THE LARGE SCALE DYNAMICS OF THE OUTER HELIOSPHERE AND THE LONG-TERM MODULATION OF GALACTIC COSMIC RAYS

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ABSTRACT

The network of cosmic-ray observatories reaching across the heliosphere has given new insight into the process of solar modulation, establishing that the decreases occur principally in the outer heliosphere and are produced by interplanetary flow systems; that the hysteresis effects appear to be produced by changes in the rigidity dependence of the diffusion coefficient and that the predicted effects on the cosmic ray gradients associated with the reversal of the solar magnetic field polarity are not observed.

1. Introduction. The study of cosmic ray modulation has traditionally been of importance in determining the local interstellar spectra of galactic cosmic rays and their transport in the heliosphere. The presence of a network of cosmic ray detectors at various heliocentric distances not only offers new insight into these areas but also offers a means of studying the dynamics of the interplanetary medium in the outer heliosphere. Pioneer 10 cosmic ray measurements now cover the period from 1972 to the present and extend to heliocentric distances beyond 32 AU (Fig. 1). Voyagers 1 and 2, launched in 1977, provide observations at intermediate heliocentric distances while Helios 1 and ISEE-3 provide "baseline" measurements at 1 AU. The data from the Goddard cosmic ray experiments (done in collaboration with the California Institute of Technology and the University of New Hampshire on Voyagers 1 and 2 and with the University of New Hampshire on Pioneers 10 and 11) on these missions give detailed differential energy spectra for galactic cosmic ray helium nuclei from 3-500 MeV/nuc and for hydroden nuclei from 3-250 MeV. The detector systems used on these various missions are similar in their method of operation but differ in detail and in their relative geometric factors. In this paper a summary overview is given of these observations along with differential measurements of the cosmic ray gradient over the last solar cycle.

2. Observations. Intensities of the higher energy He (∿185-450 MeV/nuc) and H (∿130-240 MeV) along with the integral measurements >70 MeV are shown in Fig. 2 in the form of 26 day averages. Lower energy data for 30-56 MeV/nuc H and He and the 10-21 MeV/nuc anomalous He interval are shown in Fig. 3 for Pioneer 10 and Voyager. The 1 AU data has not been included in this later plot because of the difficulty in removing the solar energetic particle contribution at low energies.

As noted previously (McDonald et al., 1981; Lockwood and Webber, 1984; McKibben et al.,1982; Van Allen and Randall, 1985) the long term decrease occurs in a series of three distinct steps between April 1978 and January 1981. These decreases propagate radially outward with a velocity of 400-500 km/sec. There is a recovery period starting in early 1981 which is interrupted by the onset of increased solar activity in 1982 which results in a fourth step decrease. In early 1981 at ~24 AU and in late 1982 at 28 AU the galactic cosmic ray intensities at energies less than 500 MeV/nuc were distinctly lower than their 1 AU solar minimum values - suggesting that the bulk of the modulation must occur in the distant heliosphere.

The recovery is more complex and will have to be examined over a larger period of time to establish a pattern. One distinctive feature is a hysteresis effect as seen from the lag in the recovery of 10-21 MeV/nuc He and 30-56 MeV H (Fig. 3) as compared to the substantial recovery of the 185-450 MeV/nuc He (Fig. 2). If a clear rigidity

