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## A durable reduction of cosmic ray intensity in the outer heliosphere

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**Abstract.** This paper reports Pioneer 10 (P10) and Pioneer 11 (P11) observations of the intensity  $J(E_p > 80 \text{ MeV})$  of galactic cosmic rays in the heliosphere near the heliographic equator during the 24-year period 1972-1996 and out to a heliocentric radial distance of 65 AU. It updates previous P10/P11 determinations of the time dependence of the radial gradient of intensity and emphasizes the recent 10-year period, especially the consequences of the great Forbush decrease in 1991. A fresh analysis compares P10 and P11 data with comparable data from IMP 8 at 1.0 AU. For this purpose, we have made a critical study of the data from three different instruments on IMP 8 and have developed a new time-dependent reference level of intensity at 1.0 AU for the period 1974-1996. Using this reference, we find that as of late 1996, recovery of intensity following the 1991 Forbush decrease has been markedly less complete in the outer heliosphere than at 1.0 AU. As a consequence, the mean radial gradient between 4 and 65 AU is now only about  $+0.3\% \text{ AU}^{-1}$ . Our findings favor the latitudinal wedge model of the heliosphere [Van Allen and Mihalov, 1990] and suggest that the modulation boundary of the heliosphere is far beyond 65 AU. Generally concordant, but less decisive, evidence of a similar nature has been reported previously by Van Allen [1993], Van Allen [1996], and Webber and Lockwood [1995b].

### 1. Introduction

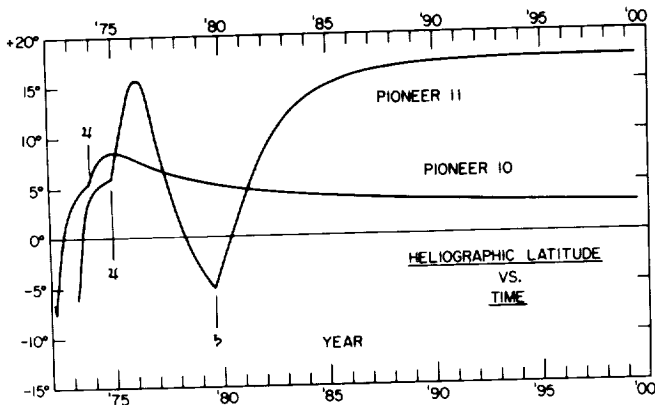
This paper reports the intensity of galactic cosmic rays  $J(E_p > 80 \text{ MeV})$  within the solar system as observed by Pioneer 10 (P10) and Pioneer 11 (P11) during a period of over 24 years (1972-1996) and out to a heliocentric radial distance of 65 AU. It updates our previous studies [e.g., Van Allen and Randall, 1985; Van Allen, 1988] of the modulation of intensity by solar activity via the magnetized plasma flowing outward from the Sun, and improves knowledge of the incomplete recovery of intensity in the outer heliosphere following the noteworthy Forbush decrease in 1991 [Van Allen and Fillius, 1992; Webber and Lockwood, 1993; Van Allen, 1993, 1996].

Longer-term and still elusive objectives are to observe transition phenomena at the modulation boundary of the heliosphere and the cosmic ray intensity beyond that boundary in the nearby interstellar medium, such intensity being by definition independent of solar activity. Because of the remoteness of all plausible sources of galactic cosmic rays, it is expected that the intensity in the interstellar medium is spatially uniform in the astronomical vicinity of the solar system and constant over time periods of the order of millennia or greater. Also it

is expected that the intensity in the interstellar medium is greater than at any point within the heliosphere. The latter expectation is an extrapolation of the fact that the observed intensity within the heliosphere is greatest when solar activity is the least and least when solar activity is the greatest, aside from a time lag of the order of a year. These simple expectations ignore the anomalous (cosmic) radiation, which is believed to consist of interstellar thermal atoms that have drifted into the heliosphere and been ionized therein, picked up by the magnetic field of the outward flowing solar wind, and accelerated at the heliospheric termination shock to energies up to some tens of MeV [Fisk et al., 1974; Pesses et al., 1981]. (See also Alfvén [1954] on the local origin of cosmic rays within the solar system and the interplanetary current sheet.) These accelerated ions are presumably emitted both inward and outward. Our P10/P11 instruments measure the integral of the cosmic ray spectrum from 80 MeV to infinity and are relatively insensitive to the waxing and waning of the anomalous component [McDonald et al., 1995; Christian et al., 1995], whose maximum contribution to our counting rates is estimated to be less than 1%. However, for instruments having substantially lower energy thresholds, the "nearby" interstellar medium may need to be regarded as beyond several hundred AU in order to lie beyond detectable contributions by anomalous particles emitted outward from the putative acceleration region at the heliospheric termination shock.

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**Figure 1.** Heliographic latitudes of the spacecraft Pioneer 10 and Pioneer 11 as a function of time. Discontinuities in the curves are identified by the planetary symbols for Jupiter (x) and Saturn (h) at the times of closest approach to those planets.

Homogeneous, nearly continuous bodies of data on cosmic ray intensity ( $E_p > 80$  MeV) have thus far been provided by University of Iowa instruments (code named UI/GTT) on the two NASA Ames Research Center spacecraft P10 and P11 as follows.

**Pioneer 10**

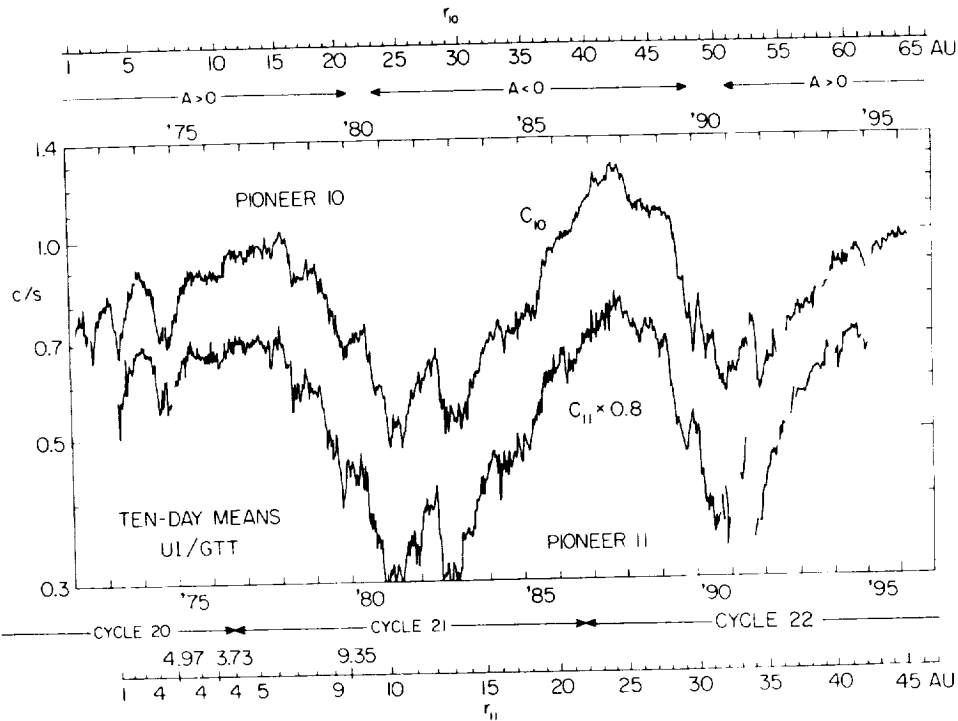
Pioneer 10 was launched at 1.0 AU on March 3, 1972, and after encounter with Jupiter on December 4, 1973,

