Voyager Measurements of the Energy Spectrum, Charge Composition, and Long Term Temporal Variations of the Anomalous Components in 1977-1982

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We have used the large collecting area and wide energy range of the cosmic ray experiment (CRS) on Voyagers 1 and 2 to examine the energy spectra, charge composition, and long term temporal variations of the anomalous components in 1977-1982. Individual energy spectra are obtained for 17 separate quiet time periods during the time interval. The composite spectra of anomalous He, N, O, and Ne are obtained to a new level of precision. This includes the spectral shape and the relative abundance. Essentially, the spectral shape of N, O, and Ne appear to be similar. The ratios of anomalous N and Ne to O are found to be different from both the solar cosmic ray and galactic cosmic ray source composition. Some evidence is found for the enhancement of Ar as well. In the case of elements such as C, Mg, S, and Fe it is difficult to separate a possible lower intensity anomalous component from a quasi-steady interplanetary component that appears to be present at the lowest energies. The long term temporal variations of the anomalous He and O components have also been studied from 1977-82, a period from minimum to maximum in the modulation cycle. The tracking between these anomalous component intensities and the integral intensity of >75 MeV protons is striking; however, the intensity decrease of the anomalous components is much greater. Whereas the >75 MeV intensity decreases by a factor ~ 2 from 1977 to 1982, the 11.5 - 30 MeV/nuc anomalous He decreases by a factor ~ 20 and anomalous O between 4.5 - 14.7 MeV/nuc decreases by a factor ~ 50! Anomalous O is still observed at the lowest intensity levels, however.

INTRODUCTION

The origin of the anomalous components of low energy cosmic rays, of which He and O are the most obvious examples, presents many intriguing questions. One would like to know where and how these particles are accelerated, what their accelerated spectrum looks like, and indeed what their charge state is. Studies of the effects of solar modulation on these components, their radial gradients, and the relative composition of the various anomalous species should in principle provide answers to some of these questions. Previous studies of these components [e.g., *Bastian et al.*, 1979; *Klecker et al.*, 1977; *Webber et al.*, 1981] have usually been constrained by combinations of limited statistics and/or limited energy range and therefore cannot examine all of these questions completely. The Voyager 1 and 2 data, upon which this paper is based, overcomes several of these limitations, utilizing data from eight low energy telescopes (LET) with a total collecting area ~ 3.5 cm^2 sr, and four double ended high energy telescopes (HET) with a total collecting area ~ 4 cm^2 sr. The energy range covered, from ~ 4 - 124 MeV/nuc for oxygen nuclei, enables the transition from a quasi-steady interplanetary component at the lowest energies to the anomalous components and then to the galactic cosmic ray components at the highest energies to be observed. Individual energy spectra for the various charges are obtained for 17 separate quiet time periods during 1977-82. These quiet time intervals are restricted so that there is negligible contamination of the data for $Z \geqslant 2$ nuclei above ~ 4 MeV/nuc by corotating streams or solar energetic particles. Overall, these quiet time intervals contain about 65% of the total active time of the two spacecraft over the entire time period.

