THE COSMIC RAY INTERPLANETARY RADIAL GRADIENT FROM 1972 - 1985

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1. Introduction It is now established that the solar modulation of the cosmic-rays is produced by turbulent magnetic fields propagated outward by the solar wind. Observations show that the modulation effects themselves propagate outward from the sun with speeds of the order of the solar wind speed [1, 2, 3, 4]. Therefore, changes in the cosmic-ray intensity are not simultaneous throughout the modulation region, thus requiring time-dependent theories for the cosmic-ray modulation [e.g., 5] . Fundamental to an overall understanding of this observed time-dependent cosmic-ray modulation is the behavior of the radial intensity gradient with time and heliocentric distance over the course of a solar modulation cycle.

We have focussed our attention primarily on the period from 1977 to 1985 when data are available from the cosmic-ray telescopes on Pioneer (P) 10, Voyager (V) 1 and 2, and IMP 8 spacecraft. Additional data from P10 and other IMP satellites for 1972 to 1977 can be used to determine the gradient (G_R) at the minimum in the solar modulation cycle and as a function of heliocentric distance R. All of these telescopes have thresholds for protons and helium nuclei of E $\gtrsim$ 60 MeV/nucleon.

2. Observations In order to compare the cosmic-ray intensity at different heliocentric distances over a long time period we have calculated the 26-day average counting rates of the IMP 8, V1, V2 and P10 cosmic-ray telescopes. The normalized rates of these telescopes are shown in Fig. 1 along with the heliocentric distances of V1 and P10. There are several striking features about these normalized rates. First, the progressive separation of rates is a clear measure of a radial gradient. Second, time lags in specific decreases at the different spacecraft beginning about 1977 indicate an outward radial propagation speed for the solar modulation comparable to the solar wind speed [1,2]. Third, there is also an apparent time lag during the recovery phase seen in specific increases starting in early 1983. Fourth, the fractional decrease from late 1977 to the end of 1982 at earth and at P10 ($\sim$ 30 AU) are comparable in magnitude.

We can use the data shown in Fig. 1 to obtain the heliocentric radial gradient, keeping in mind that the gradient must be computed including the time delay noted above.

The differential radial gradient g_R is defined by:

$$g_R = 1/N\ (\partial N/\partial R) \qquad (1),$$

where N, the cosmic-ray intensity, is taken to be a separable function of R and t. Hence, N can be written:

$$N(R,t) = n_o f(R) h(t) \qquad (2),$$

where h(t) accounts for this delay time and f (R) represents the radial dependence of the quasi-stationary intensity.

Thus,
$$g_R = \frac{1}{f(R)} \frac{df}{dR} \qquad (3),$$

In general, we use spacecraft at different R to determine the gradient, with one spacecraft remaining near earth (R = 1 AU). Then,

$$\int_{R_1}^{R_2} g_R dR = \int_{f_1}^{f_2} \frac{df}{f} = \ln \frac{N(R_2)}{N(R_1)} = G_R(R_2 - R_1) \qquad (4),$$

where G_R is an integral gradient and $N(R_2)$ is taken at the time $t + (R_2-R_1)/V_{SW}$.

In Fig. 2 we have plotted G_R for P10/IMP as a function of R. There are several interesting features in this plot. First, G_R reaches a maximum around 5 AU, which is seen in all three panels of Fig. 2. Second, G_R is nearly constant as a function of both R (beyond $\sim$ 5 AU) and t between 1976-1982. During this period the cosmic-ray intensity at earth decreased in 1982 to 32% of the intensity in 1976 and the solar magnetic field reversed in 1980 with no apparent change in the gradient. Third, the decrease in G_R seen after 1982 indicates a different state in the cosmic-ray modulation in the heliospheric cavity.

