paper presented at 24th International Cosmic Ray Conference, Int. Union of Pure and Appl. Phys. Rome, 1995.
McDonald, F. B., N. Lal, and R. E. McGuire, Cosmic ray recovery and solar minimum phase of solar cycle 22: An interim report, *J. Geophys. Res*., *103*, 373, 1998.
O'Gallagher, J. J., A time-dependent diffusion-convection model for the long term modulation of cosmic rays, *Astrophys. J*., *197*, 495, 1975.
Pesses, M. E., J. R. Jokipii, and D. Eichler, Cosmic ray drift, shock wave acceleration, and the anomalous component of cosmic rays, *Astrophys. J*., *246*, L85, 1981.
Potgieter, M. S., and J. A. le Roux, A numerical model for a possible modulation barrier in the outer heliosphere, *Astron. Astrophys*., *209*, 406, 1989.
Quenby, J., J. A. Lockwood, and W. R. Webber, Cosmic ray gradient measurements and modulation beyond the inner solar wind termination shock, *Astrophys. J*., *365*, 365, 1990.
Stone, E. C., R. E. Vogt, F. B. McDonald, B. J. Teegarden, J. H. Trainor, J. R. Jokipii, and W. R. Webber, Cosmic ray investigations for the Voyager missions, energetic particle studies in the outer heliosphere and beyond, *Space Sci. Rev*., *21*, 355, 1977.
Stone, E. C., A. C. Cummings, and W. R. Webber, The distance to the solar wind termination shock in 1993 and 1994 from observations of anomalous cosmic rays, *J. Geophys. Res*., *101*, 11,017, 1996.
Van Allen, J. A., and R. W. Fillius, Propagation of a large Forbush decrease in cosmic-ray intensity past the Earth, Pioneer 11 at 34 AU, and Pioneer 10 at 53 AU, *Geophys. Res. Lett*., *19*, 1423, 1992.
Van Allen, J. A., and B. A. Randall, A durable reduction of cosmic ray intensity in the outer heliosphere, *J. Geophys. Res*., *102*, 4631, 1997.
Webber, W. R., and J. A. Lockwood, Interplanetary radial cosmic ray gradients and their implication for a possible large modulation effect at the heliosphere boundary, *Astrophys. J*., *317*, 534, 1987.
Webber, W. R., and J. A. Lockwood, Giant transient decreases of cosmic rays in the outer heliosphere in September 1991, *J. Geophys. Res*., *98*, 7821, 1993.
Webber, W. R., and J. A. Lockwood, Intensities of anomalous and galactic cosmic rays in the outer heliosphere near the heliosphere equator in 1987 and during the period from 1994 to 1996, *J. Geophys. Res*., *102*, 9773, 1997.
Webber, W. R., and J. A. Lockwood, The inner heliosphere-outer heliosphere comparison for cosmic ray modulation, *Space Sci. Rev*., *83*, 159, 1998.

B. Heikkila and N. Lal, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

F. B. McDonald, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742-2431. (fm27@umail.umd.edu)

E. C. Stone, California Institute of Technology, Pasadena, CA 91109.

(Received July 7, 1999; revised August 16, 1999;
accepted August 18, 1999.)