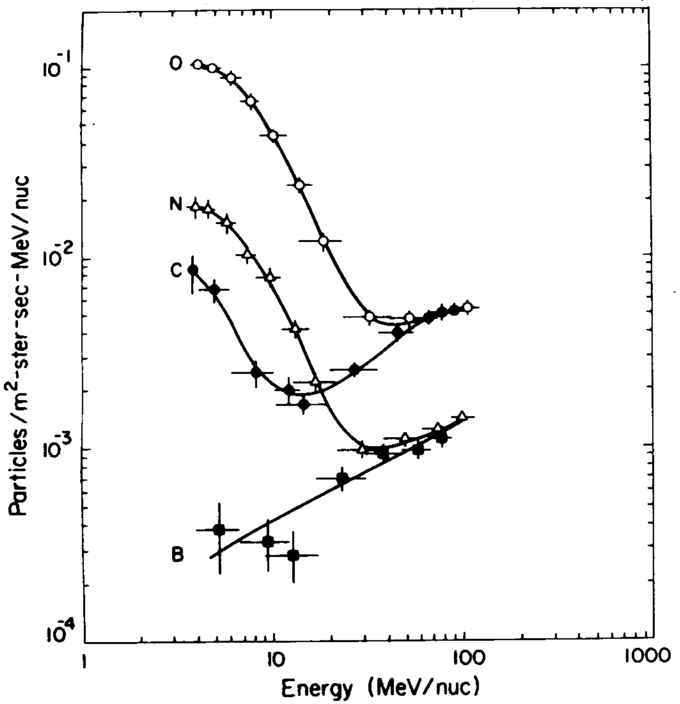

Fig. 1. Composite V1 and V2 spectra for B, C, N, and O nuclei.

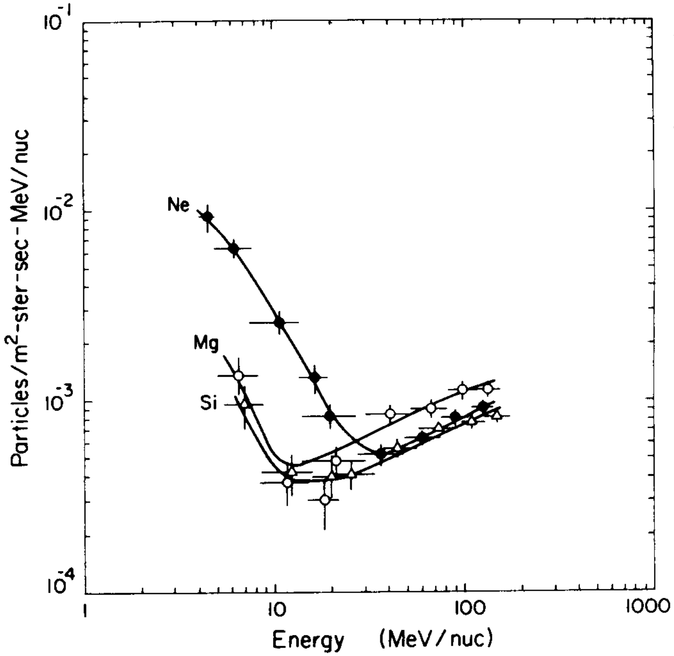

Fig. 2. Composite V1 and V2 spectra for Ne, Mg, and Si nuclei.

OBSERVATIONS - SPECTRA AND COMPOSITION

Composite spectra for the entire time period, constructed using both V1 and V2 data, are shown in Figures 1, 2, and 3. In Figure 1 the overall details of the anomalous oxygen spectrum are shown clearly, from the initial rise above the galactic component at ~50 MeV/nuc to the maximum intensity at ~5 MeV/nuc. The anomalous nitrogen spectrum is remarkably similar. The carbon spectrum falls off like a modulated galactic component down to ~10 MeV/nuc, below which it begins to increase. It never seems possible to be completely free of this low energy turn-up for carbon and it is not clear whether this is also an anomalous component, but at a much lower intensity, or a quasi-stationary interplanetary component, possibly originating on the Sun and probably accelerated separately from the anomalous components. The boron spectrum falls off like a modulated galactic component down to ~4 MeV/nuc with no evidence of a turn-up.

In Figure 2 the behavior of the anomalous neon component is shown clearly for the first time and looks very similar to that for N and O. The Mg and Si spectra look very similar to the C spectrum, exhibiting a fall off consistent with galactic modulation down to ~10 MeV/nuc with a turn-up at lower energies. The origin of this turn-up is probably similar to that for C. The S and Fe spectra in Figure 3 show a similar behavior although the turn-up below 10 MeV/nuc is not as well defined. The Ar spectrum shows evidence of a turn-up at lower energies and is well fit by the Ne spectrum divided by ~20. We believe that this is the first suggestion that Ar is enhanced as might be expected because of its high ionization potential.

