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FINAL REPORT **NASA GRANT : NAGW-3454**

PROJECT TITLE - Studies Using IMP, Voyager and Pioneer Cosmic Ray Data to Determine the Size of the Heliosphere

PRINCIPAL INVESTIGATOR: John A Lockwood
Space Science Center
University of New Hampshire
Durham, NH 03824

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SUMMARY

The purpose of this project was to use the cosmic ray data from the IMP, Voyager and Pioneer spacecraft in the heliosphere out to ~ 65 AU to estimate the size of the heliosphere. We used several techniques to develop a consistent picture of the size of the heliosphere. The first method used a response function approach which determined the intensity as a function of time by scaling the modulation effect as they move outward and eventually reach the boundary of the heliosphere. In this model the effects of transient cosmic ray disturbances is included (see attachment #2). A second approach using the perturbation method in which drifts are considered as a perturbation to the standard diffusion-convection modulation models was not fully developed. In a third approach the location of the modulation boundary beyond the termination shock was estimated using observations of the intensity and radial gradients between Voyager 2 and Pioneer 10 along with new estimates of the interstellar intensity of >70 MeV galactic cosmic rays (see attachments #2 & 3). Using this method we found that for 7 years from 1983 to 1990 the modulation boundary remained constant at 83 ±5 AU. We infer from these studies that a modulation boundary can be estimated only by extrapolating the observed radial gradients when the solar magnetic field polarity is such that cosmic-ray particles are drifting in the heliosphere inward toward the Earth along the neutral sheet. The boundary distance is larger than the estimates of the location of the termination shock at 67±5 AU using the same method.

Two other studies partially supported by this grant are attached. The first deals with the recovery period of the >70 MeV cosmic rays in the outer helicsphere from 1992-1995 (attachment #4). In the second paper we compare the rigidity dependence of the 11-year cosmic ray variation at the Earth in two cycles of opposite solar magnetic field polarity (attachment #5)

In the spring of 1994 we hosted the *Second Pioneer-Voyager Symposium on Energetic Particles and Fields in the Outer Heliosphere.* at the New England Center on the campus of the University of New Hampshire. It was attended by about 90 scientists from around the world. From all the comments, we believe that this was a highly successful symposium. No formal proceedings were published so that more discussion could take place. A copy of the program is attached.

PUBLICATIONS:

1. Interplanetary E>70 MeV Cosmic Ray Radial and Latitudinal Gradients, *Proc 23rd Int Cosmic Ray Conf (Calgary)* 3, 469, 1993 (J.A. Lockowd & W.R. Webber)

2. A Simple Response Function Simulation That Reproduces in Detail the Heliospheric 11-year Intensity Time Variations of >70 MeV Particles Observed at IMP, V2 and P10, *Proc 23rd Int Cosmic Ray Conf (Calgary)* 3, 485, 1993 (W.R. Webber, J.A. Lockwood & M.A. Lee)

3. 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, 853, 1995 (J.A. Lockwood & W.R. Webber)

4. Intensity Variations of >70 MeV Cosmic Rays Measured by Pioneer 10, Voyuager 1 & 2 and IMP in the Heliosphere During the Recovery Period from 1992-1995, *Geophys. Res Lett.* 1995, (W.R. Webber and J.A. Lockwood)

5. Comparison of the Rigidity Dependence of the 11-year Cosmic Ray Variation at the Earth in Two Cycles of Opposite Magnetic Polarity, accepted for publication in *J. Geophys. Res.* ,1996 (J.A. Lockwood & W.R. Webber)

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Interplanetary E>70 MeV Cosmic Ray Radial and Latitudinal Gradients

J. A. Lockwood[1] and W. R. Webber[2]
[1]Space Science Center, University of New Hampshire, Durham, NH
[2] Astronomy Department, University of New Mexico, Las Cruces, NM

ABSTRACT

We have measured the temporal history of the radial and latitudinal gradients of E>70 MeV cosmic ray particles from 1972 to 1993 using data from the IMP, Voyager and Pioneer spacecraft. The radial gradients are a strong function of cosmic ray intensity when A<0 but are essentially independent of the intensity when A>0. We also determined the ratios of the cosmic ray intensity at ~ 16° and ~30° heliographic latitude to the intensity near the equator. These ratios are correlated with the tilt angle of the neutral sheet when the tilt is <30° and a negative latitudinal gradient was observed.

1 INTRODUCTION

Numerous measurements of the radial and latitudinal gradients of cosmic rays have been reported [For a detailed list of these measurements see Webber and Lockwood, 1992]. In this paper we present an updated set of E>70 MeV radial and latitudinal integral cosmic ray gradients covering two 11-year modulation cycles. We have used data from Voyagers 1 and 2 (V1, V2), Pioneer 10 (P10) and also Pioneer 11 {(P11), the latter provided by J. A. Van Allen} to determine the time dependence of the magnitudes of the radial and latitudinal gradients.

2 OBSERVATIONS

2.1 Data Reduction

The counting rates of the identical cosmic ray telescopes on the IMP, V1, V2, and P10 spacecraft were normalized when the spacecraft were at the Earth. A new feature of the measurements is the use of the 26-day average count rate of the University of Iowa (E>80 MeV) cosmic ray detector on P11 kindly provided by Prof. J. A. Van Allen. These data are very useful for studying the latitudinal gradient because the heliographic latitude of P11 is ~16° between 1986 and 1991, which is intermediate to the the ~30° latitude of V1. The P11 data were carefully normalized to the V1 and V2 count rates at selected time periods [Lockwood and Webber, 1992].

2.2 Radial Gradients

We show in Fig.1 the 26-day average count rates for E>70 MeV cosmic ray particles at IMP near the Earth and the yearly running averages of the integral >70 MeV instantaneous radial gradients deduced from the P10 and IMP rates for 1972 to 1993. The integral instantaneous radial gradient is defined by

$$G_r(N_{P10}/N_{IMP})_{INST} = \{1/(R_P-1) \bullet \ln(N_{P10} / N_{IMP})\} \quad 1,$$

where N_{P10} and N_{IMP} are corresponding 26-day average count rates. The yearly running averages of the radial gradients are shown in order to give an overview of the long term changes. A similar plot for $G_r(N_{V2}/N_{IMP})_{INST}$ and the V2 count rates for 1977 to 1993 is shown in Fig. 2. In Fig. 3 we have plotted $G_r(N_{P10}/N_{V2})_{INST}$ and the P10 26-day rates for the corresponding time period. The P10 to IMP gradient is greater than ~3%/AU for the first two years when P10 was less than ~5 AU from the Earth. By 1978-1979 when P10 was at 15-20 AU, this gradient was still ~3.0-3.5%/AU, about the same as the V2 to IMP gradient at the same time when V2 was at 2-6 AU. It is seen that all three gradients remained roughly constant at a value of ~3.0-3.5%/AU between 1977-1981 when the cosmic ray intensity decreased by a factor ~3. After 1982 as the intensity recovered the gradients all decreased, reaching a minimum of ~1.0-1.5%/AU in 1987 when the intensity was at a maximum. After

1987 the intensity decreased rapidly to a minimum in 1990 and the gradients all increased again to a value ~2.5%/AU, nearly as large as observed during the 1977-1981 period. After 1990 as the intensity began to recover, the radial gradients have decreased again to values ~1.0-1.5%/AU between all spacecraft, the smallest yet observed.

2.3 Latitudinal gradients

During the entire period from 1978 to 1993 both V2 and P10 remained within a few degrees of the heliographic equator. On the other hand, P11 climbed above the heliographic equator in 1979 and has since remained at ~16° latitude. V1 moved away from the equator in 1981 and from 1984 to 1993 has been at > 25°. In order to determine the latitudinal gradient, since V2 and V1, as well as V2 and P11, are at different heliocentric distances, it is necessary to first calculate the expected count rates of V2 at the radial locations in the equatorial plane of V1 and P11 spacecraft using the appropriate instantaneous integral radial gradients. The count rate of the V2 detector at the radial distance of V1, designated $N_{V2}(V1)$, assuming $G_r(N_{P10}/N_{V2})_{INST}$ is independent of r, is

$$N_{V2}(V1) = N_{V2} \bullet \exp\{ G_r(N_{P10}/N_{V2})_{INST} (R_{V1} - R_{V2})\} \qquad 2.$$

We can calculate $N_{V2}(P11)$ from a similar expression. We show in Fig. 4 the ratios $N_{V1}/N_{V2}(V1)$ and $N_{P11}/N_{V2}(P11)$ from 1982 to 1993. In the bottom portion of Fig. 4 the average neutral sheet tilt angle α is plotted, where α has been shifted to the location of V1. It is clear that during 1985-1988 when α was <30° the latitudinal gradient became negative and ranged from -0.2 to -2.2 %/deg at P11 and from -0.5 to -1.7 %/deg at V1. It is important to note, however, that even after 1988 a significant latitudinal gradient remained between V1 and V2 when the current sheet tilt was large; and as the tilt continued to decrease in 1992, and after the solar magnetic polarity changed, this negative latitudinal gradient has persisted.

4 ACKNOWLEDGMENTS

The P10 data were provided by F. B McDonald and the IMP data by Tycho von Rosenvinge. James A. Van Allen kindly provided the P11 data. This research was supported in part by the National Science Foundation (ATM 9123815), Jet Propulsion Lab. (959160), and University of Maryland (26015A).

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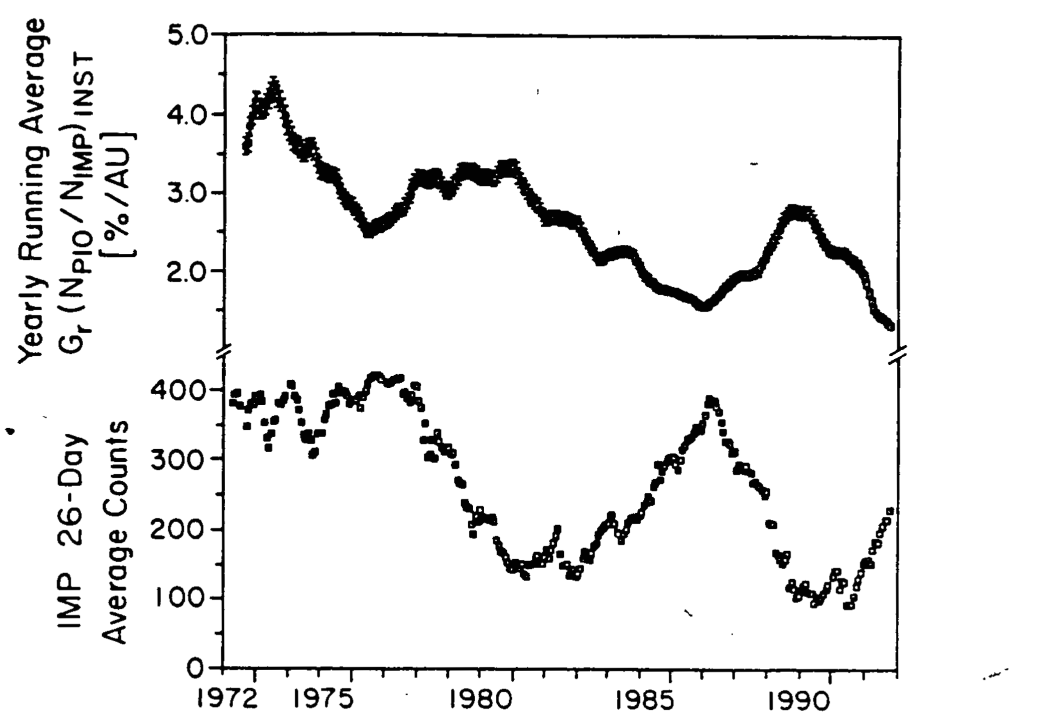

Fig.1 26-d average normalized count rates of the IMP >70 MeV detector and yearly running averages of $G_r(P10/IMP)_{INST}$ from 1972-1992.

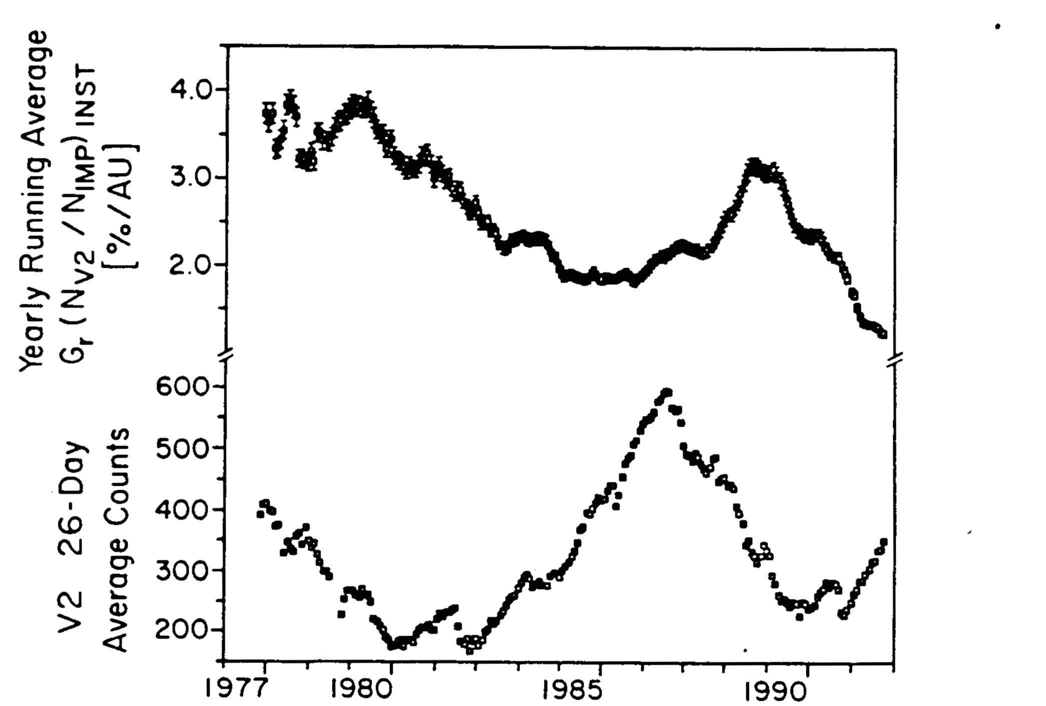

Fig. 2 26-d average normalized count rates of the V2 >70 MeV detector and the yearly running averages of Gr(V2/IMP)INST from 1977-1992.

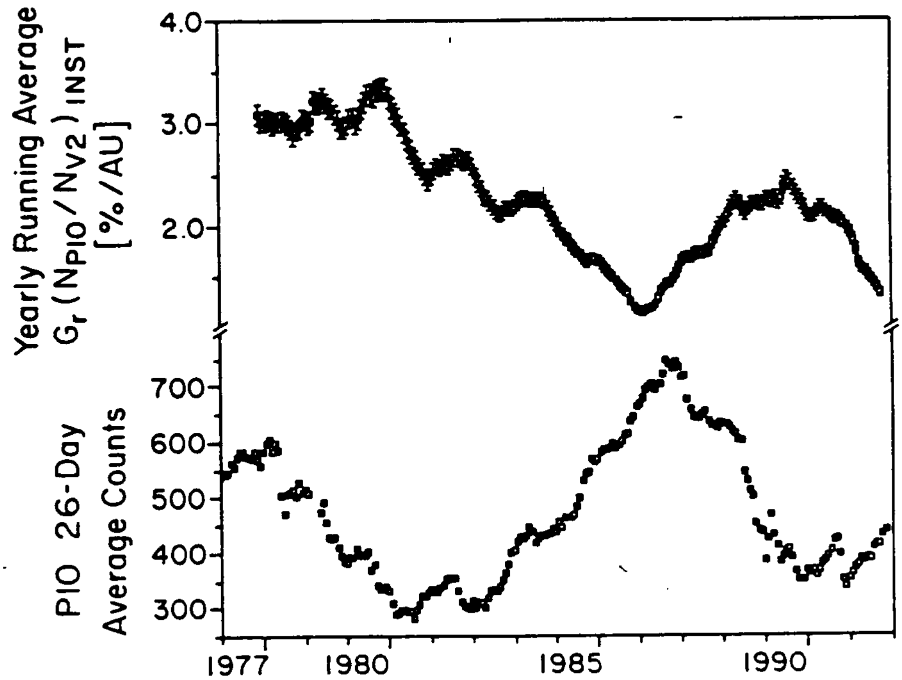

Fig.3 26-d average normalized count rates of P10 >70 MeV detector and the yearly running averages of $G_r(P10/V2)_{INST}$ from 1977-1992.

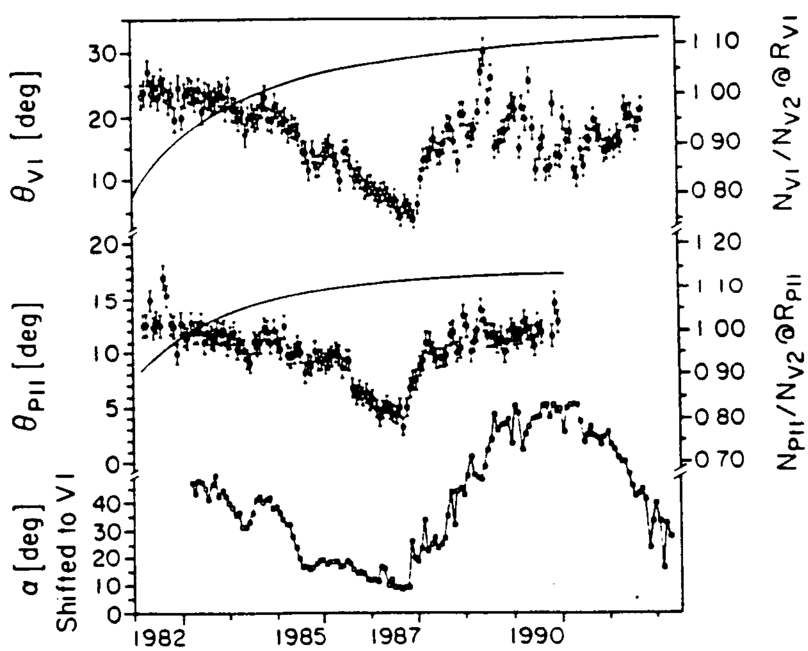

Fig. 4 Ratios N_{V1}/N_{V2}(V1) and N_{P11}/N_{V2}(P11) along with α from 1982-1993.

