THE LARGE-SCALE MODULATION OF COSMIC RAYS IN MID-1982: ITS DEPENDENCE ON HELIOSPHERIC LONGITUDE AND RADIUS.

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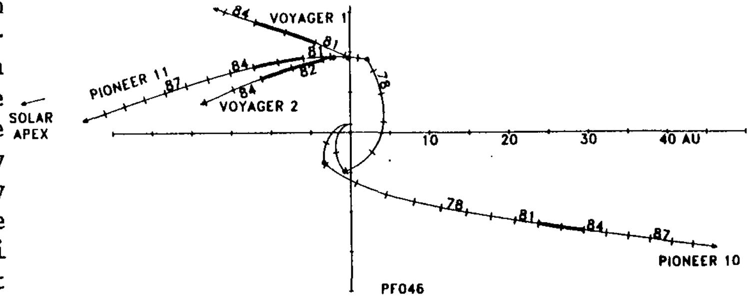
ABSTRACT. Near solar maximum, a series of large radial solar wind shocks in June and July 1982 provided a unique opportunity to study the solar modulation of galactic cosmic rays with an array of spacecraft widely separated both in heliocentric radius and longitude. By eliminating hysteresis effects we can begin to separate radial and azimuthal effects in the outer heliosphere. We have been able to show that, on the large scale, changes in modulation (both the increasing and recovery phases) propagate outwards at close to the solar wind velocity, except for the near-term effects of solar wind shocks, which may propagate at a significantly higher velocity. We show that, in the outer heliosphere, azimuthal effects are small in comparison with radial effects for large-scale modulation at solar maximum.

INTRODUCTION. The radially-propagating shock events of mid-1982 provide an exceptional opportunity to examine the dynamic response of the heliosphere to a large, sudden increase in modulation and to study the modulation onset and recovery mechanism as a function of magnetic rigidity and heliospheric radius and longitude. This large series of solar events has been studied intensively over the past several years, both in its modulation effects (e.g. Lockwood and Webber, 1984) and in the shock acceleration of energetic charged nucleons and electrons as far as 28 AU from the sun (Pyle et al. 1984). Observations from a variety of instruments aboard the Pioneer and Voyager spacecraft demonstrate that modulation increases propagate outwards at approximately the solar wind velocity (Pyle et al. 1979; Lockwood and Webber, 1984; McDonald et al. 1981). Fillius and Axford (1985) have reported an outward propagation of recovery from modulation in the 11-year solar cycle, based on a comparison of neutron monitor intensity at 1 AU with Pioneer relativistic cosmic ray measurements. The outward progression of recovery could be due to off-ecliptic fluxes or, as in the model of Perko and Fisk (1983), due to the longer intervals between shocks during the declining phase of solar activity. In a companion paper at this Conference (McKibben et al. 1985) we also discuss the large-scale propagation of solar modulation, showing that both modulation increases and decreases propagate outwards.

In this paper we examine the 1982 large-scale modulation event and its recovery, using a counting rate responding to CNO-Fe nuclei in the approximate energy range 200-1000 MeV/n, measured by identical instruments on Pioneers 10 and 11. We show that for both the onset and recovery of this large modulation event the dominant effect is one of outward propagation at approximately the solar wind velocity, and is relatively independent of heliospheric longitude.

INSTRUMENTATION AND TRAJECTORY. It is well-established that during relatively rapid changes in modulation there is a hysteresis effect whose magnitude is dependent on magnetic rigidity (Simpson 1963; Cooper and

Simpson 1979). Therefore, to eliminate this rigidity-dependent effect, we have used the F2 counting rate from the two identical Fission Cells developed to measure the intense fluxes of protons during the Pioneer 10 and 11 encounters with Jupiter, and later, Pioneer 11 with Saturn. In interplanetary space these counting rates are sensitive to a variety of galactic cosmic ray species, (H-He 1%, C-Ne 14%, Na-V 28%, and Cr-Ni 56%) (see Simpson et al., 1974 and especially McKibben,1983 for a detailed discussion of the Fission Cell response). The energy interval for response is ~200-1000 MeV/n (~1-3 GV rigidity). These counting rates provide relatively good statistics and permit a fairly precise measure of modulation changes. The overall elemental response is expected to be insensitive to any long-term instrumental drifts.