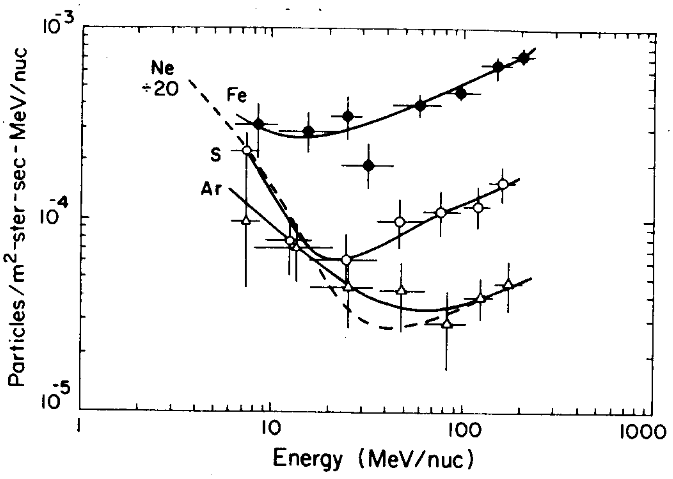

Fig. 3. Composite V1 and V2 spectra for S, Ar, and Ne nuclei.

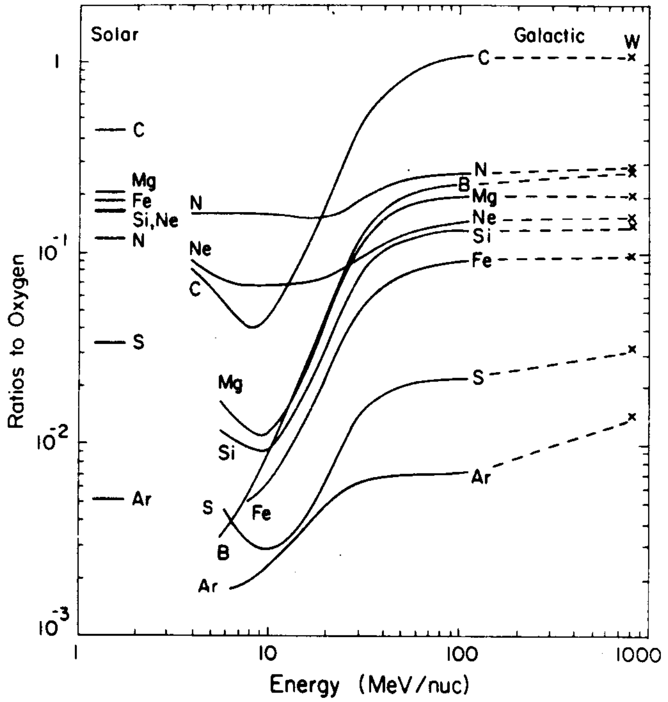

Fig. 4. Abundance of various charges relative to O derived from smooth curves drawn through the data in Figures 1, 2, and 3.

The abundance of the various charges as a function of energy is shown, relative to O, in Figure 4. The values on this Figure are obtained from smooth curves drawn through the data in Figures 1-3. Figure 4 illustrates a progression from a galactic composition above ~50 MeV/nuc, down to an intermediate energy range where the anomalous components are dominant, and to the energy range below a few MeV/nuc, where the abundance ratios should approach values more representative of the quiet time interplanetary components which may have a "solar" composition. This new data provides accurate determinations of the various galactic abundance ratios at ~100 MeV/nuc. These low energy ratios are in excellent agreement with ratios measured at higher energies [*Engelmann et al.*, 1981] and will be the subject of future study. At the lowest energies the turn-up in the C, Mg, and Si ratios toward the solar value is possibly indicative of a quiet time interplanetary component of solar composition as noted earlier.