proceeded along an escape trajectory from the solar system in approximately the solar antapex direction. Data acquisition is continuing at the date of writing (October 1996), and the present position is as follows: heliocentric distance  $r = 65.9$  AU, ecliptic longitude  $\ell = 75^\circ$ , ecliptic latitude  $\beta = +3.0^\circ$ , and heliographic latitude  $\beta' = +3.1^\circ$ . The present radial component of heliocentric velocity is  $2.61 \text{ AU yr}^{-1}$ . The entire trajectory has been, and will continue to be, within the heliographic latitude range  $-7.6^\circ < \beta' < +8.6^\circ$  (Figure 1).

**Pioneer 11**

Pioneer 11 was launched at 1.0 AU on April 6, 1973, and after encounters with Jupiter on December 3, 1974, and with Saturn on September 1, 1979, continued along an escape trajectory from the solar system in approximately the solar apex direction until termination of telemetry in early January 1995 due to inability to maintain antenna pointing toward the Earth. Position at that time was  $r = 42.3 \text{ AU}$ ,  $\ell = 271^\circ$ ,  $\beta = +15.5^\circ$  and  $\beta' = +17.4^\circ$ . The entire trajectory up to that date was within the heliographic latitude range  $-6.0^\circ < \beta' < +17.4^\circ$  (Figure 1).

Detailed descriptions of the UI/GTT instruments, the two nearly identical spacecraft, and their trajectories and missions are given by Van Allen *et al.* [1974, 1980], Fimmel *et al.* [1980], and Van Allen and Randall [1985] and in a personal memoir by Van Allen [1996].



**Figure 2.** Corrected counting rates of a matched pair of Geiger tubes,  $C_{10}$  on Pioneer 10 and  $C_{11}$  on Pioneer 11, as a function of time. Heliocentric radial distances  $r_{10}$  and  $r_{11}$  are shown at the top and bottom, respectively, of the figure. Also shown are the spans of conventionally defined solar activity cycles and the epochs of positive ( $A > 0$ ) and negative ( $A < 0$ ) polarity of the general magnetic field of the Sun.

## 2. Nature of Our Data

Figure 2 presents a comprehensive time history of the cosmic ray counting rates of a pair of single Geiger tubes, C<sub>10</sub> and C<sub>11</sub> on P10 and P11, respectively. Essentially identical pairs of curves represent the counting rates of two other pairs of Geiger tubes. There is no end-to-end in-flight calibration of these tubes and their associated electronics, but reliability of the data is strongly supported by this threefold agreement, by rigorous preflight testing and selection of detectors, and by internal consistency checks among the in-flight outputs of the several detectors on each spacecraft throughout their missions. Also, similar results are provided by a fourth pair of more heavily shielded Geiger tubes ( $E_p > 90$  MeV) of substantially smaller dimensions and quite different design. Counting rates such as those shown in Figure 2 are taken to be proportional to the omnidirectional intensity  $J$  of cosmic rays, integral above an energy threshold of 80 MeV for protons and corresponding energy thresholds for heavier nuclei. The energy thresholds are determined solely by passive physical shielding. The absolute geometric factor of these tubes is  $0.16 (\pm 0.04) \text{ cm}^2$ . For example, a counting rate of  $1.0 \text{ c s}^{-1}$  corresponds to  $J = 6.3 (\pm 1.6) \text{ particles (cm}^2 \text{ s)}^{-1}$ .

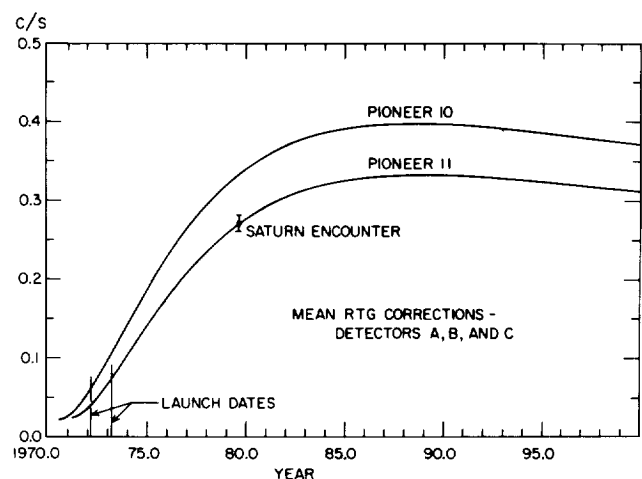
All single Geiger tube counting rates used in our cosmic ray papers in 1985 and thereafter, including this one, are corrected rates, derived from raw rates by procedures and with uncertainties described by *Van Allen and Randall* [1985]. The first of the corrections is for temperature, using temperature coefficients measured on the complete flight instruments before launch. The temperature of each instrument during flight was provided by an internally mounted thermistor until it reached the lower end of its range at  $-20^\circ\text{C}$  in January 1989 on P10 and March 1988 on P11. Thereafter, the temperature has been inferred by a previously determined interpolation relationship of that temperature to the temperatures provided by thermistors at two nearby points on the supporting platform of the spacecraft. The latter two thermistors have a lower limit of  $-53^\circ\text{C}$ . The mid-1996 temperature of the P10 instrument is estimated as  $-42^\circ\text{C}$  and the early 1995 temperature of the P11 instrument is estimated as  $-37^\circ\text{C}$ . Both are within proper operating ranges. The experimental variation of counting rate with temperature is of the form  $[1 + \alpha(T - 23.9^\circ\text{C})]$ . Raw rates are divided by this bracketed quantity to adjust them to a standard temperature of  $23.9^\circ\text{C}$ . The value of  $\alpha$  for all detectors whose rates are used in this paper is  $+7.16 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$  for P10 and  $+6.65 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$  for P11. Thus the value of the bracketed quantity above has decreased slowly from 1.00 at launch to about 0.95 at present.