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A SIMPLE RESPONSE FUNCTION SIMULATION THAT REPRODUCES IN DETAIL THE HELIOSPHERIC 11-YEAR INTENSITY TIME VARIATIONS OF > 70 MeV PARTICLES OBSERVED AT IMP, V2 AND P10

W.R. Webber, J.A. Lockwood and M.A. Lee
Space Science Center, University of New Hampshire, Durham,NH

What are the physical mechanisms that actually cause the 11-year heliospheric cosmic ray modulation? From the observational point of view the decrease in cosmic ray intensity from 1978 to 1981 in the last 11-year cycle occurred in several discrete steps from which the intensity apparently did not recover. (e.g. McDonald et.al.,1981). In the latest cycle from 1987 to 1990, the same kind of step like decreases were observed, with little if any recovery after each step. (Webber and Lockwood,1993) These authors, in fact, attributed most of overall 11-year decrease during this period to these transient decreases at all heliospheric radii. After reaching the intensity minima in 1981 and again in 1990, the cosmic ray intensity recovered smoothly for several years - occasionally interrupted by transient decreases.

From the theoretical point of view, drift models associated with a wavy heliospheric current sheet are in vogue to describe the 11-year modulation. (e.g. Mc Kibben,1990) However the intensity time changes associated with such models would be expected to be relatively slow (perhaps several months) as the changes in the current sheet tilt pattern propagate outward in the heliosphere and the drift patterns slowly rearrange themselves - in contrast to the discrete nature of the intensity decreases that were actually observed in 1978 - 1981 and again in 1987 - 1990.

At the other extreme from the theoretical point of view are models in which the 11-year modulation represents the cumulative effect of the many transient decreases. This model, first suggested by Lockwood (1960) and discussed in various forms many times since, has not been amenable to detailed physical modelling. Recently valuable progress has been made in this area by Le Roux and Potgieter (1992) who showed for the first time that, in a 2D model, a slow recovery rate, t_r, from MIR (transient) induced cosmic ray decreases allows successive MIR's to contribute more toward the 11-year modulation. These authors have combined both MIR's and drifts in a model to describe the 11-year modulation. Their resultant calculations give a poor fit to the actual modulation observed during the 1987-1990 time period, however, (Fig. 1) predicting a much larger decrease than is actually observed as well as too small radial gradients.

To try to understand the comparative roles of transients and slower longer term changes such as might be caused by global drift and changes in other global properties such as the wavy heliospheric current sheet and the diffusion coefficient, we have developed a simplified simulation of the solar modulation, described in the next section, which reproduces the modulation observed at several heliospheric radii over 2 successive 11-year cycles from 1972 onwards, and, most importantly, enables one to assess the relative importance of transients and other global properties.

THE RESPONSE FUNCTION SIMULATION

The simulation we use is essentially a diffusion - convection (force field) model in which the diffusion coefficient, K_r, and boundary distance, R, are variable and the effects of transients are included. Recall that in the diffusion - convection model the intensity at any distance r from the sun at time t is described as:

$$I_r(t) = I_R \cdot \exp^{-\int_r^R \frac{CV}{K_r} dr} \quad (1),$$

where I_R is the interstellar cosmic ray intensity, C is the Compton - Getting factor, V the average solar wind speed and K_r the diffusion coefficient as a function of r. The exponential term, which is continuously changing with time, can be described as the "resistance" between the spacecraft and the boundary. We rewrite this term as a time dependent response function as follows:

$$I_r(t) = I_R \cdot \exp \sum \Delta\tau \cdot S_r(t-\tau_B) \cdot F_d(\tau) = I_R \cdot \exp R_s(t) \qquad (2),$$

where $I_r(t)$ is the observed intensity at time t and τ_B is the time taken for the solar wind to reach the boundary of the modulating region, $R = V_{sw} \cdot \tau_B$. The term $R_S(t)$ is the effective resistance between the spacecraft and the boundary. $I_r(t)$ may be evaluated simultaneously at three different locations: the Earth, V2 and P10 by summing the resistance term from each spacecraft to the boundary. In keeping with past analyses using a response function approach e.g. Nagashima and Morishita [1980] the source function, S, could be any solar parameter, for example, the solar flare index. In this case we use the heliospheric current sheet tilt as a "measure" of solar activity - for reasons discussed below. The time sequence in equation (2) is started in 1972 at the time when P10 data and heliospheric current sheet tilt data became available and thus covers nearly two full 11-year cycles of opposite heliospheric polarity. It proceeds in 26-day intervals. The distance to the boundary may be varied through the value of τ_B chosen. The term $S_t(t-\tau_B)$ is slowly changing with time and is a function of the tilt of the heliospheric current sheet as it propagates outward. It is a measure of the length of this current sheet integrated between the observer and the boundary. This has been used, for example by Williams and Potgieter (1991) as an effective measure of the modulation. However this simple integral value has been modified to take into account the observation of Cummings et.al(1991) that it is effectively the integral of the diffusion coefficient along this current sheet that determines the amount of modulation plus the fact that, as the tilt becomes ≥ 30° in the outer heliosphere, the particles effectively short-circuit the wavy current sheet. The actual resistance term used in the calculation is therefore:

$$R_S(t) = 6\left\{[1+[.2(4n+1)(\frac{\alpha n}{10})(1 \quad \frac{\alpha n(1+n/40)}{30+\alpha n+n})\right\}(\frac{3}{6n+3})F_d(n)/A(t) \qquad (3),$$

This term is evaluated at successive values of n (once every 26 days) during which the solar wind travels ~ 6 AU at 400 km/sec. The number n = 0,1,2 etc represents the sequence of 26-day intervals as a specific value of the current sheet tilt, α_n (in degrees) moves outward at the solar wind speed to a boundary at 6·n AU. The quantity A(t) is different when the solar magnetic polarity changes and this is accounted for by the difference in heliospheric propagation in the two magnetc cycles. The part of this expression up to the vertical line gives the actual length along the wavy current sheet to the boundary, the term following is a modification to take into account the short-circuiting effect when $_n$ becomes ≥ 30°. The next term outside the bracket takes into account the radial dependence of the diffusion coefficient along the current sheet. The last term takes into account the effects of transient decreases. A total of 26 transients, of which 8 occur during the decreasing phase between 1978 and 1981 and 12 between 1987-1990 are considered. These transients and their magnitudes are determined from the P10 or V2 data beyond 15 AU from the sun. This transient term is written as

$$F_d(n) = (1 + M_i \exp^{-} \frac{n}{t_r}) \qquad (4),$$

where M_i are the observed fractional magnitudes of the individual decreases. These transients move outward in the heliosphere with the solar wind speed and decay with time according to a recovery time scale t_r (in units of 26 days) which may also be varied. When the transients reach the location of each spacecraft they effectively modify the resistance term. Successive overlapping transients are additive in their effects.

The observed intensities in 1977 and early 1987 when essentially no transients are in the system, are simultaneously fit at all radii. This specifies the interstellar intensity along with the value of R and the values of A in the two polarity cycles. The model thus becomes essentially a diffusion - convection model in which the time varying current sheet is used to describe the variable resistance in both polarity cycles. Thus the parameter A provides a measure of the different sensitivity of the cosmic ray intensity to the current sheet tilt in the different polarity cycles.

A COMPARISON OF DATA WITH PREDICTIONS FOR IMP, V2 AND P10

A comparison of the 26-day average rates for IMP, V2 and P10 and the predictions from 1972 to the present is shown in Fig. 2,3 and 4. By comparing features of the data and the predictions for a wide range of values for R, I_R, and the transient term F_d as well as A we are able to make the following general comments.

The value of A required to best fit the data is such that the response to a changing resistance to the boundary is only about 30% less in the qA+ cycle than in the qA- cycle.

The location of the modulation boundary, R_b, is mainly sensitive to the intensity time profiles of V2 and P10 at the times of maximum modulation in 1981 and again in 1990 when the two spacecraft are at greatly different radii. It is not sensitive to the intensity time profiles near the time of the 1987 maximum as might be expected mainly because the differential resistance becomes independent of radius beyond ~ 25 AU so the effects of the longer transit times to more distant boundaries are not seen. Overall the data at the different spacecraft are better fit with a boundary in the range 96 - 120 AU. It is hoped that further refinement of the simulation will reduce this uncertainty.

The overall variation of the resistance term at the Earth is a factor ~ 2 from 1979 to 1981, and 2.5 between 1987-1990. This variation becomes less as one goes outward in radius. It should be stressed that although we have attributed this variation to changes in the total pathlength along the current sheet it could also be accounted for by building a temporal variation of K into the model. This factor is also sensitive to the importance of the transients in the simulation.

The transients play a key role in the decreasing phase of the modulation cycle. - where they influence both the change in resistance needed to produce the modulation and the relationships between the value of R_b and the absolute value of A necessary to fit the data. This role is dependent on the recovery time of the transients. If this recovery time is less than 7-10·n, then the transients essentially mimic the shorter term temporal variations seen at each spacecraft. If this recovery time is in the range 14-21·n the superposition of the transients plays a role the overall depth of 11-year modulation as well - e.g. they influence the change in resistance needed to describe the modulation. If the recovery times become much longer than 21·n then they begin to dominate the entire 11-year cycle including the recovery phase of the cycles - e.g. 1983-1987, 1991-onwards.

ACKNOWLEDGEMENTS

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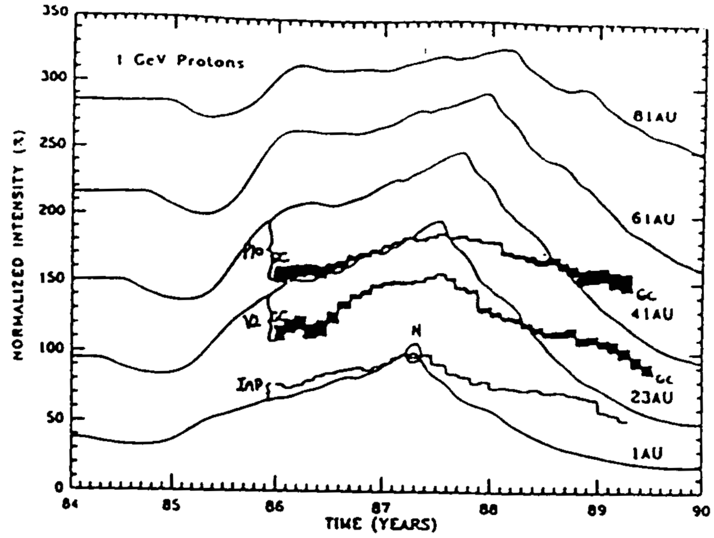

Figure 1. Comparison of predicted (Potgieter et.al.,1992) and observed intensity changes for IMP, V2 and P10 from 1986-1989. Predicted and observed curves are normalized to IMP count rate at the intensity peak in 1987. Envelope of observed data for V2 and P10 show the gradient corrected (GC) and uncorrected data.

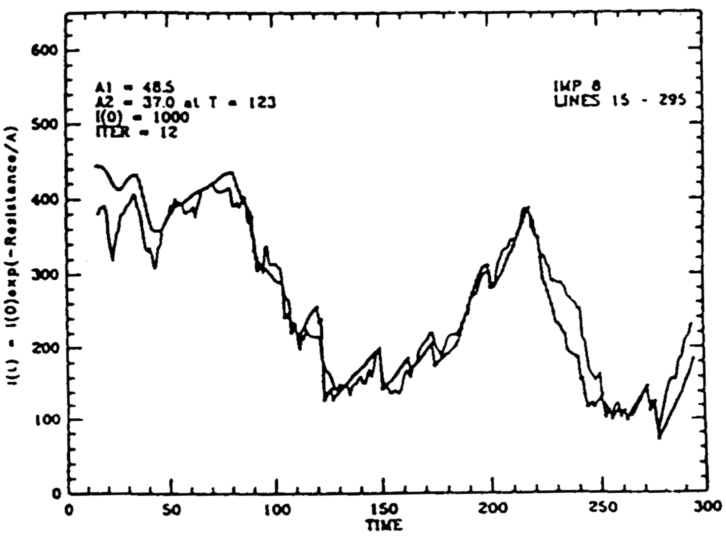

Figure 2. Observed 26 day average rate at IMP (solid line). Predicted rate from simulation model with R_B = 96 AU.

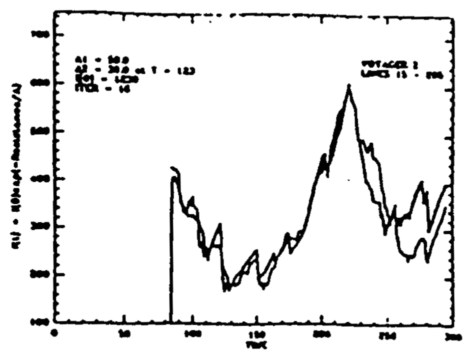

Figure 3. Same as Figure 2 but for V2.

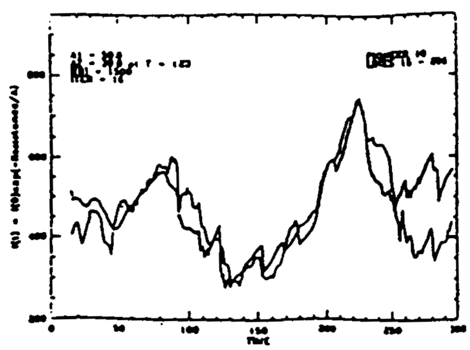

Figure 4. Same as Figure 2 but for P10.

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AN ESTIMATE OF THE LOCATION OF THE MODULATION BOUNDARY FOR $E > 70$ MeV GALACTIC COSMIC RAYS USING *VOYAGER* AND *PIONEER* SPACECRAFT DATA

J. A. LOCKWOOD[1] AND W. R. WEBBER[2]
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ABSTRACT

We have estimated the location of the modulation boundary for >70 MeV per nucleon Galactic cosmic rays using observations of their intensity and radial gradients between *Voyager 2* (*V2*) and *Pioneer 10* (*P10*) in the outer heliosphere along with new estimates of the >70 MeV interstellar cosmic-ray intensity. In the first case, we have used the method described by Cummings et al. (1994) in which the local current sheet tilt is correlated with the radial gradient between the two spacecraft when the tilt is <30° to extrapolate the intensity to the boundary. By this method we obtain a boundary at an average distance of 79 ± 3 AU between 1986.5 and 1987.5. In the second instance, we have also used the summation procedure of Cummings et al. (1994), the only difference being that we did not correlate the local radial gradient with the tilt of the neutral sheet but simply used the observed radial gradient between *V2* and *P10* in the summation. Using this method we find that for 7 years from 1983 to 1990 this modulation boundary remained constant at 83 ± 5 AU. We infer from these studies that a modulation boundary can be estimated only by extrapolating the observed radial gradients as we have done when the solar magnetic polarity is such that the cosmic-ray particles are drifting in the heliosphere inward toward Earth along the neutral sheet. These boundary distances are larger than estimates of the solar wind termination shock distance of 67 ± 5 made using the same method for the anomalous cosmic rays (Cummings et al. 1993), but well inside the heliopause distance of 112–177 AU recently determined by Gurnett et al. (1993). The fact that this modulation boundary is not much farther out than the termination shock suggests that modulation effects within the heliosheath region between the termination shock and the heliopause are probably not a major contributor to the overall solar modulation at this time and at these energies.

Subject headings: cosmic rays — Sun: activity

1. INTRODUCTION

Near the time of the last sunspot minimum in 1986–1988, when the cosmic-ray modulation effects were also at a minimum, the integral radial interplanetary gradients of >70 MeV per nuclear cosmic rays measured between Earth and *Voyager 2* (*V2*) at ~24 UV and *Pioneer 10* (*P10*) at ~42 AU near the ecliptic plane decreased dramatically (Lockwood & Webber 1993). Specifically Cummings, Stone, & Webber (1990) showed that this decreasing gradient, which they also observed for anomalous oxygen (anomalous cosmic ray [ACR]), was a strong function of the local time-averaged heliospheric neutral sheet angle when this angle decreased to ~30° or less. These authors demonstrated that this observed correlation was consistent with the particles drifting and diffusing inward along the neutral sheet whose length was proportional to its tilt angle during this time period. A more detailed analysis of the particle behavior at this time and its relationship to the perpendicular diffusion coefficient and drift speed was carried out by Moraal (1991). The time period over which this correlation was observed lasted from roughly early 1986 to early 1988 which is around the minimum in the modulation that occurred in 1987.

A similar behavior for the integral radial gradient of >70 MeV particles was observed by Webber & Lockwood (1991). At the same time a distinct negative latitudinal gradient appeared for these >70 MeV particles (Lockwood & Webber 1993), also lasting from early 1986 to beyond 1988. Lockwood and Webber discussed the relationship between the radial and latitudinal gradients of these particles at this time and concluded that the description used by Moraal (1991) and also Cummings, Stone, & Webber (1990) for anomalous oxygen also applied to the normal Galactic cosmic rays during this time period. The value of this picture is that with a simple assumption that both the shape of the neutral sheet and the diffusion coefficient, $K_\perp$ ($\sim K_r$), in the outer heliosphere scale as R, the dependence of the radial gradient between *V2* and *P10*, $G_r(N_{P10}/N_{V2})$, on the tilt angle should be independent of heliospheric radius. This permits an extrapolation of the dependence of intensity on the tilt beyond *P10* and, because the time history of the tilt angle is known, allows a straightforward extrapolation of the flux of ACR or Galactic cosmic rays beyond *P10*. In the case of ACR, Cummings, Stone, & Webber (1994) have used this approach along with the added assumptions that the location of the termination shock (T.S.) and the flux of ACR, presumed to be accelerated at the termination shock, remained constant over this 2 yr period to estimate the average distance of the T.S. to be 67 ± 5 AU at this time.