At intermediate energies the behavior of the N and Ne ratios is almost identical to that of O indicating that all 3 anomalous components have essentially the same spectrum. However, the abundance ratios of these anomalous components change from the higher energy galactic value to a value that is also not equal to the solar value. The average observed values N/O = 0.16 and Ne/O = 0.07 for these anomalous components could be the result of a different composition of the source of these particles from that of the galactic or solar cosmic rays, or to preferential effects in acceleration and subsequent modulation, although this must be tempered by the fact that the resultant spectra are nearly identical. The Ar ratio is not well defined at low energies, but it appears that the anomalous Ar/O value must be less than the solar value of 0.005 as well.

OBSERVATIONS - TIME VARIATIONS

We next turn our attention to the long term temporal variations observed during the time period 1977-82. The striking and large short term variations are discussed in an accompanying paper. For the temporal variations we shall use the most abundant components - anomalous He and O as well as C as a reference. The variations of these components in 3 energy ranges are shown for the 17 quiet time intervals in Figure 5. It is seen that the amount of solar modulation is large and progressively increases as one goes to lower energies. C + O nuclei between 60 - 104 MeV/nuc represent the modulation of the galactic component - both C and O show identical variations in this energy range. The total intensity decrease of these components is a factor ~8. Helium in the energy range 11.5 - 30 MeV/nuc represents the peak of the anomalous He component. The overall decrease here is a factor of nearly 20. Oxygen in the energy range 4.5 - 14.7 MeV/nuc represents the peak of the anomalous O component. The overall decrease here is a factor ~50! The variations of all 3 components ap-

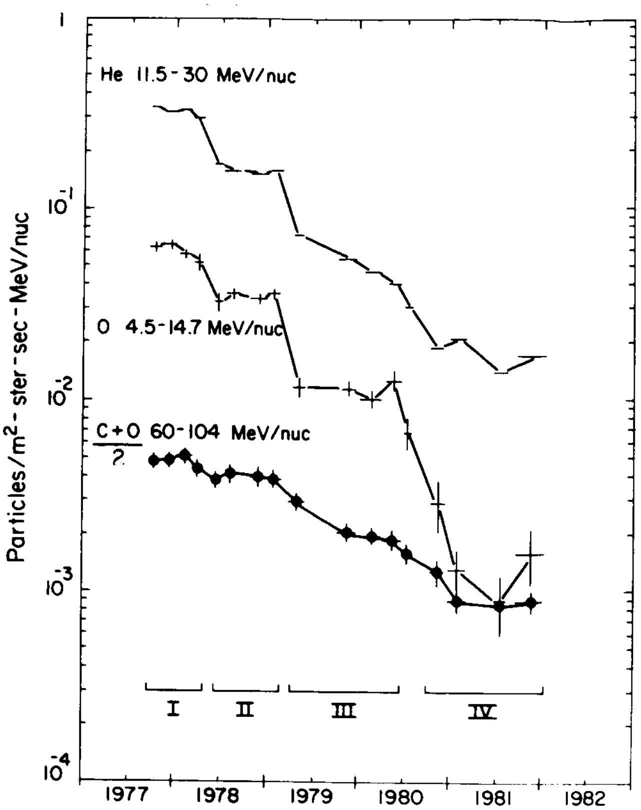

Fig. 5. Temporal variations of He, C, and O nuclei during the 1977-82 time period.