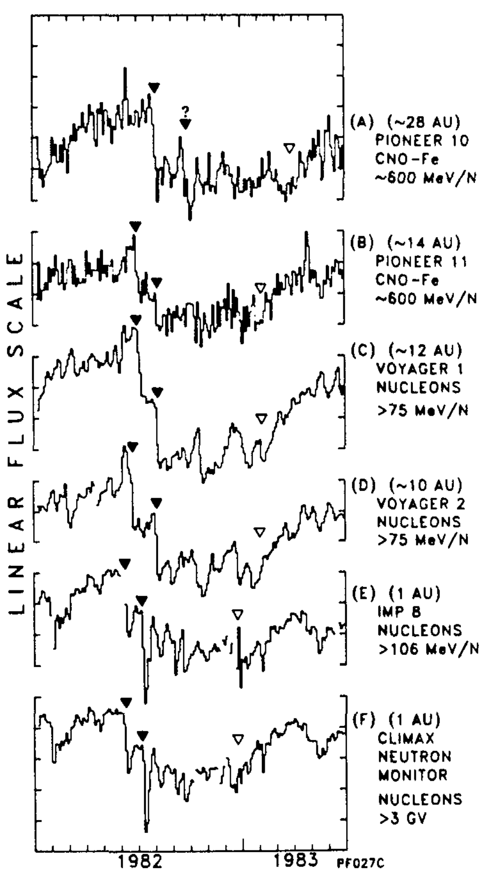


--- FIGURE 1 ---

For comparison we have used the Voyager 1 and 2 counting rates for nucleons >75 MeV (Stone et al., 1977), kindly made available by the Voyager CRS experimenters.

In Figure 1 we have plotted the trajectories of Pioneers 10/11 and Voyagers 1/2, projected onto the ecliptic plane. Pioneer 10, alone among the 4 spacecraft, is moving away from the solar apex, in the direction of the heliospheric tail. The time interval studied here, 1982-3, is indicated by the heavy lines along the trajectories.

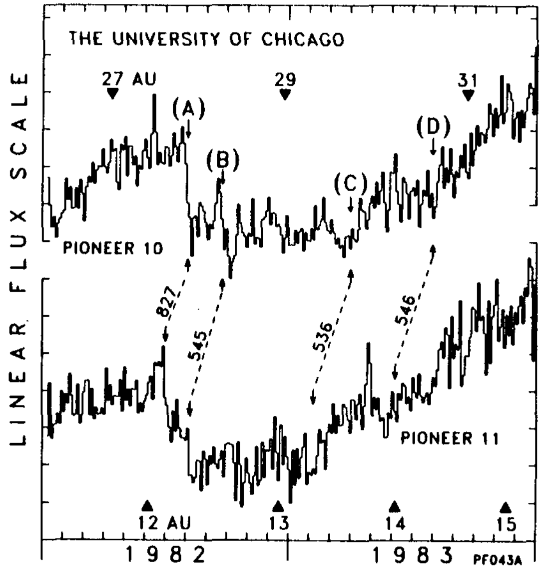
<u>OBSERVATIONS.</u> In Figure 2 we have plotted 3-day averages of counting rates, showing the behavior of the event at various radii and longitudes in the heliosphere. The two large Forbush decreases seen at 1 AU in mid-1982 (Fig. 1 E,F) are the result of intense solar activity early in June and early in July, 1982. The first of these is apparently caused by the large solar wind shock associated with a flare occurring on 3 June, on the back side of the sun as seen from the earth (Pyle et al. 1984). The longitude of this flare placed it almost directly "under" Pioneer 10. The second decrease (in July), originated with a large solar flare event visible from Earth. In the Figure we have indicated (filled triangles) the outward progression of the modulation. The outward propagation of the recovery is indicated by the open