The second and much more important correction is a subtractive one in order to remove the background caused by the decay products of the minor (order of parts per million) impurity  $\text{Pu}^{236}$  in the primarily  $\text{Pu}^{238}$  source in the radioisotope thermal generators (RTGs) which supply electrical power to the spacecraft. The magnitude of this correction and its dependence on time are discussed by *Thomsen and Van Allen* [1976]

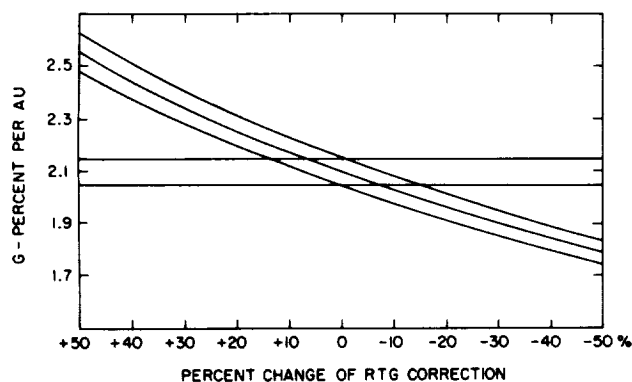
and *Van Allen and Randall* [1985]. The preflight values of the RTG corrections as reported in the earlier of these two references were found to be substantially too great (presumably because of room scattering) when Pioneer 11 passed under the rings of Saturn and in to 1.34 planetary radii in September 1979. All of our subsequent interplanetary work has used the revised corrections, as described in the second of the aforementioned references and summarized in Figure 3, reproduced therefrom. The time dependence of the correction is derived from basic nuclear physics using Atomic Energy Commission data on impurity levels of  $\text{Pu}^{236}$  and separation ages of the fuel in each of the four RTG units on each spacecraft. It is noted that the estimated magnitudes of the corrections for both P10 and P11 (Figure 3) have been nearly constant since 1984. The sensitivity of a radial P10/P11 gradient to an error in the magnitude of the RTG correction is illustrated in Figure 4, also from *Van Allen and Randall* [1985]. The counting rates as corrected by the procedures described above are referred to herein as "observed" rates.

## 3. Temporal Variations

The observed counting rates are, of course, a composite function of time (i.e., solar activity) and of the positions of the two spacecraft in the solar system. The most prominent feature of the data is the 11-year cyclic variation of intensity over two solar activity cycles in anticorrelation with the level of solar activity as measured by sunspot numbers, a well-known effect first found in ground-based ionization chamber data [*Forbush*, 1954]. The three successive P10 maximum/minimum (max/min) intensity ratios in Figure 2 lie in the range 2.2 to 2.8 and the three P11 ratios in the range 2.4 to 2.7. Interplanetary data of a similar nature ( $E_p > 55$  MeV) were obtained during a 5.5-year



**Figure 3.** Time dependence of subtractive corrections to the raw counting rates of single Geiger tubes on Pioneer 10 and Pioneer 11, as adopted following the 1979 Saturn encounter of Pioneer 11. These corrections are attributed to the radioisotope thermal generators (RTGs), which supply electrical power to the spacecraft and their instruments [*Van Allen and Randall*, 1985].

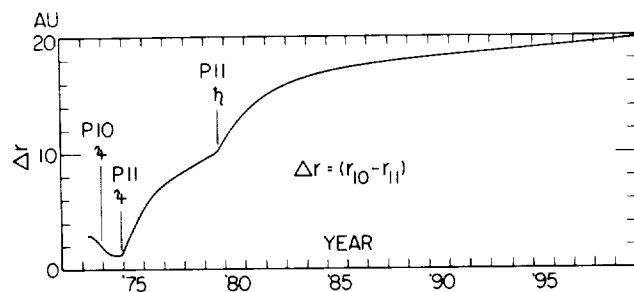


**Figure 4.** An example of the sensitivity of a radial gradient calculated from P10/P11 data to an error in the magnitude of the RTG corrections [Van Allen and Randall, 1985].

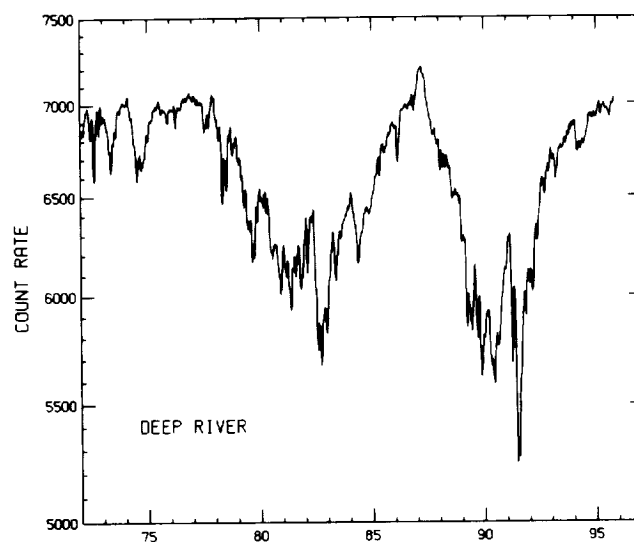
period 1967–1972 by the solar-cell-powered Explorer 35 at 1.0 AU [Van Allen, 1972]. These earlier observations encompass the 1969–1970 minimum but not the subsequent 1977–1978 maximum. The maximum/minimum intensity ratio during this partial cycle of solar activity is about 1.9.

The major features of the time dependence of intensity and most, but not all, of the recognizable minor features are well correlated between P10 and P11 with a time delay corresponding to outward propagation within the solar wind of clouds of plasma in which the diffusion coefficient for cosmic rays is presumed to be distinctively less than usual. Conversely, the speed of propagation can be derived from detailed overlay plots, in favorable cases to an uncertainty of  $\lesssim 10\%$  [Van Allen, 1976, 1979]. Since the encounter of P11 with Jupiter the difference of radial distances  $\Delta r = (r_{10} - r_{11})$  of the two spacecraft (Figure 5) has increased monotonically from a local minimum of 1.21 AU at that time to the present value of 19.2 AU. Since 1982,  $\Delta r$  has been greater than 15 AU; its asymptotic rate of increase is  $0.18 \text{ AU yr}^{-1}$ . It is noted that a typical solar wind speed of  $450 \text{ km s}^{-1}$  [Gazis, 1996] corresponds to a purely radial time delay  $\Delta t / \Delta r = 3.85 \text{ d AU}^{-1}$ .

The full run of data shown in Figure 2 has general similarity to the run of data for the same epoch (Figures 6 and 7) from terrestrial neutron monitors (Solar-Geophysical Data), though the maximum/minimum in-

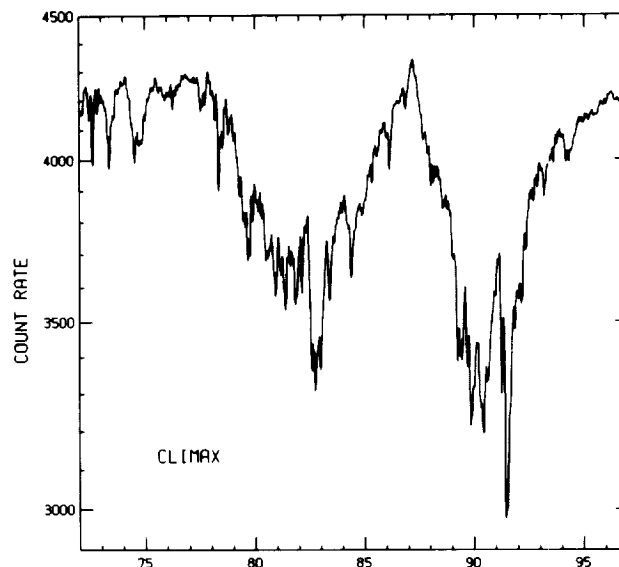


**Figure 5.** Time dependence of the difference  $\Delta r = (r_{10} - r_{11})$  between the heliocentric radial distances of P10 and P11.