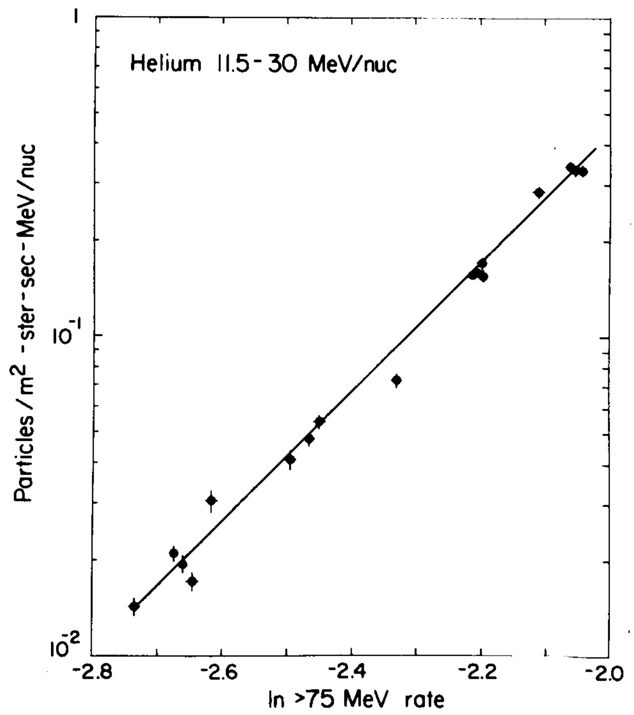

Fig. 6. Regression curve of 11.5 - 30 MeV/nuc He intensity and integral rate >75 MeV/nuc during the 1977-82 time period.

pear to track well despite a factor of 10 difference in energy and possibly different origins. The changes of these components also track closely the changes in the higher energy integral rate corresponding mainly to protons >75 MeV as indicated in Figure 6. [See also *Hovestadt et al.*, 1979, and *Webber et al.*, 1979, for earlier studies.]

It is to be noted that the intensity drops in several steps and for each step the intensity remains roughly constant for several months to a year or longer. For a detailed analysis of spectral changes we have, therefore, grouped the data into 4 separate time intervals as indicated in Figure 5. The He and O spectra observed for these 4 intervals are shown in Figures 7 and 8. Only spectral points are shown in these figures that are uncontaminated by lower energy particles of solar or interplanetary origin. It is clear that there are large and dramatic changes in the spectra of the anomalous components, although a clear signature of anomalous O remains present even at the lowest intensities.

We have tried to analyze the intensity variations of all the components in a systematic manner by constructing plots of β ln (J_1/J_2) vs ρ (rigidity). (J_1 and J_2 are the intensities at two different times, β is the velocity.) The quantity β ln (J_1/J_2) is related to the modulation parameter of the steady state modulation theories. Even though there is considerable uncertainty about the applicability of these theories, plotting the relative modulation of the various components in this way should help to illustrate possible fundamental differences in modulation of the various charges. This data is shown in Figure 9. Consider first the C and O modulation. Carbon is assumed to be a normal A/Z = 2 component undergoing modulation. This also applies to oxygen above ~50 MeV/nuc where the spectra of C and O are the same. The rigidity equivalent to this energy is shown by a dashed line in Figure 9. Above this energy the modulation of these two charges should be identical and this is essentially what the data shows. Below this energy the spectra of C and O are different and the relative modulation of O clearly becomes progressively larger than for C. This might be accounted for purely by the difference in spectra of the two components coupled with the effects of energy loss, or by this fact plus the additional assumption that anomalous O has a different A/Q than C (e.g., O is singly charged as in the model of *Fisk, Kovlovsky, and Ramaty* [1974]).

Comparing now the modulation of two anomalous components He and O we see that, at the same rigidity, the modulation of He is always larger than O. This is true even though the He spectrum is flatter than O; thus it is not easy to account for this difference purely in terms of differences in spectral shapes which should act to produce a larger O modulation in conventional theories because of the larger

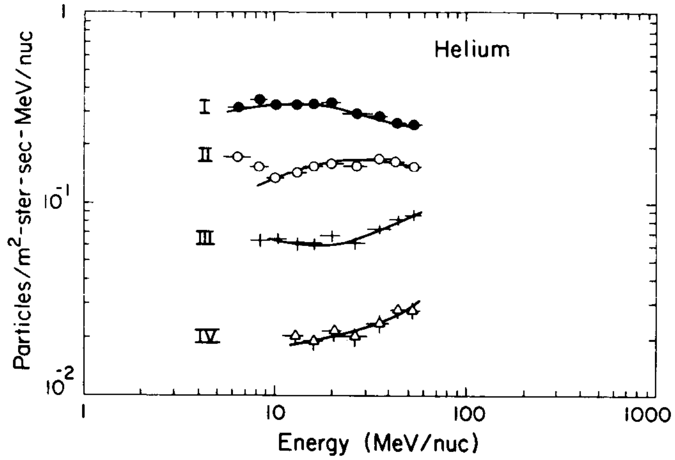

Fig. 7. Helium spectra measured during four time periods.