In this paper we follow a similar procedure to extrapolate the intensities of Galactic cosmic rays beyond the location of *P10*. The intensities are extrapolated outward beyond *P10* until they are reach a projected value of the interstellar (IS) intensity for the >70 MeV cosmic rays. This extrapolation is first carried out for the period around the solar modulation minimum in 1987 when the average tilt angle of the neutral sheet is <30° and then extended to the entire period from 1978 to 1993 using a slightly different approach to try to understand the limits on the application of this procedure. The projected IS intensity of the >70 MeV cosmic rays is determined from Galactic propagation models which reproduce the observed

[1] Space Science Center, University of New Hampshire, Durham, NH 03824.
[2] Astronomy Department, New Mexico State University, Las Cruces, NM 88003.

secondary ^{2}H and ^{3}He abundances as well as the modulated H and He spectra observed in 1987 at both *V2* and *P10* (Webber et al. 1992; Seo et al. 1993).

2. METHOD OF ANALYSIS

Our method of analysis follows closely, in the first instance, that used for ACR by Cummings et al. (1993). We assume that the observed correlation of the instantaneous radial gradient for the >70 MeV Galactic cosmic rays between *V2* at ~24 AU and *P10* at ~42 AU with the tilt angle of the neutral current sheet, α_{V2}, evaluated in between the two spacecraft, can be applied to distances beyond *P10* when that angle is <30° from mid-1985 to late-1987. Using the previous time history of the tilt angle, this intensity is then extrapolated beyond *P10* out to the distance at which the IS intensity is reached.

Then, as a second approach, we used the past time history of the measured radial gradient between *V2* and *P10* to extrapolate the >70 MeV flux beyond *P10* out to the distance at which the IS intensity was reached for the entire period from 1978 to 1993 without the intermediate step of correlating the gradient with the tilt angle. This extrapolation is then compared with the earlier results of Webber & Lockwood (1987) for the period 1977–1986 which used the time-shifted >70 MeV cosmic-ray intensities at *IMP*, *V2*, and *P10* to estimate the apparent location of the modulation boundary.

The observed 26 day average intensities for >70 MeV cosmic rays at *V2* and *P10* along with the radial positions of the spacecraft from 1978 to 1993 are shown in Figure 1. The instantaneous integral radial gradients between *V2* and *P10* for the same period and the tilt angles are plotted in Figure 2. From Figure 1 we see that during the period from 1983 to 1990 the cosmic-ray intensity recovers from the minimum in 1982 to a maximum in 1987 and then decreases rapidly toward the minimum in 1990.

The observed correlation of the average tilt angle of the neutral sheet, α, with the local radial gradients of the >70 MeV cosmic ray intensity is shown in Figure 3. The data are plotted for a period from the beginning of 1986 to mid-1988, when the projected current sheet tilt angle varied from 9° to 56° at the mid-distance between *V2* and *P10* in order to illustrate the correlation that appears mainly for angles <30° more clearly. The correlation with the tilt is very good for $\alpha < 30°$ as shown in Figure 3, but it is not as good for larger tilt values. We also find that the regression of G_r with α_{V2} is different before and after the intensity maximum at *V2* in 1987 August. The best-fit regression lines for G_r versus tilt when $\alpha_{V2} < 30°$ are shown in Figure 3. Using the values of G_r determined from the regression curve of G_r with α_{V2} in effect smooths the gradient values so that there are smaller excursions in the deduced values of the cosmic ray modulation boundary.

During the entire time period from 1981 to 1990 the drift of positively charged particles was inward in the heliosphere toward Earth along the neutral current sheet. Cummings et al. (1990) demonstrated that the observed time variations of the

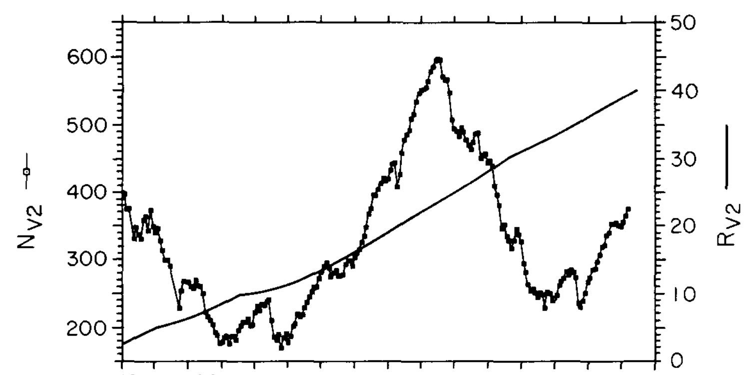

FIG. 1*a*

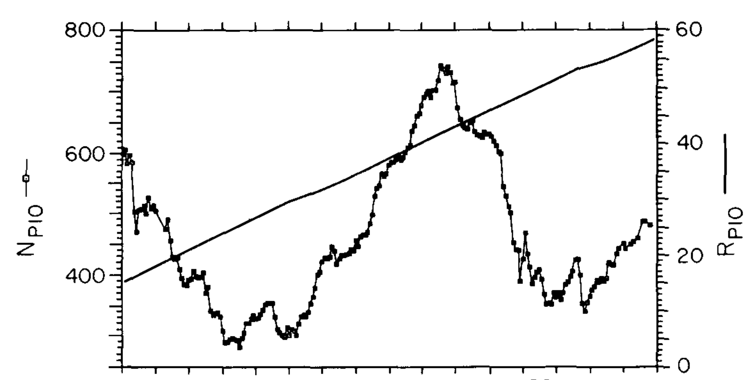

FIG. 1*b*

FIG. 1.—(*a*) The 26 day average >70 MeV cosmic-ray intensity at *V2* and the radial position of *V2* from 1978 to 1992. (*b*) Same as (*a*) for *P10*.

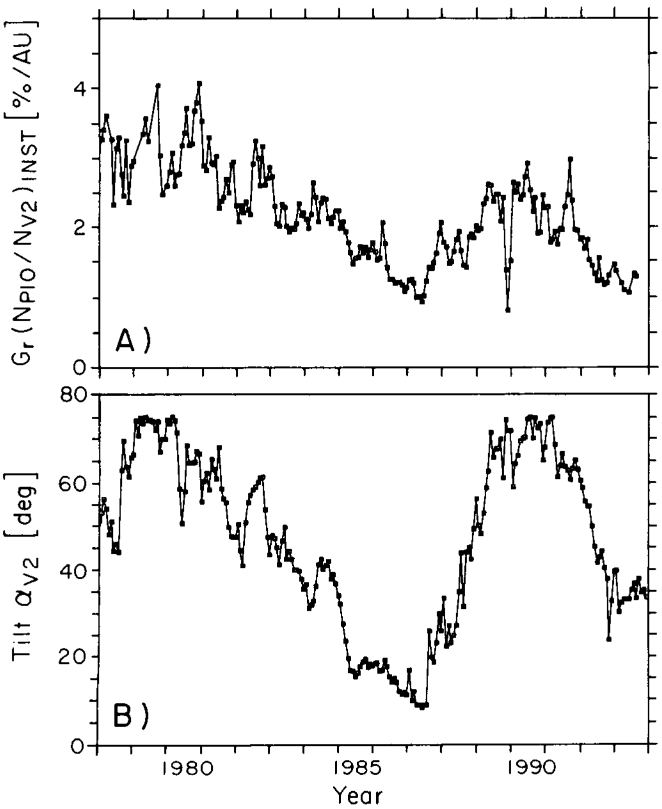

FIG. 2.—Panel (*a*) shows the instantaneous integral radial gradient between *V2* and *P10* from 1978 to 1992 for >70 MeV cosmic rays, and panel (*b*) shows the average tilt angle of the neutral current sheet shifted to the midpoint between the locations of *V2* and *P10*.

gradient of ACR between *V2* and *P10* during part of this period were consistent with particles drifting and diffusing inward along a neutral sheet whose length was proportional to its tilt. This behavior was subsequently explained by Moraal (1991) in a model in which the perpendicular diffusion coefficient, $K_\perp$, is proportional to the heliocentric radius *R*.

This same picture was shown to apply to Galactic cosmic rays >70 MeV at these times as well in order to explain the radial and latitudinal gradients of these particles observed between *V2*, *V1*, and *P10* (Lockwood & Webber 1993). With the assumption that both the shape of the neutral sheet and $K_\perp$ in the outer heliosphere scale as *R*, the dependence of G_r on tilt angle should be independent of radius. Note that it is not required that the neutral sheet have a perfect sinusoidal shape of amplitude α; *rather*, only that the distance along the sheet for a given radial separation be proportional to some amplitude factor which is $\sim\alpha$ and the radius *R*. It should be emphasized that this does not imply that G_r itself is independent of *r*. In fact G_r determined this way depends on *r* in a way that is consistent with the radial dependence of G_r found earlier by Lockwood & Webber (1993).

The best-fit regression line between the tilt angle and the gradient that is derived above allows us to use the temporal dependence of the tilt angle of the outwardly propagating neutral sheet to estimate the value of G_r at distances beyond *P10*. Since the best fit lines were derived for a radial separation ~18 AU between *P10* and *V2* when *P10* was between 39 and 44 AU at this time, it seems reasonable to expect that this relationship applies to distances ~18 AU beyond *P10*.

If at a given time, *t*, these local gradients, $G_r(t)$, are known out to some distance, then the observed intensity $N_{V2}(t)$ at *V2* can be related to the intensity at a greater distance, let us say the modulation boundary, $N_{MB}(t)$, by

$$N_{MB}(t) = N_{V2}(t) \times \exp\left\{\sum_{n=1}^{n=n_{max}} [a\,\alpha_{V2}(t - n \times \Delta t) + b]\Delta R\right\}, \quad (1)$$

where *a* and *b* are found from the correlation of $G_r(N_{P10}/N_{V2})$ versus $\alpha_{V2}(t)$, $\Delta R = V_{SW} \times \Delta t = 6$ AU for the 26 day averages with $V_{SW} = 400$ km s^{-1}, and $n_{max} = [R_{MB} - R_{V2}(t)]/\Delta R$. The summation is carried out to different values of n_{max}. The value of R_{MB} can then be found by interpolation of the dependence of *R* upon *N* for the assumed interstellar intensity $N(R_{MB})$ of >70 MeV cosmic-ray particles in 26 day intervals. The value of the radius *R* required to obtain the projected IS intensity is then assumed to be the location of the modulation boundary at this particular time.

In the second approach we use the past time history of the measured radial gradient between *V2* and *P10* to extrapolate the >70 MeV flux beyond *P10*. In this approach the temporal dependence of the radial gradient is taken as if it were propagating outward like the neutral sheet. The intensity at the modulation boundary $N_{MB}(t)$ is given by

$$N_{MB}(t) = N_{V2}(t) \times \exp\left[\sum_{n=1}^{n=n_{max}} G_r(t - n \times \Delta t)\Delta R\right], \quad (2)$$

where $G_r(N_{P10}/N_{V2})$ is the observed 26 day average radial gradient between *V2* and *P10*, and the summation in 26 day intervals (~6 AU steps) is carried out until the ISM intensity is reached. So this approach is identical to the first approach with the exception that G_r is not correlated with α. In both approaches we ignore any changes in the radial gradient that may occur near and/or beyond the T.S. which probably lies inside the heliospheric modulation region.

The extrapolation procedure in both equations (1) or (2) does not assume that the instantaneous integral radial gradient is constant as a function of heliocentric radius. To illustrate this point, we have selected two different 26 day intervals: the first is the sixth period in 1983 during the recovery of the >70 MeV cosmic-ray intensity, and the second is the eighth interval in 1987 which is the time of maximum intensity at *V2*. We have plotted in Figure 4 the 26 day average radial gradients between *V2* and *P10* contained in the summation in equation (2) and then propagated in radial distance from the location of *V2* out to the modulation boundary. The locations of *V2*, *P10*, and the modulation boundary for the two cases are indicated on Figure 4. In 1983 this gradient decreases with increasing *r*. Again in 1987, when the cosmic-ray intensity was a maximum at *V2* spacecraft, G_r also decreases with *r* out to the estimated modulation boundary. These radial dependences of G_r are similar to those derived from the *IMP*, *V2*, and *P10* data for >70 MeV particles by Lockwood & Webber (1993) using the expression $G_r(t) = G_0 r^{-x}$.

3. DERIVATION OF THE INTERSTELLAR INTENSITY FOR >70 MeV GALACTIC COSMIC RAYS

An important key to determining the overall effects of solar modulation and the location of the modulation boundary is an accurate estimate of the interstellar spectra of protons and helium nuclei. There have been several estimates of these

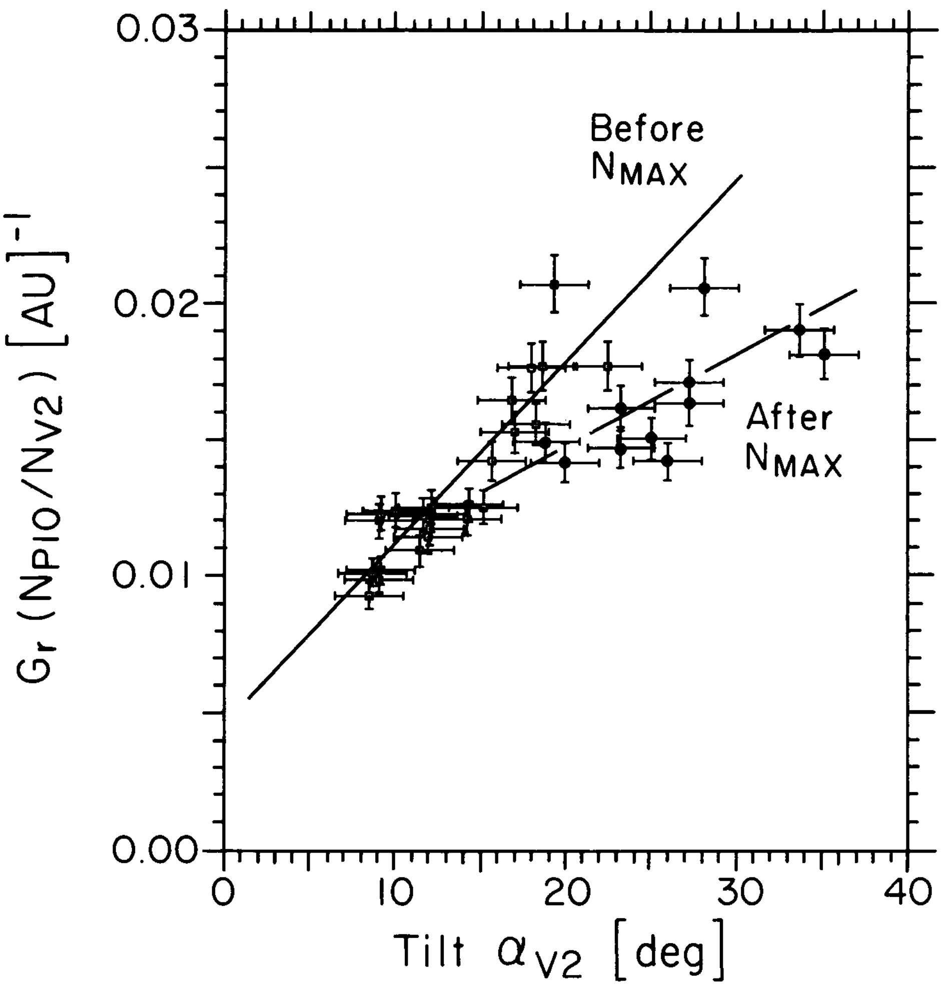

FIG. 3.—The instantaneous integral radial gradient for >70 MeV cosmic rays between *V2* and *P10* as a function of the average tilt angle of the neutral sheet evaluated at the midpoint between *V2* and *P10* for 1986 to mid-1988. The data before the N_{max} in 1987 are indicated by open circles and after 1987 by solid circles. The regression curve before N_{max} is given by $G_r = 0.0046 + 0.00066\,\alpha_{V2}(R^2 = 0.84)$ and after N_{max} by $G_r = 0.0079 + 0.00034\,\alpha_{V2}(R^2 = 0.28)$.

