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FORBUSH DECREASES AND PARTICLE ACCELERATION IN THE OUTER HELIOSPHERE

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Abstract. Major solar flare activity in 1989 has provided examples of the local acceleration of protons at 28 AU (Pioneer 11) and of the propagation of Forbush decreases in galactic cosmic ray intensity to a heliocentric radial distance of 47 AU (Pioneer 10). The combination of these and previous data at lesser distances shows (a) that Forbush decreases propagate with essentially constant magnitude to (at least) 47 AU and with similar magnitude at widely different ecliptic longitudes and (b) that the times for recovery from such decreases become progressively greater as the radial distance increases, being of the order of months in the outer heliosphere. A phenomenological scheme for (b) is proposed and fresh support is given to the hypothesis that the solar cycle modulation of the galactic cosmic ray intensity is attributable primarily to overlapping Forbush decreases which are more frequent and of greater magnitude near times of maximum solar activity than at times of lesser activity.

Introduction

Major solar flares during the period 6–19 March 1989 produced a rich variety of geophysical effects [Solar-Geophysical Data, 1989; Allen et al., 1989], the most noteworthy of which were a great magnetic storm, bright low latitude aurorae, and a large Forbush decrease in cosmic ray intensity, all beginning on 13 March (DOY 72) (DOY = Day of Year with 00^h UT on 1 January being DOY 1.0). These events are plausibly attributed to the solar flare (3B X 4.5) (N31 E22) of 10 March (DOY 69) and consequent increases in the speed, density, and magnetic field of the solar wind.

We report herein the delayed effects from this flare and a subsequent one as observed in the interplanetary medium at Pioneer 11 (heliocentric radial distance $r \approx 28$ AU) and Pioneer 10 ($r \approx 47$ AU), the latter being the most remote spacecraft in the solar system though still clearly interior to the heliopause. The new data are combined with earlier data to extend knowledge of the propagation of Forbush decreases into the outer heliosphere.

Observations at Pioneer 11

In the center panel of Figure 1 is plotted the cosmic ray intensity ($E_p > 80$ MeV) at Pioneer 11 as measured by the daily mean counting rate of two omnidirectionally shielded Geiger-Mueller tubes, B and C. [See Van Allen et al., 1980 for a description of the instrument.] The onset of the decrease occurred on DOY 149, with an uncertainty of one day. The intensity decreased by about 13 percent below its pre-event value

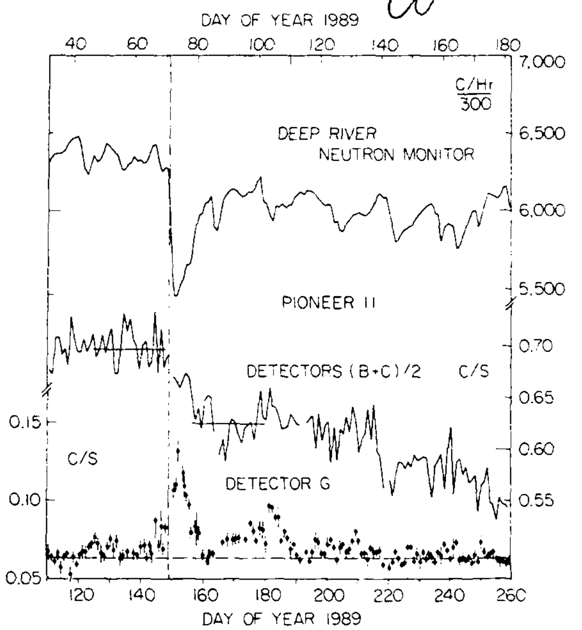

Fig. 1. Upper Panel: Daily mean cosmic ray intensity as measured by the Deep River Neutron Monitor on the Earth. Center Panel: Cosmic ray intensity as measured by the daily mean counting rates of two nearly identical Geiger-Mueller tubes (B and C) on Pioneer 11. The horizontal line segments are numerically averaged rates for the time periods covered by the segments. Lower Panel: Spin averaged values of the counting rate of Detector G (a thin single element solid state detector with a physical collimator) (protons, $0.61 < E_p < 3.41$ MeV) (insensitive to electrons) on Pioneer 11, at the highest useful time resolution. The absolute geometric factor of G is 0.044 cm^2 sr. The dashed horizontal line at 0.0635 c/s gives the average background rate (Am^{241} α-particle calibration source) during the pre-events period DOYs 80–120 and post-events period DOYs 220–260. Note the 78-day shift in time scale between the terrestrial and Pioneer 11 graphs as defined by the dashed vertical line.

