

8. The Ionic Charge Composition of Anomalous Cosmic Rays

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8.1. INTRODUCTION

It is now generally accepted that the source of ACRs is interstellar neutral particles, which become ionized by either solar UV or by charge exchange with solar wind protons, and are then convected with the solar wind and accelerated in the outer heliosphere as originally proposed by Fisk *et al.* (1974). The unique prediction of this theory was that ACR ions should be singly charged, in contrast to solar energetic particles (SEP) or galactic cosmic rays (GCR), which have high charge states. The hypothesis of an interstellar source was supported by a number of indirect methods to determine the ionic charge based on modulation arguments (see e.g. Klecker, 1995 for a recent review). Only recently was the theory fully confirmed by a more direct measurement of the ionic charge of ACRs using the Earth's magnetic field as a magnetic spectrometer: at energies of ≈ 10 MeV/nuc a mean ACR oxygen charge of $0.9 (+0.3 / -0.2)$, Adams *et al.*, 1991), $O^{2+}/O \lesssim 15\%$ (Klecker *et al.*, 1995), and a large number of N^+ and Ne^+ ions at low magnetic latitudes (Klecker *et al.*, 1995) have been found. More recently, multiply charged ACR oxygen has been discovered at energies $\gtrsim 16$ MeV/nuc (Mewaldt *et al.*, 1996b) and it has been shown that the abundance is roughly consistent with charge exchange cross sections and acceleration at the termination shock (Jokipii, 1996).

In this report we summarize the present status of the ACR ionic charge analysis. With the now much improved statistics of more than 3 years of SAMPEX data, the determination of the ionic charge composition has been extended to the energy range 8–100 MeV/nuc (for oxygen) and to the less abundant elements nitrogen and neon.

8.2. OBSERVATIONS OF THE IONIC CHARGE COMPOSITION OF ACR IONS

The observations summarized here were made with instruments on board the SAMPEX satellite, which was launched into a 510×675 km, 82° inclination Earth orbit on July 3, 1993 (Baker *et al.*, 1993). The ACR fluxes were measured with two sensors, the Heavy Ion Large Telescope (HILT, Klecker *et al.*, 1993) and the Mass Spectrometer Telescope (MAST, Cook *et al.*, 1993) which provide very large sensitivities of $60 \text{ cm}^2\text{sr}$ and $\sim 14 \text{ cm}^2\text{sr}$, respectively, and cover the wide energy range from ~ 8 –160 MeV/nuc (for oxygen) required for precise ACR studies. With the recent approach to solar minimum, ACR fluxes at Earth began rising significantly in early 1992 (Mewaldt *et al.*, 1993) with a gradual increase until 1996, providing sufficient counting statistics for ionic charge analysis.

The analysis of the ionic charge of ACR ions is based on the limiting ("cutoff") magnetic rigidity, or momentum per unit charge, P_c , for which a particle can reach

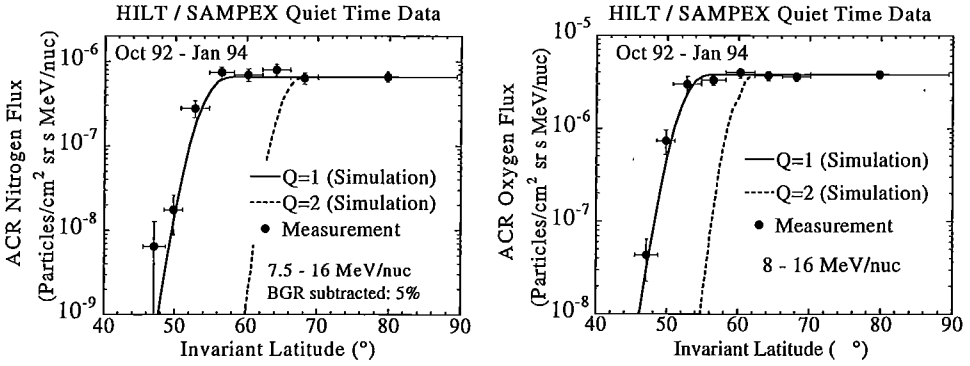


Figure 22. Flux of ACR nitrogen (left) and oxygen nuclei (right) in the energy range 8–16 MeV/nuc as a function of invariant latitude. The solid and dotted lines show the expected flux for singly and doubly ionized N and O, respectively.