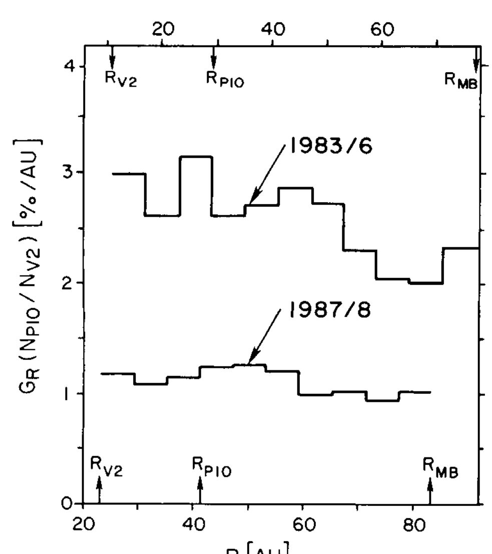

FIG. 4.—The 26 day average instantaneous integral radial gradients which appear in eq. (2) for the sixth interval in 1983 and the eighth period in 1987 and are propagated as a function of distance from *V2* to the modulation boundary. For details, see the text.

spectra made in the past, e.g., Ip & Axford (1985) and Webber (1987). These have been based on an assumed source spectrum modified by the effects of interstellar propagation such as ionization energy loss. Recently Seo et al. (1994) have provided an improved estimate of these spectra, particularly at lower energies, using the same approach as these earlier studies but using the recently measured spectra of the primary ^{1}H and ^{4}He nuclei and the secondary ^{2}H and ^{3}He nuclei at *V2* in 1987. The secondary ^{3}He comes mainly from primary ^{4}He. The ^{2}H secondaries come from ^{4}He and also from ^{1}H via the reaction $^1\mathrm{H} + {}^1\mathrm{H} \Rightarrow {}^2\mathrm{H}$ which has its peak cross section at $\sim$600 MeV. The low-energy ^{2}H spectrum observed by *Voyager 2* is thus strongly dependent of the magnitude and shape of the interstellar ^{1}H spectrum below $\sim$1 GeV per nucleon. The actual intensities of the secondary ^{2}H and ^{3}He depend on the amount of solar modulation, but the best self-consistent spectrum for interstellar ^{1}H based on interstellar propagation models as discussed by Seo et al. (1994) lies within the shaded region in Figure 5 which shows the best-fit spectra with uncertainties of $\pm 25\%$. This spectrum corresponds to a source rigidity (P) spectrum with an index of $\sim$2.3 modified by interstellar propagation including energy loss and interstellar fragmentation assuming an escape length $\lambda_{esc} = 35.1\beta P^{-0.60}$ above 3.3 GV flattening to 16.9β below 3.3 GV. The flattening of the inter-

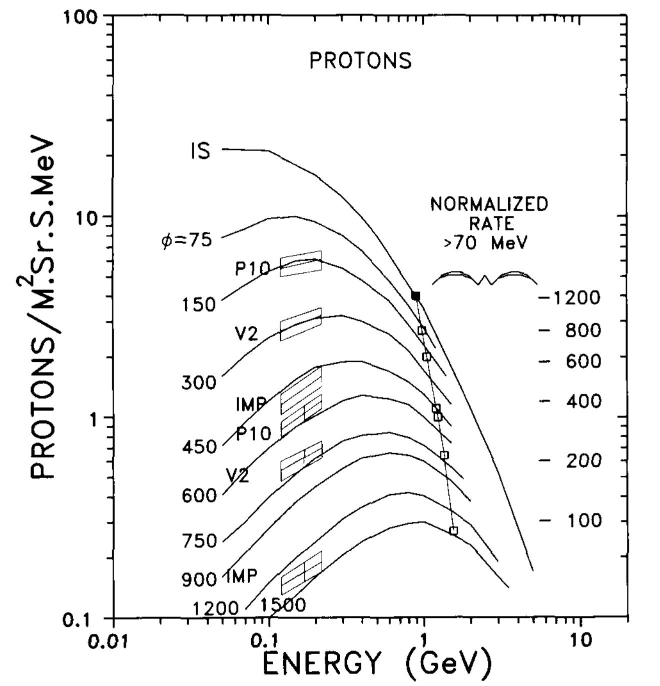

FIG. 5.—Estimated interstellar proton spectrum and modulated proton spectra used to estimate > 70 MeV intensity at various modulation levels.

stellar spectrum at low energies in Figure 5 is mainly due to ionization energy loss and the dependence of escape length on rigidity.

The > 70 MeV integral point is put on Figure 5 in the following manner. We have taken the interstellar proton spectrum described above and modulated it using a simple force-field approximation where the modulation parameter ϕ is given by

$$\phi(r, t) = \frac{1}{3} \int [C V_{SW}(r, t) dr] / K_r(r, t) , \qquad (3)$$

where C is the Compton-Getting factor, V_{SW} is the solar wind speed, and K_r is the radial component of the diffusion tensor. Values of ϕ were chosen ranging from 75 to 1500 MV. These curves are shown in Figure 5. We have then integrated under each of these modulated spectral curves to obtain the total intensity of protons > 70 MeV at each modulation level. This intensity is then normalized to the > 70 MeV rate of 380 observed at Earth at the 1987 minimum for a corresponding value of $\phi = 500$ MV. The solid vertical line at ~1 GeV per nucleon in Figure 5 shows this normalized rate as a function of different modulation parameters. The maximum *P10* intensity observed in 1987 (740 on the normalized scale as shown by the topmost open square) corresponds to a value of $\phi = 150$ MV and is a factor of ~1.6 below the interstellar normalized intensity of 1200, shown by the solid square in Figure 5. Note that the solid line is not exactly vertical because the mean energy for the > 70 MeV channel decreases as the modulation becomes less.

4. RESULTS

The distance of the modulation boundary as determined using the procedures that involve the radial gradient versus tilt correlation for > 70 MeV Galactic cosmic rays for the period from 1986 to mid-1988 is shown in Figure 6. The time periods before 1986.5 and after 1987.5 contain transient events moving outward past *V2* and *P10* and are not included in the final analysis. The average distance of the modulation boundary between 1986.5 and 1987.5 when the tilt is < 30° is 79 ± 3 AU. The effect of an uncertainty of ±25% in the interstellar intensity is also indicated. It is seen from Figure 6 that the apparent location of this modulation boundary is constant to within 5% when the relationship between the tilt angle and G_r is most clearly observed (e.g., when the tilt angle is < 25°).

Next we determined the location of the boundary position using equation (2). In this procedure we no longer retain the previous time history of the tilt angle to determine the radial gradient but instead use the past history of the radial gradient itself. In Figure 7 we plot the location of the boundary position for > 70 MeV particles for the entire period from 1978 to 1993, and in the insert we show the yearly averages of R_{MB} obtained using this approach. The uncertainty in the interstellar intensity for the > 70 MeV cosmic rays introduces an uncertainty of ±5 AU in the absolute value of the boundary location. We see that from 1978 to 1982 this apparent boundary monatonically increased from ~40 to ~80 AU. From 1983 through to the end of 1989 the modulation boundary estimated in this way remained nearly constant at 83.5 ± 2.5 AU, and after 1990 the apparent boundary again moved outward reaching a value of 120 AU by the end of 1993.

To attempt to illustrate more clearly this different behavior of the apparent boundary in the two polarity cycles described above, and from a different point of view, we show in Figure 8 the cosmic-ray intensities measured at *IMP*, *V2*, and *P10* in yearly intervals during the 1982–1990 period when the solar magnetic polarity is negative, and in Figure 9 we show the same for the 1978–1981 and 1991–1993 time periods when the solar magnetic field polarity is positive. These semilog plots are such that when the intensity points are connected, a straight line indicates a constant radial gradient.

For 1982–1990 period it is seen that when the straight lines connecting the intensities at *V2* and *P10* are extrapolated outward for *both* periods of increasing intensity (1983–1987) and decreasing intensity (1987–1990) in Figure 8, they intersect

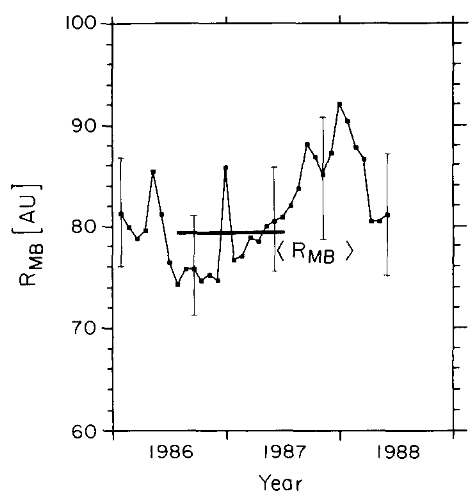

FIG. 6.—Location of the modulation boundary for > 70 MeV per nucleon particles as described in the text for the period 1986 to the end of 1988 using the gradient-tilt correlation method of Cummings et al. (1994). The heavy solid line represents the average for the period mid-1986 to mid-1987. The effect of a ±35% uncertainty in the IS spectrum is indicated by the error bars.

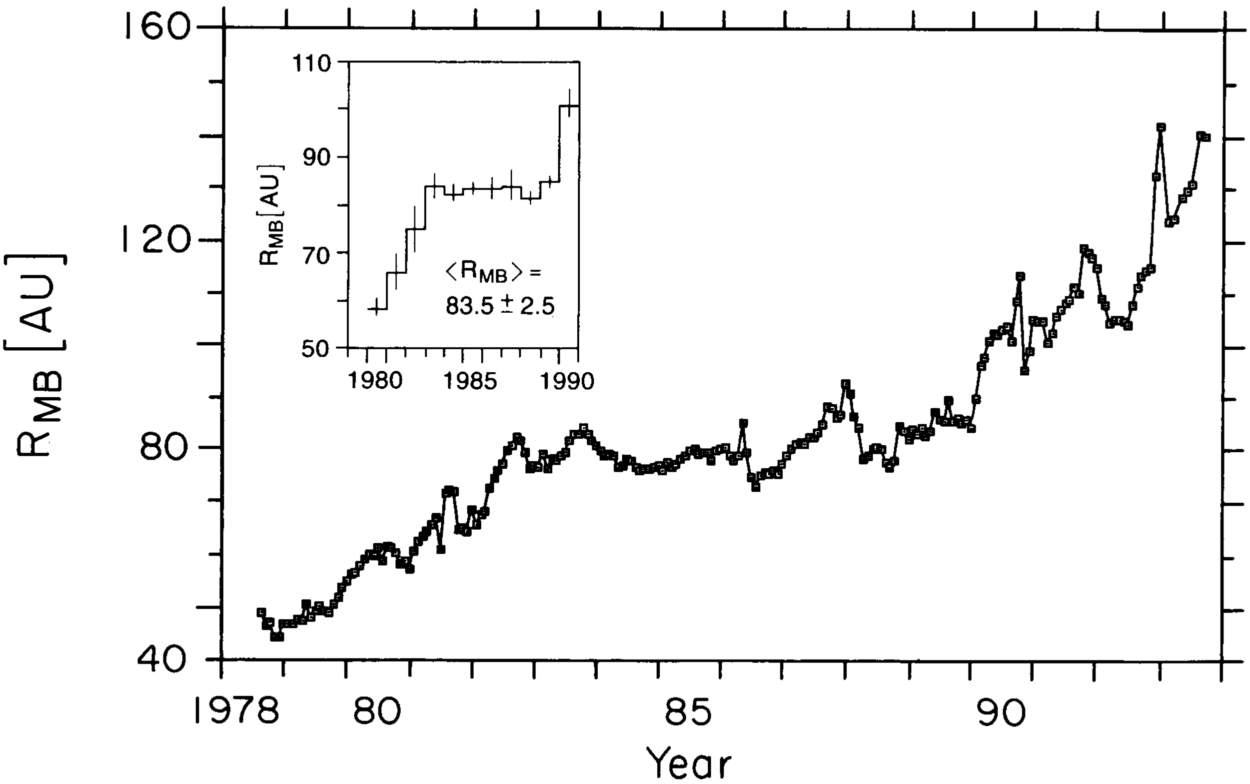

FIG. 7.—Location of the modulation boundary for the period from 1978 to 1992 obtained by using the summation procedure of Cummings et al. (1994) directly with the observed radial gradients. The yearly averages are shown in the insert.

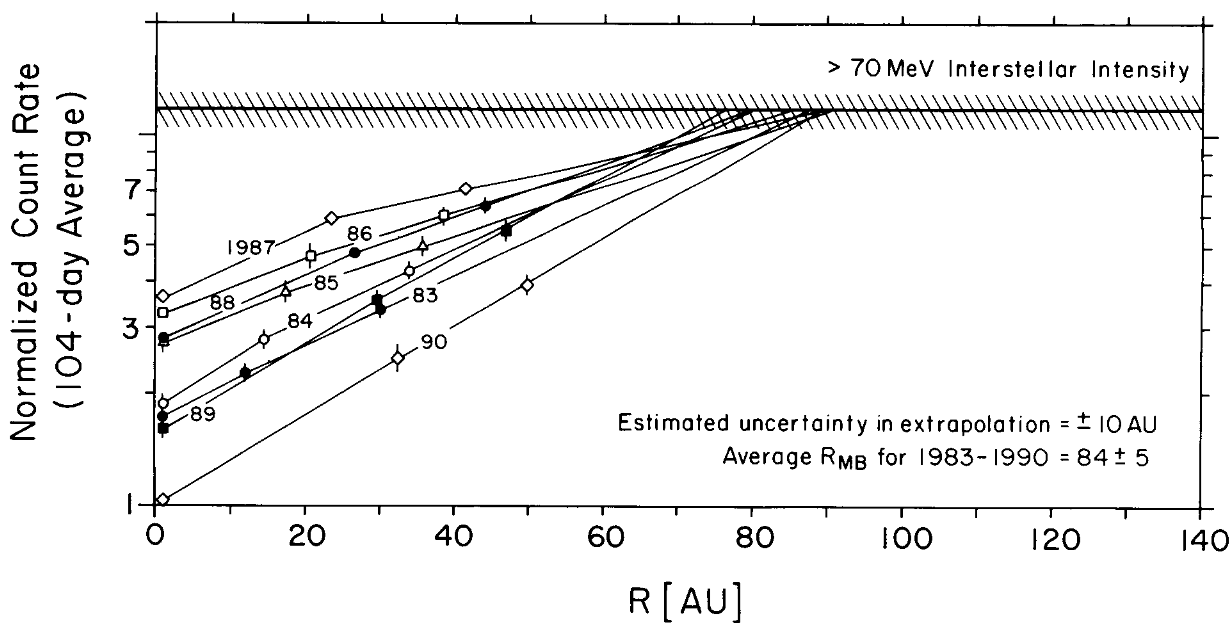

FIG. 8.—Cosmic-ray intensities at *IMP*, *V2*, and *P10* evaluated for 104 day intervals centered at yearly intervals between 1983 and 1990 when particles are drifting in along the heliospheric current sheet. The estimated IS intensity is shown as a shared region. R_{MB} is where the extrapolated *V2*–*P10* gradient reaches the IS intensity for each interval. The lighter lines are for periods of decreasing intensity, and the darker lines are for periods of increasing intensity. The selected periods are as follows: 1983.5, filled circles; 1984.5, open circles; 1985.5, open triangles; 1986.5, open squares; 1987.5, open diamonds; 1988.5, filled circles; 1989.5, filled squares; 1990.5, open diamonds.

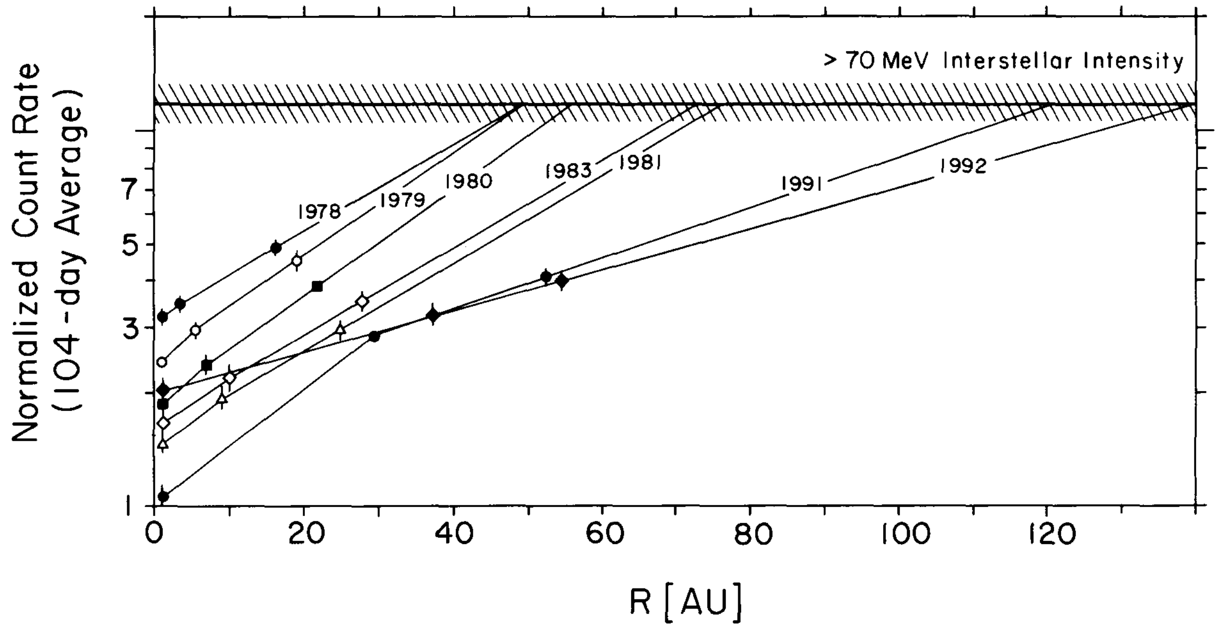

FIG. 9.—Same as Fig. 8 but for 1978–1981 and 1991–1994 time intervals when particles are drifting in from the solar polar regions. The dashed lines are for 1978–1981, and the solid lines are for 1992–1994. The selected periods are as follows: 1978.0, filled circles; 1979.0, open circles; 1980.0, filled squares; 1981.0, open *triangles*; 1983.0, open diamonds; 1991.0, filled circles; 1992.0, filled diamonds.

the estimated interstellar intensity at between 75 and 95 AU. Thus during the entire time period from 1982 to 1990 the location of the modulation boundary stayed at roughly the same distance even though the intensity first increased and then decreased by a factor ~3, because the gradient changed in a compensatory way. This figure enables one to visualize why the apparent boundary remained constant during this time period and also why the extrapolation procedure works over the whole time period, not just the period around 1987.

During both of the periods from 1978 to 1981 and from 1991 to 1993 shown in Figure 9 when the cosmic-ray drift pattern was such that the particles were drifting onto the equatorial plane from the polar regions, the apparent boundary moved outward with time. From 1978 to 1981 this boundary moved from ~40 AU to 80 AU. This is a consequence of the fact that the integral radial gradient remained almost constant during this period, but the intensity decreased by a factor ~3 so that one must extrapolate outward further to reach the same interstellar intensity (Fig. 9, *dashed lines*). This boundary moved outward in such a way that it stayed about 2.5 times the radial distance of *P10*.

In 1991–1993, after the change of the solar magnetic field direction and the drift pattern back to that during 1978–1981, the apparent boundary again began to move outward from ~80 AU in late 1989 to >120 AU by early 1993. During this time the intensity increased by a factor of ~2 but the gradient had decreased in such a way that the boundary still moved outward (Fig. 9, *solid line*). During this time the boundary is about 2 times the radial distance of *P10*.

