THE RECOVERY OF THE COSMIC RAY FLUX FROM MAXIMUM SOLAR MODULATION AT IMP-8 (1 AU) AND AT PIONEER 10 (R > 30 AU)

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ABSTRACT: In the period 1980-84, observations of relativistic and low energy ($30 \lesssim E \lesssim 70$ MeV/n) cosmic ray nuclei from Pioneer 10 in the outer heliosphere and from IMP-8 at 1 AU show that increases as well as decreases in intensity propagate outward at velocities equal to or greater than the average solar wind velocity.

INTRODUCTION: In the period of increasing and maximum solar modulation (1977-81), observations of the galactic cosmic ray intensity from Pioneer 10/11 and Voyager 1/2 have shown that intensity decreases propagate outward at near the average solar wind velocity (e.g. Lockwood and Webber, 1984; McDonald et al., 1981; McKibben et al., 1982, 1985a; Van Allen and Randall, 1985; Venkatesan et al., 1985). Since 1981, solar activity has been decreasing, and following a prolonged depression caused by a series of large interplanetary shocks in 1982, (Lockwood and Webber, 1984; Pyle and Simpson, 1985), the cosmic ray flux has been increasing towards solar minimum levels. Therefore, it is now possible to determine whether intensity increases propagate outward in the same manner as decreases. In earlier work dealing with relativistic cosmic rays, Van Allen (1979) has reported that the recovery from an isolated Forbush decrease was more rapid near 1 AU than in the outer heliosphere, and Fillius and Axford (1985) have reported that recovery from maximum solar modulation began earlier at 1 AU than in the outer heliosphere.

In this paper we use observations from University of Chicago instruments on Pioneer 10 and on IMP 8 (described respectively by Simpson et al. (1980) and Garcia-Munoz et al. (1977)) to investigate the radial propagation of the recovery for both relativistic cosmic rays and for low energy galactic protons and helium in the energy range $30 < E < 70$ MeV/n.

In comparing observations at 1 AU and at Pioneer 10, we have been careful to use well matched energy intervals from the two spacecraft. Under conditions of changing modulation, even at one location significant delays between changes in intensity for particles of different energies arise from energy dependent hysteresis effects (e.g. Cooper and Simpson, 1979). Thus, use of poorly matched energy intervals may lead to confusion between phase shifts caused by radial propagation and shifts arising from the energy dependent hysteresis.

RADIAL DEPENDENCE OF THE RECOVERY: In Figure 1A, we compare simultaneous 27 day gradient-corrected averages of the integral intensity of cosmic rays above 67 MeV from Pioneer 10 and above 106 MeV from IMP 8 in the period 1980-84. These counting rates are dominated by relativistic cosmic rays with a mean energy of ~ 2 GeV. During the period shown, Pioneer 10 moved outward from ~ 20 to ~ 34 AU from the sun. As a result of this motion, and of the measured radial gradient of 2.5 %/AU for the relativistic particles (McKibben et al. 1985b), increases in intensity in uncorrected data from Pioneer 10 are caused partly by Pioneer 10's outward motion, and partly by the decreasing level of solar