the detector for a specific incident trajectory. If a non-trapped particle reaches the sensor, then the upper limit of the particle's ionization state, q_u , is given by

$$q_u = (mv)/(eP_c) \quad (12)$$

where m is the particle mass, v is the velocity, and e is the electron charge. Since m and v are determined by the measurement, the charge state upper limit, q_u , for each ion can be found by calculating the cutoff rigidity for its trajectory, and then using equation (12). The ionic charge composition can be derived from the measured flux as a function of invariant latitude (λ). This can be accomplished by comparing the measured intensity–profiles with calculations for different ionic charge states (see e.g. Klecker *et al.*, 1995; Mewaldt *et al.*, 1996b). Figure 22 shows, as an example of this method, the measured intensity–profiles for ACR nitrogen and oxygen in the energy range ~ 8 –16 MeV/nuc, together with the expected flux variation for singly and doubly ionized nitrogen and oxygen, computed with a relation between cutoff rigidity and invariant latitude derived from trajectory calculations. Figure 22 demonstrates that in the energy range 8–16 MeV/nuc the flux profile is consistent with ACR nitrogen and oxygen being predominantly singly ionized.

With another method introduced recently, instead of invariant latitude, the coordinate q_u , the upper limit of the ionic charge, q , is used for binning the data. In this representation the contributions from individual charge states, q_i , to the total intensity are step functions in q_u . The ionic charge composition can be derived with a least squares fit procedure from a superposition of step functions for the individual charge states q_i (Oetliker *et al.*, 1997b; Selesnick *et al.*, 1997). As an example, the measured charge profiles of oxygen in 5 energy bands between 8 and 26 MeV/nuc are shown in Figure 23 (from Klecker *et al.*, 1997). In this analysis four contributions were used for the fit of the charge distribution, $q = +1, +2, +3$, and ≥ 4 . Figure 23 demonstrates that the ionic charge composition of ACR oxy-

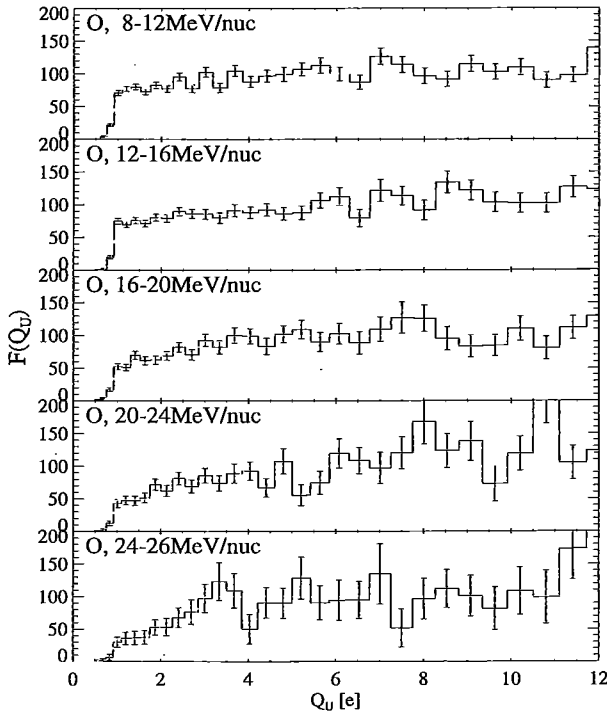


Figure 23. Ionic charge profiles with fit for 5 energy ranges of ACR oxygen between 8 and 26 MeV/nuc (from Klecker *et al.*, 1997).

gen in this energy range is continuously changing with energy, with singly ionized ions dominating at 8–12 MeV/nuc and higher charge states dominating above ~ 20 MeV/nuc.

