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MULTIPLY CHARGED ANOMALOUS COSMIC RAYS ABOVE 15 MEV/NUCLEON

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ABSTRACT

Ionic charge states of anomalous cosmic ray nitrogen, oxygen, and neon with kinetic energies above 15 MeV/nucleon have been measured using the geomagnetic field as a rigidity filter. Data from the MAST instrument on the polar-orbiting SAMPEX satellite taken during the period from 1992 to 1996 show that all three elements are predominantly multiply charged at high energies, confirming the earlier result for oxygen alone based on a smaller data set. Energy spectra of the singly charged and multiply charged components of each element are compared with model predictions.

INTRODUCTION

The ionization states of the anomalous cosmic rays (ACRs) have not been measured directly, but have been inferred from geomagnetic cutoff locations with measurements from the polar orbiting satellite SAMPEX. At low energies the ACR oxygen are predominantly singly ionized (Klecker et al., 1995) while at higher energies ($E \gtrsim 20$ MeV/nucleon) they are predominantly multiply ionized (Mewaldt et al., 1996). We have now extended these results using a larger data set from the MAST instrument on SAMPEX, and measured the ionic charge states of ACR nitrogen, oxygen, and neon.

The distributions of the N, O, and Ne ions in kinetic energy E and invariant latitude Λ are shown in Figure 1. The data were taken during the period from July 1992 through February 1997, excluding ~100 days when significant solar energetic particle fluxes were evident and excluding the trapped ACR component (Selesnick et al., 1997). Also shown are curves representing the approximate vertical cutoffs for low charge states and the fully stripped charge state of each element. The galactic cosmic rays (GCRs) are generally located at latitudes higher than the fully stripped cutoff, while the low energy ACRs extend to the charge state 1 cutoff. Particles observed between the the charge state 2 and fully stripped cutoffs can be multiply charged ACRs. While the charge state of a single particle cannot be uniquely determined, the distribution of charge states in a population of particles can be estimated.

DATA ANALYSIS

The analysis technique is similar to the one used previously (Mewaldt et al., 1996), but instead of binning the data by invariant latitude, we use the coordinate $Q^* = Q\mathcal{R}/\mathcal{R}_c$ which represents an approximate upper limit to the true charge state Q. As a function of Q^* instead of Λ the cutoff locations corresponding to a given cutoff rigidity $\mathcal{R}_c$ are nearly independent of energy. The product of Q with the rigidity $\mathcal{R}$ is simply the momentum p which is measured for each particle, so Q^* is easy to calculate.

The data are binned by Q^* and E, and effective geometry factors for each bin and each possible charge state are calculated by Monte Carlo integration. Particle trajectories generated at intervals along the SAMPEX orbit are required to be above cutoff for the given E and arrival direction, to enter through the MAST aperture for the given satellite orientation, and to satisfy the same selection criteria as are applied to the real data. Effective livetimes are also obtained separately for each E bin by summing the true livetimes during the time spent in each Q^* bin.

