GALACTIC COSMIC RAY RADIAL GRADIENTS AND THE ANOMALOUS He COMPONENT NEAR MAXIMUM SOLAR MODULATION AND TO RADII BEYOND 34 AU FROM THE SUN

R. B. McKibben, K. R. Pyle, and J. A. Simpson
Enrico Fermi Institute, The University of Chicago
Chicago, Illinois 60637 (U. S. A.)

ABSTRACT: Radial gradients for relativistic galactic cosmic rays (E > 70 MeV) remained nearly constant at ~2.5 %/AU from 1978-84, which includes the period of maximum solar modulation in 1981-82. For energies 30-70 MeV/n, gradients decreased at solar maximum to values of 1 %/AU (protons) and 4 %/AU (helium), and appear to be increasing again in 1983-84 toward the values found for solar minimum. The anomalous helium component has not reappeared, either at 1 AU or at Pioneer 10 at R > 34 AU.

1. INTRODUCTION:

Our observations of the radial and temporal variations of the modulated cosmic radiation and anomalous helium to the time of maximum solar modulation in 1981-82 (McKibben et al., 1983, 1985) showed that, at solar maximum, radial gradients for low energy (E < 100 MeV/n) cosmic rays measured between 1 and 31 AU were sharply reduced from their values at solar minimum. At relativistic energies, however, the radial gradient was not strongly affected by the level of solar modulation. We now extend our observations to the end of 1984, by which time the cosmic ray intensity had begun to recover from maximum modulation both at 1 AU and in the outer heliosphere. The Pioneer and IMP instruments used in this study have been described by Simpson et al. (1980), and by Garcia-Munoz et al. (1977). By late 1984, Pioneer 10 had reached a radial distance of > 34 AU from the sun, as shown in Figure 1C.

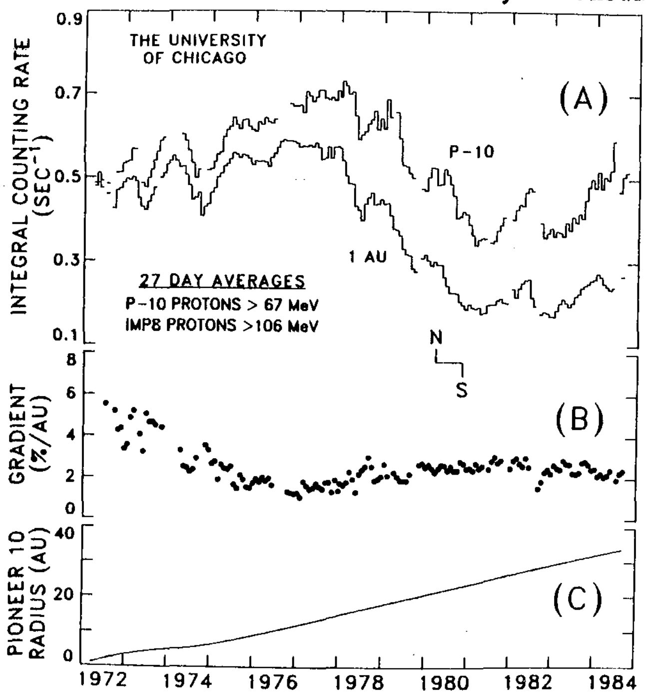

FIGURE 1

2. INTEGRAL GRADIENTS (E $\gtrsim$ 70 MeV):

Figure 1A shows simultaneous 27 day averages of integral counting rates from Pioneer 10 (protons $\gtrsim$ 70 MeV) and IMP 8 (protons $\gtrsim$ 106 MeV), selected to exclude contributions from solar particles. These counting rates are dominated by relativistic particles with a mean energy of the order of 2 GeV. The time variations observed at Pioneer 10 remain well correlated with variations at 1 AU after a time shift corresponding to outward propagation at near the solar wind speed (McKibben et al. 1982). In late 1984, the flux at Pioneer 10 at 34 AU was increasing from the maximum modulation observed in 1981-82, but was still not significantly greater than that observed at 1 AU at solar minimum in 1972. Therefore, the flux at Pioneer 10 remained heavily modulated in 1984.

Figure 1B shows the radial gradient of the integral intensity as a function of time. As in McKibben et al. (1983), a 400 km/s propagation delay from 1 AU to Pioneer 10 has been assumed. Although there are significant variations during the near-solar-minimum period (1972-1978), since 1978 the gradient has remained nearly constant at $\sim$2.5 %/AU despite large changes in the intensity at both Pioneer and IMP. The transient decrease in the gradient in 1982 is an artifact of the high velocity [$\gtrsim$ 800 km/s (Lockwood and Webber, 1984)] of the shocks which produced the intensity decrease in 1982.

