Changes in the Energy Spectrum of Anomalous Oxygen and Helium During 1977-1985

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We have used data from the cosmic-ray experiment on the Voyager spacecraft to measure the energy spectrum of anomalous O and He during the period 1977 to 1985. We find that these spectra change dramatically after the middle of 1980, with the peak or plateau region of the differential spectrum shifting to a higher energy. This change appears to be related to the reversal of the solar magnetic field and could imply that particle drifts are important to the acceleration or propagation of these particles.

1. Introduction. The study of the anomalous component of cosmic rays over the solar cycle may prove to be key to the understanding of the role of drifts in cosmic-ray modulation. *Pesses et al.* [1981] have suggested that the acceleration site of the anomalous component is most likely in the polar regions of the solar wind termination shock. In their model the particles drift latitudinally toward the neutral sheet from the polar regions during the last solar cycle, but drift radially inward along the neutral sheet during the current solar cycle. Consequently, they predict a strong dependence of the intensity of the anomalous component near the solar equator on solar magnetic field polarity. In this analysis we make use of measurements of the spectra of O and He from the Cosmic Ray Subsystem (CRS) [*Stone et al.,* 1977] on the Voyager 1 (V1) and 2 (V2) spacecraft to address whether or not these spectra exhibit changes associated with the polarity of the solar magnetic field.

2. Observations. The general features of the 11-year cosmic-ray modulation cycle are evident in the counting rate of the particles which penetrate the high energy telescope on V1, shown in Fig. 1 for 1977-1985. In order to minimize the contamination by solar and interplanetary energetic particles, quiet times were selected by setting limits to the maximum low-energy He flux, in a manner similar to that described in *Cummings et al.* [1984]. The six quiet-time periods that were selected for analysis for V1 are shown as horizontal bars in Fig. 1 and are labeled A through F. Also shown are the approximate times of the reversal of the solar polar magnetic fields [*Webb et al.,* 1984]. Note that the field reversal occurs approximately between periods C and D.

The anomalous O spectrum for the Voyager measurements is derived from the observed total O spectrum for a particular time interval by subtracting a low-energy solar or interplanetary component and the high-energy galactic cosmic-ray component. This subtraction procedure is illustrated in Fig. 2 for two extreme examples. The low-energy component is scaled and extrapolated from a power-law fit to the observed He spectrum in the energy range 3-6.1 MeV/nuc using a ratio He/O$=100\pm50$ (see *Gloeckler et al.* [1979]). The galactic cosmic-ray O component is estimated by normalizing the observed carbon spectrum to the O intensity in the 66-125MeV/nuc energy interval.

Figure 3 shows the spectra of anomalous O for the six quiet-time intervals A through F derived from the V2 observations in the manner just described. The a and b panels show the spectra for the three intervals before and after the solar magnetic field reversal in 1980, respectively. The spectra for intervals A, B, and C are essentially monotonic with a tendency to flatten into a peak or plateau at less than $\sim$6MeV/nuc. It is clear from Fig. 3b that the energy dependence of the spectra for the intervals after the field reversal (D, E, and F) is significantly different, having a peak or plateau at $\sim$10-20 MeV/nuc.

A similar change in the energy spectrum is also apparent in the V1 data. In Fig. 4a we show the V1 observed O spectra for intervals B and F. The galactic cosmic-ray intensity is dom-