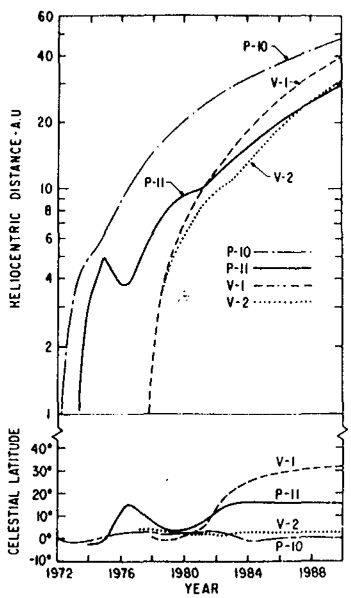

Fig. 1

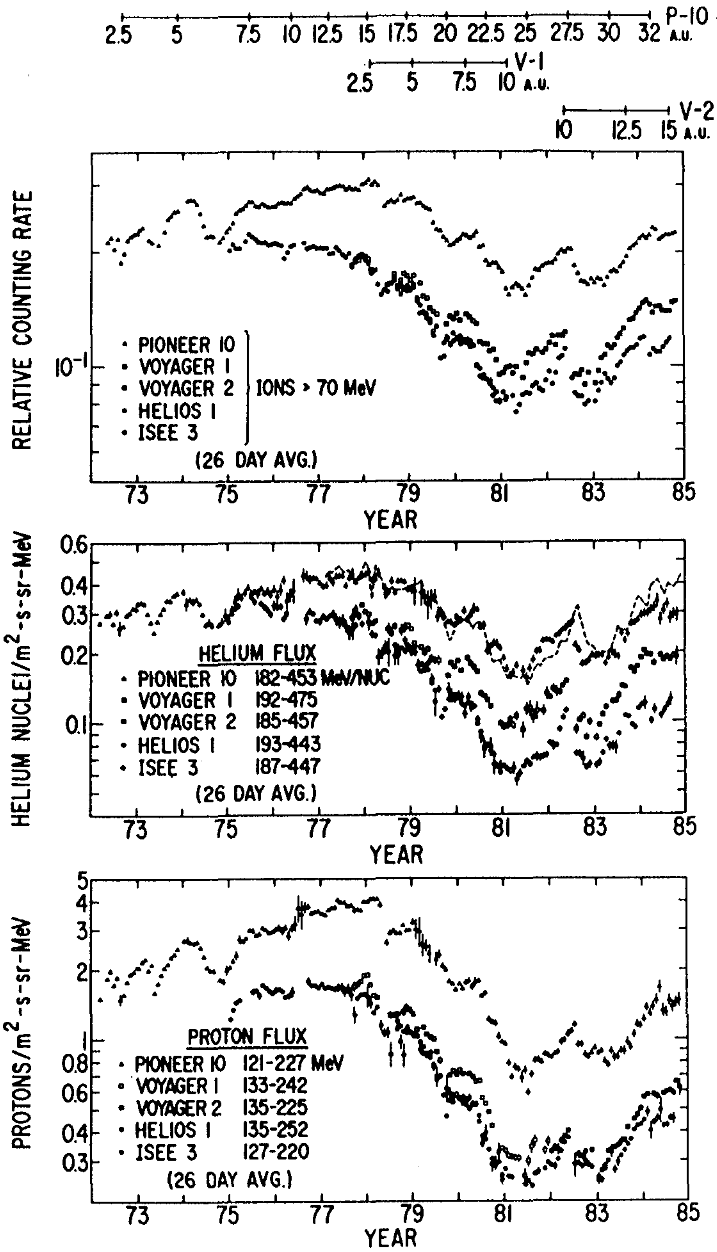

Fig. 2. The dashed line in the center panel is the extrapolation of the Helios/ISEE-3 data to the orbit of Pioneer 10 assuming a constant 4% AU gradient and a solar wind velocity of 550 km/sec.

dependence can be established for this effect it may offer a method of determining the charge state of the anomalous component (McKibben, 1973; Paizis and von Rosenvinge, 1981). It is also seen that the decreases propagate rapidly outward for the first three steps, this concept breaks down after ∿ 1982. This breakdown probably reflects large heliolongitude asymmetries resulting from a few very strong shocks.

Measurements of the differential gradient are shown for the solar minimum period (3/77, 12/77) and the plateau regions between the step decreases (Fig4). At solar minimum (3/77) the gradients in the inner solar system are substantially higher than those in the outer heliosphere. With the onset of increased solar activity, they show a complex change. For the high energy He (150-380 MeV/nuc), the gradient approaches a value of ∿4%/AU for both sets of measurements. A similar pattern is observed for 30-56 MeV/nuc H and He and in the outer heliosphere for the high energy protons. However this latter component has a very small gradient in the inner solar system after the onset of the first recovery period in early 1981. The anomalous He interval approaches a value of ∿10%/AU until this same recovery period and then also shows a sharp decrease in the outer heliosphere - in agreement with the observations of McKibben, et al., 1985.