**Figure 6.** Counting rate, divided by 300, of the Deep River neutron monitor versus time (Solar-Geophysical Data).

tensity ratios are in the range 1.23 to 1.37 for Deep River; 1.29 to 1.44 for Climax; 1.29 to 1.42 for Calgary; and 1.22 to 1.37 for Moscow vis-à-vis the corresponding ratios for P10 and P11 data in the range 2.2 to 2.8 as quoted above, thereby demonstrating the greater modulation factor for lower energy particles in the primary cosmic ray spectrum. The nominal proton energy thresholds (geomagnetic) for the neutron monitors listed above are 450, 2200, 500, and 1660 MeV, respectively, though their specific yield functions (count per primary particle) are a complex function of energy and altitudes of the stations, whereas the efficiency of our detectors is believed to be independent of energy above an effective threshold of 80 MeV.



**Figure 7.** Counting rate, divided by 100, of the Climax neutron monitor versus time (Solar-Geophysical Data).

The Climax neutron monitor data (*Simpson [1994]* plus recent updates in Solar-Geophysical Data) cover an observing period of over 43 years, 1953–1996. The following features of that body of data are noteworthy: Despite the irregular nature of the intensity-time curve and the individualistic nature of each 11-year segment of the overall record, the intensities at all four well-established maxima and at the almost current fifth maximum are remarkably similar. The highest monthly rates during these successive maxima (in units of 100 counts  $\text{hr}^{-1}$ ) are 4287, 4340, 4287, 4325, and 4224. The mean of the first four maximum values is 4310, and their standard deviation from that mean is  $\pm 0.6\%$ . In contrast, the lowest monthly rates during the four successive minima are 3369, 3652, 3324, and 3005, with a mean of 3338 and a standard deviation of  $\pm 7.9\%$ . Thus the relative variability of maximum values is less by an order of magnitude than that of minimum values. Contrasting facts on the temporal variability of P10 and P11 data are deferred to a later section.

#### 4. Apparent Radial Gradient of Intensity

The intensity  $J$  as measured by the UI/GTT instruments is of course a composite function of time, as was sketched in section 3; of positional coordinates; and of changes in energy spectra and relative abundances of particle species. Our instruments do not measure the latter two properties of the radiation, and therefore our quantity  $J$  must be understood to be a kind of overall average over these properties, some of which are measured by the more complex instruments of other investigators on P10, P11, Voyager 1 (V1), Voyager 2 (V2); and Ulysses (Ulys).

It is clear in Figure 2 that the peak-to-peak dependence of  $J$  ( $E_p > 80$  MeV) out to at least 65 AU is of lesser magnitude than the cyclic temporal variation. In a broader context it is also clear that a full determination of the separate temporal and spatial dependences of  $J$  within the heliosphere challenges or exceeds the combined efforts of the investigators on the four outer heliospheric spacecraft (P10, P11, V1, and V2) as well as those on Ulys at high latitudes ( $-80^\circ < \beta' < +80^\circ$ ) within the inner heliosphere because of the paucity of observing sites and the plethora of potentially significant independent variables.

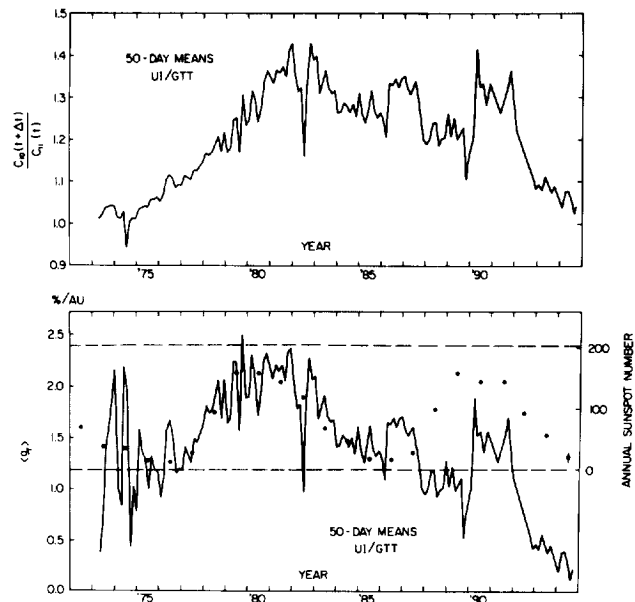
Nonetheless, the determination of radial and latitudinal dependences of intensity is one of the important objectives of the extended phases of these missions. The present paper is one of numerous contributions to this subject by diverse authors. See reviews by *Filius [1989]*, *McKibben et al. [1982, 1995]*, and *McKibben [1986]* and references to original papers in these reviews. See also the comprehensive original papers by *Lockwood and Webber [1990]*, *Webber and Lockwood [1990]*, *Lopate and Simpson [1991]*, and *McDonald et al., [1992]*, and two recent high-latitude survey papers by *Heber et al. [1996]* and *Simpson et al. [1996]*.

Because of the nature of the trajectories of P10 and P11 (Figure 1) the data shown in Figure 2 refer to ob-

servations in the range of ecliptic latitude  $-3^\circ < \beta < +17^\circ$ . As was discussed in section 2, the major features of the data and most, though not all, of the more detailed features are well correlated between P10 and P11, despite large differences in longitude, with a time delay approximated by

$$\Delta t = \frac{r_{10} - r_{11}}{v_{sw}} = \frac{\Delta r}{v_{sw}}, \quad (1)$$

where  $v_{sw}$  is the speed of the solar wind or of solar shock waves. Equation (1) ignores longitudinal delays due to narrow-angle solar streams [*Van Allen, 1976*] having reduced diffusion coefficients. Such delays may be of either algebraic sign. However, we find that the delayed ratio of 26-day mean rates  $C_{10}(t + \Delta t)/C_{11}(t)$  is insensitive to substantial variation of  $v_{sw}$ , except transiently in cases of large and rapid temporal variations. In previous papers (*Van Allen [1988]*) and an update in Figure 16 of *Van Allen [1996]*) we have, in effect, assumed that the counting rate ratio  $C_{10}(t + \Delta t)/C_{11}(t)$  is the simultaneous ratio of intensity at  $r$  and at  $r + \Delta r$ , ignoring the differences in latitude ( $\Delta\beta$ ) and in longitude ( $\Delta\ell$ ). The value of  $\Delta t$  for an adopted  $v_{sw} = 450 \text{ km s}^{-1}$  lies in the range 7 to 74 days. The time dependence of the ratio is plotted in the top panel of Figure 8 and the corresponding values of  $r_{10}$  and  $r_{11}$  and  $\Delta r$  are shown in Figure 2 and Figure 5. In the context of the present paper the most important feature of these data is the rapid decline of the counting rate ratio in recent years to a value approaching unity. The inference of an apparent radial gradient proceeds as follows: An idealized



**Figure 8.** (top) Time-delayed ratios  $C_{10}(t + \Delta t)/C_{11}(t)$  as a function of  $t$ , updated from *Van Allen [1988]*. The time delay  $\Delta t = (r_{10} - r_{11})/450 \text{ km s}^{-1}$ , and (bottom) the corresponding mean radial gradients  $\langle g_r \rangle$  inferred from the delayed ratios, ignoring differences of latitude and longitude [*Van Allen, 1996*]. See text for our current reservations on the previous interpretation of these inferred gradients.

