Studies of Low Energy Cosmic Rays - The Anomalous Component

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We have used data from the cosmic ray subsystem on the Voyager spacecraft to measure the spectra of He, C, N, O, and Ne with ~4-124 MeV/nuc (for O) near 1 AU. By subtracting both a low-energy solar/interplanetary component and the high-energy galactic component we have determined the energy spectra of the anomalous cosmic ray species He, N, O, and Ne. We suggest that the shapes of these spectra carry information about the charge state of the particles and the rigidity dependence of the diffusion coefficient. For similar power-law source spectra at the boundary of the modulation region, we find the location of features in the energy spectra indicate that the anomalous particles are singly ionized.

1. Introduction. The origin of the anomalous component of low energy cosmic rays, of which He and O are the most obvious examples, presents many intriguing questions, such as where and how these particles are accelerated, what their accelerated spectrum looks like, and what their charge state is. One possibility is that they are normal, fully ionized particles, presumably arriving from outside the solar system. The other is that they are singly charged particles accelerated in the solar system from local interstellar neutrals penetrating the solar system [*Fisk et al.*, 1974]. This latter model provides a natural explanation for why only particles with 1st ionization potentials ⩾13.6 eV are observed to be anomalous.

Previous studies of this component [e.g., *Klecker et al.*, 1977; *Bastian et al.*, 1979; *Webber et al.*, 1981] have usually been constrained by limited statistics or limited energy range. The Voyager 1 and 2 data, upon which this study is based, overcomes 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 similar collecting area. The measured energy range includes the solar/interplanetary component with a steep spectrum at the lowest energies, the anomalous component at the intermediate energies, and the galactic component at the highest energies.

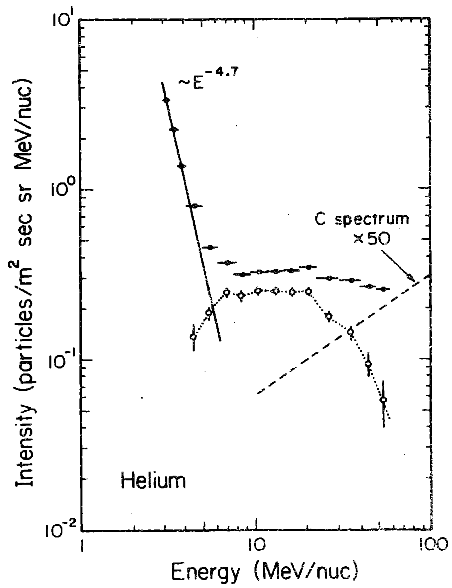

Fig. 1. Composite V1+V2 quiet-time He spectrum for Sept. 1977-Feb. 1978 time period. Quiet-time solar/interplanetary component is shown as a solid line and estimated galactic component scaled from C is shown as the dashed line. Resulting anomalous component points (o's) are shown connected by the dotted line.

2. Data Analysis. In this analysis individual spectra are obtained for He, C, N, O, and Ne nuclei for a 90 day quiet period between September 1977 and February 1978. During this time period the Voyager spacecraft are near Earth and the cosmic ray intensity is at sunspot minimum modulation conditions. The quiet-time intervals are selected such that the 4.5-7.8 MeV/nuc He intensity is typically <0.7 particles/m^2 sec sr MeV/nuc.

The composite spectrum for He nuclei is shown in Fig. 1 and those for other nuclei in Figs.

