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

Lockwood, J. A. and W. R. Webber
Space Science Center, University of New Hampshire
Durham, New Hampshire 03824 USA

Jokipii, J. R.
Department of Planetary Sciences, University of Arizona
Tucson, Arizona 95721 USA

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 $\sim$ 1 AU. Near earth these are referred to as Forbush decreases, associated with a shock or blast wave passage. At R $\gtrsim$ 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 $\sim$ 1.7 GV) and the Mt. Washington neutron monitor (P median $\sim$ 5 GV) were analyzed to determine the characteristic recovery time t_o at earth. Certain selection criteria were applied to these decreases: a) magnitude $\gtrsim$ 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 $n = \ln N_o - \ln N$ and $n_o = \ln N_o - \ln N_m$. 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(MW) = t_o(IMP) with an average $\cong$ 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 $\gtrsim$ 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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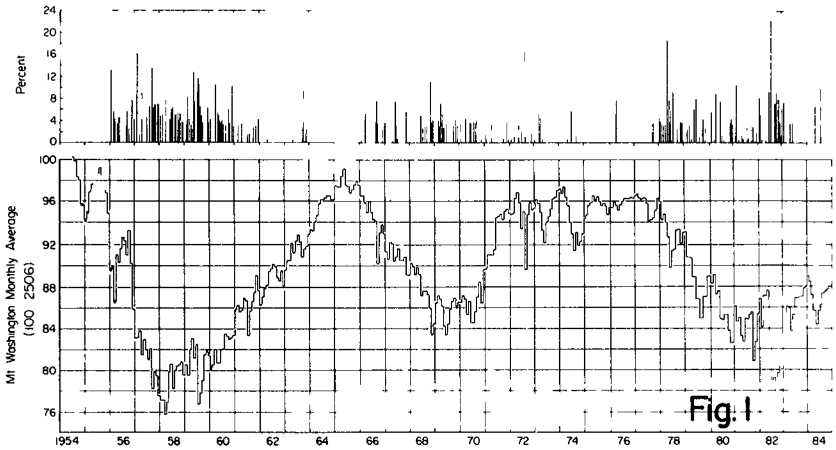
Figure Captions

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.


Percent
Mt Washington Monthly Average
(100 2506)
Fig. 1

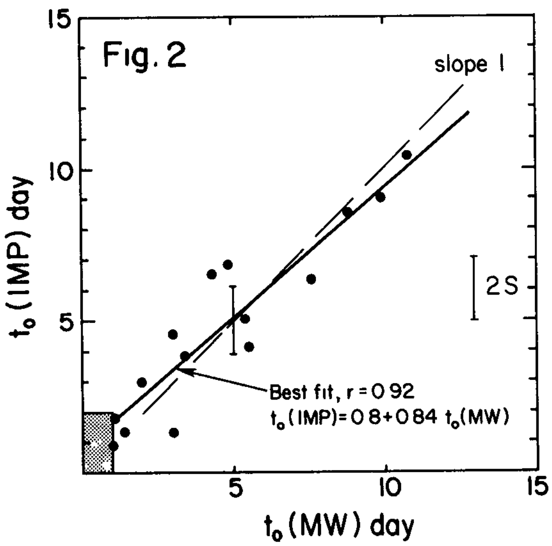
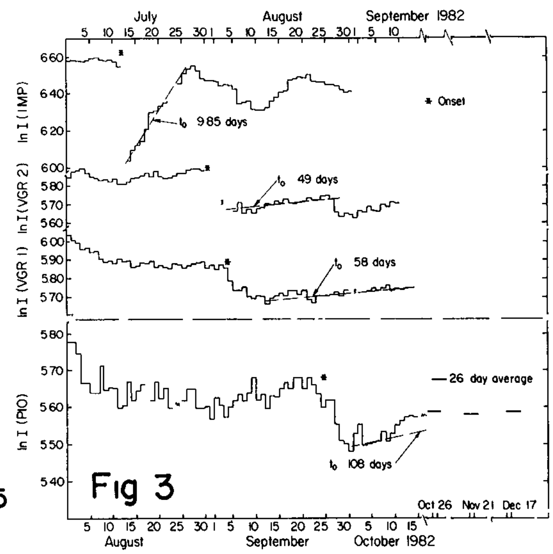
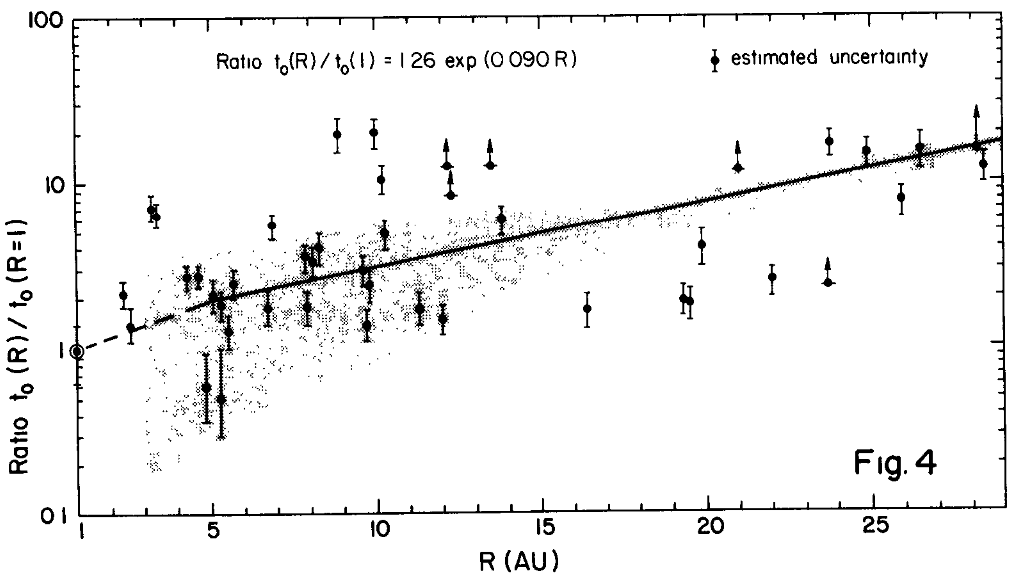


Fig. 2
slope 1
2S
Best fit, r = 0.92
t_o (IMP) = 0.8 + 0.84 t_o (MW)
t_o (IMP) day
t_o (MW) day


July
August
September 1982
* Onset
t_o 9.85 days
t_o 49 days
t_o 58 days
26 day average
t_o 108 days
ln I (IMP)
ln I (VGR 2)
ln I (VGR 1)
ln I (PIO)
Fig 3
Oct 26 Nov 21 Dec 17
August
September
October 1982


Ratio $t_o(R) / t_o(1)$ = 1.26 exp (0.090 R)
estimated uncertainty
Ratio $t_o(R) / t_o(R=1)$
R (AU)
Fig. 4