SH 4.3.04

Anomalous Cosmic Ray Spectra in the Outer Heliosphere: 1992-1998

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Abstract

As the Voyager 1 and 2 spacecraft travel through the outer heliosphere, the Low Energy Charged Particle instruments onboard have been making composition measurements of energetic ions above about 0.3 MeV/nucleon. During the years 1992 through 1998, a period of declining solar modulation in the outer heliosphere, V1 traveled from 47 to 72 AU and V2 traveled from 36 to 57 AU. We have constructed annual energy spectra for several ACR species that, in general, show monotonic flux increases over that period, typically by a factor of about 100 for the flux near the ACR spectral peaks. This increase appears to be largely temporal rather than spatial. These observations have implications for ACR acceleration and transport.

1 Introduction:

In the outer heliosphere the ion population in the energy range 0.3 to 30 MeV/nucleon may contain contributions from interplanetary acceleration, remnants of large solar energetic particle events, and the anomalous cosmic ray component (ACRs). Observations from the Voyager 1 and 2 Low Energy Charged Particle (LECP) instruments indicate that the ACR component becomes dominant with the approach to solar minimum (Hamilton et al., 1997). In this paper we present data from Voyager 1 covering the years 1992-1998, a period during which V1 traveled from 47 to 72 AU and maintained a relatively constant heliographic latitude of 32°-33° N (see Figure 1). The period begins just after the Solar Cycle 22 maximum and ends just after the subsequent solar minimum. The ACR fluxes increased by large factors over these years, while interplanetary acceleration events dropped to an extremely low level at Voyager 1, as can be seen in the plot of the 0.57-1.78 MeV proton flux in Figure 1 of companion paper SH 4.2.07 by Decker et al. (1999). Here we present Voyager 1 observations of the variations of the proton, helium, and oxygen fluxes during the last seven years, noting that the Voyager 2 data are qualitatively similar.

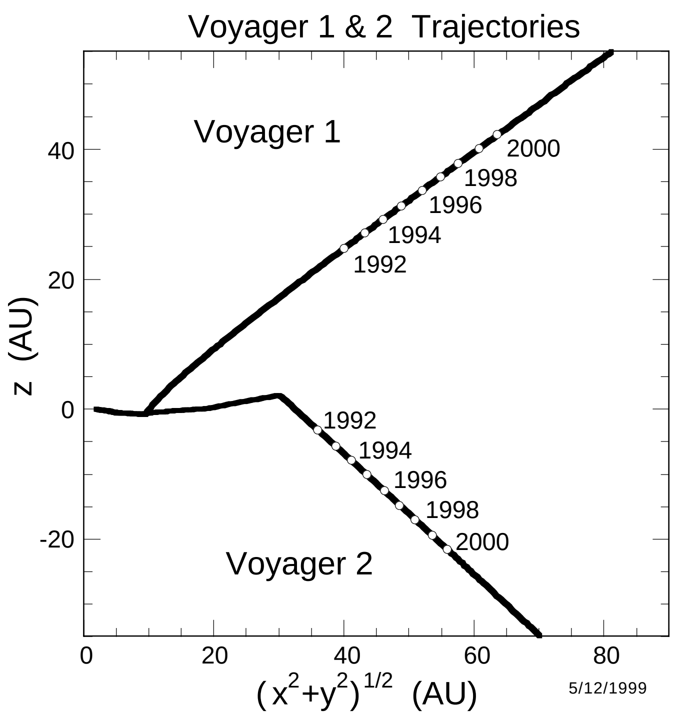

Figure 1: Trajectories of Voyager 1 and 2 in heliographic coordinates. Open circles indicate the beginning of years.