The cosmic-ray drift pattern in 1978–1981 and 1991–1993 was such that the particles were drifting into the equatorial plane from the polar regions, and there appears to be little relationship between the integral radial gradients and the cosmic-ray intensity as we have noticed before (and is clearly shown in Fig. 9) (Webber & Lockwood 1991). If this is the situation, then the apparent modulation boundary cannot be determined by extrapolating the radial gradient between *V2* and *P10* outward during these time periods. Indeed, during this modulation cycle, because of the cosmic-ray drift patterns, considerable modulation probably occurs between the solar polar region and the neutral sheet as the cosmic rays drift downward after entering the heliosphere. Thus, the region of the interstellar intensity may be further away from the location of *V2* and *P10* as one extrapolates outward in the equatorial region.

Obviously the actual boundary probably remained at a roughly constant distance during both of the above positive polarity time periods. The apparent motion that is observed is presumably related to changes in the global drift patterns that distribute the cosmic rays in a systematic way along the solar equatorial plane. Certainly the change in the behavior of the apparent boundary location from 1983 to 1990 when the particles were drifting in along the current sheet and in the 1971–1982 and 1991–1993 periods when both the solar magnetic field polarity and the drift patterns had changed is suggestive that global drift plays a significant role in distributing the cosmic-ray particles throughout the heliosphere. A further challenge to drift theories of solar modulation will be to predict the particular combination of intensity and gradient changes so as to produce the monotonic increasing apparent boundary location observed during the 1978–1981 and 1991–1993 periods of similar solar magnetic field polarity but opposite to the 1983–1990 period.

5. INTERPRETATION OF RESULTS

What is the significance of our conclusion which places the location of the modulation boundary at 79 ± 5 AU in 1986.5–1987.5 using the local radial gradient versus tilt correlation method of Cummings et al. (1994) or at 83 ± 3 AU during the entire period when $A < 0$ from 1983 to 1990 by using the actually observed radial gradient between *V2* and *P10* in the summation procedure? First of all, this result on the location of the cosmic-ray modulation boundary is of interest in light of recent observations on the scale size of the heliosphere.

Recall that a currently favored picture for estimating the size of the heliosphere is one in which the solar wind flows radially outward to a distance at which the solar wind dynamic pressure just balances the pressure due to the interstellar magnetic field. At this location a termination shock (T.S.) forms which is the expected location for the acceleration of the anomalous cosmic ray component. Beyond the T.S. the solar wind speed decreases and the plasma becomes more turbulent until eventually at the heliopause, the solar wind plasma merges with the interstellar plasma. This is believed to be the outermost region where cosmic rays modulation effects could occur. Recently Gurnett et al. (1993) have interpreted a giant VLF radio emission event seen on *V1* and *V2* starting in 1992 July as being due to the arrival at the heliopause of plasma from a massive interplanetary shock that originated from a period of intense solar activity in late May and early June of *1991*. From the travel time of $\sim$410 days they infer a distance to the heliopause in the range from 116 to 177 AU. Our inferred distance to the modulation boundary is clearly less than this.

At the other limit of scale size is the recent determination that the T.S. is at a distance of 67 ± 5 AU by Cummings et al. (1993). This study used anomalous O and He, assumed to originate and be accelerated at the T.S., and an extrapolation procedure to the boundary identical to that used here (and upon which our analysis is based). On the face of it, it would seem that our result for the location of the modulation boundary is somewhat larger but perhaps marginally consistent with that obtained by Cummings and colleagues for the T.S. However, the assumptions regarding how the location of the boundaries is determined are somewhat different in the two analyses. Cummings et al. (1993) determined the T.S. distance by requiring the intensity at the T.S. to be constant and the location of the T.S. remained fixed for about 2 years. They then defined its distance as the position at which this intensity is most nearly constant, e.g., 67 ± 5 AU, over the roughly 2 year period. In our procedure we extrapolate the observed >70 MeV intensity at *V2–P10* outward using equation (2) until the intensity reaches the IS value. The radial distance of the modulation boundary is then taken to be the distance at which this intensity is reached.

We should note that earlier Webber & Lockwood (1987) estimated the location of the modulation boundary to be $\sim$55 AU in 1977–1978 and suggested that the apparent outward movement of the boundary that was also observed in their analysis between 1978 and 1981 was due to additional modulation occurring at the boundary (e.g., a barrier) and the actual boundary distance did not change significantly (see Fig. 9 which also shows this behavior). These estimates by Webber & Lockwood (1987) were made using the measured time delayed integral radial gradients for >70 MeV cosmic rays and assuming that the gradients were independent of radius out to the assumed boundary distance. This earlier approach is clearly different from the method which we have used here in which we propagate the time history of the radial gradients out to the boundary and the radial gradient is not assumed to be independent of *r*. Also, according to the discussion earlier in this paper, we now believe that it is not possible to reliably estimate the location of the boundary using any similar approach during positive polarity periods (e.g., 1978–1981).

We have summarized these earlier estimates, labeled "Apparent Boundary" in column (4) along with the more recent estimates in column (5) of Table 1. As we noted earlier, only those estimates made in the $A < 0$ cycle when the gradients can be extrapolated according to the approach of Cummings et al. (1993) are reliable.

For completeness here we also discuss other recent estimates of a modulation boundary location. Webber, Lockwood, & Lee (1993) have developed a simplified simulation of the solar modulation for >70 MeV cosmic rays which includes the global drift effects, diffusion, and the role of transient decreases. It is basically a diffusion-convection (force field) model. This simulation reproduced the 26 day average cosmic-ray intensities at *IMP* and *V2* and, to a somewhat lesser extent, the variations at *P10*. In this model the data were best fitted with a

TABLE 1

LOCATION OF THE MODULATION BOUNDARY FOR >70 MeV COSMIC RAYS FROM 1977 TO 1993

Period (1)	Average Count Rate at Earth[a] (2)	Relative Intensity at Earth (3)	I. Apparent Boundary (AU)[b] (Webber & Lockwood 1987) (4)	II. Apparent Boundary (AU)[c] (This Paper) (5)
1977 Nov 9–Dec 30	404.5	1.0	55	...
1978 Nov 9–Dec 30	316.4	0.782	64	47 ± 4
1980 Jan 27–Mar 19	215.3	0.532	76	56 ± 3
1981 Apr 15–Jun 3	136.5	0.337	84	66 ± 3
1982 Dec 5–1983 Jan 26	136.2	0.335	83	76 ± 4
1984 Jun 6–Jul 27	198.8	0.492		78 ± 4
1985 Jun 6–Jul 27	268.8	0.664		80 ± 4
1985 Dec 5–1986 Jan 26	304.3	0.752		80 ± 4
1987 Feb 22–Mar 19	389.7	0.963		81 ± 5
1989 Nov 9–Dec 4	104.9	0.259		85 ± 5
1991 Jul 28–Sep 17	100.8	0.249		103 ± 5
1992 Oct 14–Dec 4	225.0	0.556		114 ± 5

[a] Variation in count rate as per cent during any interval is $\sim$5%.

[b] Location of modulation boundary obtained by fitting the normalized intensity at *IMP*, *V2*, and *P10*, the latter time-shifted, then extrapolating to the boundary where $N = 1855$.

[c] From eq. (2) in text with intensity at modulation boundary $N = 1175$. Uncertainty determined from normalized interstellar intensity range of 1050–1300.

modulation boundary at 96–120 AU. However, this was an average over both cycles, and the results were not very sensitive to the boundary location.

Williams & Potgieter (1991) used a simple sinusoidal wavy heliospheric neutral sheet propagated outward from the Sun to the modulation boundary to estimate its location. Using the *V2* > 70 MeV data their best results gave $R_{MB} \sim 90$ AU which is not much larger than the value of 83 ± 5 AU obtained here. This value for R_{MB} produced the minimum hysteresis between the recovery and decrease phases of the cosmic-ray intensity at *V2* from 1982 to 1989. Although the method of extrapolation is similar to our approach, the method to decide where the boundary is located is very different.

McDonald et al. (1992) assumed that $G_r \propto r^{-0.7}$ for 180–450 MeV per nucleon He particles and found that $R_{MB} = 162 \pm 40$ AU. Since the radial dependence of the gradient changes with both time and the cosmic-ray intensity level as well as depending on the radius itself (Webber & Lockwood 1991) and since the location of the boundary is very sensitive to the assumed radial dependence, the errors of this method are very large as indicated above.

6. SUMMARY

The modulation boundary deduced from the >70 MeV cosmic-ray radial gradients in the outer heliosphere appears to remain at a distance of 83 ± 5 AU over the entire period from 1983 to 1990 when the solar magnetic polarity was negative. It is difficult to evaluate the significance of the difference between this distance and the inferred distance to the termination shock of ~67 AU found by Cummings et al. (1994). The suggestion is strong, however, that the cosmic-ray modulation boundary is somewhat beyond the T.S. but by no means as far out as the heliopause. Thus the region between the T.S. and the heliopause may have some effectiveness in modulating cosmic rays but probably does not play a dominating role at least at these energies.

It appears that estimates of the location of the modulation boundary can be made only by extrapolating the radial gradients observed in the outer heliosphere outward as we have done when the cosmic rays are drifting inward to Earth along the neutral sheet as was the case for the negative polarity period from 1983–1990.

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Intensity variations of > 70-Mev cosmic rays measured by Pioneer 10, Voyager 1 & 2 and IMP in the heliosphere during the recovery period from 1992-1995

W. R. Webber

New Mexico State University, Department of Astronomy, Las Cruces

J. A. Lockwood

University of New Hampshire, Space Science Center, Durham

Abstract. Using data from the >70-MeV channel on the Pioneer 10 and Voyager 1 & 2 spacecraft we have examined the gradients and intensities of cosmic rays in the outer heliosphere between 1992 and 1995. During this time there is a slow increase of intensity towards the next maximum in ~1997 and the radial gradient is small - decreasing to ~0.8%/AU at the end of this period. The latitude gradient has also decreased to only ~0.1-0.2%/AU but remains negative as it was in the previous 11-year cycle. These gradients are similar to those for >70-MeV particles reported recently in the inner heliosphere but quite different from the positive gradients observed at this time throughout the heliosphere by the Ulysses and Voyager spacecraft for anomalous cosmic rays. Overall the cosmic ray intensity is almost uniform in radius, azimuth and latitude at this time in the outer heliosphere - and far lower than the estimated interstellar intensity. The intensities are, in fact, much lower than would be expected based on data from the previous cycle. This, along with the very slow increase that is observed, suggests that, at the same radial distance, the intensity in 1977 will be much less than in the previous cycle in 1987 - resulting in a large 22-year modulation wave. The data show some features which suggest that large scale drift patterns, which change when the solar magnetic polarity changes every 11 years, play a important role in the overall intensity distribution in the outer heliosphere - but specific details, particularly in the present positive polarity cycle beginning in 1990 are not well predicted by current models.

Introduction

The Pioneer 10 and Voyager 1 & 2 spacecraft in the outer heliosphere, along with the IMP spacecraft at the Earth, form a unique combination to study global cosmic-ray modulation effects in the heliosphere. In the 1992-1995 time period the cosmic ray intensity was recovering from the minimum intensity at the last sunspot maximum of the 11-year modulation cycle in 1990-1991 - heading towards a maximum intensity at the next sunspot minimum probably in 1997. The polarity of the solar polar magnetic field also had changed from negative to positive in 1990-1991 so that, according to drift modulation theory, positive particles were drifting from the polar regions of the heliosphere toward the solar equatorial plane after 1991. This is in contrast to the previous period from 1980-1990 when the solar polarity was such that positive particles were drifting in directly along the equatorial heliospheric current sheet from the boundary. This was the case at the time of the previous intensity maximum in 1987 when Voyager 2 and Pioneer 10 were at 24 and 42 AU respectively. At this earlier time in 1987 it was argued that it was possible to extrapolate the observed radial intensity gradient, which was ~1.2%/AU, outward in a direct fashion, to reach the estimated interstellar intensity at a distance ~83 AU which was then proposed as a nominal boundary of the modulation region around the Sun [*Webber and Lockwood*, 1995]. In early 1995 P10 was at ~62 AU and heliographic latitude ~3° and V2 at ~45 AU and latitude -14° along with V1 at ~60 AU and latitude of 34°. The intensities and radial and latitudinal gradients between these spacecraft will be examined and compared with those observed in the corresponding part of the previous modulation cycle which had opposite solar magnetic polarity.

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The Data

The basic data are in the form of 26-day averages for >70-MeV cosmic-rays shown for IMP, Voyager 2 and Pioneer 10 in Fig. 1. These counting rates were carefully normalized to ~1% or better when the spacecraft were near the Earth and this data set has been used extensively by us in cosmic-ray time variation studies [*Lockwood and Webber*, 1990]. The database is shown from 1985 onwards. During this time period the spacecraft are moving outward at ~3 AU per year.

Intensity Variations

It is obvious from the data in Fig. 1 that the intensity has recovered much more rapidly after 1991 at Earth than in the outer heliosphere relative to what it was at the maximum of the previous cycle in 1987. This is evident in spite of the fact that the spacecraft are ~20 AU further out in 1995 than in 1987. This additional distance along with the positive radial gradient should lead one to expect possibly higher intensities in 1995 relative to 1987 if the properties of the modulation were the same in each polarity cycle. This is clearly not the case.

To put these effects on a quantitative basis we compare in Table 1 the intensities observed in 1995 with those at the previous intensity maximum in 1987 corrected to the same radial location. For the intensity

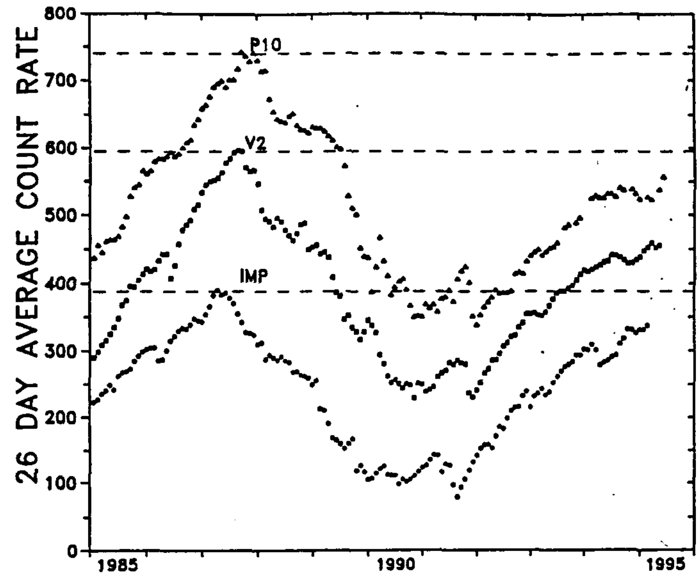

Figure 1. Normalized 26-day average cosmic ray count rates at IMP, V2, and P10 from 1985-1995. The dashed lines show the maximum intensities in 1987.

comparison we take a 78-day interval around the maximum in 1987 and a 78-day interval from day 27 of 1995 onwards. It is convenient to compare the intensities in the 1987 and 1995 since P10 in 1987 and V2 in early 1995 are at almost the same radial distance. To compare the P10 intensity at 62 AU in 1995 with that expected in 1987 we have used the P10 intensity at 42 AU in 1987 and extrapolated it outward to 62 AU using the gradient of 1.2%/AU measured in 1987 between V2 and P10 - according to the arguments for extrapolating the gradients discussed in *Webber and Lockwood* [1995].

It is seen from the Table that, at the Earth, the recovery in early 1995 is almost complete (0.88) to the level observed in 1987. However, at 42 AU the intensity in 1995 is only 0.60 of that in 1987 and in 1995 at 62 AU it is only 0.57 of that estimated at this same radius in 1987. Allowing for the added propagation times between the 1987 and 1995 radial distances changes these values to 0.66 and 0.63 respectively. These relatively low intensities in the outer heliosphere in 1995 require a large modulation between the spacecraft at ~60 AU and the modulation boundary. A dramatic difference in the modulation characteristics (intensity levels) between the two cycles is clearly evident from the above discussion - and this difference between cycles actually seems to be getting larger the further one goes out in the heliosphere.

We can also look at this situation from a different point of view. In Table 1 we show the recovery of intensity from 1992.3 to 1995.3 - a three-year time period. Here again the data are corrected to a constant radius and the recovery time period is started ~6 months after the large transient decreases in 1991 to be free of the initial rapid recovery from the decreases. The recovery relative to the maximum intensity in 1987 is greatest at Earth and decreases as one goes to larger and larger radii. This is just another way of presenting the fact that the intensity, particularly in the outer heliosphere, is much lower than would be expected based on data from the previous 11-year cycle. This seems to be a powerful argument for the fact that the global modulation effects must be strongly different in the outer heliosphere in the two cycles. It is suggestive that the solar magnetic polarity - as manifested by the drift patterns of the cosmic rays as described earlier - plays a very important role in controlling the cosmic-ray intensity pattern. As yet we are not aware, however, that drift dominated modulation theories are able to explain the magnitude of the asymmetry between cycles that is reported here. In fact, if one believes that the new modulation cycle will be well set in by 1998.3, then the intensity at 42 AU, and even more strongly at 62 AU, may never recover to the same level observed in the previous polarity cycle - another unanticipated aspect of the modulation asymmetry between cycles.

Gradients and their variations

The global intensity pattern throughout the heliosphere may be seen from Fig. 2 which shows the 78-

Table 1. Comparison of Intensities in 1987 and 1995 (in normalized units).