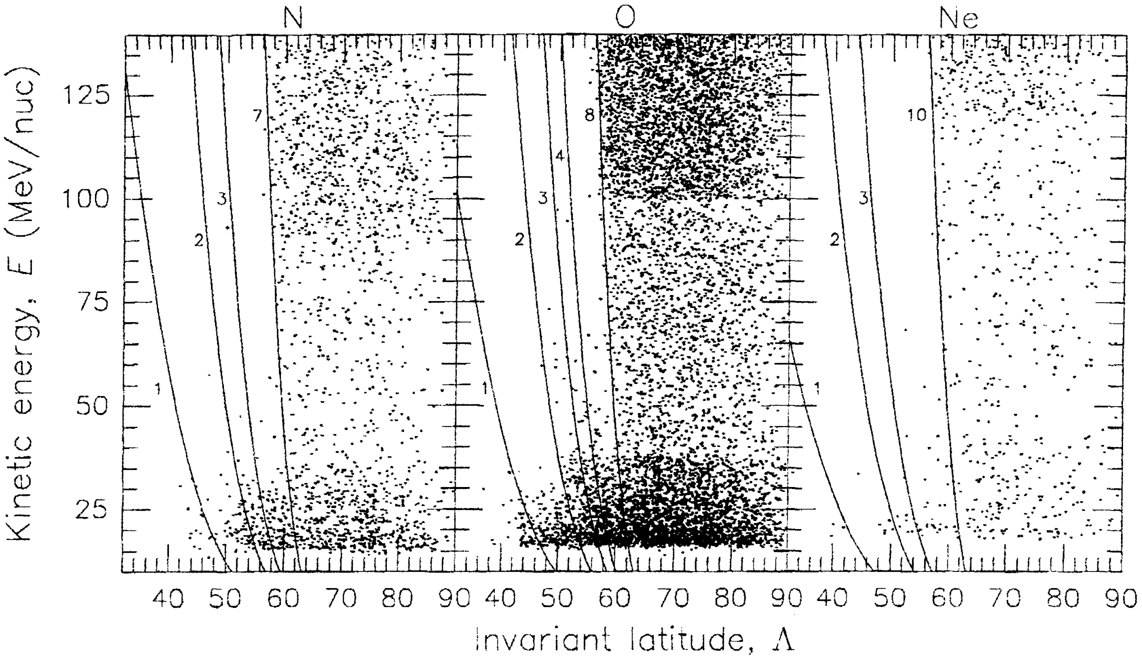

Fig. 1: Energy versus invariant latitude for the individual N, O, and Ne ions included in the data analysis. Vertical cutoff locations (solid curves) are labeled by charge state. The bands of lower data density at mid-energies are due to non-continuous coverage (a malfunctioning detector was turned off after July 1994) which is accounted for in the data analysis.

The observed counting rate in each Q^* and E bin is linearly related to the intensities for each ACR charge state by the set of effective geometry factors. Inverting this relationship, we find the maximum likelihood set of intensities based on Poisson counting statistics and with the additional constraint that all intensities be non-negative.

Examples of such fits to the data are shown in Figure 2. The energy ranges of the data are from 15 to 100 MeV/nucleon for N, 16 to 100 MeV/nucleon for O, and 18 to 100 MeV/nucleon for Ne. These ranges are divided into 6 logarithmically spaced bins. The Q^* bin boundaries are at integer values. Histograms of the rate versus Q^* for the third energy bin are shown in the figure along with the fit to the data representing the sum of all of the charge states included, which were 1, 2, 3, and 7 for N, 1, 2, 3, 4, and 8 for O, and 1, 2, 3, and 10 for Ne. The contributions of the different charge states can be seen from the large steps in the model histogram. If only $Q = 1$ ACRs were present then the only significant step would be at the fully stripped charge state, representing the contribution of the GCRs.

Results of the model fits are shown in the form of energy spectra of the ACRs in Figure 3. The $Q = 1$ contributions are shown separately, while the contributions of $Q > 1$ charge states have been combined because of statistical and model uncertainties. The total spectra for all charge states do not include the GCR (fully stripped) contribution. These results show that the ACR N, O, and Ne all are multiply ionized at high energies and singly ionized at low energies, confirming the previous result for O only that was based on a smaller data set. The energies below which the charge states are predominantly singly ionized and above which they are predominantly multiply ionized are 26 ± 4 MeV/nucleon for N, 23 ± 2 MeV/nucleon for O, and $\lesssim 21$ MeV/nucleon for Ne.