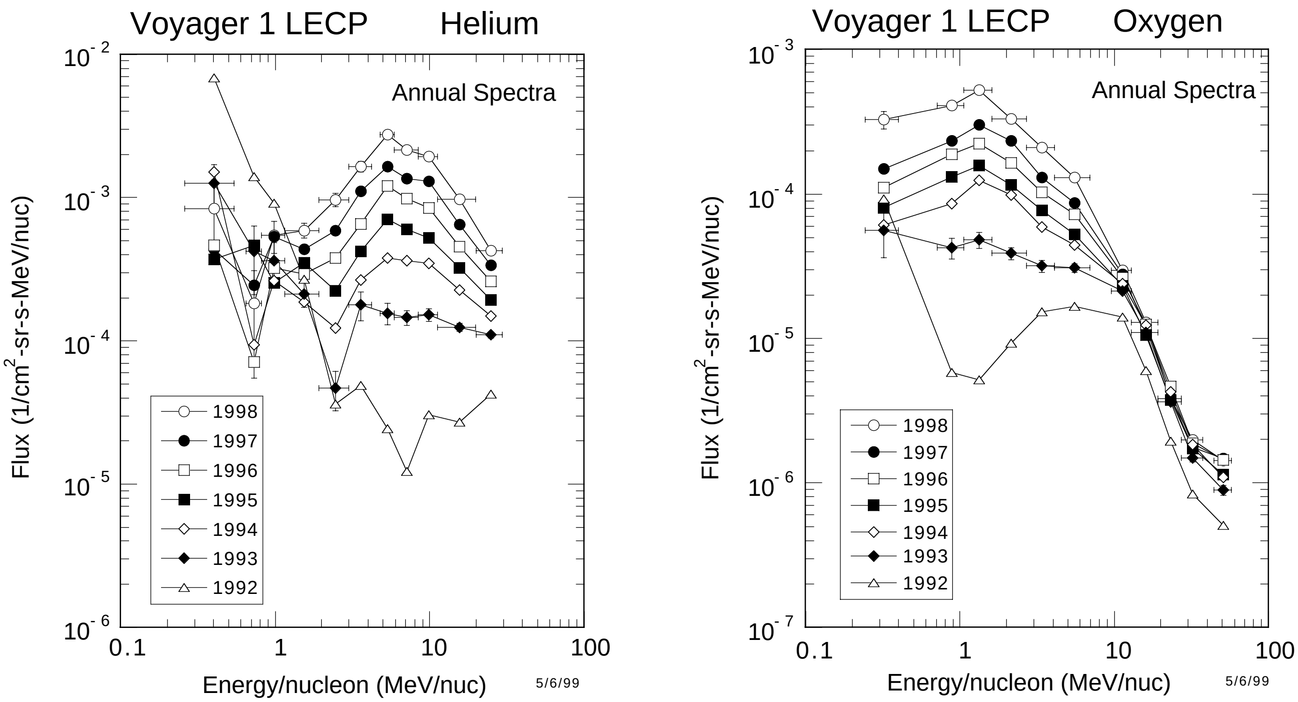

Figure 2: Annual averaged energy spectra of helium and oxygen from Voyager 1. For clarity error bars are shown only for 1993 and 1998.

2 Spectral Evolution:

The annual averaged helium and oxygen spectra at Voyager 1 are shown in Figure 2. The time variations are dominated by a relatively monotonic increase in the anomalous component from year to year. For helium a spectral peak formed near 5.5 MeV/nucleon by 1994, and the peak flux remained at that energy through 1998. The largest flux increase occurred at that energy, but there were year to year increases from 1.5 MeV/nuc to 23 MeV/nuc, indicating the domination of that portion of the spectrum by the increasing ACR flux. Below about 1 MeV/nuc the story is different. In 1992 the flux of <1MeV/nuc helium was relatively high, and there was a falling spectrum from 0.4 MeV/nuc to 2 MeV/nuc. This spectral form reflected the higher level of interplanetary activity and acceleration in 1992. In later years the flux of low energy helium decreased as interplanetary conditions quieted.

The evolution of the oxygen spectrum was qualitatively similar to that of the helium. By 1994 (with a hint even in 1993) a spectral peak had formed at 1.3 MeV/nuc. Again the peak flux remained at that energy through 1998, and the largest flux increase occurred at that energy. For the oxygen, however, the flux in the energy range 10-30 MeV/nuc remained relatively constant after a sizeable increase between 1992 and 1993. At low energies the oxygen behavior also differed from the helium. In 1992 there is evidence of interplanetary acceleration only in the enhanced flux at the lowest measured energy of 0.3 MeV/nuc. At that time there was already a well-developed ACR peak near 6 MeV/nuc. The flux decrease at 0.3 MeV/nuc after 1992 was very modest and by 1994 it appears that ACR oxygen is dominating the spectrum down to the lowest energy measured by the LECP instrument. The 0.3 MeV/nuc flux then participates in the general ACR increase after 1994. A slight flattening of the spectrum at 0.3 MeV/nuc in 1998 suggests a possible contribution to the flux at that energy by increasing interplanetary activity. In general, however the oxygen spectrum from 0.3 MeV/nuc to 30 MeV/nuc appears to be dominated by ACRs from 1993-1998.