(relative) radial gradient, integral over the cosmic ray spectrum but differential in radius  $r$ , is defined by

$$g_r = \frac{1}{J} \frac{dJ}{dr} = \frac{d(\ln J)}{dr} \quad (2)$$

and is usually quoted in percent per AU. The mean value of  $g_r$  over a finite radial distance  $\Delta r$  (sometimes called an integral gradient, denoted by  $G_r$ ) is

$$\langle g_r \rangle = \frac{\int_r^{r+\Delta r} g_r dr}{\int_r^{r+\Delta r} dr} \quad (3)$$

Hence

$$\langle g_r \rangle = \frac{1}{\Delta r} \ln \left( \frac{J_{r+\Delta r}}{J_r} \right) \quad (4)$$

The observed quantity

$$\frac{C_{10}(r + \Delta r)}{C_{11}(r)} = k \left( \frac{J_{r+\Delta r}}{J_r} \right), \quad (5)$$

where  $k$  is the ratio of geometric factors of the two detectors. Hence by (4) and (5)

$$\langle g_r \rangle = \frac{1}{\Delta r} \left[ \ln \left( \frac{C_{10}}{C_{11}} \right) - \ln k \right] \quad (6)$$

Our best previous efforts to determine  $\langle g_r \rangle$  from  $C_{10}(r + \Delta r)/C_{11}(r)$  are illustrated in the bottom panel of Figure 8, an extension of results reported by *Van Allen* [1988], who adopted  $k = 1.0$ . These results resemble those based on data from various combinations of spacecraft detectors having similar spectral coverage [*McKibben et al.*, 1982; *McKibben*, 1986; *Lopate and Simpson*, 1991; *Webber and Lockwood*, 1995a]. The accuracies of all such inferred values of  $\langle g_r \rangle$ , including ours, and of the latitudinal gradient  $\langle g_\beta \rangle$  are dependent on exactly known values of the relative geometric factors and energy thresholds of different, albeit similar, instruments on different spacecraft at different times  $t$ , radii  $r$ , latitudes  $\beta$ , and longitudes  $\ell$ . The problem is especially severe for small counting rate ratios ( $\approx 1.2$ ), small  $\Delta r$  ( $\approx$  few AU) and small  $\Delta\beta$  ( $\approx 10^\circ$ ). It is also exacerbated by the inevitable coupling of  $\langle g_r \rangle$  and  $\langle g_\beta \rangle$ , often assumed to be independent, and by dissimilar temporal variations at two different spacecraft.

Realistic examples of the  $k$  sensitivity of  $\langle g_r \rangle$  as shown for our data in Figure 8 are as follows, using equation (6). As one example, if  $C_{10}(t + \Delta t)/C_{11}(t) = 1.4$  and  $\Delta r = 15$  AU, then  $\langle g_r \rangle$  is equal to  $+2.24\%$   $\text{AU}^{-1}$  if  $k = 1.0$  but is equal to  $+1.61\%$   $\text{AU}^{-1}$  if  $k = 1.1$  and is equal to  $+2.94\%$   $\text{AU}^{-1}$  if  $k = 0.9$ . As a second example, if  $C_{10}(t + \Delta t)/C_{11}(t) = 1.04$  and  $\Delta r = 19$  AU, then  $\langle g_r \rangle$  is equal to  $+0.21\%$   $\text{AU}^{-1}$  if  $k = 1.0$  but is  $+0.76\%$   $\text{AU}^{-1}$  if  $k = 0.9$  and  $-0.29\%$   $\text{AU}^{-1}$  if  $k = 1.1$ .

A more general presentation of the problem of separating positional from temporal variations using a small number of observing spacecraft in the heliosphere is along the following lines: Suppose that a spacecraft is observing  $J(\vec{r}, t)$  as it moves at velocity  $\vec{V}$ . Then

$$\frac{dJ}{dt} = \frac{\partial J}{\partial t} + \vec{V} \cdot \text{grad } J \quad (7)$$

The observed quantity is the total derivative  $dJ/dt$  but there is, in general, an unknown combination of contributions by the two terms on the right-hand side of this equation. This uncertainty also prevails for an integration of (7) over a finite interval  $t$  to  $t + \Delta t$  and over the corresponding motion in spatial coordinates. It is often hoped that time-delayed comparisons of  $J$  at two nearby spacecraft minimize the contribution of the first term and make possible a determination of  $\text{grad } J$ . However, this may not be true.

Because of the aforementioned considerations we have investigated a different, and perhaps clearer, approach to the analysis of our P10 and P11 data, as described in the following section. However, even this approach has some of the same hazards as well as additional ones.

## 5. Comparison of P10 and P11 Data with IMP 8 Data

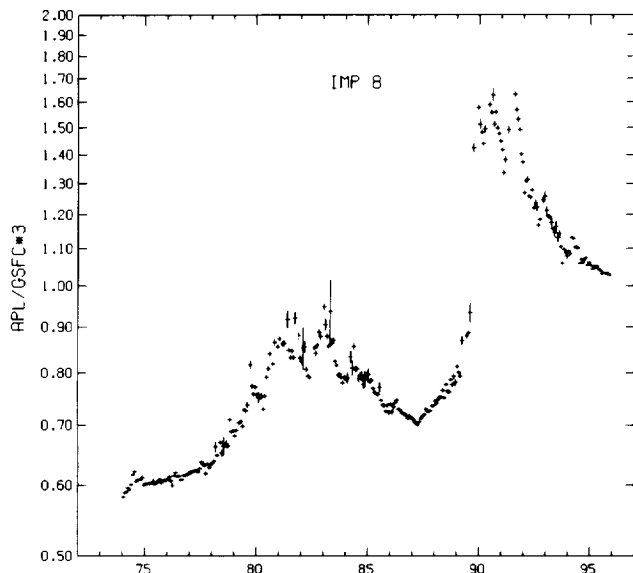
Interplanetary Monitoring Platform 8 (IMP 8, also designated IMP-J, Explorer 50, and 1973-78A) was launched on October 25, 1973, into a loose Earth orbit that is subject to substantial solar-lunar (primarily lunar) perturbations. A comprehensive listing of the gross elements of IMP 8's orbit has kindly been supplied to us by R. Parthasarathy of the National Space Science Data Center for the period 1974-1999. An overall summary is as follows:  $4^\circ < \text{inclination} < 55^\circ$ ,  $23 < \text{perigee (radial)} < 33 R_E$ , and  $37 < \text{apogee (radial)} < 46 R_E$ , with the semimajor axis substantially constant at  $35 R_E$ . By virtue of the orbit of this satellite, all detectors on it with energy thresholds  $E \gtrsim 60 \text{ MeV}$  are immune to magnetospheric particles, though they record occasional sporadic bursts of solar energetic particles. The latter can usually be recognized and the brief periods of their presence can be omitted in order to obtain a nearly continuous record of cosmic ray intensity at 1.0 AU.