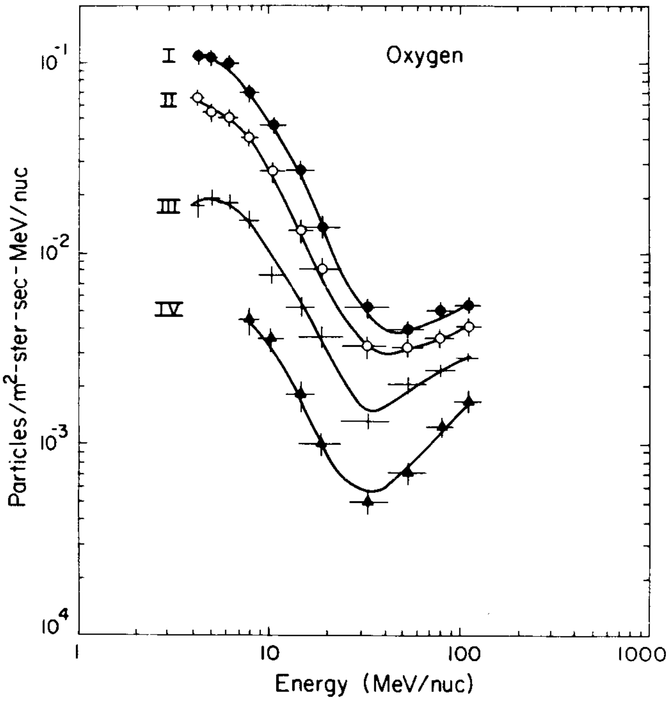

Fig. 8. Oxygen spectra measured during four time periods.

Compton-Getting coefficient associated with the spectrum.

We are continuing to study the implications of this modulation. We are hopeful that having accurate modulation data from 3 charges in overlapping energy ranges and with different spectra should enable one to uniquely determine the A/Z of the charges involved, with a minimum of necessary assumptions regarding the modulation itself.

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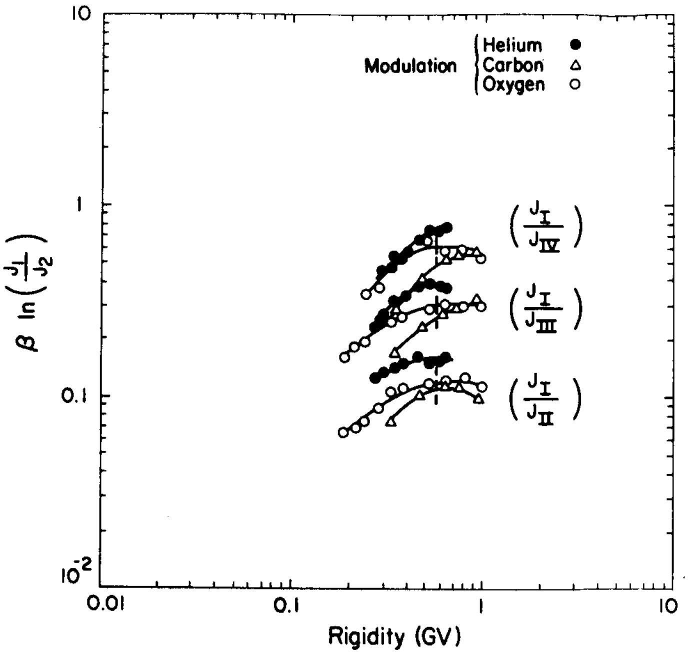

Fig. 9. Modulation parameters observed for He, C, and O nuclei intensity changes in 1977-82.

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