during the subsequent 18 days and did not recover significantly during 50 days thereafter; a second and more rapid decrease of lesser relative magnitude began on DOY 216. The upper panel of Figure 1 shows the daily mean cosmic ray intensity as measured by the high latitude Deep River Neutron Monitor on the Earth. At Deep River the intensity fell on DOY 72 by 13 percent below its pre-event value within one day and recovered to a value about 3 percent below the pre-event value during the subsequent 15 days. The relative signatures of the Forbush decreases at 1 AU and at Pioneer 11 are reminiscent of

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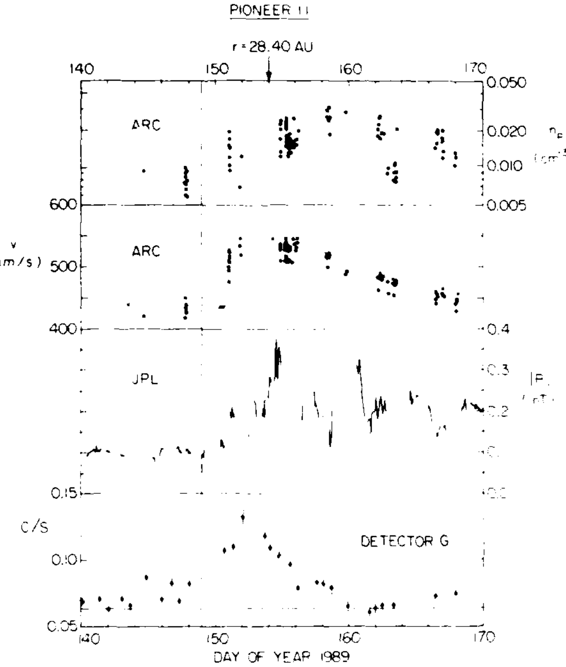

Fig. 2. Comparison of the Ames Research Center data on the solar wind (upper two panels), Jet Propulsion Laboratory magnetic field data (third panel), and University of Iowa energetic proton data (fourth panel). The dashed vertical line is at DOY 149. The dashed horizontal line in the fourth panel is the average background counting rate for the periods specified in the caption of Figure 1.

those of April–May 1978 when Pioneer 11 was at 15.9 AU [Van Allen, 1979]. A second clear Forbush decrease at Pioneer 11, beginning on DOY 216, has a relatively unconvincing but perhaps real association with a dip in intensity at Deep River beginning on DOY 142, 74 days earlier. Locally accelerated protons ($0.61 < E_p < 3.41$ MeV) as measured by Detector G (a thin solid-state detector) occurred in clear association with the first cosmic ray decrease (lower panel of Figure 1). Confirmatory peaks in the counting rate of Detector A (a thin window Geiger-Mueller tube having the same proton energy threshold) were also observed. The proton events shown in Figure 1 are the first ones of this great an intensity to be detected by the University of Iowa/Pioneer 11 instrument since early 1986 at 20.5 AU [Van Allen, 1987].

The scalar magnetic field intensity |B| from the Jet Propulsion Laboratory magnetometer on Pioneer 11 is plotted for the period DOYs 140 to 170 in Figure 2 as is the Ames Research Center data on solar wind speed v and number density of protons n_p. The lower part of Figure 2 is a replot of the data on locally accelerated protons for comparison. The solar wind speed v increased from 430 to about 540 km s^{-1} during the five days following DOY 151 and the proton number density n_p increased from about 0.006 to about 0.020cm^{-3} during the same period. The magnetic field intensity increased from its pre-event value of 0.10 to a maximum of 0.38 nT.

The temporal association of the three bodies of data is unmistakable, as is the association of the solar wind data with the first Forbush decrease shown in Figure 1. The brief duration of the energetic proton events in and of itself establishes local acceleration as the cause of the events, as observed extensively at much lesser radial distances [Armstrong et al., 1985].