There are three different energetic particle instruments on IMP 8 as follows: Johns Hopkins University Applied Physics Laboratory (APL; principal investigators (PIs), S. M. Krimigis and T. P. Armstrong); Goddard Space Flight Center/University of New Hampshire (GSFC; PI, F. B. McDonald); and University of Chicago (Chi; PI, J. A. Simpson). Through the courtesy of the principal investigators and the National Space Science Data Center, we have been able to examine all three bodies of data.

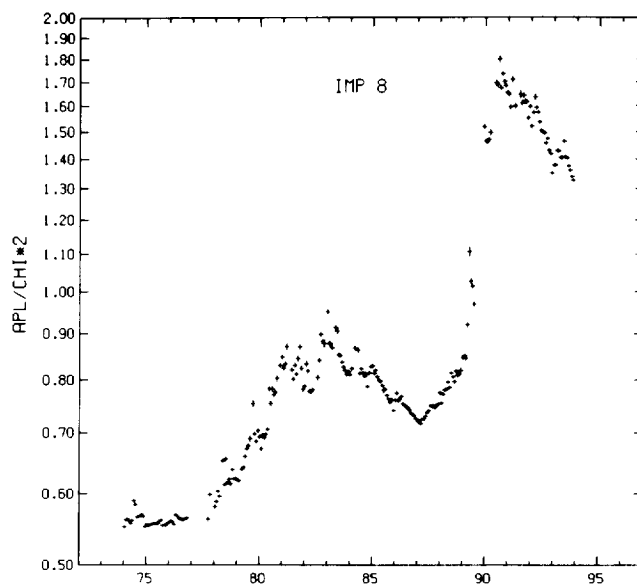
Data from any one of these instruments provide 1.0 AU reference data for the outward moving spacecraft P10 and P11. However, we find disparities among the three bodies of IMP 8 data which seriously affect inferred values of the apparent radial gradient. On the one hand, the GSFC ( $E > 70 \text{ MeV}$ ) and Chi ( $E > 105 \text{ MeV}$ ) rates have a solar cycle max/min ratio of 4 to 5, about twice that for our P10 and P11 ratios as well as that for our earlier Explorer 35 ratio. Inasmuch as our Geiger tubes are reasonably certain to integrate the cosmic ray spectrum with equal weight from 80 MeV to infinity, it appears that the GSFC and Chi telescopes do not count protons having near-minimum

specific ionization and therefore give greater weight to lower-energy particles whose solar cycle modulation is greater than that for the entire cosmic ray spectrum. Also, we find that the regression loops of both bodies of data against neutron monitor data drift monotonically as a function of time in the direction of slowly diminishing sensitivity. On the other hand, the APL data have a solar cycle max/min ratio of about 2.5, similar to that for P10 and P11. Also, prior to September 1989 the APL data show no temporal drift in their regression relationship to neutron monitor data (Climax or Deep River) which we regard as the most trustworthy standards of cosmic ray intensity at 1.0 AU, albeit with a different energy sensitivity than that of any of the spacecraft detectors. On the basis of these considerations we judge that the APL data are the most appropriate for comparison to our P10 and P11 data. However, in early September 1989 the anticoincidence shield of the APL telescope suffered a failure which, in effect, increased the telescope's geometric factor (T. P. Armstrong, private communication, 1995), and there was a discontinuous increase in the reported rates.

In Figures 9 and 10 we plot the ratio of reported 26-day simultaneous rates APL/GSFC versus time and APL/Chi versus time, respectively. These two figures exhibit the relative solar cycle modulations, the gradual temporal drifts of the GSFC and Chi sensitivities, and the September 1989 discontinuity in the APL rates. A specific objective of more detailed analysis is to determine the magnitude of the APL discontinuity. To this end, we adopt a five-parameter relationship, including a quadratic temporal variation in GSFC sensitivity, between the APL and GSFC rates and determine the parameters by a multidimensional least squares analysis. The resulting values of the normalized, detrended GSFC data are denoted by the symbol  $\overline{\text{GSFC}}$ . In Figure 11 the ratios  $\text{APL}/\overline{\text{GSFC}}$  are shown as a function



**Figure 9.** Time dependence of simultaneous 26-day ratios of reported rates APL/GSFC on the same spacecraft, IMP 8 at 1.0 AU.

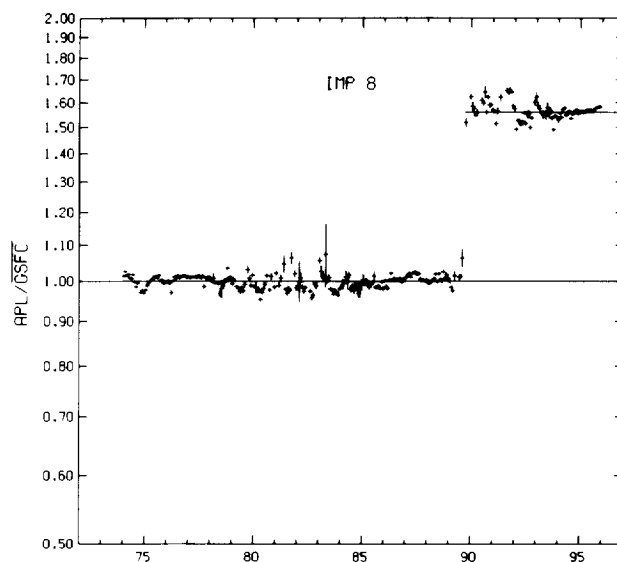


**Figure 10.** Time dependence of simultaneous 26-day ratios of reported rates APL/Chi on the same spacecraft, IMP 8 at 1.0 AU.

of time. The same procedure was applied to the Chi data, and the resulting ratios  $\text{APL}/\overline{\text{Chi}}$  are shown as a function of time in Figure 12. From the numerical analysis and Figures 11 and 12 we find  $0.64 (\pm 0.01)$  as the factor by which APL rates after day of year (DOY) 246, 1989, must be multiplied in order to adjust them to the same basis as before that date.

