EVOLUTION OF THE ENERGY SPECTRA OF ANOMALOUS COSMIC RAYS IN THE OUTER HELIOSPHERE

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ABSTRACT

We present energy spectra of anomalous cosmic ray hydrogen, helium, and oxygen derived from data collected from experiments on the Voyager and Pioneer spacecraft from 1993 through 1996. The sequence of energy spectra show the effects of decreasing modulation as the solar cycle approaches and reaches solar minimum conditions. We suggest a number of factors that may be responsible for the spectral evolution, including the approach of the spacecraft to the source region of the particles (the solar wind termination shock), possible changes in the source strength, decreasing tilt of the neutral current sheet, and changes in the diffusion mean free path. We find that the data are inconsistent with source strength changes, but changes due to the other factors are possible and will require more complete 2 and 3-dimensional propagation models to make quantitative assessments. We find evidence for anomalous cosmic ray hydrogen up to energies as high as 400 MeV/nuc.

INTRODUCTION

Anomalous cosmic rays (ACRs) are thought to be accelerated at the solar wind termination shock (Pesses et al. 1981). The three spacecraft in the outer heliosphere, Pioneer 10 (P10), and Voyagers 1 and 2 (V1 and V2), are currently (1 Aug 1997) located at 68.0, 67.4, and 52.4 AU, respectively, from the Sun, traveling outward at velocities of 2.6, 3.6, and 3.0 AU/yr, respectively. The P10 instruments were recently powered off; however, cosmic ray data is available thru mid-1996. V1 and V2 are headed generally toward the nose of the heliosphere and, based on recent estimates of the shock location, they may cross the shock in the next few years. In this paper we examine the energy spectra of ACR H, He, and O at P10, V1, and V2 over the four year period 1993-1996 and discuss possible causes of the observed evolution of the spectra.

OBSERVATIONS

Table 1: Average locations of the spacecraft for the time periods in Figures 1 - 4

Time Period	Plot Symbol	Voyager 1 r AU	Voyager 1 Θ deg	Voyager 2 r AU	Voyager 2 Θ deg	Pioneer 10 r AU	Pioneer 10 Θ deg
1993/ 1-183	cross	51.7	32.2	39.7	-8.9	56.7	3.2
1993/184-365	open square	53.6	32.3	41.1	-10.2	58.0	3.1
1994/ 1-183	solid triangle	55.4	32.5	42.6	-11.4	59.3	3.1
1994/184-365	open diamond	57.2	32.6	44.0	-12.5	60.6	3.1
1995/ 1-183	solid circle	59.0	32.7	45.5	-13.6	61.9	3.1
1995/184-365	open triangle	60.8	32.8	47.0	-14.6	63.2	3.0
1996/ 1-183	solid square	62.6	32.9	48.5	-15.5	64.5	3.0
1996/184-366	open circle	64.4	33.0	50.0	-16.4	65.8	3.0