Observations at Pioneer 10

At r ≈ 47 AU, Pioneer 10 observed large and distinctive Forbush decreases in cosmic ray intensity beginning on DOY 184 (≈ 15% decrease) and on DOY 264 (≈ 12% decrease), thereby providing a substantial extension of knowledge of the propagation of such decreases into the outer heliosphere. A comparison of data from Pioneer 10 and Pioneer 11 is presented in Figure 3. The signatures of the two Forbush decreases at Pioneer 11 (onsets on DOYs 149 and 216) are remarkably similar to those at Pioneer 10 (onsets on DOYs 184 and 264). As at Pioneer 11, the recovery of cosmic ray intensity at Pioneer 10 has a time scale of at least several months.

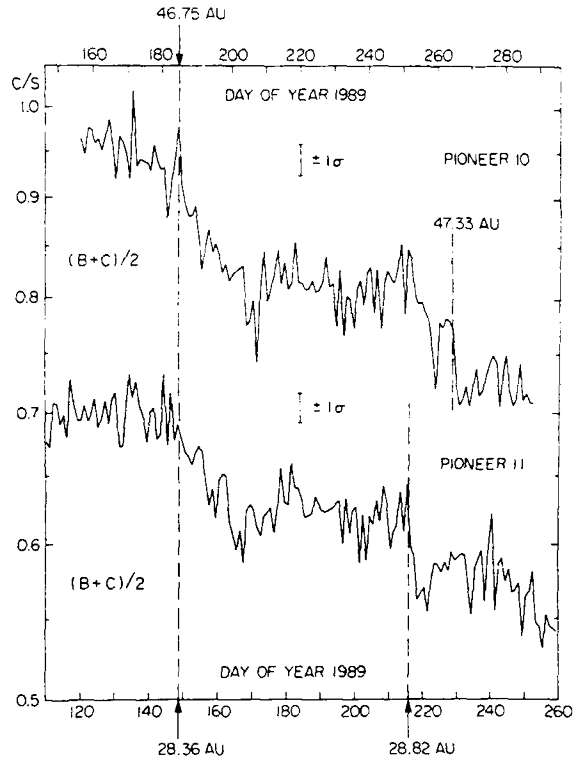

Fig. 3. A comparison of Forbush decreases of cosmic ray intensity at Pioneer 11 and Pioneer 10. The dashed vertical line on the left defines the adopted shift of 36 days in the time scales corresponding to the first event. The two dashed vertical lines on the right represent the respective onsets of the second Forbush decrease. Spacecraft radial distances are shown.

Analysis

Tables 1 and 2 give a summary of positional and other basic data relevant to discussion of the events described in the two previous sections and in Figures 1, 2, and 3. Table 3 gives apparent mean radial speeds of propagation of Forbush decreases $\Delta r/\Delta t$, ignoring differences in longitude and latitude of the several observing points. The nominal uncertainties of the tabulated values of $\Delta r/\Delta t$ are some ±5%. The Table 3 values of $\Delta r/\Delta t$ in Cases a, b, c, and d, are all compatible with a common value of about 650 km s^{-1}. However, the value in Case e (Pioneer 10/Pioneer 11) is decidedly incompatible with 650 km s^{-1}. The directly measured value of the solar wind speed v at Pioneer 11 (Figure 2) did not exceed 540 km s^{-1} at any time during the period DOYs 140–170. Hence it ap-

TABLE 1. Summary of Recent Events and Approximate Times Thereof

Event		Day of Onset 1989
1	Hα Solar Flare (N31 E22) (18:48 UT) (Max. at 19:08 UT)	DOY 69 (Mar. 10)
2	Magnetic Storm and Forbush Decrease at Earth (10:00 UT) (Fig. 1)	DOY 72 (Mar. 13)
3	Energetic Particle Event and Forbush Decrease at Pioneer 11 (Figs. 1–4)	DOY 149 (May 29)
4	Forbush Decrease at Pioneer 10 (coincident with a rapid increase of solar wind speed from 475 to 535 km s^{-1})	DOY 184 (July 3)
5	Forbush Decrease at Earth	DOY 142 (May 22)
6	Forbush Decrease at Pioneer 11	DOY 216 (Aug. 4)
7	Forbush Decrease at Pioneer 10 (coincident with a rapid increase of solar wind speed from 470 to 535 km s^{-1})	DOY 264 (Sept. 21)