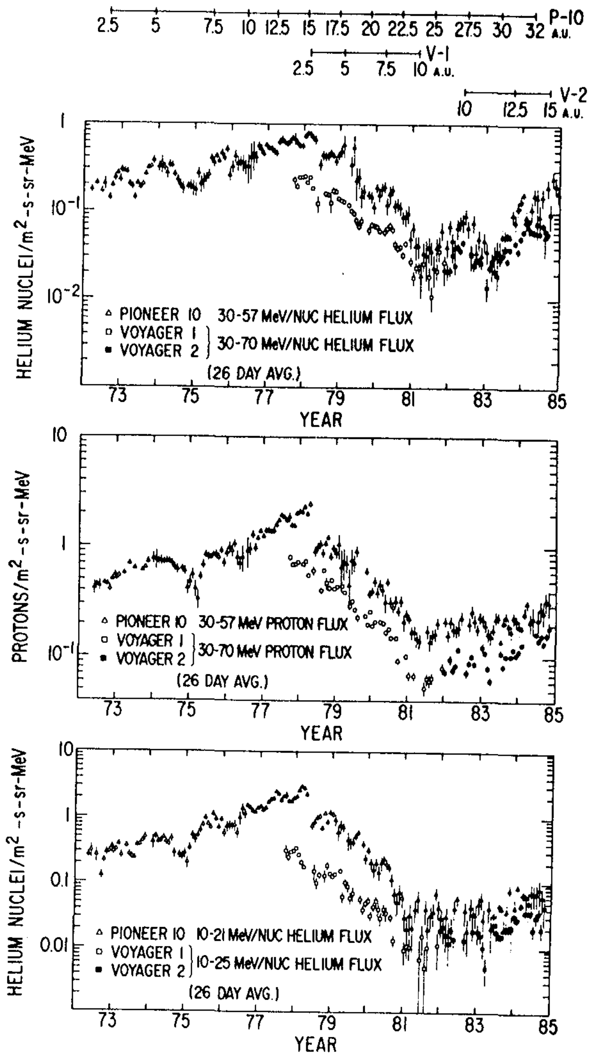

Fig. 3

3. Discussion. The step decreases have been explained in broad outline by Burlaga, et al., 1984, in terms of interplanetary flow systems containing a number of transient shocks and post shock flows. These systems of transient flows should evolve into expanding pressure waves such that the systems would merge and the outer heliosphere would be a region of enhanced turbulance. With such a system there would not be corresponding "step-increases" and the hysteresis effect would be explained by changes in the rigidity dependence of the diffussion coefficient in the outer region. If particle drifts play a major

role in the transport of galactic cosmic rays then an increase in the radial gradient is expected in the inner heliosphere at the time of the reversal of the solar magnetic field polarity (1980) (Jokipii and Kopriva, 1979). The gradient observations show either a decrease or no change. The failure of the anomalous He to recover has been predicted by drift models (Pesses et al., 1981) but there is no corresponding prediction for protons.

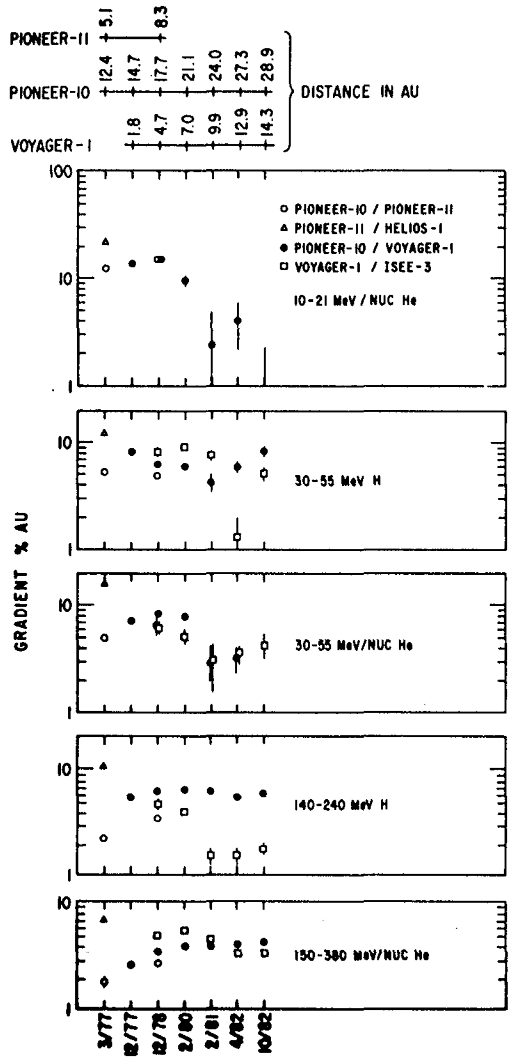

Fig. 4

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