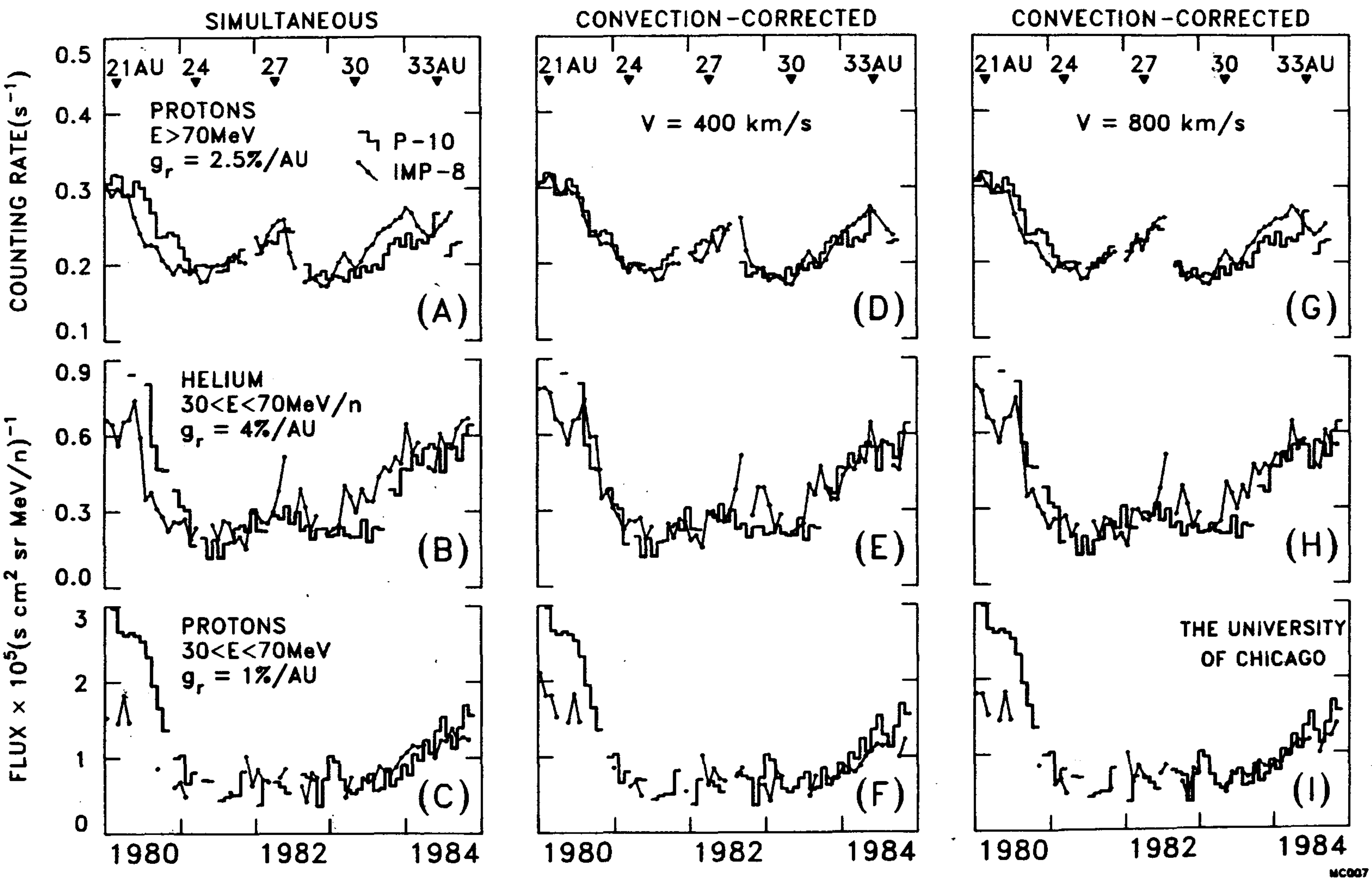

FIGURE 1

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modulation. To reduce the effects of the radial motion, we have extrapolated the intensity measured at Pioneer 10 back to 1 AU assuming a gradient of 2.5 %/AU. Thus, in Figure 1A we have plotted I(1) = I(R)exp(-0.025(R-1)) where I(R) is the counting rate measured by Pioneer 10 at radius R AU.

Figure 1A shows that during periods of increasing modulation (1980, 1982), intensity changes occur later at Pioneer 10 than at IMP 8. During the period of decreasing modulation in 1981, there is no clear delay between the recovery at 1 AU and at Pioneer 10, although the data suggest that the intensity increase began earlier at IMP 8 than at Pioneer 10. In 1983-84, on the other hand, the recovery from the effects of the 1982 shocks clearly began first at 1 AU, as reported by Fillius and Axford (1985) and Pyle and Simpson (1985). In Figure 1D, we show the same data, but with the IMP measurement shifted in time by an amount $\Delta t = (R-1)/V$, where V is taken to be 400 km/s, and Δt is taken to be the nearest integral multiple of 27 days. Over the period shown, Δt increases from 81 to 135 days. Compensating for propagation in this way greatly improves the agreement of the intensity profiles at the two spacecraft. The main exceptions are 1) the period of decreasing modulation in 1981-82, where agreement is better using simultaneous observations than shifted observations, and 2) the period in 1982 immediately following passage of the shocks, which propagated more rapidly than 400 km/s.