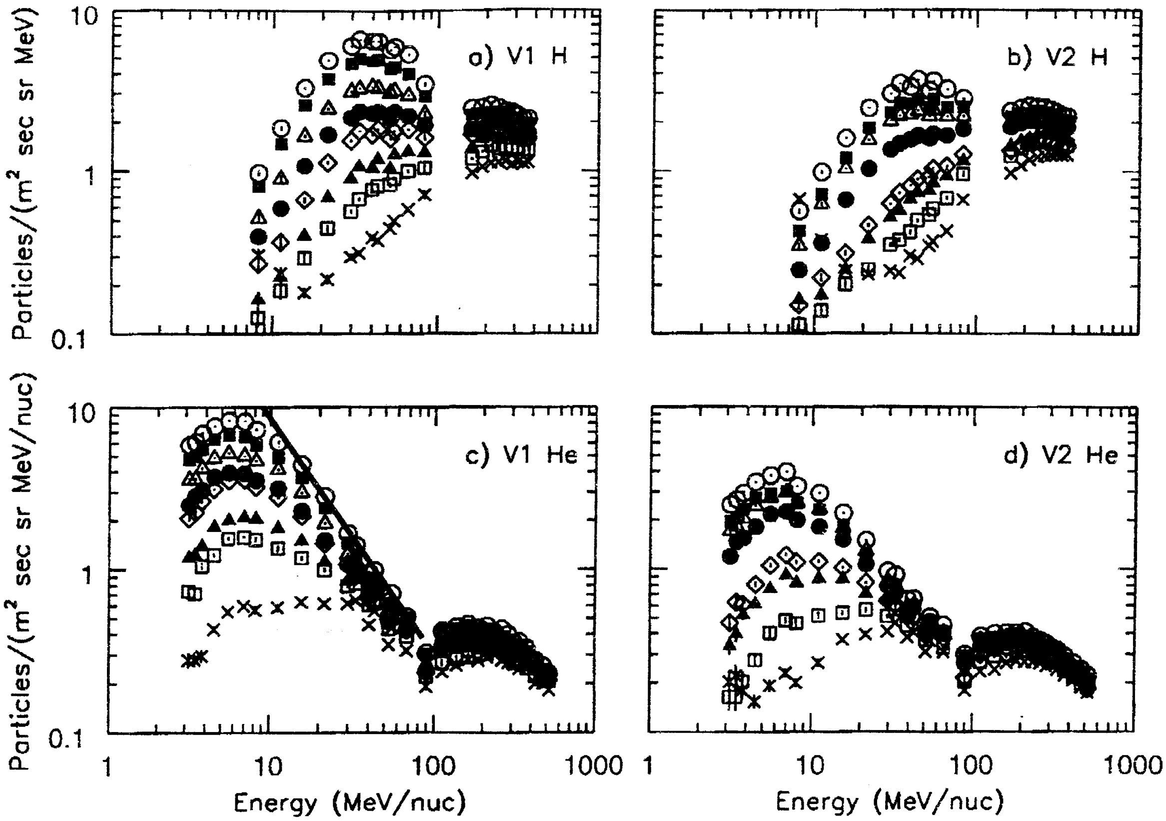

Fig. 1: Energy spectra of H and He at V1 and V2 for 8 half-year averaged periods from 1993/1 through 1996/366. The symbols are described in Table 1. The intensities are generally monotonically increasing with time. The solid line in panel c) is $\propto E^{-1.45}$ and is an approximation of the V1 high energy ACR He spectrum for 1996/184-366.

Half-year averaged energy spectra of H, He, and O at V1, V2, and P10 are shown in Figures 1, 2, 3, and 4.

DISCUSSION

The ACR spectra provide evidence of dramatic decreases in the level of solar modulation over the four year period shown. The increased fluxes are most obvious at energies <100 MeV/nuc. It is interesting to note, however, that the H spectrum from 150 to 400 MeV shows a much larger increase over this time period than is the case for GCR He. This is consistent with a significant contribution of ACR H in this energy interval.

The full interpretation of the evolution requires consideration of a number of factors that would con-

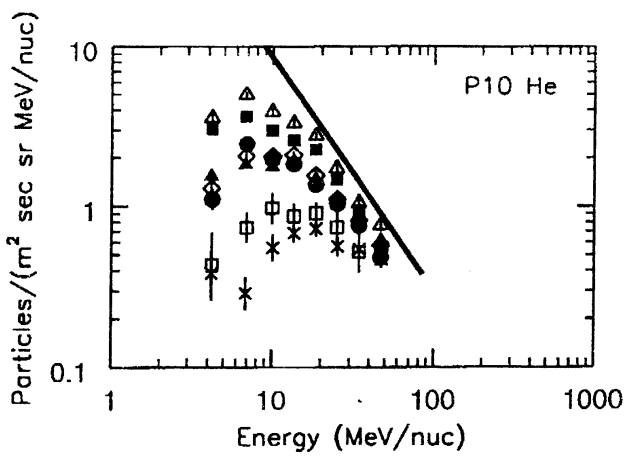

Fig. 2: Energy spectra of He at P10 for 7 half-year averaged periods from 1993/1 through 1996/183. The symbols are described in Table 2. The solid line is from Figure 1c and is to be compared with the P10 spectrum at the same radial distance (solid squares = 1996/1-183 for P10).