--- FIGURE 2 ---

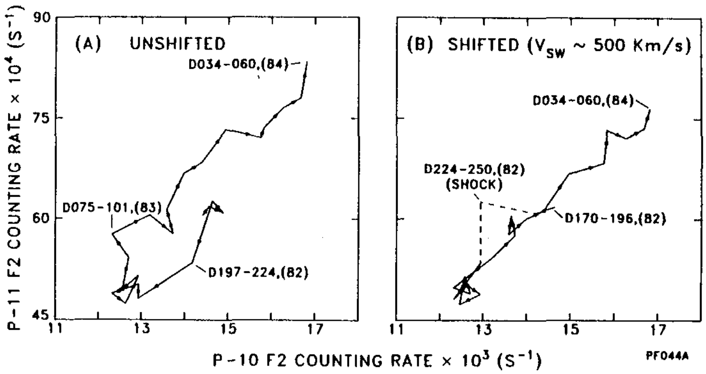
triangles. At 1 AU the two intensity decreases are distinct in time and superimposed on a general downward trend of flux (Fig. 1E,F). The two decreases are similarly resolvable at 10-14 AU (Fig. 1B,C,D). However, at Pioneer 10 (Fig. 1A) the modulation increased over a ten-day period, and remained more or less constant for a six-month period before a relatively sharp onset of recovery (open triangle). At Pioneer 10 the second shock has no significant effect on the overall intensity level (filled triangle with "?").

It is clear from Figure 2 that <u>both</u> the initial Forbush decreases as well as the subsequent rise from the depressed flux levels (open triangles) propagate outwards. Calculation of an accurate value for the radial velocity of the <u>increase</u>, based on this Figure, is difficult owing to the possibility of hysteresis between many of the counting rates shown. To accurately determine the outward velocities we have isolated the two identical CNO-Fe 3-day averaged counting rates from Pioneer 10 and Pioneer 11, between which there are no significant energy hysteresis effects, and plotted them on an expanded scale in Figure 3. The dashed arrows indicate the time shifts necessary to best align the four intensity changes labelled A-D. The triangles show the distance of the two spacecraft from the sun. The initial modulation increase (event (A)) is nearly azimuthally symmetric: we find that the modulation increase propagates outward with approximately the same velocity towards Pioneer 11 and Pioneer 10. However, event (B)'s transit velocity from Earth to Pioneer-11 is approximately 700 Km/sec, but from Pioneer 11 to Pioneer 10 only 545 Km/sec, indicating either a) a large deceleration or b) a significantly higher velocity towards Pioneer 11 (700 Km/sec) than towards Pioneer 10 (600 Km/sec earth-Pioneer 10).



--- FIGURE 3 ---

Events (C) and (D) are intensity recoveries where the propagation velocities are near the solar wind velocity, indicating a very small, if any, azimuthal dependence. Near each dashed line in Figure 3 we have indicated the calculated propagation velocity for the feature, <u>assuming azimuthal symmetry</u>. In Figure 4 the Bartels solar rotation averages of the CNO-Fe counting rates for Pioneer 10 and 11 are plotted against each other. In panel (A) the data, covering mid-1982 to mid-1983, are plotted with no time-shifting; in panel (B)



--- FIGURE 4 ---

the Pioneer-11 data have been shifted two solar rotations, equivalent to a solar wind velocity of ~500 Km/sec. This time-shift has placed all of the data points on the same regression line except the one corresponding to the large modulation increase associated with the high-velocity, radial shock. Thus, the assumptions of a) azimuthal symmetry and b) outward propagation at near the solar wind velocity result in a near-perfect alignment of the data at the two spacecraft, differing by ~16 AU in heliospheric radius and by nearly 180 degrees in longitude.

SUMMARY AND CONCLUSIONS. In order to determine the outward velocity of the onset and recovery from modulation of galactic cosmic rays in the heliosphere it is essential to eliminate all magnetic rigidity dependent effects so that rigidity-dependent hysteresis in the heliosphere does not lead to erroneous conclusions.

We have, therefore, selected sets of nucleon-intensity data whose magnetic rigidity ranges are close to each other. The solar-flare generated series of radially-propagating shocks which passed outward through the heliosphere in 1982 provide a unique test of the dynamical processes resulting in large-scale heliospheric modulation.

We have shown that major increases and decreases in solar modulation are primarily radially dependent and not strongly azimuthally dependent.

Not only is the increase in solar modulation an outward propagating effect, as has been shown earlier (e.g. Lockwood and Webber, 1984; Fillius and Axford, 1985) but the recovery from the 1982-3 enhanced modulation period also propagates outward at the approximate solar wind velocity.

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