Figure 1(B, E) shows the same analysis for 30-70 Mev/n helium, assuming a constant gradient of 4 %/AU. As reported by McKibben et al. (1985b), the radial gradient was larger before the middle of 1980, so that the gradient correction is inadequate for the earlier data. After 1980, however, the gradient was nearly constant at ~ 4 %/AU, and agreement between the intensity profiles for low energy helium at 1 AU and at Pioneer 10 is improved by assuming that all changes in modulation, both increases and decreases, propagate outward with a velocity of about 400 km/s. However, in 1982, there is a large increase in the helium flux at 1 AU that has no analogue at Pioneer 10.

Similar analysis for 30-70 MeV protons is shown in Figure 1(C, F), for a gradient of 1 %/AU. This value of the radial gradient was observed only from mid-1980 until late 1983, after which the gradient began a gradual increase (McKibben et al., 1985b). Therefore, since we have used a constant gradient of 1 %/AU to correct the Pioneer data to 1 AU, comparison between the gradient-corrected intensity profiles is meaningful only from mid-1980 to late 1983. In this period the low energy proton flux was nearly constant, and no conclusions can be drawn.

DISCUSSION: The observations may be summarized as follows. In the recovery from the modulation produced by the shocks in 1982, the intensity increase occurred first at 1 AU and propagated outward with a velocity near 400 km/s both for relativistic cosmic rays and for low energy (30-70 MeV/n) helium. In 1981-82, however, when the modulation was not dominated by any single event, the recovery was more nearly simultaneous at 1 AU and at Pioneer 10.

In considering the propagation of changes in modulation in the heliosphere, Forman and Jones (1985) have pointed out that for models in which the modulation at any point is produced by numerous scattering centers convected outward by the solar wind and distributed along the radial path of a particle inward from a fixed boundary of the modulation region, the recovery from maximum modulation should begin first in the inner heliosphere. Their arguments show that individual features propagate outward at the solar wind velocity but that the overall pattern propagates twice as fast. These conclusions are also implicit in the work of Perko and Fisk (1983). Figure 1(G-I) repeats the analysis of Figure 1(D-F) using a convection velocity of 800 km/s. In 1981-82, when modulation was most likely produced by many disturbances between 1 AU and the boundary, assuming a velocity of 800 km/s significantly improves the agreement between profiles for the relativistic particles at 1 AU and at Pioneer 10. In 1982-84, however, when modulation was dominated by a single event, the data are better organized by a velocity of 400 km/s. The accuracy of the measurements does not allow similar conclusions to be drawn for lower energy particles. For 30-70 MeV protons, agreement is improved in 1983-84 for a velocity of 800 km/s, but, as noted above, changes in the gradient after 1983 make such a conclusion questionable.

An alternative model for explaining outward propagation of the recovery involves 3-dimensional propagation of particles in the heliosphere, leading to the filling in of the inner heliosphere from regions off the ecliptic plane (e.g., Van Allen, 1979). In this model, the radial gradient in the ecliptic could become negative, whereas a negative radial gradient would be inconsistent with the model of Forman and Jones. We find, however, that radial gradients were positive at all times (McKibben et al., 1985b, cf. also Fillius and Axford, 1985).

Our observations of the outward propagation of the recovery from maximum solar modulation are consistent with either the model of Forman and Jones (1985), or with propagation from regions off the ecliptic plane to the inner heliosphere. A definitive observational test to discriminate between the two models must await further explorations by spacecraft off the ecliptic plane.

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