# TEMPORAL AND SPATIAL VARIATIONS IN THE SPECTRA OF LOW ENERGY IONS IN THE OUTER HELIOSPHERE

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**ABSTRACT**

The LECP instruments on the Voyager 1 and 2 spacecraft make composition measurements of energetic ions above about a half an MeV/nucleon. We have constructed annual energy spectra of the species H, He, C, and O during the years 1992-1996 as the two Voyager spacecraft traveled through the outer heliosphere from 36 to 65 AU. These years include periods of recurrent events showing CIR acceleration up to an MeV/nucleon or slightly higher and those that appear quiet down to half an MeV per nucleon. Within the LECP energy range of 0.5 to 30 MeV/nuc, the spectra for some species show a transition from a low energy component apparently accelerated locally to the anomalous cosmic ray component at higher energies, although in the years 1995 and 1996, little local acceleration is evident. We discuss compositional changes as a function of energy as well as temporal variations in the spectra over this five-year period. These low energy ions may be a sensitive indicator of the expected approach to the termination shock.

## INTRODUCTION

As Voyager 1 and Voyager 2 make their way out of the heliosphere the Low Energy Charged Particle (LECP) instruments are making composition measurements of the evolving ion fluxes in the 0.5-30 MeV/nuc energy range. The heliocentric radial position of Voyager 2 increased from 36 to 51 AU during the 1992-1996 period while Voyager 1 moved from 47 to 65 AU. Their radial separation increased from 11 to 14 AU. The difference in the absolute values of their heliographic latitudes decreased from 25° to 17° as Voyager 1 remained at 32°-33° N while Voyager 2 moved from 7° S to 16° S. The solar cycle progressed from just past maximum in 1992 to solar minimum in 1996, and the decline in solar modulation of the anomalous cosmic ray component (ACRs) combined with a decline in interplanetary activity dominate the changes observed in the energetic ion fluxes. Voyager 1 observed considerable activity at 1 MeV/nuc due to CIRs in 1992, but that activity largely subsided thereafter. Voyager 2, closer to the ecliptic, saw CIR activity from 1992-1994, but 1995 and 1996 were very quiet. These transitions may be easily observed in Figure 2 of companion paper SH 3.3.4 by Krimigis et al. (1997). In this paper we present preliminary results of composition and spectral changes in the energetic ion fluxes in the outer heliosphere during the decline of the last solar cycle.

## SPECTRAL EVOLUTION

In Figure 1 we show the evolution of the helium and oxygen energy spectra at Voyager 1 over the five-year period 1992-1996. The yearly-averaged spectra are shown without individual data points to facilitate observation of the general trends. The spectra show very systematic evolution during this transition from solar maximum to solar minimum. In the helium spectrum we observe a relative minimum at about 7 MeV/nucleon in 1992 that gradually filled in to become a

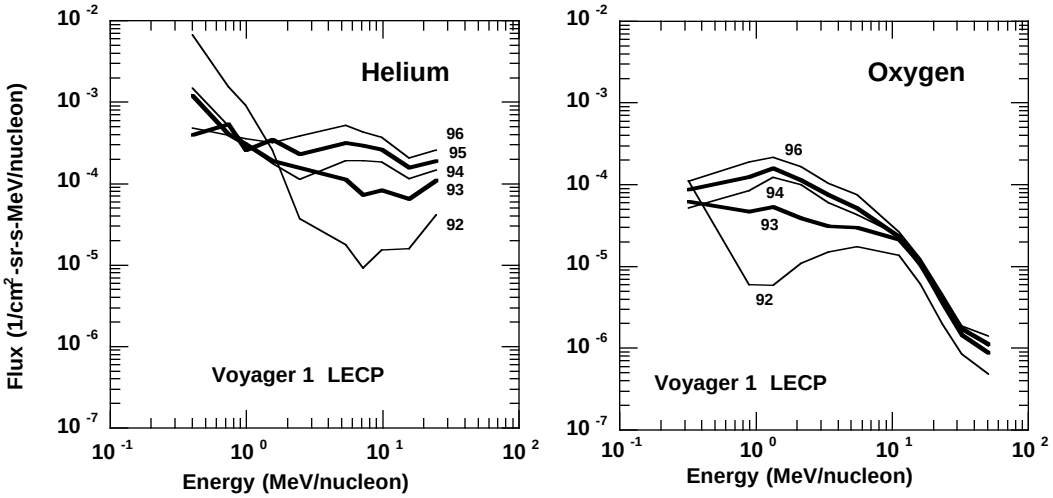


*Fig. 1. Evolution of the yearly-averaged helium and oxygen energy spectra at Voyager 1 for the five years 1992-1996.*

relative maximum at 5-6 MeV/nucleon in 1996 as the modulation of the ACR component declined. The factor of 30 change at these energies from 1992 to 1996 was accompanied by a smaller factor of 5 increase at 25 MeV/nuc, the highest helium energy measured. Below about 1 MeV/nuc, however, an opposite trend is observed as a relatively high flux associated with CIR activity in 1992 decreasesd with time as that activity subsided.