3. LOW ENERGY (E < 70 MeV/n) DIFFERENTIAL FLUXES: Figure 2A shows the low energy (30-70 MeV) cosmic ray proton flux as observed at Pioneer 10, Pioneer 11, and IMP 8 starting in 1977, shortly before the onset of renewed solar activity, continuing through solar maximum in 1981-82 and into 1984 when recovery of the cosmic ray flux had begun. After 1979, measurements in this energy range are not available from Pioneer 11 because a detector problem has blocked analysis of particles with energy > 20 MeV/n. As reported earlier (McKibben et al., 1985), at solar maximum (1981-82) for low energy protons, nearly the same flux was measured at Pioneer 10 (R > 20 AU) and at 1 AU. At both Pioneer 10 and IMP 8 the proton flux remained essentially constant during 1981-82, and the shocks that produced such strong effects at higher energies had little effect on the low energy proton flux. As the recovery began in 1983-84, the flux at Pioneer 10 once again increased above that at 1 AU.

Figures 2B-D show the 27-day-average radial gradients measured for 30-70 MeV protons, 11-20 MeV/n helium, and 30-70 MeV/n helium. The accuracy of the measurements is reflected in the scatter of the points. All three gradients decrease at solar maximum. The largest decrease is shown by the gradient of 11-20 MeV/n helium and corresponds to the disappearance of the anomalous helium in 1980-81. The shocks in 1982 appear to have produced a further decrease, lasting 6 months or more, in the 30-70 MeV/n helium gradient. No clear corresponding effects are observed for lower energy helium. After maximum modulation, the gradient of 30-70 MeV protons increased slightly, and the data also suggest an increase in gradients for helium.

The observations are summarized in Figures 3A-C, which contain yearly snapshots of the convection-corrected intensity of 30-70 MeV protons, and of 11-20 and 30-70 MeV/n helium. Open