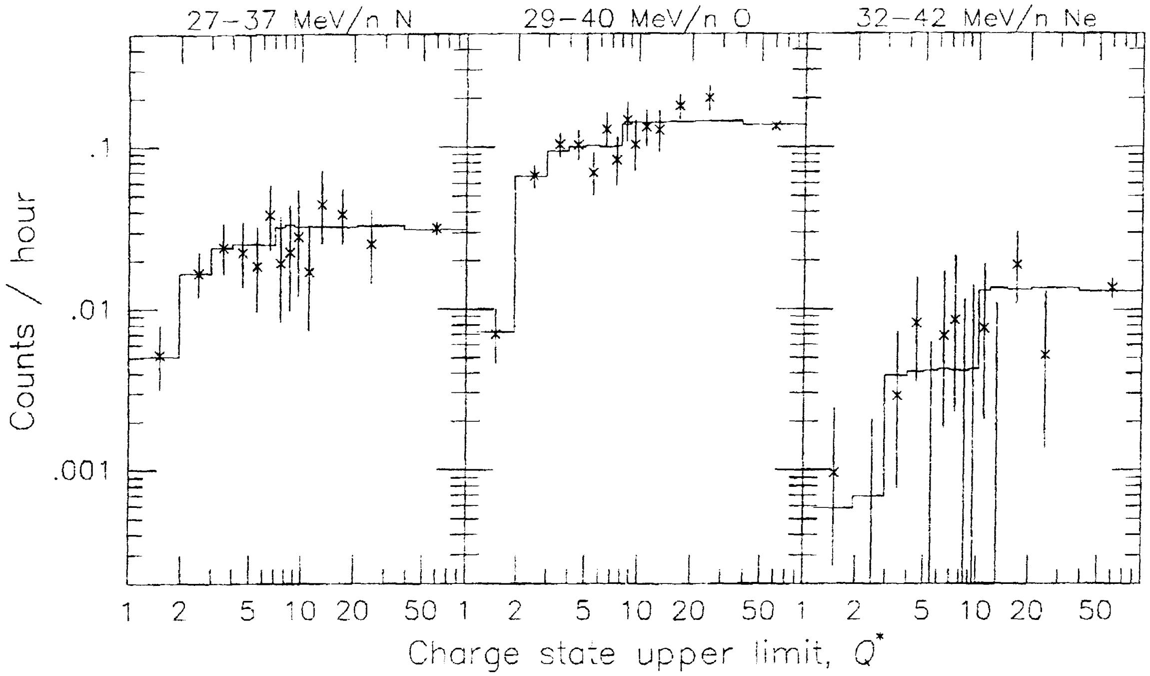

Fig. 2: Observed counting rates (data points with error bars) versus charge state upper limit from the third energy interval for each element, and model fits to the data (histograms) based on a combination of charge states.

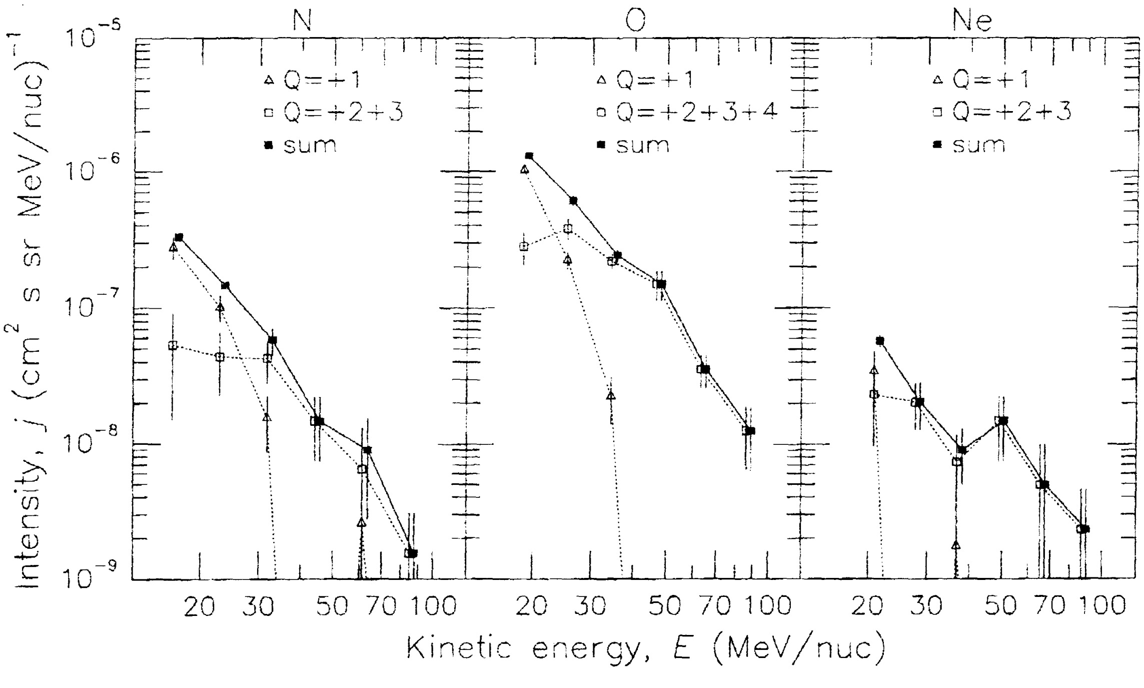

Fig. 3: Energy spectra for ACR N, O, and Ne. The $Q = 1$ and $Q > 1$ contributions are shown separately (dotted lines). The data points are plotted at the geometric means of the energy intervals, except those for the sum of all charge states (solid symbols) are shifted to slightly higher energies for clarity.

DISCUSSION

Multiply charged ACR oxygen was explained by Mewaldt et al. (1996) as a result of additional electron stripping during the acceleration process at the solar wind termination shock, after the initial ionization, pick-up, and transport by the solar wind. This placed new constraints on the acceleration time-scale and also helped to explain how ACRs can be accelerated to high energies. Detailed modeling of the acceleration and stripping processes was done by Jokipii (1996). We have confirmed the expectation that further electron stripping should also occur during the acceleration of other ACR ions. The variation with energy of the relative abundances of the singly charged and multiply charged ACR components can provide a strong constraint on acceleration models. In particular, the decreasing energy per nucleon with atomic number above which the multiply charged components are dominant, observed for N, O, and Ne, is consistent with an electrostatic acceleration mechanism producing common spectra in total energy per charge.

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