<u>3. Discussion</u> There are several significant implications in the data shown in Figs. 1 and 2. We shall discuss two of them here.

a) The constancy of G_R over extended periods of time and radius as observed between 1976 and 1982 can be related to limits on the interstellar cosmic-ray intensity. Between 1976 and 1982 the normalized counting rate at earth decreased from 1.0 to 0.32, with a comparable decrease at P10 so that G_R remained essentially constant throughout this period. This behavior is indicated in Fig. 3 for six time periods of relatively constant intensity (no large transient variations propagating outward) between 1976 and 1984 as indicated by shaded areas in Fig. 1. We can use Fig. 3 to determine the fraction of total modulation beyond a given R. First, we need to estimate the residual modulation at earth at sunspot minimum [6]. We assume that the interstellar proton spectrum can be parameterized by the form dJ/dT = constant $\cdot$ $T^{0.3}(T + T_o)^{-3.0}$, where T = kinetic energy and T_o is a variable parameter between 0.3 - 0.5 GeV/nuc. This corresponds to a residual modulation parameter $\phi = 450 \pm 100$ MV at sunspot minimum [7]. We have integrated interstellar spectra for this range of T_o to determine the expected rate for T > 60 MeV/nuc as indicated on Fig. 3. Thus, for 1976 the reduction in the intensity between the heliospheric boundary and earth is calculated to be a factor of 4.3 if T_o = 0.4 GeV/nuc. In 1977 when P10 is at $\sim$ 15 AU about 60% of the modulation must occur beyond this distance. During 1981-82 about 85% of the modulation must occur beyond 30 AU. Thus, at solar minimum, and even more so at solar maximum, most of the modulation is occurring in the outer heliospere beyond 15-30 AU!

b) It appears from Fig. 2 that the conditions in the heliospheric cavity were different after 1982 since G_R in the inner heliosphere decreased from $\sim$ 2.8%/AU to $\sim$ 1.8%/AU. This is shown more clearly in Fig. 3 where it is evident that this is a temporal effect and the gradient remains relatively constant as a function of radius.

From a study of the heliocentric radial dependence of the characteristic recovery time t_o of 19 transient Forbush-type decreases occurring from 1980 to 1984 we found that t_o is about 20 times longer at 30 AU [8]. We would then expect that at R ∿ 30 AU a typical transient would take ∿ 100 days to recover to 1/e whereas near earth it is only ∿ 5 days. In a simple model then the intensity will recover first at earth as the transient decreases pass outward beyond earth and become less frequent. This more rapid recovery at earth produces a lower G_R. We would expect this situation of a smaller G_R to persist until the number and magnitude of the transient decreases are insignificant. At that time (∿ 1988) one might expect the gradient to return to its sunspot minimum value of ∿3%/AU. In 1988 when P10 will be at ∿ 45 AU we would estimate that the normalized intensity at 1 AU would be unity. If at that time G_R ∿ 3%/AU, the normalized intensity at P10 relative to earth would be ∿ 3.5, so P10 would then possibly be sampling the interstellar spectrum. However, if the gradient remains ∿ 2%/AU, P10 at 45 AU would still be well within the modulation region. An important clue as to the origin of the modulation in the distant heliosphere will be obtained from observations of this gradient between now and 1988.

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5. References

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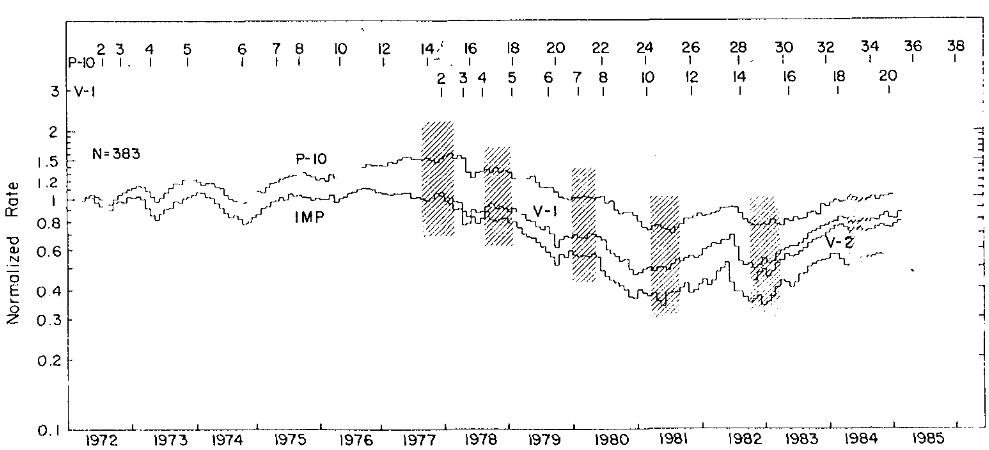