	1987	Ratio	1995	Recovery Ratio (1995.3/1992.3)
1 AU (IMP)	384	0.880 ± 0 .026	338	(340/162) = 2.100
42 AU (P10, V2)	740	0.602 ± 0.020	445	(456/303) = 1.505
62 AU (P10, P10)	942	0.569 ± 0.016	536	(531/406) = 1.308

Errors in intensities estimated at ±2%

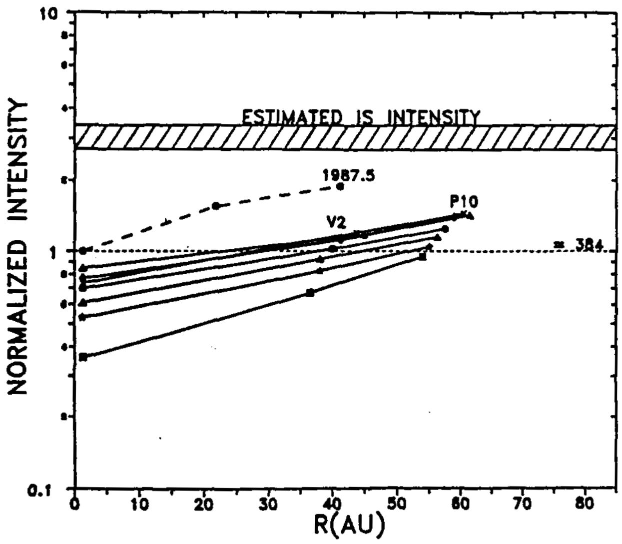

Figure 2. 78-day average intensities at IMP, V2 and P10 at 6-month intervals during the recovery starting from 1992.0 to 1995.0. Also shown as a dashed line are the intensities at these three spacecraft at the maximum in the previous cycle in 1987. The estimated interstellar intensity is also shown after *Webber and Lockwood* [1995].

day average 70-MeV intensities at IMP, V2 and P10 plotted at 6 month time intervals starting at 1992.0. The slope of the line connecting the intensities gives the approximate radial gradient at each of these times. However to determine the exact radial gradient, G_r, we need to consider the fact that V2 is now moving away from the heliographic equator (~14°S in 1995) and also to utilize V1 which is at 34°N to obtain the latitudinal gradient G_θ. For this we used the following relations:

$$\ln (N_{V2}/N_{V1}) = G_\theta(-\theta_{V1} + |\theta_{V2}|) + G_r(R_{V2} - R_{V1})$$

$$\ln (N_{V1}/N_{P10}) = G_\theta(-\theta_{V1} - |\theta_{P10}|) + G_r(R_{V1} - R_{P10})$$

$$\ln (N_{V2}/N_{P10}) = G_\theta(-\theta_{V2} + |\theta_{P10}|) + G_r(R_{V2} - R_{P10})$$

where N_{V2}, N_{V1} and N_{P10} are the >70-MeV cosmic-ray intensities at V2, V1 and P10. We have assumed azimuthal symmetry (that P10, V1 and V2 differ only in radius). We have also assumed the latitudinal gradient to be symmetrical with respect to the heliographic equator and that G_r is independent of r between the V2 and P10 spacecraft. We can solve directly any pair of the above three equations (which will contain the intensities from all three spacecraft) to find G_r and G_θ. It is also useful to compute G_z, the latitudinal gradient expressed as %/AU for direct comparison with G_r. For this we have taken $Z = R_{V1} \bullet \sin\theta_{V1}$ which means that $Z \sim 0.5 \bullet R_{V1}$.

We have plotted in Fig. 3a the 26-day running averages over three 26-day intervals of the radial and latitudinal gradients of >70-MeV galactic cosmic rays in the outer heliosphere from 1992 to 1995. The gradients measured at a corresponding time in the previous cycle from 1985 to 1987 are also shown for comparison. These gradients are not time-shifted for the outward propagation of the solar wind in the heliosphere. It is seen that in the 1992 to 1995 time period the radial gradient slowly decreases from ~1.5% per AU at the beginning of the 3-

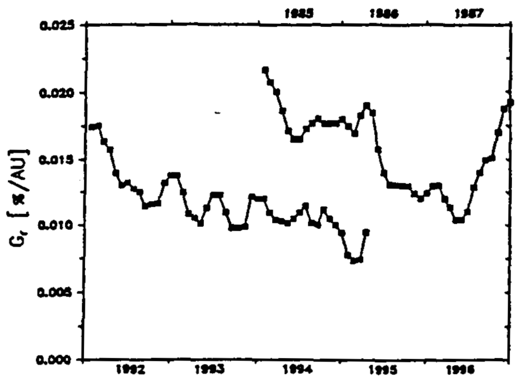

Figure 3a. Three period 26-day running averages of G_r between V2 and P10 in 1992-1995 (solid squares) and 1985-1987 (open squares).

year period to ~0.8% per AU in 1995. At the same time the latitudinal gradient, G_z, is small but negative; decreasing from ~ -0.4%/AU at the beginning to between -0.1 and -0.2%/AU at the end of the time period (Fig. 3b). In effect the cosmic-ray distribution in the outer heliosphere has become remarkably uniform and by 1995 is almost completely spherically symmetric. In fact, from the projected rate of decrease, the latitudinal gradient will become ~ zero in late 1995 or 1996 and only then possibly become positive. *Cummings et al.* [1995] have noted that the latitude gradients of both anomalous Oxygen and Helium became positive in 1992-1993, reversing the relatively large negative gradients observed in the previous cycle - consistent with the predictions of drift theories. Thus it is clear that the expected change in the latitude gradients from the negative solar polarity cycle to the positive polarity cycle is not simple and is probably energy-, time- and species-dependent.

We should note that during the last positive polarity cycle in 1975-1976, using P11 and IMP when these spacecraft were much nearer to the Sun and nearer to the heliographic equator, *McKibben* [1989] also observed a positive latitudinal gradient for anomalous He as has now been observed in the latest positive polarity cycle in 1994-1995 by Ulysses and Voyager, [*Cummings et al.*, 1995, *Simpson*, et al., in press]. For >70-MeV particles *McKibben* [1995] observed a small latitudinal gradient

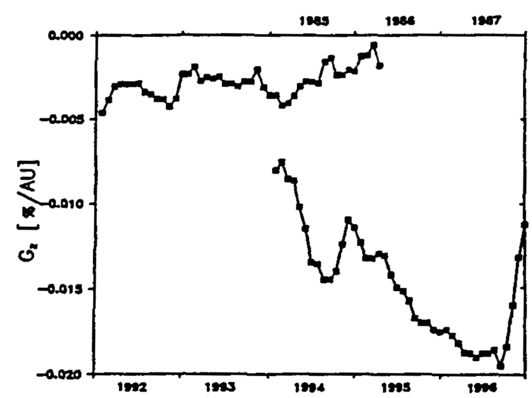

Figure 3b. Three period 26-day running averages of G_z in 1992-1995 (solid squares) and 1985-1987 (open squares).

consistent with zero for >70-MeV particles in the inner heliosphere much like what we are observing now in the outer heliosphere.

Summary and conclusions

We have examined the temporal intensity variations and the radial and latitudinal gradients of >70-MeV cosmic rays that existed in the heliosphere during the 1992-1995 time period. When the intensities are compared with those observed at the time of the 1987 intensity maximum it is found that intensity recovery is almost complete at the Earth in early 1995, but at larger and larger radial distances the fractional recovery becomes less and less. This is a result of the fact that the recovery time constant becomes longer as one goes further out in the heliosphere.

During the time period from 1992-1995 the radial intensity gradient decreased by a factor ~2 and is only ~0.7%/AU in 1995 and the latitudinal gradient also decreases to only ~0.1%/AU in 1995 but still remains slightly negative. The overall picture is one of a remarkably uniform cosmic-ray distribution in latitude and in azimuth in the direction of both V1 & V2 and P10 on opposite sides of the Sun in the outer heliosphere. This, coupled with the very slow increase in intensity that is observed, suggests that in the outer heliosphere the intensity may not fully recover to its value in the previous cycle at the same radius thus producing a 22-year modulation wave in the outer heliosphere - larger and in a reverse fashion to the 22-year intensity wave identified at the Earth and in the inner heliosphere at 18 AU [*Lockwood and Webber*, 1995].

The most obvious explanation for the behavior of the cosmic-ray intensity and gradients that we observe is the change in the magnetic polarity of the Sun and its effects on the global drift of cosmic-rays in the heliosphere. In the period from 1980 to 1990, including the 1987 intensity maximum, according to drift theories, positive particles were drifting and diffusing directly in along the equatorial heliospheric current sheet, and then drifting and diffusing away from the current sheet to higher latitude. This produced the larger radial and latitudinal gradients as shown in Fig. 3a and b and allowed relatively easy access of galactic cosmic rays from the boundary to the spacecraft that are close to the heliospheric equator.

In the period after 1990, when the solar magnetic polarity changed, galactic cosmic-rays began to drift in from the polar regions towards the heliospheric equator. There was no longer a simple direct connection between the spacecraft near the equator and the interstellar intensities at the modulation boundary, hence the observed intensities remained lower in the outer heliosphere. The details of how the particles reach the heliospheric neutral sheet in this polarity cycle are obviously a complicated function of latitude, radius and rigidity and depend importantly on parameters in the polar regions of the heliosphere. As a result, although the general picture to describe the global cosmic ray modulation probably follows quite well the simple description given above, the details have yet to be fit into specific drift models, particularly to explain observations in this positive polarity cycle in the outer heliosphere both near to the heliographic equator and at higher latitudes.

For example, *Potgieter and Moraal* [1995], show examples of the intensities of ~100 MeV cosmic-rays in the heliosphere under equilibrium conditions in both positive and negative cycles. A very small radial gradient is predicted in the positive cycle - very similar to that now observed. However, the latitude gradient is large and positive. As a result the uniform distribution of cosmic-rays that is observed is not well predicted. The slow temporal evolution of intensities in this polarity cycle also needs to be explained in a manner similar to the time variable models that have been applied successfully to explain the intensity variations observed in the negative cycle [[*Potgieter et al.*, 1993]. We hope that the observations reported here will lead to a better understanding of the global modulation problem in this part of the modulation cycle.

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W.R. Webber, New Mexico State University, Department of Astronomy, Box 30001/Dept. 4500, Las Cruces, NM 88003-0001

J.A. Lockwood, University of New Hampshire, Space Science Center, Morse Hall, Durham, NH 03824-3525

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Comparison of the Rigidity Dependence of the 11-Year Cosmic Ray Variation at the Earth in Two Solar Cycles of Opposite Magnetic Polarity

J. A. Lockwood

Space Science Center, University of New Hampshire, Durham

W. R. Webber

Astronomy Department, New Mexico State University, Las Cruces

Abstract. We have found that there is a significant difference in the rigidity dependence of the 11-year variation of the galactic cosmic rays in the rigidity interval from 0.6 to 100 GV between the $A > 0$ modulation cycle from 1977 to 1981 and the $A < 0$ cycle from 1987 to 1990. The overall intensity decrease from 1977-1981 is found to have a rigidity dependence given by $F(P) = \exp(-1.46 \times P^{-1.22\pm0.05})$, where $F(P)$ is the modulation function and P is the rigidity [GV] and for 1987-1990 $F(P) = \exp(-1.75 \times P^{-1.02\pm0.05})$. For the conventional diffusion-convection theory of modulation the rigidity dependence of the modulation is equal to the rigidity dependence of the interplanetary diffusion coefficient. For a selected number of Forbush decreases we found that the rigidity dependence of the decreases occurring near the period of minimum solar modulation was steeper than for those occurring later in the solar cycle. In no case was the rigidity dependence of any transient decrease much different from that of the 11-year variation, however. The crossover in the 1977 and 1987 primary proton energy spectra at $E \sim 400$ MeV observed near sunspot minimum shifts to ~650 MeV at the time of the maximum solar activity or minimum cosmic ray intensity.

Introduction

Few observations have been made of the rigidity dependence of the 11-year cosmic ray modulation over the entire rigidity range from 0.6 to 100 GV using both ground-based neutron monitor data and primary cosmic ray data from spacecraft near the Earth. Such a study of the rigidity dependence of the 11-year variation may lead to a better understanding of the relative importance of cosmic ray drifts and diffusion and of the rigidity dependence of the diffusion coefficient in the modulation process. In an early investigation by *Lockwood and Webber* [1967, 1968], neutron monitor data and direct cosmic ray measurements at low energies made on balloons were used to distinguish between the different forms of the solar modulation from 1965 to 1966, e.g., $F(P) = \exp(-K/P)$ or $F(P) = 1-K/P$, where $F(P)$ is the modulation function, P is the rigidity [GV], and K is a constant. In a second study [*Lockwood and Webber*, 1979] both neutron monitors and $E > 70$-MeV data from near-Earth spacecraft were used, concentrating on the differences in the high-energy and low-energy modulation observed between 1965 and 1976. The difference between the low and high energies was explained by assuming that the rigidity dependence of the diffusion coefficient changed from $K(P) \propto P$ to $K(P) \propto P^2$ at some rigidity 10 GV < P < 25 GV, depending upon the phase of the solar cycle modulation [*Jokipii*, 1971]. Recently, *McDonald* et al. [1992] have compared the energy spectra of H and He at solar minimum in 1977 and

1987, two periods of opposite solar magnetic polarity, but only over the energy range from 20 to ~500 MeV.

The 11-year variation has been characterized to occur in a series of well-defined step decreases, each of which may be followed by a relatively flat plateau region [*Lockwood*, 1960; *McDonald et al.*, 1981]. These step decreases are associated with Merged Interaction Regions (MIRs) produced by strong interplanetary shocks as they propagate outward in the heliosphere [*Burlaga et al.*, 1985]. The effects of these step decreases on the overall 11-year decrease (if indeed they are separable) can be seen in Figure 1 for the periods 1955-1960, 1965-1969, 1977-1981, and 1987-1990 and, in more detail, in Figures 3a and 3b for the latter two intervals. We will later compare the rigidity dependence of a few of these step or Forbush decreases with that of the slower overall 11-year variations.

A 22-year modulation of the cosmic rays of energies to which neutron monitors (NMs) respond has been observed [*Nagashima and Morishita*, 1980; *Webber and Lockwood*, 1988]. The latter authors found that the NM intensity was ~1.5% higher at the time of the 1987 maximum and also in 1965, as compared to the maximum in 1976. When the proton intensities at lower energies ($E \leq 200$ MeV) were compared, it was found that the proton intensities were higher in 1976 than in 1965 [*Evenson et al.*, 1983]. This is exactly opposite of what the NMs recorded. *Moraal et al.* [1989] found that the differential response functions of NMs at the 1987 solar minimum agreed well with those measured in 1965, but both these functions were significantly different from those in 1976 and 1954, thus exhibiting a 22-year cycle. The 22-year cosmic ray cycle seems to manifest itself in the $A > 0$ cycle by a larger flux of low-energy ($E \leq 200$ MeV) protons. The proton flux below ~400 MeV in 1977 was greater than that in 1987, and above ~400 MeV to ~3.0 GeV it was less in 1977 than in 1987. Consequently, there is a crossover in the comparative energy spectra at solar minimum for the $A > 0$ and $A < 0$ cycles, an effect that is predicted by drift models of the modulation [*Reinecke and Potgieter*, 1994]. This 22-year behavior may also manifest itself by a difference in the rigidity dependence of the overall cosmic ray decrease in the two periods.

It therefore seems appropriate to examine the rigidity dependence of the slow "11-year" cosmic ray intensity decreases in two different solar magnetic cycles, 1977-1981 and 1987-1990, using neutron monitor and lower-energy data from the IMP 8 spacecraft, which remained close to the Earth.

Data Set

The neutron monitor data were selected from the worldwide network using those stations which had as different response functions as possible and had operated throughout the period to be analyzed. From the dependence of the NM response function on rigidity [*Lockwood and Webber*, 1967; *Lockwood et al.*, 1974, 1991], the expected magnitude of the intensity decrease for the 11-year variation at a particular cutoff rigidity can be calculated using an assumed rigidity dependence of the cosmic ray modulation during the decrease. In the analysis used here we assume a modulation function $F(P) = J_t(P)/J_0(P)$, where $J_0(P)$ and $J_t(P)$ are the primary differential rigidity spectra just before the decrease started and at the end of the decrease period, respectively. We have assumed that the modulation extends to 100 GV. We can write for the fractional decrease observed by a NM [*Lockwood et al.*, 1991]:

$$\frac{\Delta N}{N} = \frac{N_0(P_c) - N_t(P_c)}{N_0(P_c)} = \frac{\int_{P_c}^{100} [1-F(P)](dN/dP)_0\, dP}{\int_{P_c}^{100} (dN/dP)_0\, dP} \qquad (1)$$

where N_t and N_0 are the NM counting rates after and before the decrease, P_c is the vertical cutoff rigidity of the NM, $(dN/dP)_0$ and $(dN/dP)_t = F(P)(dN/dP)_0$ are the NM differential responses to the primary cosmic ray spectrum just before the start of the decrease and at the end of the decrease period, and $F(P)$ is the modulation function describing the change in the primary spectrum during the decrease. The differential response of a NM is given by

$$(dN/dP)_O = S(P) \times J_0(P) \qquad (2)$$

where $J_0(P)$ is the primary differential rigidity spectrum and $S(P)$ is the specific yield function of a NM which depends on the altitude of the NM. We picked NMs at altitudes of 1030 (sea level), ~840 g/cm^2, and ~680 g/cm^2 for which we have deduced the NM response functions [*Webber and Lockwood*, 1967; *Lockwood et al.*, 1974]. We first calculated the median rigidity P_m of the neutron monitors which respond over a wide range of energies (or rigidities) to the modulated cosmic ray intensity as follows:

$$\int_{P_m}^{100} [1 - F(P] \,(dN/dP)_0\, dP = 1/2 \int_{P_c}^{100} [1 - F(P)]\,)dN/dP)_0\, dP \qquad (3)$$

For the > 70-MeV rate of the IMP 8 detector an equation similar to (3) is used, but $S(P)$ is taken to be unity. Then we compared the calculated magnitudes to the observed magnitudes of the decrease at the calculated median rigidity for an assumed modulation function. In such a comparison we must take into account the fact that the median rigidity is a function of the modulation function $F(P)$. The modulation function was assumed to be of the form

$$F(P) = \exp(-K/P^{\delta}) \tag{4}$$

where K and δ are constants for a particular decrease period. In Figure 2 we have plotted the median rigidities of the Mount Washington NM and the IMP 8 > 70-MeV/nucleon channel for different values of δ in (4). For the IMP 8 rate it is necessary to distinguish between the response to the two different primary proton spectra at low energies in 1977 and 1987, which does not, however, significantly affect the response of the neutron monitors. As expected, the median rigidity decreases with increasing δ because more of the modulation is occurring at lower rigidities.

