THE INTENSITY RECOVERY OF FORBUSH-TYPE DECREASES AS A FUNCTION OF HELIOCENTRIC DISTANCE AND ITS RELATIONSHIP TO THE 11-YEAR VARIATION

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1. Introduction. Recent observations of the cosmic-ray modulation, including particularly interplanetary radial gradient studies, have helped to identify two key questions which need to be answered in order to understand the cosmic-ray modulation process. One question is related to the importance of cosmic-ray particle drifts in both the short-term and 11-year modulation process. The other question is related to the degree to which the 11-year modulation process represents a superposition of transient (Forbush) decreases. Recent data indicating that the solar modulation effects are propagated outward in the heliospheric cavity [1,2,3,4] suggest that the 11-year cosmic-ray modulation can best be described by a dynamic time-dependent model.

In this context an understanding of the recovery characteristics of large transient Forbush-type decreases is important. This includes the typical recovery time at a fixed energy at 1 AU as well as at larger heliocentric radial distances, the energy dependence of the recovery time at 1 AU, and the dependence of the time for the intensity to decrease to the minimum in the transient decrease as a function of distance. We characterize these transient decreases by their asymmetrical decrease and recovery times, generally 1-2 days and 3-10 days respectively at ∿ 1 AU. Near earth these are referred to as Forbush decreases, associated with a shock or blast wave passage. At $R \geq 10$ AU, these transient decreases may represent the combined effects of several shock waves that have merged together.

2. Observations. About thirty transient decreases from 1972-1984 observed at 1 AU (Fig. 1) for which data were available from the IMP spacecraft (P median ∿ 1.7 GV) and the Mt. Washington neutron monitor (P median ∿ 5 GV) were analyzed to determine the characteristic recovery time t_o at earth. Certain selection criteria were applied to these decreases: a) magnitude $\geq 3\%$ as seen in daily average count rate of the Mt. Washington neutron monitor; and, b) effects of solar particles in the IMP cosmic-ray data should be small or negligible. The fractional decrease $(\Delta N/N)$ was calculated from the logarithmic difference of the daily average counting rates recorded for three days before the decrease and at the minimum. For the recovery it is assumed that $n = n_o \exp(-t/t_o)$, where $n = \ell n\, N_o - \ell n\, N$ and $n_o = \ell n\, N_o - \ell n\, N_m$. N_o is the 3-day average intensity before the event, N is the intensity on day t and N_m is the minimum intensity (for details see [5]). In all cases the recovery could be fitted well by this form.

In Fig. 2 we have plotted the characteristic recovery time, t_o, derived in the manner described above for the IMP detector versus that for the neutron monitor at Mt. Washington. Clearly the data are fitted by $t_o(\text{MW}) = t_o(\text{IMP})$ with an average ≅ 5 days which implies that the decay time in these events is on the average the same for the two instruments differing by a factor of 3 in the rigidity of their mean responses. We also observe that: 1) there is no significant difference in recovery times for events classed as Co-rotating Interaction Regions (CIR), having a more symmetrical decrease and recovery time, and the classical Forbush-type transients; 2) t_o does not depend upon the magnitude of the decrease; 3) t_o does not change significantly before and after the solar magnetic field reversal in 1980; and 4) t_o is the same in the decreasing phase of the solar cycle (before 1981-1982) and in the recovery part of the cycle.

We have investigated the heliocentric radial dependence of t_o for 19 transient decreases, of which 16 were included in the analysis of the energy dependence of t_o above, utilizing additional data from cosmic-ray telescopes ($E > 60$ MeV) on Voyagers 1 and 2, and Pioneer 10. An additional criterion imposed for this latter study is that ($\Delta N/N$) of the transient must be $\sim$ 10% as seen in the daily average count rate of the IMP detector at 1 AU. This latter criterion enables the transient events to be more clearly identified as they move outward and possibly coalesce with other decreases at $R \gtrsim 10$ AU [6]. For 13 of the 19 events examined we believe that there is little doubt about the association at various radial distances. For only one transient decrease is t_o less at larger R. In Fig. 3 we show an example of a transient decrease which has been traced from 1 AU to 21 AU. The dependence of t_o upon heliocentric radial distance for the ensemble of all 16 events is shown in Fig. 4. It is evident that on the average the magnitude of t_o becomes much longer as R increases [see 7]. The data shown is Fig. 4 can be fitted by $t_o(R)/t_o(1) = 1.26 \exp(0.090R)$, where R is the radial distance in AU.