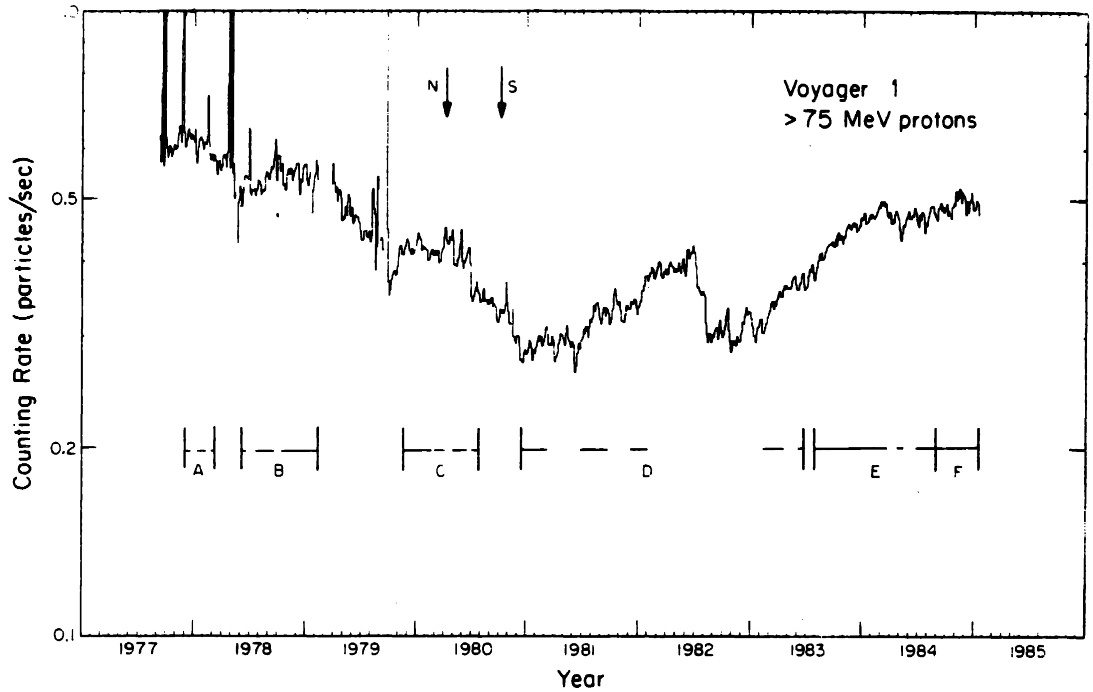

Fig. 1. Three-day average counting rate of penetrating particles in the HET 1 (High-Energy Telescope number 1) of the V1 CRS instrument from 1977 to 1986. The rate is dominated by protons with energy > 75 MeV. The bars and arrows are described in the text.

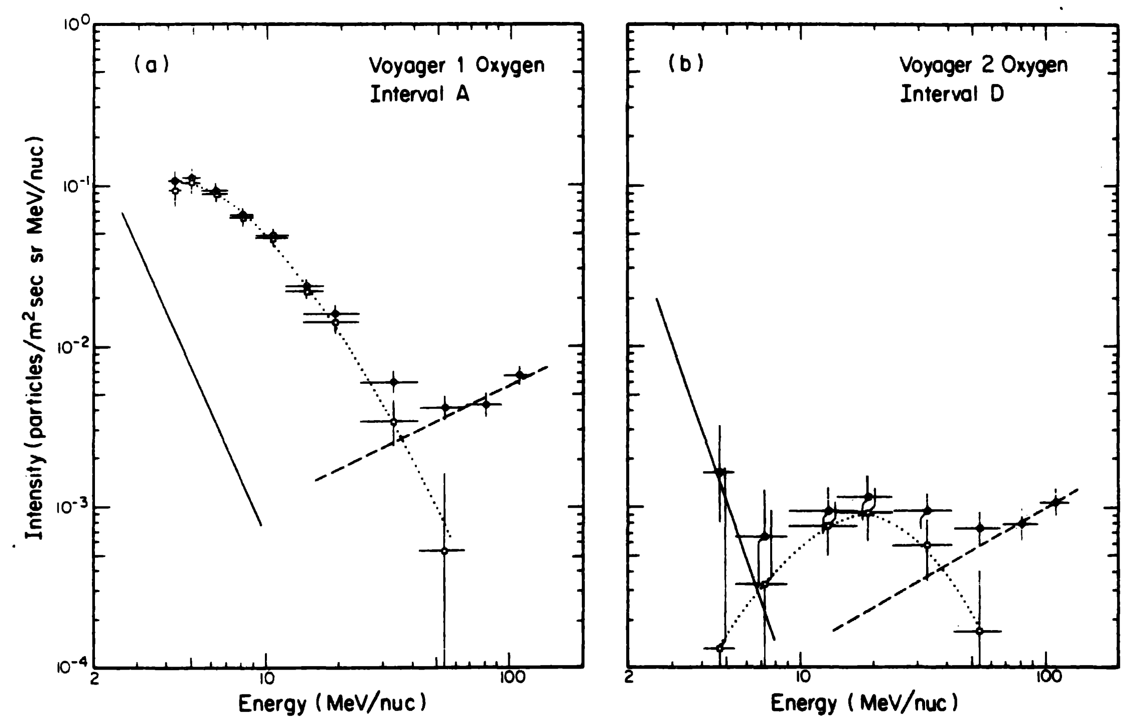

Fig. 2. Quiet-time energy spectra of O from Voyager data for two sample time intervals. The observed spectra are shown as the solid circles. Estimated spectra of interplanetary and galactic components are shown as solid and dashed lines, respectively. The spectra of anomalous O are indicated by the open squares which are joined by the dotted lines.