Comparison of the 11-Year Cosmic Ray Variation in 1977-1981 and 1987-1990

We selected two periods of opposite solar magnetic polarity in 1977-1981 and 1987-1990 during which the cosmic ray intensity steadily decreased toward its minimum values in the solar activity cycle. These periods are marked in Figure 1. In Figures 3a and 3b we have plotted the 26-day average count rates of the Mount Washington NM, the IMP 8 > 70-MeV/nucleon, 130- to 220-MeV and 30- to 60-MeV hydrogen for the two periods. Since the count rate changes are large for the lower-energy channels, we have plotted these rates on a logarithmic scale.

In order to determine the percentage decrease, e.g., from January 1977 to December 1981, for the different detectors, we fitted each data set with a straight line from which we determined the percentage decrease. We then compared this measure of the percentage decrease with that determined from the intensities at the maximum and minimum in the period and took the average of the results from the two methods. This also provides an estimate of the uncertainty in the percentage decrease. As an example, we show in Figure 4 the fit of the Mount Washington NM count rates to a straight line for 1977-1981. In Table 1 we summarize the percentage decreases of the different detectors. For the NMs we have also given the vertical cutoff rigidity P_c and the altitude of the station as well as the median rigidity of the modulated detector response to the deduced value of δ in the modulation function that we found best fit the deduced rigidity dependence of the decrease.

The measured (smoothed) primary proton energy spectra in 1977 and 1987 are compared in Figure 5. The 1977 proton spectrum represents a combination of balloon data above 100 MeV [*Webber and Yushak*, 1983] and IMP 8 data at lower energies [*McDonald et al.*, 1992]. The 1987 data combine the balloon observations of *Seo et al.* [1991] and IMP 8 data at lower energies. The small kinks in the smoothed data near 100 MeV are due to lack of a perfect fit between the high-energy balloon data and the low-energy spacecraft data. The 1977 spectrum has been used previously to deduce the NM differential response functions for a study of the rigidity dependence of some Forbush decreases [*Lockwood et al.*, 1991]. The 1977 and 1987 spectra are different for $E < 3$ GeV and crossover at E = 400 MeV ($P = 0.95$ GV).

The rigidity dependencies of the 11-year variation in 1977-1981 or 1987-1990 can be deduced as follows. Introducing the ratio $M(P)$, which is the ratio of the differential intensity at the solar minimum in either 1977 or 1987, $(dJ/dP)_0$, to $(dJ/dP)_t$, where $(dJ/dP)_t = (dJ/dP)_0 \times F(P)$ at the time t

$$M = \frac{(dJ/dP)_0}{(dJ/dP)_t} = 1/F(P) = \exp(KP^{-\delta})$$

or (5),

$$M = \frac{(dN/dP_m)_0}{F(P)\,(dN/dP_m)_t} = \exp(KP^{-\delta})$$

where $\ln M = K\,P^{-\delta}$ and M is a function of P or P_m. Therefore, if the rigidity dependence is a simple power law given by (5), a logarithmic plot of the natural logarithm of the ratio of unmodulated to the modulated differential intensity (dJ/dP or dN/dP_m) versus rigidity will be a straight line. For the neutron monitors the ratio is plotted at the median rigidity. The function M described above is just the modulaton function for the diffusion-convection modulation model as described by *Gleeson and Axford* [1968]. In this model, $M(P) \propto 1/K(P)$ so that the slope of $\ln M$ versus P curve gives the rigidity dependence of the diffusion coefficient at these rigidities.

Starting with the 1977 primary energy spectrum, we find that the 11-year variation from 1977 to 1981 is best described by $F(P) = \exp(-1.46 \times P^{-1.22\pm0.05})$, as presented in Figure 6. In the analysis we grouped together NM data for which the median rigidities are almost the same. Since both the IMP 8 > 70-MeV and the NMs are integral rate detectors, we have indicated on Figure 6, using the horizontal line, the rigidity range in which 25% of the response lies.

From Figure 3a it can be seen that the count rate of the 30- to 60-MeV channel is very small in 1981, and background effects as well as a low level of solar particles are probably present. There were frequent small solar flare increases in 1980-1981 that, on average, are very difficult to remove from the 30- to 60-MeV count rate data. The decrease of the IMP 8 30- to 60-MeV protons from 1977 to 1981 can therefore only be taken as a lower limit to the total decrease, and we excluded these data from the fit although the lower limit is indicated in Table 1. We cannot, of course, exclude the possibility that the rigidity dependence of the 11-year variation from 1977 to 1981 is not a simple power law in rigidity over the entire rigidity range but flattens at low rigidities. A simple power law fits the data quite well down to ~0.6 GV (175 MeV), however.

Starting with the 1987 primary spectrum the rigidity dependence of the 11-year variation from 1987 to 1990, as shown in Figure 7, is $F(P) = \exp(-1.75 \times P^{-1.02\pm0.05})$, a distinctly flatter rigidity dependence than for the 1977-1981 intensity decrease. Again, the observed intensity of the 30- to 60-MeV channel in 1991 appears to be uncertain (Figure 3b), probably for the same reasons as discussed earlier. Therefore we excluded this data point from the straight line fit although it may be taken as a lower limit. NMs with the same median rigidity were again grouped together in the fitting process. In Figure 7 we have indicated the rigidity dependence of the 11-year variation from 1977 to 1981. It is evident that $F(P)$ is different for the 1977-1981 decrease period, and this function for $F(P)$ does not give a good fit to the data for the decrease from 1987 to 1991. A similar line in Figure 6 indicates that the rigidity dependence of the 1977-1981 decrease is not well described by the rigidity dependence of the 1987-1990 decrease also. So it is clear that the rigidity dependence of the modulation is flatter during the $A < 0$ period from 1987-1990.

Rigidity Dependence of Forbush Decreases Compared to the 11-Year Variation

We have selected a few Forbush decreases, sometimes referred to as "step decreases," to compare with the slower 11-year variation for the 1977 to 1981 and 1987 to 1990 periods. In Table 2 we summarize the rigidity dependence obtained for six decreases using the same functional form for the decrease as in the 11-year variation, namely, $F(P) = \exp(-K/P^{\delta})$. For all the transient events the primary rigidity spectrum just prior to the decrease was first determined and then a fit was made to the observed decreases using at least six NMs and two to three lower energies from 30- to 230-MeV and the > 70-MeV channel on the IMP 8 detector. The first three events in Table 2 have been discussed in detail by *Lockwood et al.* [1991]. The last three decreases are analyzed in this study. It appears that the February 1986 and August 1987 step decreases, both occurring when the primary spectrum was close to the solar minimum spectrum, had a steeper rigidity dependence than the decreases later in the solar cycle, e.g., July 1982. The rigidity dependence of these two decreases extended down to ~0.3 GV. The decreases later in the solar modulation cycle, however, were independent of rigidity below 1-2 GV. The flatter rigidity dependence of the decreases in the 1981-1982 and 1989-1990 periods near the end of the overall 11-year decrease can be understood since the primary rigidity spectrum was depleted at lower energies (Figure 8). In no case do any of the transient decreases have a rigidity dependence greatly different from the overall dependence for either of the two 11-year variation periods. This is probably expected since these transients are believed to be a major contributor to the 11-year variation [*McDonald et al.*, 1981; *Lockwood and Webber*, 1984].

Discussion

Reinecke and Potgieter [1994] have proposed that the difference in the primary proton energy or rigidity spectra in $A > 0$ and $A < 0$ epochs can be explained in terms of a steady state drift model, with a simulated wavy neutral sheet, which includes gradient, curvature, and neutral sheet drifts. In its simplest mode the drift model predicts the crossover by just reversing the direction of the interplanetary magnetic field. In their model, which uses specific values for the diffusion coefficient ($K_{\|0} = 4.8 \times 10^{22}$ cm^2/s) and drifts of variable amplitudes, the crossover at 1 AU is found to occur at ~1000 MeV (1.7 GV). Presumably, the crossover would occur at lower energies if diffusion increases and drift becomes less important. Their calculations indicate that the ratio of the maximum proton intensities that should be observed for the $A > 0$ to $A < 0$ periods is 1.25, which is comparable to the observed ratio of 1.13 obtained from the spectra of Figure 5. In Figure 5 the experimentally determined crossover is seen to occur at ~400 MeV. In order to get the crossover at ~400 MeV, it is required that $K_{\|0}$ increase to ~9×10^{22} cm^2/s or that drifts are making a smaller contribution. In Figure 8 we have plotted the modulated energy spectra at the end of the two 11-year decrease periods in 1981 and in 1990 when the intensities were at a minimum. The spectra are now seen to cross over at a higher-energy $E \cong 650$ MeV (1.3 GV). The effect of the large merged interaction regions present in 1981 and 1990 is not included in the model of *Reinecke and Potgieter* [1994] which essentially compares the spectra at periods of small solar activity near the intensity maximum in the $A < 0$ and $A > 0$ solar magnetic cycles.

Conclusions

We conclude that there was a significant difference in the rigidity dependence of the 11-year modulation of galactic cosmic rays in the rigidity interval from 0.6 to 100 GV between the $A > 0$ modulation cycle in 1977-1981 and the $A < 0$ cycle in 1987-1990. The 11-year decrease from 1977 to 1981 had a rigidity dependence given by $F(P) = \exp(-1.46 \times P^{-1.22\pm0.05})$ and for 1987-1990, $F(P) = \exp(-1.75 \times P^{-1.02\pm0.05})$. Hence, according to the diffusion-convection model [*Gleeson and Axford*, 1968], the rigidity dependence of the diffusion coefficient was flatter for the 11-year decrease from 1987 to 1990 than for the decrease from 1977 to 1981. For a selected number of Forbush or transient decreases we found that the rigidity dependence of those decreases occurring near the period of minimum solar modulation was steeper than those occurring later in the solar cycle, however. In no case was the rigidity dependence of any transient decrease much different from that of the 11-year variation. There is still a crossover in the primary proton energy spectra at the time of the minimum intensities during the two different magnetic polarity cycles, but it shifted from E~400 MeV at the solar activity minimum to ~650 MeV at the time of the maximum solar activity or minimum cosmic ray intensity.

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J.A. Lockwood, Space Science Center, University of New Hampshire, Morse Hall, 39 College Road, Durham, NH 038224. (e-mail: lockwood @comptel.sr.unh.edu)

W.R. Webber, Astronomy Department, New Mexico State University, Las Cruces, NM 88001. (e-mail: bwebber@nmsu.edu)

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LOCKWOOD AND WEBBER: RIGIDITY DEPENDENCE OF COSMIC RAYS

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Figure 1. The 26-day average Mount Washington neutron monitor (NM) count rate from 1955 to 1995. The data for 1955 have not been normalized, and the preliminary data in late 1995 are indicated by the dashed line.

Figure 2. Median rigidity of the Mount Washington NM and the IMP 8 >70-MeV rates as a function of constant δ in the modulation function $F(P) = \exp(-K/P^{\delta})$. For the > 70-MeV rate separate, P_m versus δ curves are shown for the 1977 and 1987 primary proton rigidity spectra.

Figure 3a. The 26-day averages of the Mount Washington NM count rates (linear scale) and the IMP 8 > 70-MeV/nucleon, 130- to 220-MeV and 30- to 60-MeV proton rates (logarithmic scales) from 1977 to 1981.

Figure 3b. Same as Figure 3a, but for 1987 to 1991.

Figure 4. The 26-day average count rate of the Mount Washington NM from January 1977 to mid-1981. The best fit straight line (R^2=0.89) gives a decrease of 17.0%.

Figure 5. Comparison of the measured primary proton energy spectra from 10 to 10,000 MeV in 1977 and 1987 at the times of maximum cosmic ray intensities.

Figure 6. The ln(M) as a function of P or P_m for the 11-year variation from 1977 to 1981. The 25% spread in P_m for the Mount Washington NM and IMP 8 > 70-MeV channel is indicated by the horizontal line.

Figure 7. Same as Figure 6, but for the period from 1987 to 1991.

Figure 8. Comparison of the primary proton energy spectra from 10 to 10,000 MeV in early 1981 and 1990 at the end of the steady 11-year decrease from solar minimum activity in 1977 and 1987, calculated using the deduced modulation functions.

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We have found that there is a significant difference in the rigidity dependence of the 11-year variation of the galactic cosmic rays in the rigidity interval from 0.6 to 100 GV between the $A > 0$ modulation cycle from 1977 to 1981 and the $A < 0$ cycle from 1987 to 1990. The overall intensity decrease from 1977-1981 is found to have a rigidity dependence given by $F(P) = \exp(-1.46 \times P^{-1.22\pm0.05})$, where $F(P)$ is the modulation function and P is the rigidity [GV] and for 1987-1990 $F(P) = \exp(-1.75 \times P^{-1.02\pm0.05})$. For the conventional diffusion-convection theory of modulation the rigidity dependence of the modulation is equal to the rigidity dependence of the interplanetary diffusion coefficient. For a selected number of Forbush decreases we found that the rigidity dependence of the decreases occurring near the period of minimum solar modulation was steeper than for those occurring later in the solar cycle. In no case was the rigidity dependence of any transient decrease much different from that of the 11-year variation, however. The crossover in the 1977 and 1987 primary proton energy spectra at $E \sim 400$ MeV observed near sunspot minimum shifts to ~650 MeV at the time of the maximum solar activity or minimum cosmic ray intensity.

Table 1. Neutron Monitor and Spacecraft Data Used to Determine the 11-Year Modulation for the Periods 1977 to 1981 and 1987 to 1990

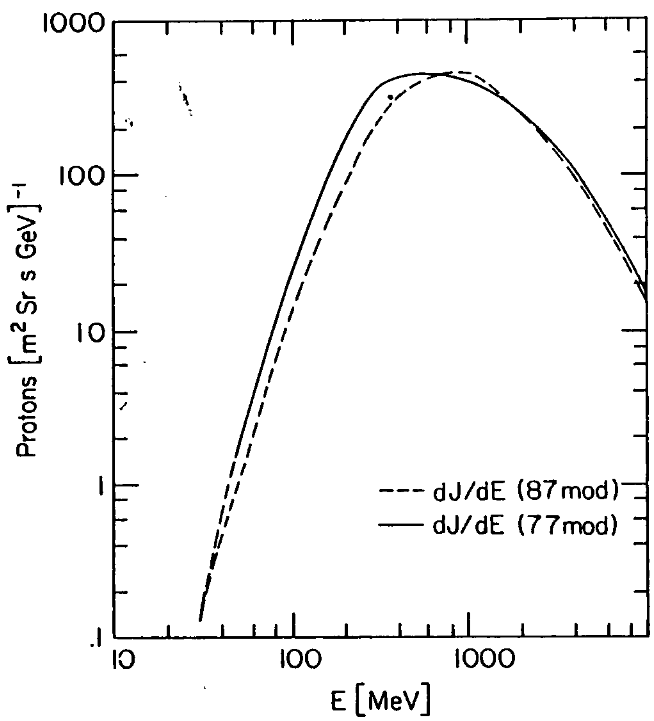
Detector	Altitude, g/cm^2	P_c GV	P_m GV 1977-1981[a]	Decrease, % 1977-1981	ln Ratio[b]	P_m GV 1987-1990	Decrease, % 1987-1990	ln Ratio[b]
Deep River NM	1030	1.0	5.6	13.2±1.0	0.146	7.5	20.6±1.5	0.230
Durham NM	1030	1.4	5.6	13.7±1.0	0.146	7.5	20.8±1.0	0.230
Mount Washington NM	840	1.25	5.4	17.0±1.5	0.186	7.0	24.5±1.0	0.280
Climax NM	680	3.3	6.4	15.6±1.0	0.170	7.3	23.9±1.2	0.250
Huancayo-Haleakala NM	680	13.5	18.5	03.45±0.5	0.037	21.5	08.2±0.6	0.086
Calgary NM	840	1.1	5.4	13.0±1.5	---	7.0	23.6±1.5	---
Moscow-Kiel NM	1030	2.45-2.3	6.3	11.9±1.5	0.127	8.0	20.5±1.5	0.243
Tokyo NM	1030	11.5	17.0	04.25±0.5	0.042	19.0	09.3±0.6	0.097
Alm Ata NM	680	6.7	10.0	12.2±2.0	---	10.3	13.9±1.5	---
Potchstrom NM	840	7.3		---	---	12.2	13.5±1.5	0.150
IMP 8 >70-MeV	---	---	1.25(2)	69.7±5.0	1.197	1.05[c]	77.0±4.5	1.50
IMP 8 130- to 220-MeV protons	---	---	0.6	92.0±6.0	2.50	0.6	90.0±6.0	2.67
IMP 8 30- to 60-MeV protons	---	---	0.295	>95.0	>3.6	0.3	>93.0	>2.7

P_c is vertical cutoff [GV]; P_m is median rigidity, and NM is neutron monitor.
[a]For the integral detectors, P_m was determined using the 1977 primary proton energy spectrum and the differential NM response functions [*Lockwood et al.*, 1991]. For IMP >70-MeV/nucleon channel, $S(P)$ was taken to be 1. For details, see text.
[b]The natural logarithm of the ratio as a function of rigidity is determined from ratio of the flux or count rate in 1977 (1987) to that at the minimum intensity in 1981 (1987) at P or P_m.
[c]In this case the 1987 primary proton energy spectrum was used.