The results are exhibited in Figure 13. The corresponding numerical table has been adopted as our IMP 8 reference standard at 1.0 AU.

Ideally, then, upon using the adjusted APL rates, the appropriately delayed P10/APL or P11/APL ratios



**Figure 11.** Time dependence of the recalculated 26-day ratios  $\text{APL}/\overline{\text{GSFC}}$  as described in the text. This graph illustrates the basis for estimating the discontinuity in APL rates that occurred on or about DOY 246, 1989.

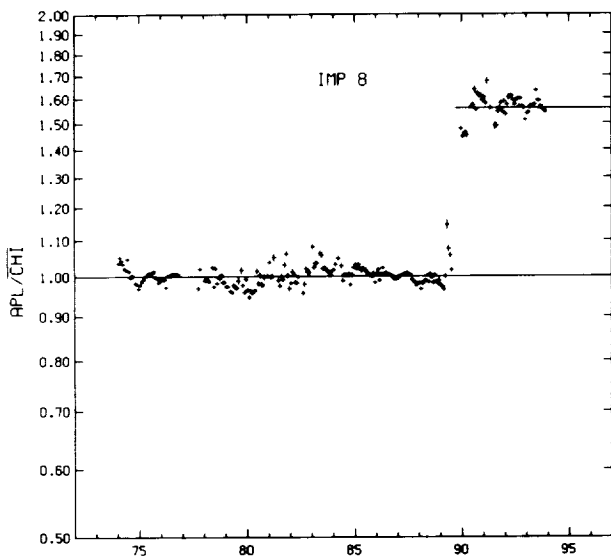


Figure 12. Similar to Figure 11 but for  $APL/\overline{Chi}$ .

represent (apart from an irrelevant constant factor) the counting rates of an hypothetical APL detector carried outward on P10 or P11.

In Figure 14 we plot the (unnormalized) time-delayed ratio of the rate of P10 detector  $C_{10}$  to the rate of IMP 8 (as adjusted) as a function of  $\Delta r = (r_{10} - 1.0)$  using a constant  $v_{sw} = 450 \text{ km s}^{-1}$  [Gazis, 1996]. The corresponding times at the Earth are also shown on these graphs. Vertical lines indicate the approximate times of reversals of the magnetic polarity of the Sun, with  $A > 0$  corresponding to the north heliographic pole being a north magnetic pole and  $A < 0$  corresponding to the north heliographic pole of the Sun being a south magnetic pole [Hoeksema and Scherrer, 1986; Hoeksema,

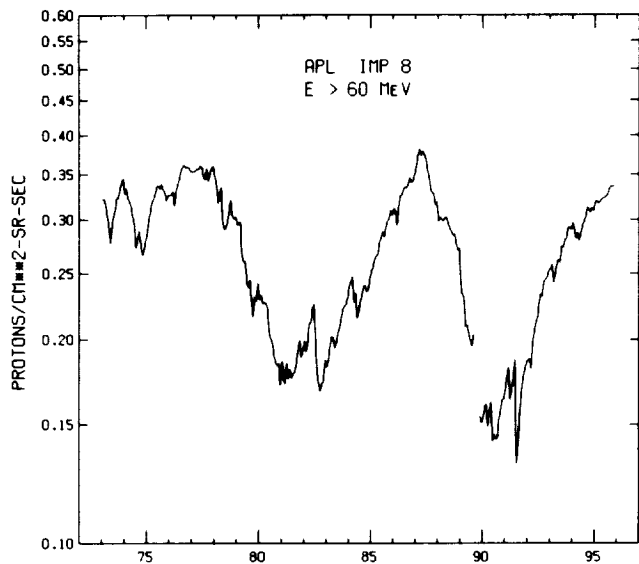


Figure 13. Our adopted time dependence of adjusted APL rates on IMP 8, 1974–1996, as described in the text.

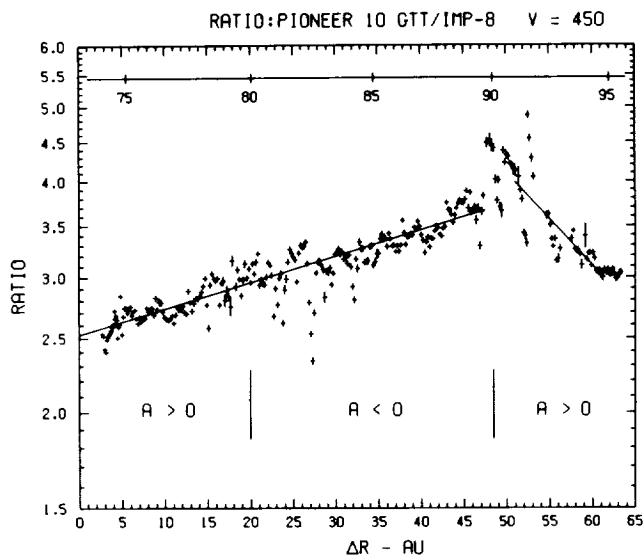


Figure 14. Time delayed 26-day ratios of  $C_{10}(t+\Delta t)$  to adjusted APL ( $t$ ) rates as a function of  $\Delta r = (r_{10} - 1.0)$ . The ordinate is in unnormalized units. Also shown is the timescale by calendar years as referred to 1.0 AU. The vertical lines show approximate times of switches in polarity of the general magnetic field of the Sun [Hoeksema, 1991].

1991]. The gross features of the semilogarithmic Figure 14 are indicated by the two least squares straight lines.

1. In the period 1974–1989 ( $4 < \Delta r < 48 \text{ AU}$ ), the slope  $S$  of the first line is

$$S = +0.8 (\pm 0.1)\% \text{ AU}^{-1}, \quad (8)$$

computed by the equivalent of equation (4).

2. Then following a brief hiatus, 1989–1991, the trend of the ratio versus  $\Delta r$  changes dramatically and the slope of the second line is

$$S = -2.7 (\pm 0.4)\% \text{ AU}^{-1} \quad (9)$$

for the period 1991–1994.

3. Finally,  $S$  appears to be approaching zero for the past 2 years.

4. Also, it is noted that the slope  $S$  over the full range  $4 < \Delta r < 64 \text{ AU}$  (1974–1996) is

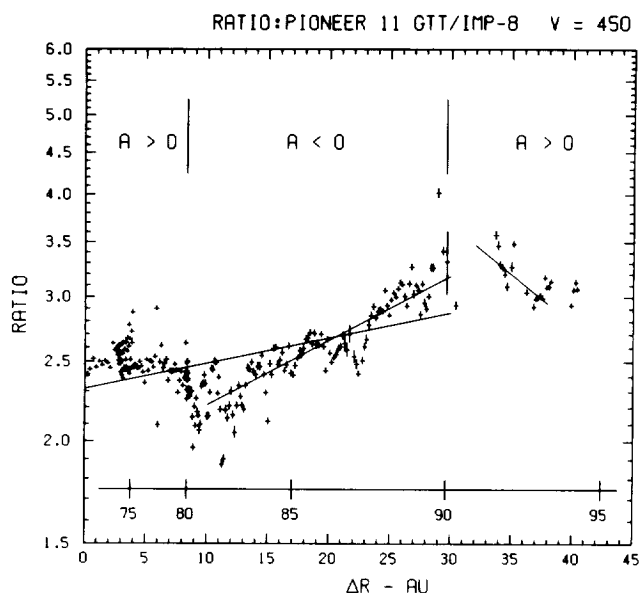
$$S = +0.3\% \text{ AU}^{-1}, \quad (10)$$

calculated for a line joining the two end points of the graph.