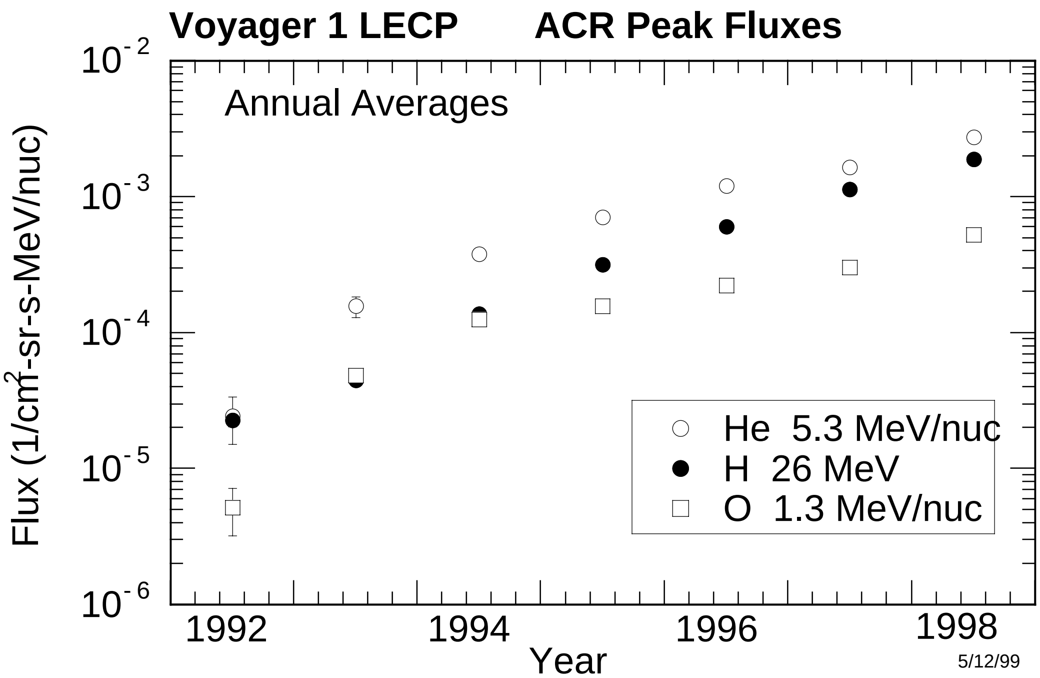

Figure 3: Annual average fluxes of protons, helium, and oxygen, taken near the peaks of the ACR spectra.

3 Flux Increases Near the ACR Spectral Peaks:

In Figure 3 we plot as a function of time fluxes taken from the ACR spectral peaks in Figure 2 as well as the 26 MeV proton flux, which is near, but slightly below the ACR proton peak (see, for example, Stone et al., 1999). The helium and oxygen fluxes show similar increases of about a factor of 100 from 1992 to 1998. The proton flux increases by a slightly smaller value of 83, but the difference is not statistically significant. The proton flux increased at a relatively steady rate over these years, but the helium and oxygen fluxes both had their largest increases from 1992 to 1993. For oxygen in particular, the rate of increase slowed markedly after 1994. The abundance ratios vary somewhat from year to year, but taking 1996 as a typical year, the relative fluxes at the ACR peaks are He:H:O = 2.0:1:0.37.

4 Discussion:

The ACR flux at Voyager 1 continued to increase after the 1996 solar minimum. The annual averages shown in Figure 3 increase in both 1997 and 1998. Shorter term averages (not shown here, but see the 22-31 MeV protons in Figure 1 of Decker et al., 1999) indicate the maximum ACR flux may have been reached sometime in the latter half of 1998. This delay from the 1996 solar minimum presumably results from the solar wind transit time to the outer heliosphere.

The ACR spectral peaks at Voyager 1 occur at about the same total kinetic energy for helium and oxygen (about 21 MeV) and at a somewhat higher energy for protons (~33 MeV). Assuming all three species are singly ionized at these energies, the rigidity values at 21 MeV total energy are 0.20 GV, 0.40 GV, and 0.79 GV for protons, helium, and oxygen, respectively. The rigidity of 33 MeV protons is 0.25 GV. It is interesting to note that the product βR, velocity times rigidity, is equal for non-relativistic, singly charged ions with the same total kinetic energy. It is often assumed that the spatial diffusion coefficient varies as βR, sometimes with a transition to rigidity-independence below 0.4 GV (e.g., Le Roux and Potgieter, 1992).

It is also interesting that the energies of the spectral peaks of helium and oxygen are established early in the recovery (1993 or 1994) and do not change through 1998. This is in spite of the fact that Voyager 1 moves outward at a rate of about 3.6 AU/year and so traveled some 18 AU during this period. One might have expected that as V1 traveled towards the termination shock, the shape of the observed spectrum would continue to approach a power law, as expected for the shock-accelerated ACR source spectrum. In this case the spectral peak would move to lower energies. It is probably important that the drift patterns during this period ($A > 0$) bring ACR particles from the high latitude termination shock to lower latitudes, rather than bringing them in along the current sheet from the low-latitude termination shock as happens during the opposite solar polarity (Jokipii, 1990). The increase in radial distance may therefore not significantly change the distance the ACRs must travel before reaching Voyager 1.

5 Acknowledgements:

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