Table 2. Rigidity Dependence of Selected Forbush Decreases During 1981-1990

Date	Decrease at Mount Washington NM, %	Rigidity Dependence δ in $F(P) = \exp(-1/P^{\delta})$
July 23, 1981[a]	9.0	0.75 ± 0.05[b]
July 12, 1982[a]	22.2	0.60 ± 0.05[b]
February 6, 1986[a]	9.1	1.1 ± 0.05
August 24, 1987	3.7	1.0 ± 0.05
March 6, 1989	16.0	0.85 ± 0.10[c]
March 18, 1990	8.8	0.75± 0.10

[a]See analysis by *Lockwood et al.* [1991].
[b]Value is independent of rigidity for $P < 2.0$ GV.
[c]Value is independent of rigidity for $P < 1.0$ GV.



1000
100
10
1
.1
Protons [m² Sr s GeV]⁻¹
10
100
1000
E [MeV]
dJ/dE (87mod)
dJ/dE (77mod)

Figure 8

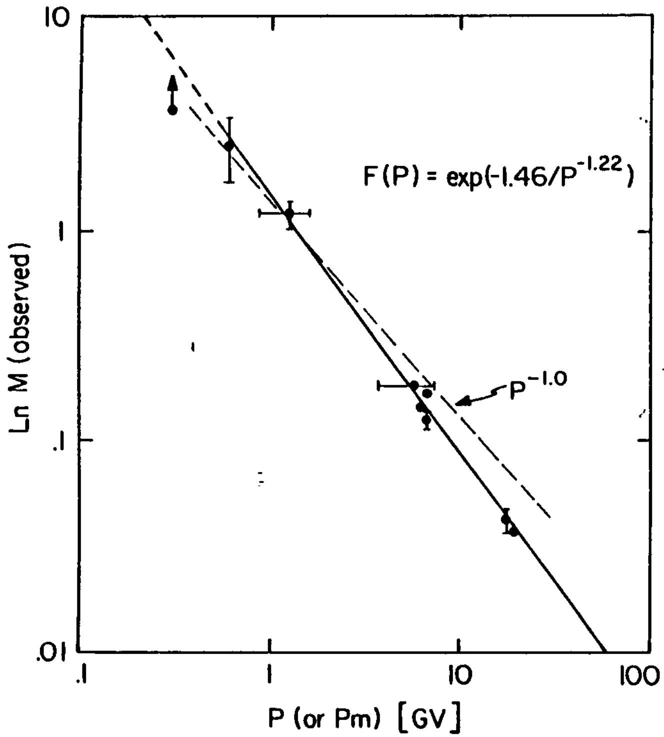


Figure 6

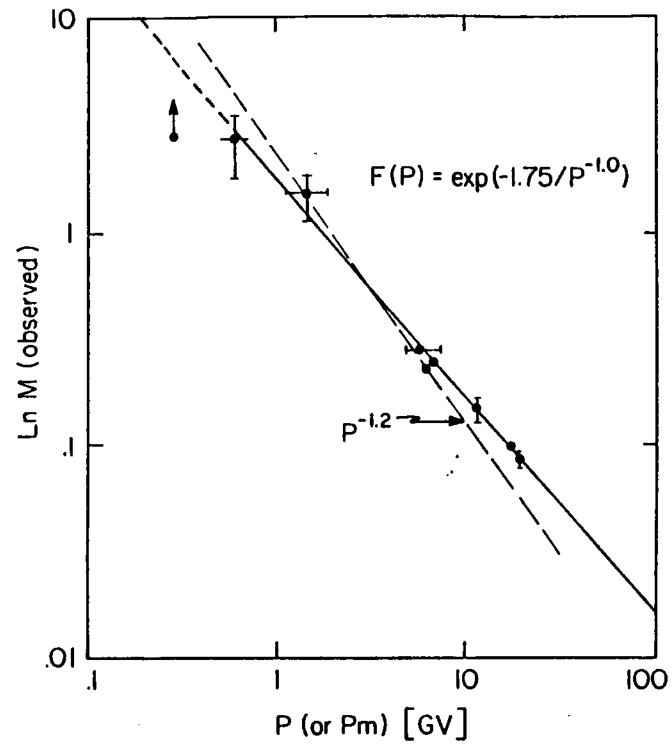


Figure 7

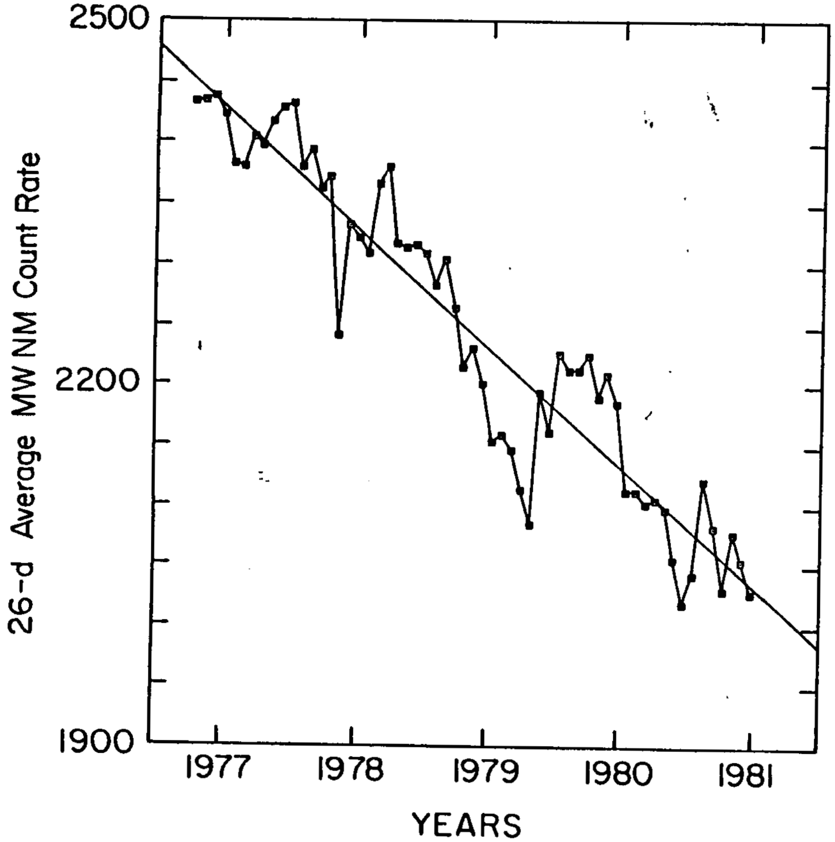


Figure 4

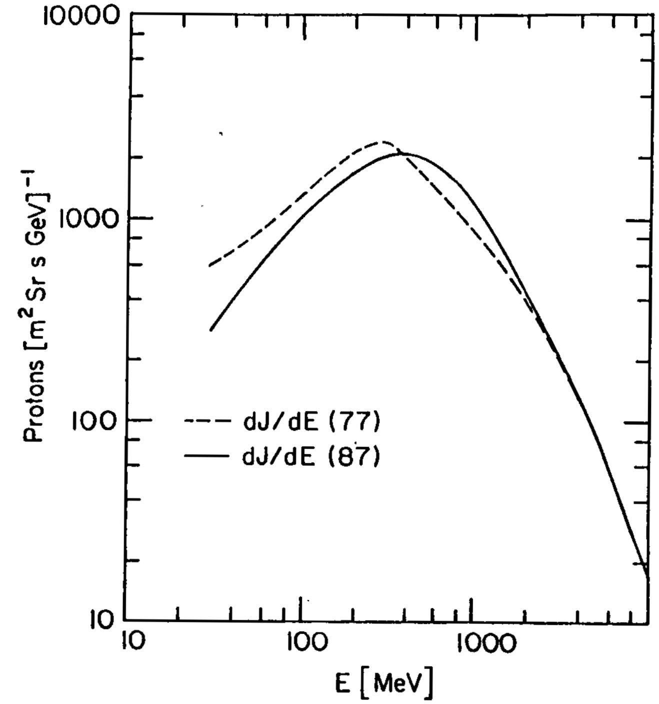


Figure 5

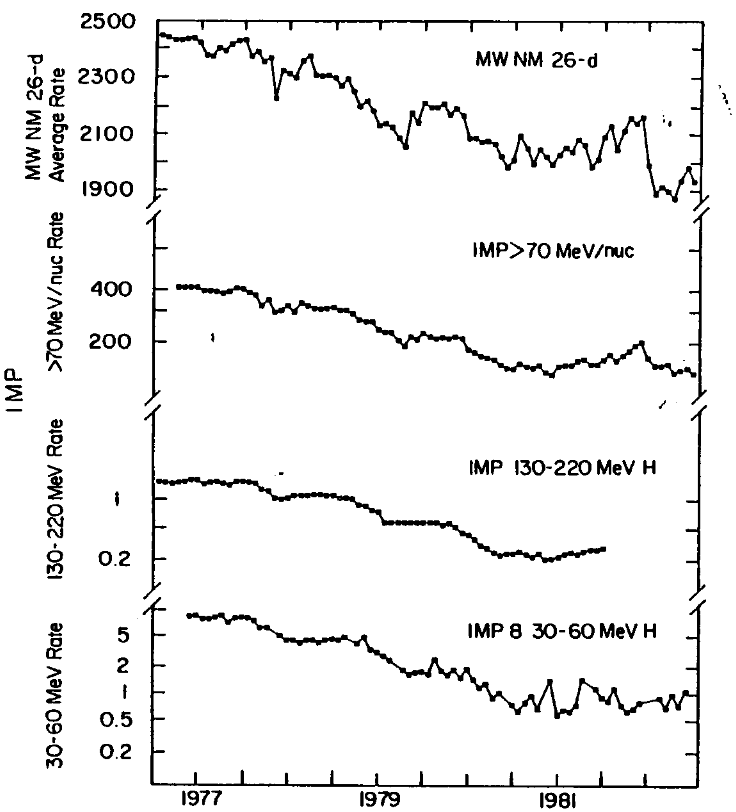


Figure 3a

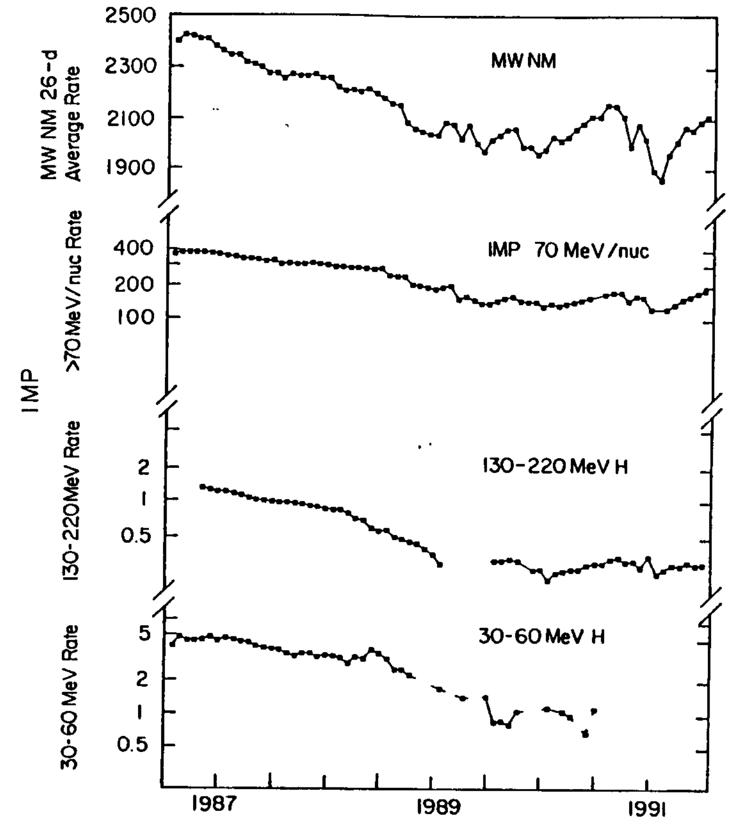


Figure 3b

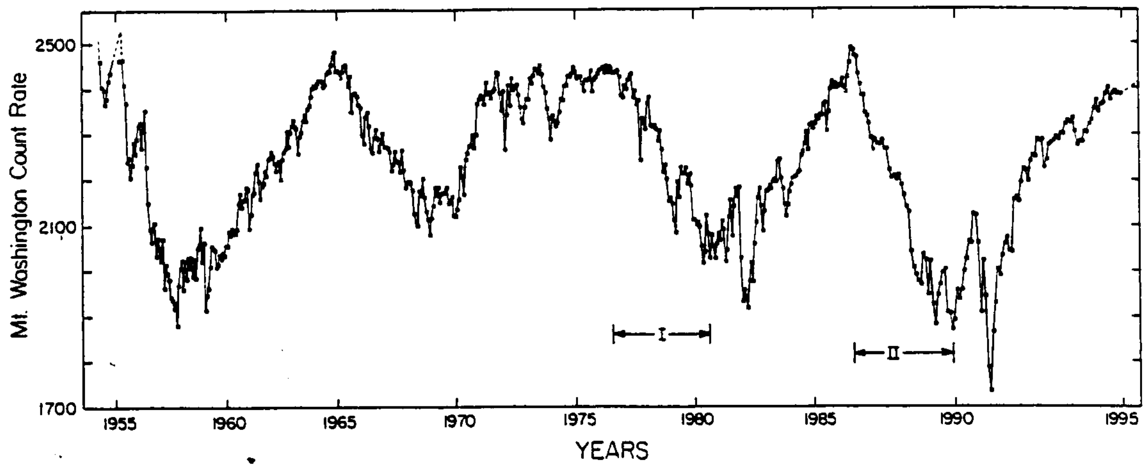


Figure 1

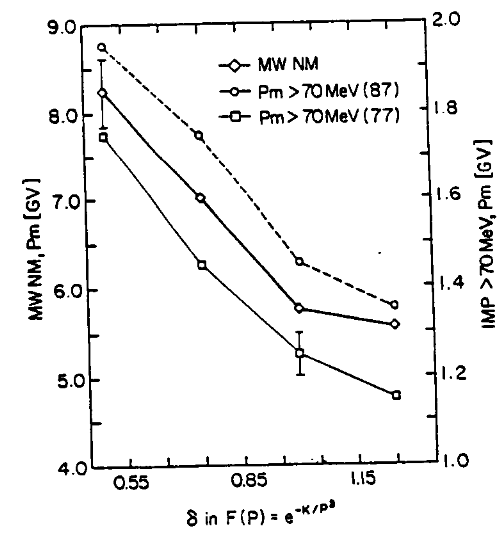


Figure 2

SECOND PIONEER-VOYAGER SYMPOSIUM ON ENERGETIC PARTICLES AND FIELDS IN THE OUTER HELIOSPHERE

UNIVERSITY OF NEW HAMPSHIRE
DURHAM NH USA

MAY 31- JUNE 3 1994

Local Arrangments

Marty Lee
Jack Lockwood
Bill Webber
Naomi Preble

Scientific Organizing Committee

L. Burlaga	A. Lazarus
A. Cummings	M. Lee
M. Forman	F. McDonald
R. Jokipii	B. McKibben
W.Kurth	E. Smith
L. Lanzerotti	W. Webber

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Naomi Preble
Space Science Center, Morse Hall
University of New Hampshire
Durham NH 03824
603-862 1061

MAY 31

EVE **<u>Welcome Reception</u>**

JUNE 1

AM **<u>Introductory Session</u>**

Opening Remarks - *(22 Years of Cosmic Ray Observations in the Outer Heliosphere).*	Webber
Status of Heliospheric Research	Fisk

<u>Heliospheric Environment</u> **(Chair: Baranov)**

Solar Wind Plasma in the Outer Heliosphere	Belcher/Lazarus

BREAK

Global and Polar Magnetic Fields	E. Smith
State of the Very Local Interstellar Medium	Lallement
Global Structure of the Heliosphere	Steinolfson/Washimi

LUNCH

PM **<u>Shocks, Propagating Structures and Heliosheath</u>** **(Chair: Suess)**

Global Structure of the Heliosheath and Heliopause	Grzedzielski/Ratkiewicz
Structure and Propagation of GMIRs	Burlaga
Shock Propagation Throughout the Heliosphere	Gosling

BREAK

Structure, Shape and Movement of the Termination Shock	Barnes
Radio Bursts and Heliospheric Structure	Gurnett/Kurth
Cosmic Rays as a Probe of Heliospheric Structure	Cummings

BANQUET

JUNE 2

AM **<u>Galactic Cosmic Rays</u>** **(Chair: Lockwood/McKibben)**

Cosmic Ray Intensity in the Local Interstellar Medium	Webber
Pioneer Observations of Cosmic Rays	Simpson
Pioneer and Voyager Observations of Cosmic Rays	McDonald

BREAK

Cosmic Ray Transients Including Forbush Decreases	Van Allen
Ulysses Observations of Cosmic Rays	Wibberenz

LUNCH

PM **<u>Cosmic Ray Transport Theory</u>** **(Chair: Forman)**

Global Modulation Theory	Moraal
Drifts and Propagating Structures	Potgieter/LeRoux
The Diffusion Tensor Throughout the Heliosphere	Ptuskin

BREAK

Modulation in the Heliosheath	Quenby/Kota/Suess
Nonlinear Theory (Waves and Shock Modification)	Zank

POSTER SESSION WITH WINE & CHEESE

JUNE 3

AM **<u>Anomalous Component and Its Origins</u>** **(Chair: Hovestadt)**

The Passage of Interstellar Gas into the Heliosphere	Fahr
Interstellar Pickup Ions	Gloeckler
Injection of Pickup Ions at the Termination Shock	Scholer

BREAK

Fractionation and the Abundances of the Anomalous Component, Pickup Ions, and the Interstellar Gas	Geiss
Voyager Observations of the Anomalous Component	Mewaldt
Acceleration and Transport of the Anomalous Component	Jokipii

LUNCH

PM **<u>Review and Discussion</u>** **(Chair: Lanzerotti)**

Termination Shock and Heliosheath	Axford/Holzer
Cosmic Ray Observations	Stone

BREAK

Transport Theory	Lee
Anomalous Component	Adams/Tyska

ADJOURN