From a comparison of the magnitude of the "same" event ($\Delta N/N$) at different R we find no strong dependence of ($\Delta N/N$) upon R. A possible reason for this behavior as opposed to a more rapid decrease in magnitude expected for a single shock is that, as suggested by [6], the transients seen at $R \gtrsim 10$ AU probably represent the coalescence of several smaller transients seen at 1 AU.

For 10 out of 19 transient decreases we also determined the time T from onset to the minimum intensity as a function of R. We find $T(R)/T(1) = 1.10 \exp(0.055R)$ where T(R) is the value at R and T(1) at earth. This means that at $R \sim 10$ AU it takes about twice as long to reach minimum. We find that from 1 to 30 AU the ratio (t_o/T) increases slowly, due to the longer recovery time at larger R. The fact that this ratio is >> 1 clearly indicates that we are observing asymmetrical transient decreases at large R, however.

3. Physical Model for the Observed Energy and Spatial Dependence of the Recovery Time. A physical model based upon a time-dependent, two-dimensional numerical solution to the cosmic-ray transport with a single shock weakening with distance has been developed by one of us (JRJ) to study these transient events [8]. The transient is represented by a disturbance propagated into the steady-state cosmic-ray distribution. The intensities at several radii and energies are studied. This model predicts that there should be only a small dependence of t_o upon energy at a given R as is observed. The variation of intensity with R depends mainly on the decay of the disturbance as it propagates through the heliosphere. For an e-folding distance of 5-7 AU for the weakening of the shock, the variation of the recovery time with energy and heliocentric radius is given in Table 1.

Table 1: Variation of Recovery Time t_o With Energy and Heliocentric Radius.

Energy [GeV]	Distance [AU]		
	1.7	3.3	5.0
1.3	5.3	7.5	9.7
3.6	5.0	7.0	8.6
9.1	4.5	5.9	7.6

These properties are in excellent qualitative agreement with the observations reported here. Precise quantitative agreement is not expected at this stage given that the model is only two-dimensional and the evolution of the disturbance is quite simple.

We conclude that for the transient decreases observed here:

1) the average recovery time t_o from transient decreases at 1 AU is energy independent and t_o is ∿ 5 days;
2) t_o is essentially the same before as after the solar magnetic field reversed in 1980;
3) t_o is constant throughout the solar modulation cycle;
4) the ratio of recovery times $t_o(R)/t_o(1)$ increases with R and is about 5 times longer at 20 AU than at 1 AU;
5) the time for the decrease to reach minimum, T, increases about 10%/AU out to 20 AU; so that at 20 AU it is ∿ 2 times longer than at 1 AU;
6) these results are well described by a two-dimensional numerical solution to the cosmic-ray transport equation which incorporates an outward moving weakening shock.

6. Acknowledgments.

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Figure Captions

Fig. 1 Mt. Washington neutron monitor monthly average count rate. Upper panel indicates transient decreases > 3% observed at Mt. Washington.

Fig. 2 t_o for IMP vs. t_o for Mt. Washington neutron monitor.

Fig. 3 Count rate of IMP8, V1,V2, and P10 for transient decrease on July 12, 1982.

Fig. 4 Ratio $t_o(R)/t_o(R = 1)$ vs. radial distance R.