pears that the shock or blast wave that caused the observed effects at the Earth and at Pioneer 11 propagated at a speed of $\gtrsim$ 100 km s^{-1} relative to the interplanetary medium. The substantially greater value of $\Delta r/\Delta t$ for Case e implies (a) an important increase in this propagation speed over the radial distance between Pioneer 11 and Pioneer 10 (28 to 47 AU), or (b) a lack of common cause for Events 3 and 4, despite the quantitative similarity of their signatures (Figure 3), or (c) a dependence of propagation velocity on longitude relative to the flare. The solar wind speed at Pioneer 10 (Event 4) increased discontinuously from 475 to 535 km s^{-1}, similar to the increase at Pioneer 11 (Event 3) from 430 to 540 km s^{-1}. This fact favors a common cause for Events 3 and 4—namely Event 1—but is not conclusive.

TABLE 2. Heliocentric Radial Distance r in AU; and Ecliptic Longitude ℓ, Ecliptic Latitude β, and Heliographic Latitude β' in Degrees

Event	Location	r	ℓ	β	β'
1	Solar Flare	0.0	150.0	–	+31.0
2	Earth	1.0	172.4	0.0	−7.2
3	Pioneer 11	28.4	261.9	+16.3	+17.0
4	Pioneer 10	46.7	72.1	+ 3.1	+3.4
5	Earth	1.0	240.9	0.0	−1.8
6	Pioneer 11	28.8	262.4	+16.3	+17.0
7	Pioneer 10	47.3	72.2	+3.1	+3.4

Note: Events 5, 6, and 7 have not been identified as attributable to any solar flare observed on the visible disk of the sun during the few days preceding Event 5.

TABLE 3. Apparent Mean Radial Speed of Propagation $\Delta r/\Delta t$ (Ignoring Differences in Longitude and Latitude)

Case	Event Comparison	Δt	Δr	$\Delta r/\Delta t$
		Day	AU	km s^{-1}
a	Event 2/Event 1	2.63	1.0	660
b	Event 3/Event 1	80	28.4	615
c	Event 3/Event 2	77	27.4	615
d	Event 4/Event 1	115	46.7	705
e	Event 4/Event 3	35	18.3	905
f	Event 6/Event 5	74	27.8	650
g	Event 7/Event 5	122	46.3	620
h	Event 7/Event 6	48	18.5	670

As noted above and in Table 2, Events 5, 6, and 7 belong to a phenomenological set that is different than that of Events 1, 2, 3, and 4. The $\Delta r/\Delta t$ values in Table 3 for Cases f, g, and h are compatible with a common value of 660 km s^{-1}.

Discussion and Conclusions

1. Figures 1 and 2 give a clear example of the fact that the physical conditions for the local acceleration of protons continue to be present in the very tenuous interplanetary plasma at 27 AU.

2. The two new examples of the propagation of large Forbush decreases (impulsive decreases of cosmic ray intensity) to 28 and 47 AU are displayed in Figures 1 and 3. The context of these events is shown in Figure 4. Three examples of the same nature have been published previously—one in April–May 1978 when Pioneer 11 was at 7 AU and Pioneer 10 at 16 AU [Van Allen, 1979] and two in June–October 1982 when Pioneer 11 was at ≈ 12.5 AU and Pioneer 10 at ≈ 28 AU [Van Allen and Randall, 1985].

3. All five of these cases show that at large radial distances the recovery from Forbush decreases has a time scale of at least several months. Such slow recoveries support the view that solar cycle modulation of the intensity of cosmic rays (in large scale) is the result of successive overlapping Forbush decreases which are more common and of greater magnitude around the time of maximum solar activity. Indeed the two Forbush de-

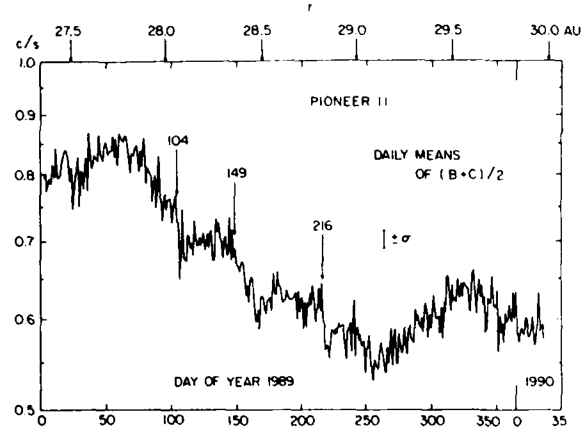

Fig. 4. An overview of daily mean counting rates of Pioneer 11 Detectors B and C during 1989 and early 1990.

creases shown in Figure 3 constitute a cumulative and durable reduction of cosmic ray intensity within an (admittedly exceptional) three month period by over 20 percent—a substantial fraction of the total reduction during a solar activity half-cycle of 5.5 years. See also Figure 4.