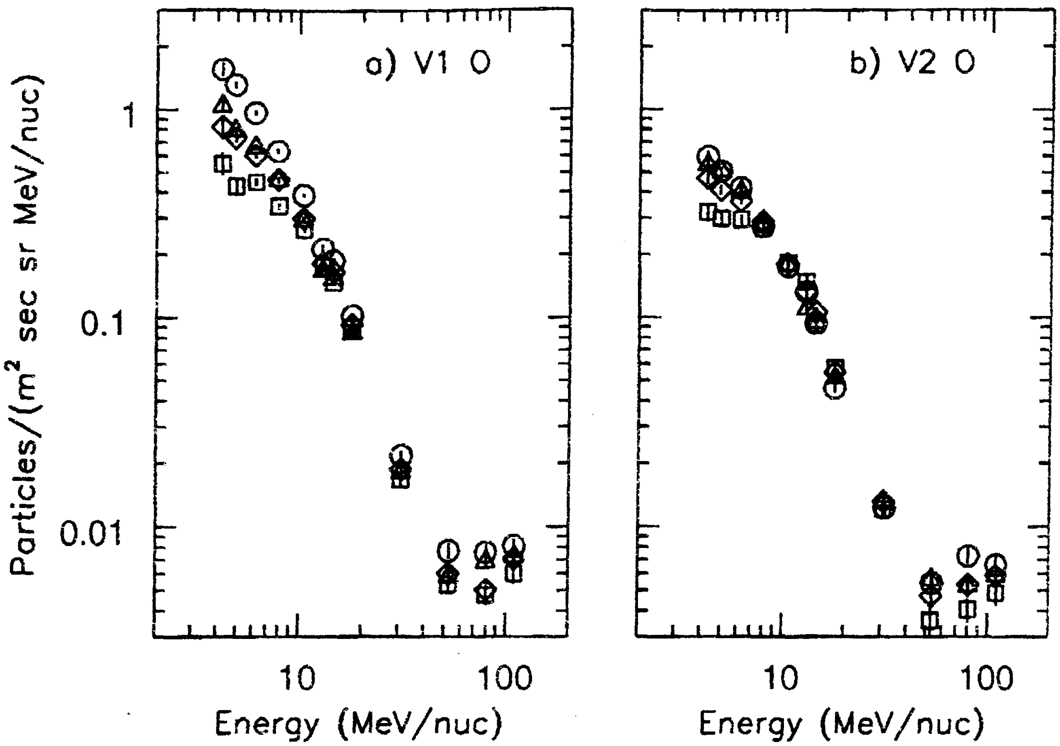

Fig. 3: a) Energy spectra of O at V1 for 4 half-year averaged periods: 1993/184-365, 1994/184-365, 1995/184-365, and 1996/184-366. The symbols are the same as in Figure 1. b) Same as a) except for V2.

tribute to the observed changes. Among these are the increasing radial and latitudinal locations of the three spacecraft (see Table 1) and possible changes in the propagation conditions (diffusion coefficient, current sheet tilt), the source spectrum at the shock, and the location of the termination shock.

One indication of the magnitude of the variation in the source strength is the small variation in the ACR O spectrum at the highest rigidities ($\geq$2.7 GV or $\geq$15 MeV/nuc). As seen in Figure 3, V2 observed little change ($\leq$25%) over 4 years, while V1 observes a somewhat larger ($\sim$33%), but still small, increase. This would suggest that temporal variation in the source strength is unlikely to be very large during the time period and cannot account for the much larger flux increases at low rigidities.

The role of changing current sheet tilt and the associated changes in the observed latitudinal gradients can be evaluated by comparing P10 fluxes for 1996/1-183 (3°, 64.5 AU) and V1 for 1996/184-366 (3°, 64.4 AU) at similar radial distances but different latitudes and times. As shown in Figure 2, for E $\geq$ 20 MeV/nuc the V1 flux is $\sim$65% greater than the P10 flux (solid squares), independent of rigidity, indicating a small latitudinal gradient (<1.7%/deg). However, at lower rigidities the ratio of V1/P10 fluxes increases with decreasing energy, indicating the latitudinal gradient is an increasingly important factor. Thus, a temporal increase in the latitudinal gradient at 33°, as might be associated with a generally decreasing current sheet tilt, could be a significant contributor to the evolution of the V1 spectrum at low rigidities.

Estimates of changes in the diffusion mean free path, λ, are discussed in a companion paper (Cummings & Stone 1997). Above $\sim$1 GV, λ decreased from $\sim$1.5 AU in 1994 to $\sim$1 AU in 1996, which taken alone would result in a decreasing flux with time. At 0.55 GV, λ increased from $\sim$0.45 AU to $\sim$0.60 AU during the same period, an increase that could have contributed to the observed evolution at lower energies. However, these estimates for λ are derived using a force-field modulation model that ignores the contribution of latitudinal gradients. As a result, further analysis is required to establish an accurate estimate of any temporal changes in λ.

Although the above considerations provide some insight into the most important factors affecting the observed spectral evolution, a quantitative assessment will require comparisons with more complete 2- and 3-dimensional modulation models that include drifts and a tilted current sheet.

ACKNOWLEDGMENTS
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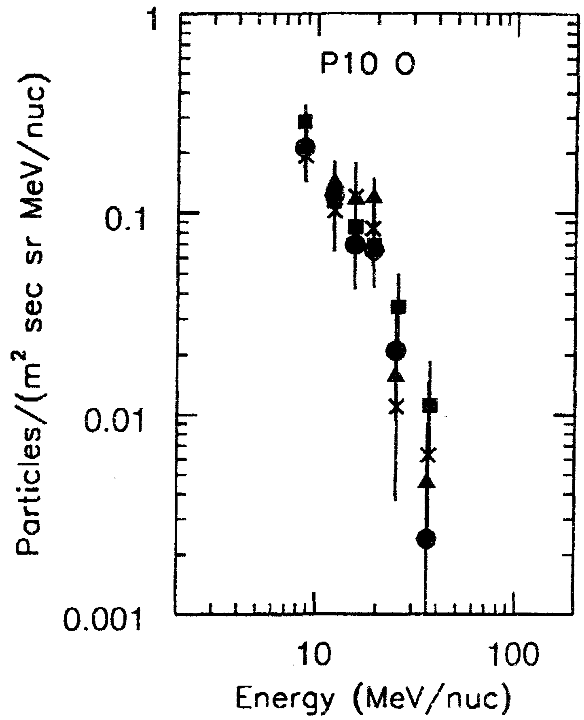

Fig. 4: Energy spectra of O at P10 for 4 half-year averaged periods: 1993/1-183, 1994/1-183, 1995/1-183, and 1996/1-183. The symbols are described in Table 1.