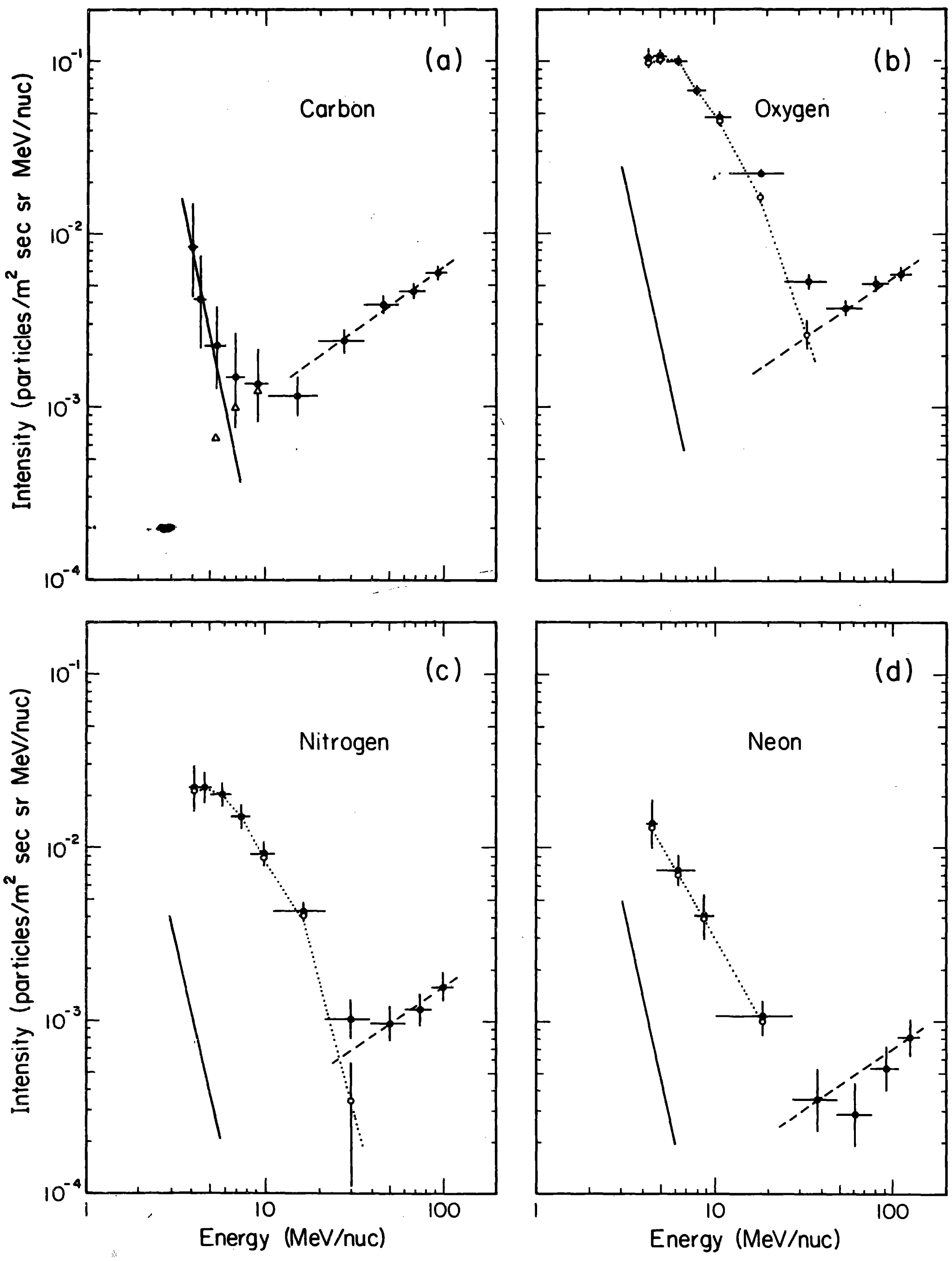

Fig. 2. Energy spectra of carbon (a), oxygen (b), nitrogen (c), and neon (d) for same period as in Fig. 1. The observed data are shown as solid circles. Estimated spectra of solar/interplanetary and galactic components are shown as solid and dashed lines, respectively. In (a) the Δ's are obtained by subtraction of solid line from data. In (b), (c), and (d) the spectra of anomalous cosmic rays are indicated by o's which are joined by the dotted lines.

2a, b, c, and d. It is to be noted that despite the stringent quiet-time criterion a turn-up exists in the low energy He and C spectra, presumably a low level solar or interplanetary component with a He spectrum proportional to $E^{-4.7}$. The solid lines in Fig. 2 are scaled from He assuming a charge composition similar to that for corotating events (He:C:N:O:Ne=16500:100:15:95:19) [*Gloeckler et al.,* 1979]. There is excellent agreement with the C data, suggesting that this low energy turn-up is of solar/interplanetary origin. The dashed lines in Figs. 1 and 2 show the estimated spectra of galactic cosmic rays scaled from the observed high-energy C spectrum with normalization of He:C:N:O:Ne=5000:100:25:91:11 [similar to ratios in *Garcia-Munoz and Simpson,* 1979]. Note that for C the subtraction of the solar/interplanetary component leaves a spectrum (triangles) consistent with a modulated galactic component with no evidence of an anomalous component. A limit $\leqslant 0.02$ can be placed on the ratio of anomalous C to O.

3. Interpretation of Data. The spectrum of anomalous He shows a peak in the 10-20 MeV/nuc region. The anomalous N and O spectra have regions with small slope, suggestive of a peak in the spectra near 5 MeV/nuc. Although the Ne spectrum is statistically less well-determined, there is no evidence for a peak down to ~ 4 MeV/nuc. Despite the differences in apparent peak locations, the general features of the spectra of the four species are very similar [also, see *Klecker et al.,* 1977]. We will now show how these spectral similarities provide information on the origin and charge state of the anomalous component.