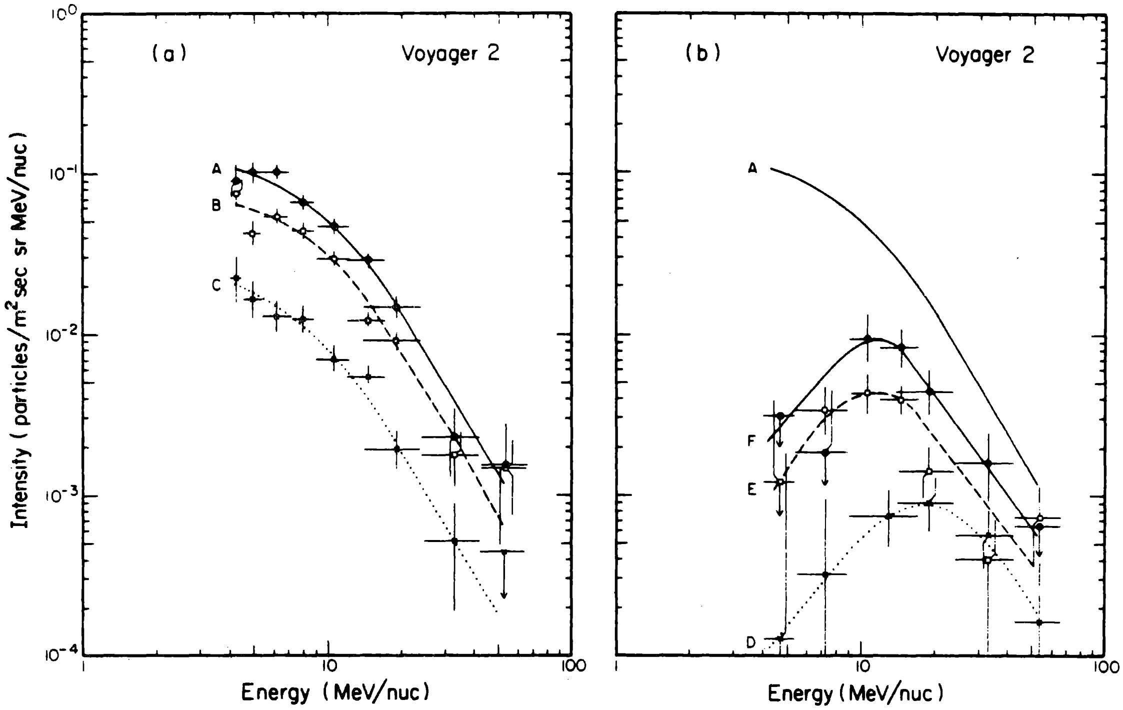

Fig. 3. Spectra of anomalous O from V2 for the six quiet-time intervals. Panels a and b show the spectra for periods before and after the solar magnetic field reversal, respectively. The smooth curves are drawn to aide the eye and are not functional fits to the data. The dashed line labeled "A" in panel b is copied from panel a to facilitate comparison. Note the higher energy of the peak (or plateau) intensity of the spectra in panel b when compared to those of panel a.

inant in the 50-125MeV/nuc energy range for both time intervals. The intensity in this energy range is only ~20% higher for interval B than for interval F, indicating that a similar level of modulation has been reached. Similarly, the anomalous O intensity in the 10-30MeV/nuc energy range is approximately the same for the two time intervals. However, below 10MeV/nuc there is a factor of 10 difference in intensity producing a striking difference in the spectrum.

This change in the energy spectrum is also evident in the He data. We show in Fig. 4b the observed He spectrum for the same two intervals as for Fig. 4a. Below ~8MeV/nuc a low-energy solar or interplanetary component is dominant and causes a sharp upturn in the spectrum. For interval B the flat region of the spectrum from ~8to50MeV/nuc indicates that anomalous He is the primary component, dominating the flux of solar and galactic cosmic rays. The period F spectrum has a much lower intensity than the period B spectrum below ~30MeV/nuc suggesting that the anomalous He spectrum has shifted to higher energies. If the particles are singly ionized, the energy dependence of the He spectrum is expected to be obtained by shifting the anomalous O spectrum by a factor of ~4 in energy [*Cummings et al.*, 1984], so that the absence of anomalous He below 30MeV/nuc is consistent with the reduced intensity of anomalous O below 8MeV/nuc.