Alternatively, the delayed P10/IMP 8 ratio may be plotted as a function of calendar date at the Earth, but inasmuch as  $dr/dt$  for P10 has been nearly constant for the past 10 years, the discontinuous change in slope at or about 1991 is essentially the same in such an alternative plot.

Figure 15 is a corresponding plot of the delayed  $C_{11}/\text{IMP 8}$  ratio versus  $\Delta r = (r_{11} - 1.0)$ . This body of data has a general resemblance to that for Pioneer 10 but differs significantly.





**Figure 15.** Similar to Figure 14 but for ratios of  $C_{11}(t + \Delta t)$  to adjusted APL ( $t$ ).

1. For the range  $0 < \Delta r < 30$  AU (1974–1990),

$$S = +0.8 (\pm 0.3)\% \text{ AU}^{-1}. \quad (11)$$

2. For the lesser range  $9 < \Delta r < 30$  AU (1980–1990),

$$S = +1.6 (\pm 0.2)\% \text{ AU}^{-1}. \quad (12)$$

3. As in Figure 14, there is a discontinuous change in slope in 1989–1991 and for the period 1991–1993

$$S = -2.7 (\pm 0.4)\% \text{ AU}^{-1}. \quad (13)$$

4. The value of  $S$  appears to be approaching zero during the subsequent 2 years.

5. Again as in Figure 14, the long period of positive  $S$  and the shorter period of greater negative  $S$  tend to cancel each other and the value of the slope of a line between the two end points of the graph in Figure 15 is

$$S = +0.5\% \text{ AU}^{-1}. \quad (14)$$

We now have tentative evidence that the downward sway in Figure 15 during 1979–1983 and the corresponding upward sway during the same period in the bottom panel of Figure 8 are attributable to too large an RTG correction to P11 rates. This possibility is noted but is not pursued further in the present paper because it has only slight relevance to the discontinuous changes in  $S$  circa 1991.

It is essential to note the striking changes from positive to negative values of  $S$  circa 1991 at both P10 and P11 are coincident in time but occur at quite different positions in the heliosphere, namely, at 50 AU in the antapex direction and at 30 AU in the apex direction, respectively. Our new analysis of cosmic ray intensity in the outer heliosphere, observed independently at P10 and P11, is the principal fresh result of the present pa-

per. Inasmuch as both temperature and RTG corrections to our P10 and P11 raw data (section 2) have changed only slightly during the past 10 years (Figure 3), the recent reversals of the algebraic sign and magnitude of  $S$  are robustly insensitive to uncertainties in these corrections.

## 6. Further Remarks on Temporal Variations

As is shown in Figures 14 and 15, the long epoch of positive  $S$  and the short epoch of greater negative  $S$  tend to cancel each other. It now (October 1996) appears that as solar activity is approaching a minimum [Wilson *et al.*, 1996], the cosmic ray intensity at 65 AU near the heliographic equator (P10) (Figure 2) is leveling off at a maximum value equal to its maximum value at 15 AU in 1977–1978 but at only 77% of its maximum value at 42 AU in 1987. Indeed, the 1996 intensity is only 70% of what it would have been if the 1974–1990 trend had continued. A similar but lesser effect is observed at P11 at 42 AU and heliographic latitude  $+17^\circ$ , as of termination of this mission in early 1995 (Figure 15). At that time the P11 intensity is leveling off at a value nearly the same as its maximum value at 6 AU in 1977–1978 and at 89% of its maximum value at 25 AU in 1987. Indeed, the intensity at P10 at 65 AU is nearly the same as that at P11 at 42 AU.

At 1.0 AU the IMP 8 (adjusted) intensity is now about 94% of its 1977–1978 maximum and about 88% of its 1987 maximum (Figure 13).

The interpretation of Figures 14 and 15 is simply that the cosmic ray intensity in the outer heliosphere has recovered less completely than has the intensity at 1.0 AU (Figure 13) following the extraordinary solar activity in 1991 that produced large Forbush decreases at all four outer heliospheric spacecraft P10, P11, V1, and V2 as well as at the Earth [Van Allen and Fillius, 1992; Weber and Lockwood, 1993; McDonald *et al.*, 1994; Whang and Burlaga, 1994] and that subsequently shocked the magnetopause into notably intense emission of 2–3 kHz radio waves [Gurnett *et al.*, 1993; Gurnett, 1995]. The latter authors estimated heliocentric distances to the magnetopause of 116–177 AU and to the termination shock of 87–133 AU. Our results also suggest that the cosmic ray modulation boundary of the heliosphere lies far beyond 65 AU because of the sluggish and incomplete recovery of cosmic ray intensity at that distance. The observed transitions of  $S$  from positive to negative values (Figures 14 and 15) were essentially simultaneous with a switch of magnetic polarity of the Sun from  $A < 0$  to  $A > 0$ , but it is a matter of conjecture as to whether this switch is the root cause of the transitions or is merely coincidental in time [Gurnett and D'Angelo, 1982].

## 7. Summary

This paper reports Pioneer 10 (P10) and Pioneer 11 (P11) observations of the intensity  $J(E_p > 80 \text{ MeV})$  of

galactic cosmic rays in the heliosphere near the heliographic equator during the 24-year period 1972–1996 and out to a heliocentric radial distance of 65 AU. It updates previous P10/P11 determinations of the time dependence of the radial gradient of intensity and emphasizes the recent 10-year period, especially the consequences of the great Forbush decrease in 1991. A fresh analysis compares P10 and P11 data with comparable data from IMP 8 at 1.0 AU. For this purpose, we have made a critical study of the data from three different instruments on IMP 8 and have developed a new time-dependent reference level of intensity at 1.0 AU for the period 1974–1996. Using this reference, we find that as of late 1996, recovery of intensity following the 1991 Forbush decrease has been markedly less complete in the outer heliosphere than at 1.0 AU. As a consequence, the mean radial gradient between 4 and 65 AU is now only about  $+0.3\% \text{ AU}^{-1}$ . Our findings favor the latitudinal wedge model of the heliosphere [Van Allen and Mihalov, 1990] and suggest that the modulation boundary of the heliosphere is far beyond 65 AU. Generally concordant, but less decisive, evidence of a similar nature has been reported previously by Van Allen [1993], Van Allen [1996], and Webber and Lockwood [1995b].

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