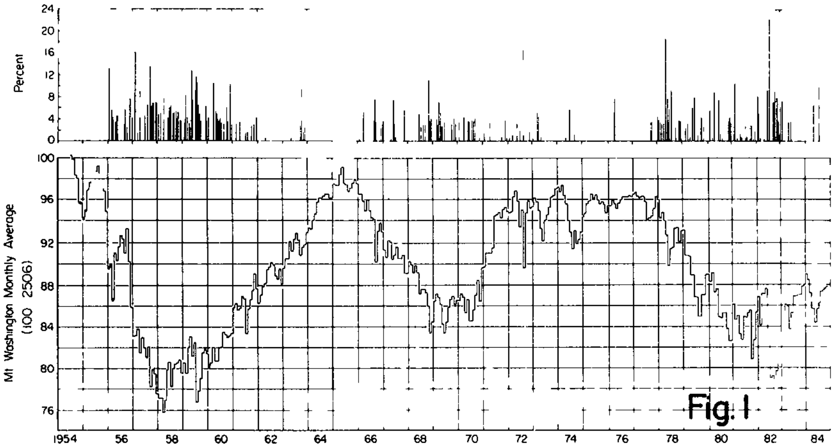

Fig. 1

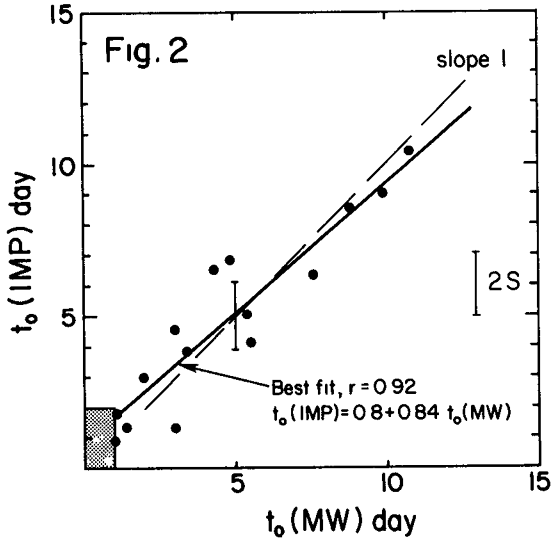

Fig. 2

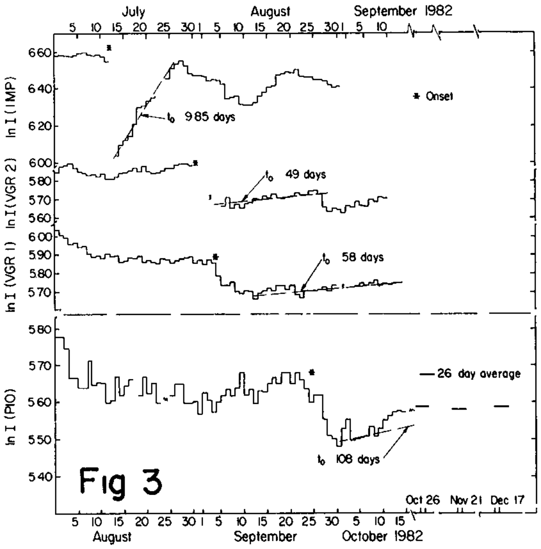

Fig 3

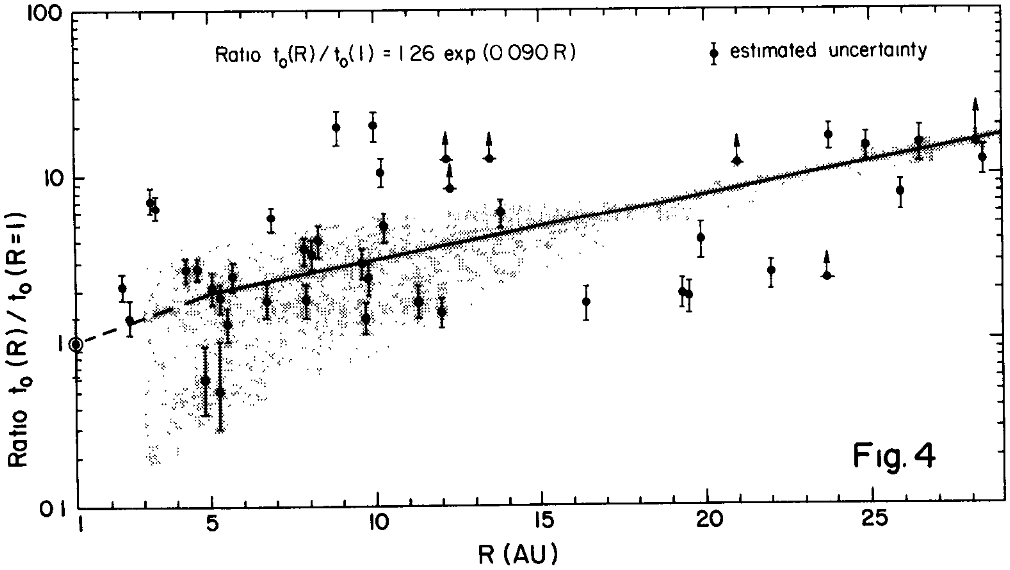

Fig. 4