Cosmic ray spectra observed near Earth are determined both by the spectra at the boundary of the modulation region and by interplanetary propagation conditions. Recently, *Fisk* [1983] has proposed that the acceleration of the anomalous component occurs at the solar wind termination shock and results in spectra for He and O which are similar in shape at the shock. His calculations show that if the input spectra at the modulation boundary are similar, then characteristic spectral features observed near Earth, such as spectral peaks, should occur at an energy for each species for which the particles have the same interplanetary diffusion coefficient κ. In general, $\kappa \sim \beta R^{\gamma}$, where β is the particle velocity and R is rigidity. For non-relativistic particles, with energy E in MeV/nuc, $R \sim AE^{1/2}/Z$ and $\beta \sim E^{1/2}$, so that $\kappa \sim (A/Z)^{\gamma} E^{(\gamma+1)/2}$. Thus for a given value of κ, the corresponding particle energies scale as

$$f_E(Z,A) \sim (A/Z)^{-2\gamma/(\gamma+1)} \qquad (1)$$

For fully ionized particles with A/Z=2, the energy scaling factor f_E is independent of Z and the location of the peaks in the spectra should occur at the same value of energy/nucleon, as is observed for several galactic cosmic ray nuclei such as C, O, Ne, Mg, and Si [*Garcia-Munoz et al.,* 1979] but not for the anomalous species shown in Figs. 1 and 2. For singly ionized particles (Z=1 in equation 1), $f_E \sim A^{-2\gamma/(\gamma+1)}$ and the spectra should peak at different energies for particles with different A.

The above argument suggests, for example, that the spectrum of O when scaled by an appropriate factor (f_E) would match that of He. In order to empirically determine these energy scaling factors for the anomalous component, we used the anomalous O spectrum as the reference spectrum (dotted line in Fig. 2b) and scaled the other spectra in energy and intensity to obtain the best fit to it. In each case the minimum reduced χ^2 was $\leqslant 1$ indicating that a good fit was obtained. The values of the energy scaling factors which minimized the χ^2 of the fit between the spectra are shown in Fig. 3. The one sigma uncertainties correspond to values of $f_E(Z,A)$ which gave $\chi^2=(\chi^2)_{min}+1$. The solid lines in Fig. 3 show the dependence of f_E on A for various values of γ, assuming Z=1. The dashed line at f_E = 1 indicates the mass-independent scaling factor for fully ionized particles.

It is clear from Fig. 3 that the observed mass dependence of f_E is inconsistent with an assumption that the particles are fully ionized. On the other hand, if the particles are assumed to be singly ionized then the mass dependence of the scaling factor is consistent with $\gamma \approx 0.7$-0.9. This value is consistent with results from solar particle and interplanetary radial gradient studies [see, e.g., *Palmer,* 1982].

Similar considerations should apply to the modulation of galactic cosmic rays of different A/Z. The peaks in the spectra for hydrogen (A/Z=1) and helium (A/Z=2) would be expected to occur at the same value of κ if the unmodulated spectra were power-laws in kinetic energy.

Measurements of these spectra at the same time in 1977-78 give a hydrogen peak at ~300 MeV/nuc and a helium peak at ~200 MeV/nuc [*Webber and Yushak*, 1983], indicating that with this simple model, γ is ~0.4, somewhat smaller than the above value. This difference may indicate that the input spectra are not simple power-laws in kinetic energy.

We also note that *Klecker* [1977] made quantitative calculations of the expected spectra and intensities of the anomalous cosmic ray species, assuming the particles are singly ionized and deriving the spectra at the boundary of the modulation region from the transit-time damping model of *Fisk* [1976]. He was able to adequately reproduce the observed spectra by using $\kappa \sim \beta R$. However, his accelerated spectra were not similar in shape for all charges and his peak locations differ somewhat from the simple scaling expected from equation 1. It is, of course, possible to produce arbitrary peak locations for the anomalous cosmic ray particles, whether singly or fully ionized, if the spectra at the boundary are not constrained to be similar for the different charges. We are suggesting, however, that a simple model in which the anomalous component is singly ionized may account for the observed spectral features of both the galactic and anomalous components.

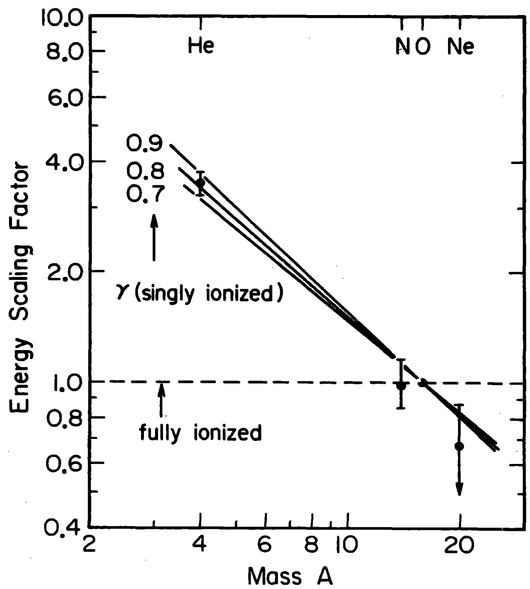

Fig. 3. Energy scaling factor f_E (defined in text) versus mass A. Determination of the data points is described in text. The solid lines show the expected dependence on mass for singly ionized particles for 3 values of γ (in $\kappa \sim \beta R^{\gamma}$). The dashed line at $f_E = 1$ indicates the expected value for fully ionized particles with A/Z=2.

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