3. **Discussion.** If the changes in the energy spectra of the anomalous component are to be explained by "conventional" modulation theory, in which the effects of diffusion, convection, and adiabatic deceleration are considered, and the effects of drifts ignored (see *Fisk* [1980], for a review of solar modulation theory), then it would require either a very prolonged "hysteresis" effect or a significant change in the rigidity dependence of the diffusion coefficient between halves of the solar cycle. A hysteresis effect (phase-lag between intensity variations of low-rigidity and high-rigidity particles) has been reported for the anomalous O component by *Klecker et. al* [1980] for the 1974-1975 period. They found a phase lag of 72 days between the intensity of

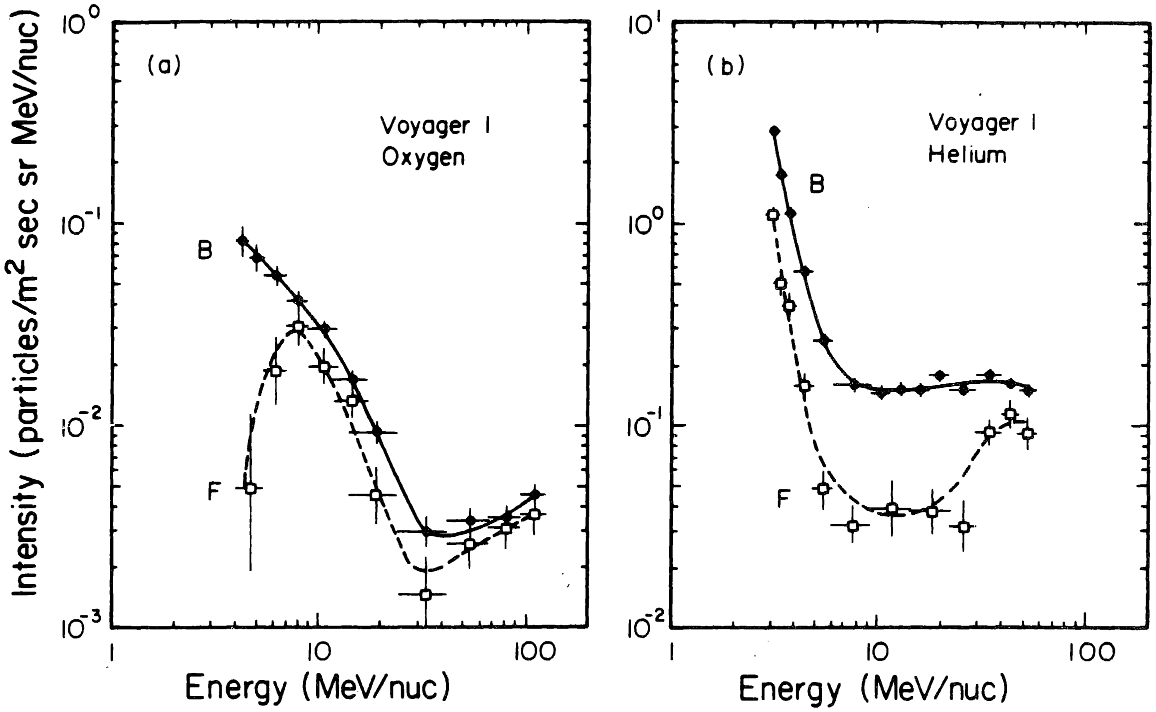

Fig. 4. Spectra of observed O (a) and He (b) for time intervals B and F from V1.

anomalous O with 7.6-24 MeV/nuc and the intensity of galactic cosmic rays with energy > 10GeV. If the energy spectrum changes in our study are to be ascribed to hysteresis, then a phase lag of ~4 years would be required between particles with only modestly different rigidities and velocities. If changes in the diffusion coefficient between halves of the solar cycle are to account for our observations then the spectra of other cosmic-ray species would show pronounced effects at the corresponding rigidities.

It appears more likely, therefore, that the observed time variation of the energy spectra of anomalous O and He may be related to changes in the acceleration of particles at the termination shock due to the change in the polarity of the solar magnetic field. Recently, *Jokipii* [1985] has used a model of the anomalous component which includes acceleration at the termination shock and particle drifts and has calculated spectra of anomalous O and He in the two halves of the solar cycle with different field polarity that resemble the observations reported here.

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