Fig 1: Normalized rates of > 60 MeV particles from IMP8, V1, V2 and P10. Heliocentric distances for V1 and P10 are shown.

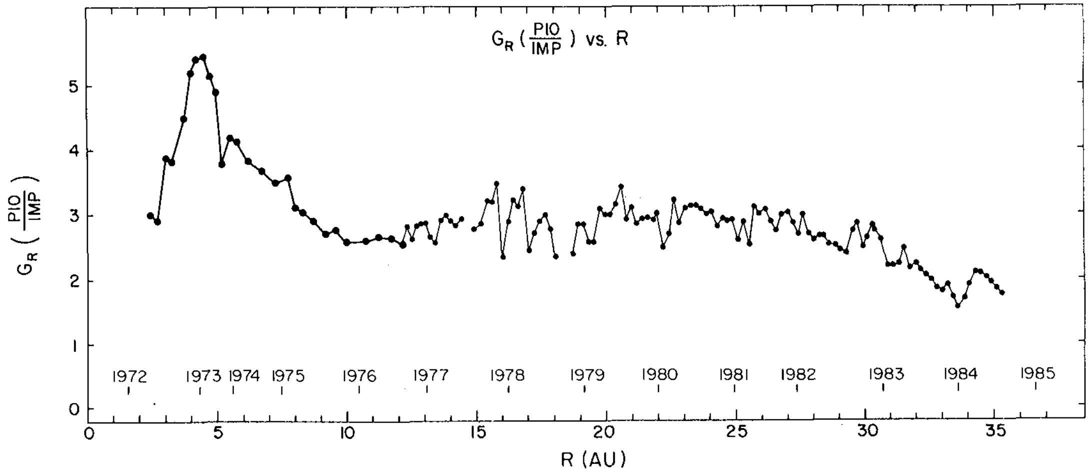

Fig. 2 G_R(%/AU) for P10/IMP8

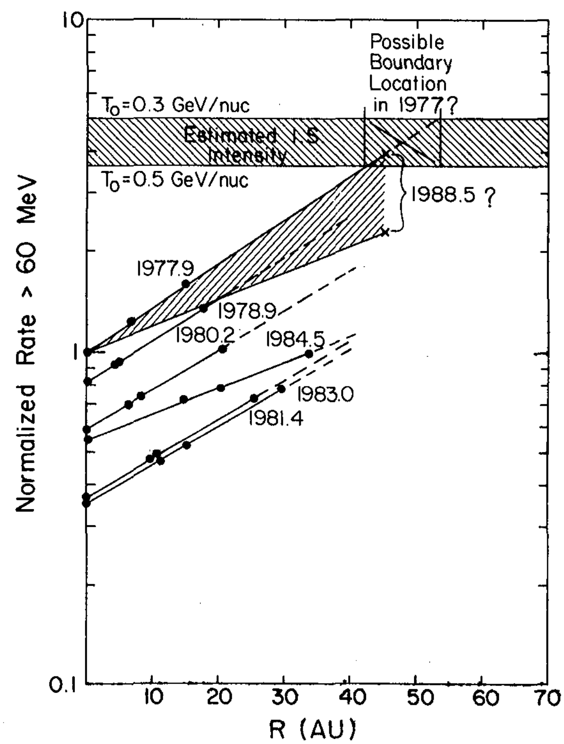

Fig 3: Radial variation of >60 MeV rate at various 26-day periods (see Fig. 1) from P10, V1, V2 and IMP8 data. Estimated interstellar rates are shown as described in text.