4. One referee of the original draft of this paper objected to the comparison of the time signatures of Forbush decreases observed with terrestrial neutron monitors with those by Pioneers 10 and 11 because of different spectral sensitivities and the possibility that the recoveries may be energy dependent. [An estimated 50% of the response of the Deep River Neutron Monitor is due to cosmic rays of energy less than 12 GeV and an estimated 50% of the responses of the P10/P11 detectors is due to cosmic rays of energy between 0.08 and 1.4 GeV.]

5. We offer contrary evidence as follows:

(a) Explorer 35 in lunar orbit at 1 AU with a detector similar to those on P10/P11 but with a somewhat lower threshold (E_p > 55 MeV) observed two large Forbush decreases (9% and 16%, respectively) in June–August 1972, from which essentially complete recovery occurred within about 30 days [Figure 1 of Thomsen and Van Allen, 1976]. The same two decreases with about the same magnitudes were observed by Pioneer 10, then at 1.8 and 2.6 AU, respectively, with essentially complete recovery in about the same time intervals. The corresponding recoveries in the Deep River Neutron Monitor from decreases of 6% on June 17 and 17% on August 4 had time scales for essentially complete recovery of over two weeks.

(b) Another valuable intermediate case was that of May–June 1978 (not previously published in detail) when Pioneer 11 was at about 7 AU and Pioneer 10 at about 16 AU. At Pioneer 11, the intensity recovered from a 27% decrease to 10% within 20 days and remained at that level whereas at Pioneer 10, the intensity decreased by 12% and exhibited essentially no recovery for over five months thereafter. The corresponding decrease at the Deep River Neutron Monitor was 15% and essentially complete recovery occurred in ten days.

6. The combination of the evidence described above reinforces the earlier suggestion [Van Allen, 1979] that refilling of the relative void in cosmic ray intensity created near the ecliptic by a major shock/blast wave occurs by translatitudinal diffusion (and/or drift) and not by inward radial diffusion from the outer boundary of the heliosphere. This suggestion is depicted in Figure 5.

7. Also the slow recoveries at large radial distances suggest that even Pioneer 10 at 47 AU is still far inside such a boundary, because close proximity (say, a few AU) to it would imply rapid recovery by inward diffusion, after the blast wave passed into the interstellar medium.

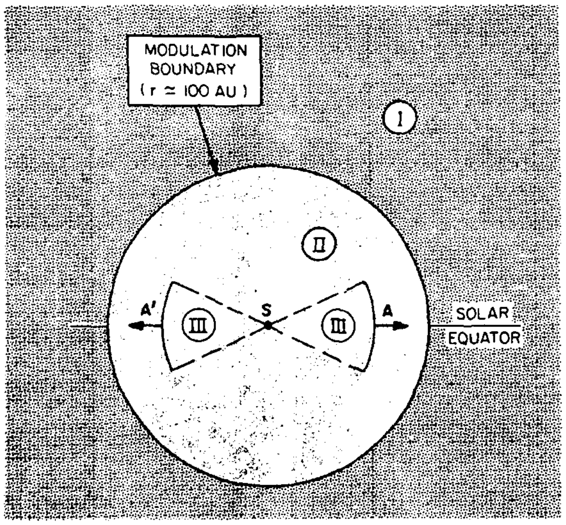

Fig. 5. A diagram to illustrate the transient depletion of the density of cosmic rays by outward moving blast/shock waves A, A′ near the solar equator and a suggested explanation for the observed slower recovery at large radial distance than at 1 AU because of progressively greater latitudinal dimensions of the depleted region. The shading gives a crude representation of the density in Regions I, the interstellar medium; II, the heliosphere (radial gradient not depicted); and III, the transiently depleted Forbush region. In this hypothesis Region II is the reservoir from which translatitudinal replenishment of Region III occurs, thereby depleting Region II. Radial replenishment of both Regions II and III from Region I is also envisioned, of course.

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