The oxygen spectra show a somewhat similar behavior. A relative flux minimum at about 1.2 MeV/nuc in 1992 filled in to become a relative maximum by 1994 and continued to increase until 1996. The oxygen flux increased by a factor of about 40 overall at 1.2 MeV/nuc with an accompanying monotonic increase of about a factor of 3 at the highest oxygen energy measured, 51 MeV/nuc. The 1992 oxygen spectrum also showed the effect of the interplanetary activity at Voyager 1 that year but only at the lowest energy measured, about 0.3 MeV/nuc. In fact for the years 1994-1996, the oxygen flux all the way down to 0.3 MeV/nuc increased slowly with time as if participating in the ACR recovery and showing essentially no evidence of local interplanetary acceleration.

## VARIATIONS IN FLUXES

The fluxes of protons, helium and oxygen ions at about 1 and 10 MeV/nuc from both Voyager 1 and Voyager 2 are plotted in Figure 2. These are annual averages, and the values are plotted at the average heliocentric distance of each spacecraft for each of the five years from 1992 to 1996. The 1 MeV protons decreased with time at both spacecraft as interplanetary activity quieted with considerably lower levels being reached at Voyager 1 in 1995-1996. A similar decrease was observed in the 1 MeV/nuc helium at Voyager 2, but at Voyager 1 flux levels were relatively constant after a large decrease from 1992 to 1993. The 1 MeV/nuc oxygen increased monotonically at both Voyager 1 and 2, the flux at Voyager 1 being about a factor of 2 higher at Voyager 1 except for 1992.

At 10 MeV/nuc the proton and helium fluxes both increased monotonically from 1992 to 1996. The helium increased by factors of 25-30 at both spacecraft. The increase in the protons was larger at Voyager 1 (a factor of 9) than at Voyager 2 (a factor of 3). The 10 MeV/nuc oxygen flux increased by less than a factor of two and was slightly higher at Voyager 1.

## VARIATIONS IN FLUX RATIOS

The data from Figure 2 were combined to produce H/He and He/O ratios that are displayed in a similar format in Figure 3. The 1 MeV/nuc H/He ratio at Voyager 2 varied between 19 and 39,

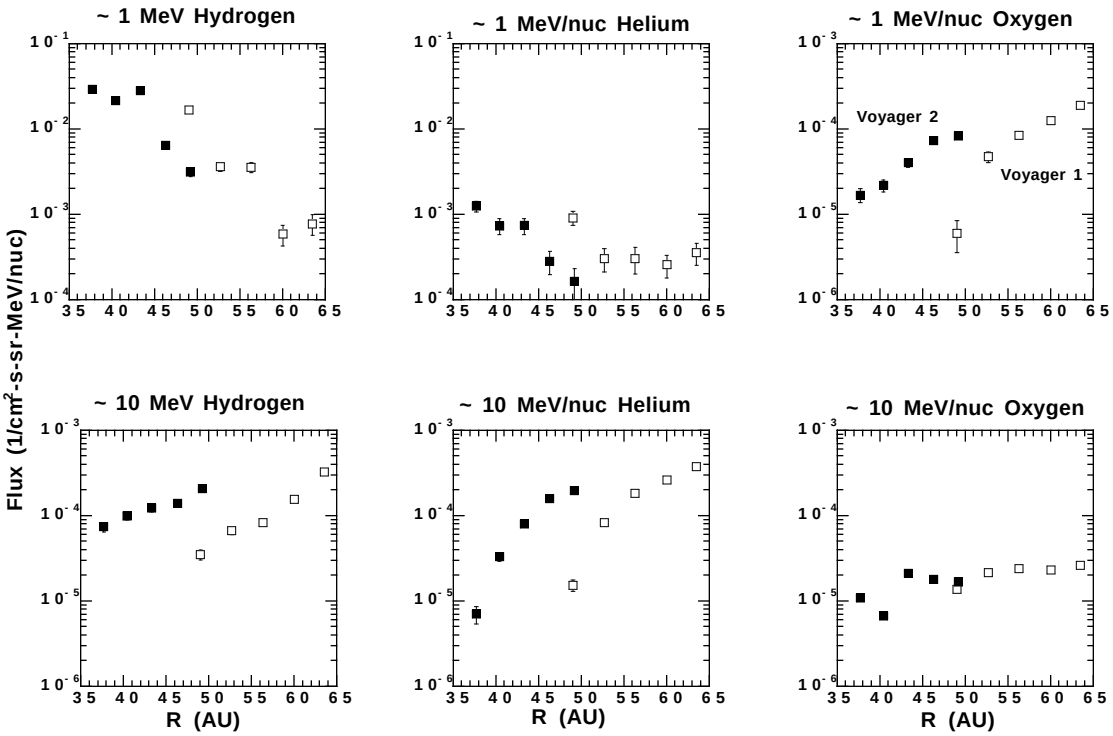


*Fig. 2. Yearly-averaged fluxes of ~1 MeV/nucleon (top row) and ~10 MeV/nucleon (bottom row) protons, helium, and oxygen for the six years 1992-1996. Filled squares are from Voyager 2 and open squares are from Voyager 1. The five data points from each of the two spacecraft are plotted at the average heliocentric distance during each year.*

typical solar particle abundance ratios. At Voyager 2 the ratio began at 18 in 1992 but dropped to about 2 in 1995 and 1996 as the proton flux decreased. The 1 MeV/nuc He/O ratio decreased markedly from a solar-type value of 70 at Voyager 2 in 1992 to about 2 in 1996 as the ACR oxygen made its recovery. The decline at Voyager 1 was even larger with the largest drop occurring between 1992 and 1993.