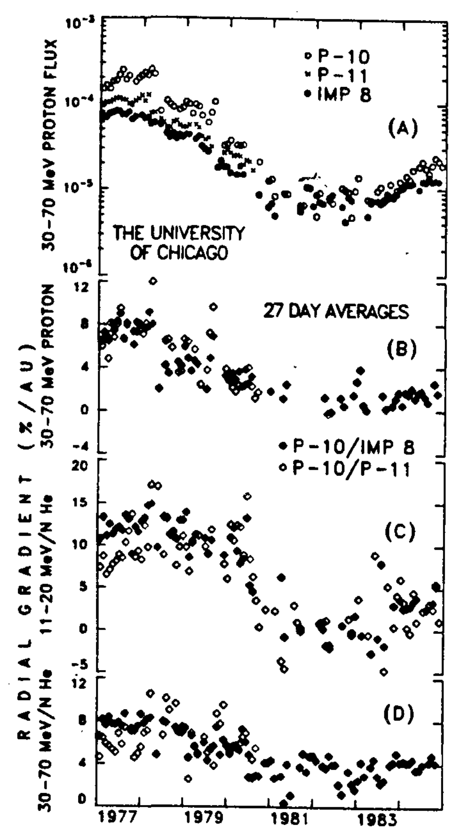

FIGURE 2

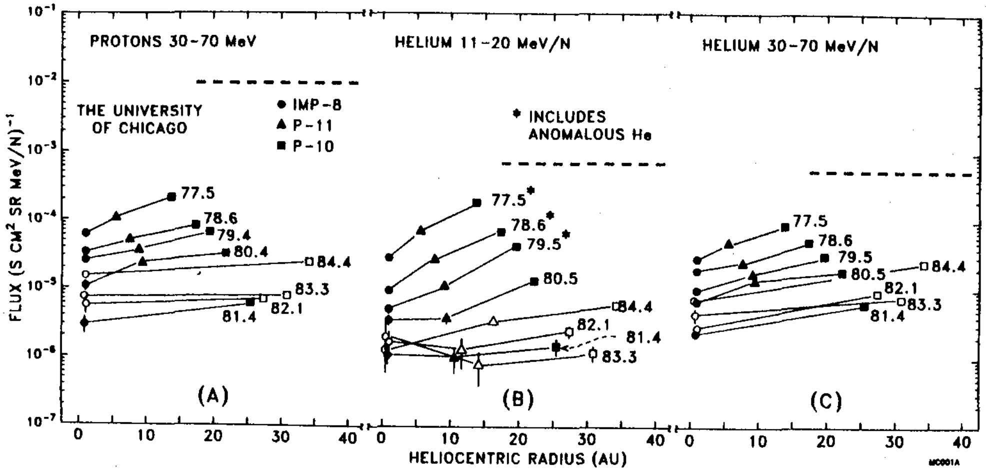

FIGURE 3

symbols correspond to data obtained since maximum modulation in 1981, and the heavy dashed lines indicate estimated interstellar galactic cosmic ray fluxes from the model of Evenson et al. (1983). For all three components, the flux measured in 1984 at Pioneer 10 remains below that measured at 1 AU at solar minimum in 1977. Comparing the observed fluxes in 1984 to the interstellar fluxes, at least 95% of the modulation takes place outside R = 34 AU. Linear extrapolation of the gradients observed in 1984 to the interstellar fluxes suggests modulation boundaries in the range 100-300 AU. However, modulation models suggest that the radial gradient may not remain constant to the boundary, so that linear extrapolation provides no reliable estimate of the boundary location. Furthermore, the radius of the boundary itself may vary with solar activity. Thus, based on our observations to date, we conclude only that the current radius of the modulation region is much larger than 35 AU.

IV. ANOMALOUS HELIUM: The anomalous helium component was present from 1972-79 at Earth and at Pioneer 10 and 11. It disappeared at 1 AU in 1979 and at Pioneer 10 (R > 20 AU) in 1980-81, at roughly the same time as the reversal of the sun's polar magnetic fields. Alternate models for the acceleration and modulation of this component predict either that it will be observed near the ecliptic only when the north pole of the sun is magnetically positive (Pesses et al., 1981), or that it will be observed whenever modulation is sufficiently weak (Garcia-Munoz et al., 1983).

The anomalous component helium spectrum is significantly softer than the spectrum of modulated galactic cosmic rays. Figure 4 displays the correlation observed at Pioneer 10 between the power law spectral index (i.e. γ for a spectrum of the form $dJ/dE \propto E^{+\gamma}$) for helium between 11 and 70 MeV/n, which indicates the strength of the anomalous component, and the flux of 29-67 MeV/n helium, which measures the level of solar modulation. From 1972-1980, the correlation is well defined, and weaker modulation corresponds to a larger contribution from the anomalous component. At solar maximum in 1981-82, the spectral indices cluster near the value of $\sim$+1.0 expected for normally modulated galactic helium. In 1983-84, as shown by the large unfilled data points, the helium flux began to recover, and by the end of 1984, the helium flux had reached levels where in previous years the spectrum had shown clear evidence of the anomalous component. As of late 1984, however, the spectrum remained consistent with the presence only of galactic cosmic ray helium. These observations show that the presence of the anomalous component near the ecliptic is not a function only of the strength of modulation. Alternatives include 1) existence of a hysteresis effect, in which case the anomalous helium should reappear at Pioneer 10 in the near future, 2) sensitivity of the anomalous helium to the sign of the heliospheric magnetic field, as suggested by Pesses et al. (1981), or 3) dependence of acceleration or modulation of the anomalous helium on some as yet undefined characteristic of heliospheric structure.

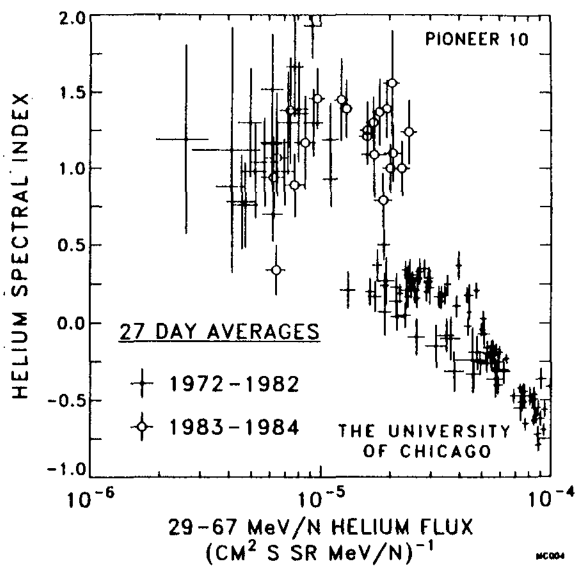

FIGURE 4

4. SUMMARY AND CONCLUSIONS: 1. For relativistic cosmic rays, the radial gradient measured between 1 AU and Pioneer 10 at R > 30 AU was nearly independent of the level of modulation throughout the period 1978-84, remaining approximately constant at $\sim$ 2.5 %/AU.

2. For cosmic rays below 100 MeV/n, the radial gradient was much smaller at maximum modulation than at solar minimum. As the flux increased in 1983-84 after solar maximum, the gradient also began to increase.

3. The cosmic ray flux at Pioneer 10 at > 34 AU remains as heavily modulated as it was at 1 AU in 1972, so that Pioneer 10 is still far from the boundary of the modulation region. Based on estimates of the interstellar spectra, for energies < 100 MeV/n more than 95% of the modulation was occuring beyond 34 AU in 1984.

4. The anomalous helium has yet to reappear at either 1 AU or Pioneer 10.

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