At 10 MeV/nuc the H/He ratio at Voyager 2 declined from a value of 10 in 1992 to about 1 in 1995-1996. The ratio at Voyager 1 started at a lower level of 2-3 in 1992 and declined to even lower levels of 0.5 by 1994. The He/O ratios at both Voyager 1 and 2 increased from about 1 in 1992 to about 12 in 1996 as the ACR He at this energy recovered.

## DISCUSSION

The recovery of the ACR component over the years 1992-1996 was dramatic in the outer heliosphere. The LECP data reported here extend the results of the CRS instruments on Voyager 1 and 2 (e.g., Cummings and Stone, 1996) to lower energies by nearly a factor of ten. The peak in the anomalous oxygen spectrum at about 1.2 MeV/nuc is well observed in these data as is the less pronounced peak in the anomalous helium at about 5-6 MeV/nuc. In the quietest years of 1995 and 1996, we see little evidence for local acceleration of oxygen even down to 0.3 MeV/nuc, but the ACR flux continued to recover. This indicates that interplanetary pre-acceleration may not be an important requirement of ACR production. We shall continue to monitor these low energy fluxes as the Voyager spacecraft travel out of the heliosphere to search for an early indication of the approach of the heliospheric termination shock.

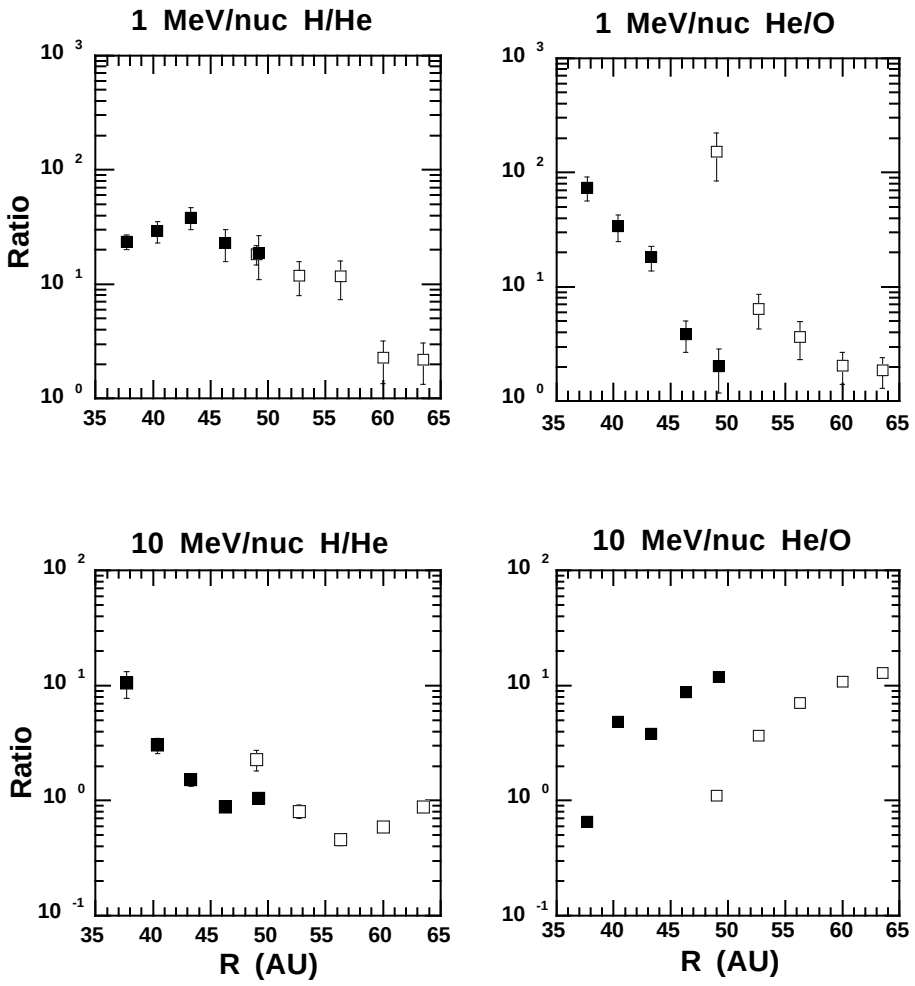


*Fig. 3. Yearly-averaged flux ratios at ~1 MeV/nucleon and ~10 MeV/nucleon. Data points from Voyager 1 (filled squares) and Voyager 2 (open squares) are plotted at their mean radial positions as in Figure 2.*

ACKNOWLEDGMENTS

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