The energy dependence of the ionic charge composition of ACR N, O, and Ne is shown quantitatively in Figure 24. Here we combined measurements of the charge composition in the energy range 8–100 MeV/nuc reported by Klecker *et al.* (1997) and Selesnick *et al.* (1997) and show the abundances of singly ionized N, O, and Ne relative to the sum of charge states 1–3 as a function of energy. It is evident from Figure 24 that not only ACR O, but also N and Ne at energies $\lesssim 20$ MeV/nuc are predominantly singly ionized. Above ~ 20 MeV/nuc the abundances of singly ionized ions fall off sharply and multiply charged ions become dominant. Figure 24 also suggests that the energy of the sharp drop, e.g. the energy where the abundances of singly charged ACR ions drop to 50% ($E_{50\%}$) is mass dependent, as was also pointed out by Selesnick *et al.* (1997). We estimated $E_{50\%}$ with a logarithmic fit of the abundances in the energy range of the sharp abundance drop ($E \gtrsim 13$ (10) MeV/nuc for N, O (Ne), dashed line in Figure 24). The corresponding values of $E_{50\%}$ are 25.5 ± 2.5 , 22 ± 2 , and 17.5 ± 2.0 (MeV/nuc) for N, O, and Ne, respectively. Although the statistical uncertainty is large, the results suggest a trend with higher-

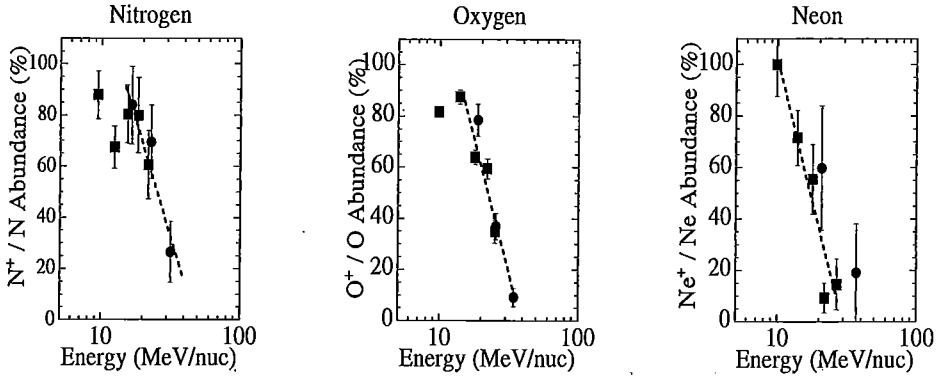


Figure 24. Relative abundance of singly ionized ACR N, O, and Ne as a function of energy (from Klecker *et al.*, 1997 (squares), and Selesnick *et al.*, 1997 (circles)).

mass singly-charged ACRs dropping off at lower energy per nucleon with a drop-off total energy of ~ 350 MeV.

8.3. DISCUSSION AND SUMMARY

The observations of the ACR N, O, and Ne ionic charge composition with SAMPEX show that singly charged ions, originally expected for the interstellar source suggested by Fisk *et al.* (1974), dominate only at energies below ~ 20 MeV/nuc. At higher energies, multiply charged ions become more abundant. It has been pointed out by Jokipii (1992) and Klecker (1995) that the low abundances of multiply charged ions at ~ 10 MeV/nuc place important constraints on the acceleration time scales in the outer heliosphere. The acceleration process has to be sufficiently fast to compete with losses by charge exchange reactions with the ambient interstellar neutral hydrogen and by adiabatic deceleration (see also Mewaldt *et al.*, 1996b). Figure 25 shows the time scale for stripping of O^+ as a function of energy per nucleon, using stripping cross sections compiled by Spjeldvik (1979), a neutral hydrogen density of 0.1 cm^{-3} , and assuming stripping of 30% of O^+ . Also shown are the convection time scales for a solar wind velocity of 400 km/s. Figure 25 illustrates that most of the stripping occurs at low energies of $\sim 0.1\text{--}1$ MeV/nuc, as pointed out by Mewaldt *et al.* (1996b), and that the convection time scales are of the order of the time scales for stripping at these low energies. This provides severe constraints for pre-acceleration models because it limits the transport time scales to the outer heliosphere at these low energies.

The dominance of ions with $q > 1$ at high energies implies that multiply charged ions have gained more energy during the acceleration process and explains how ACRs get accelerated to energies approaching 100 MeV/nuc (Mewaldt *et al.*, 1996a). This is consistent with most of the stripping occurring at low energies, and an acceleration of these multiply charged ions at the termination shock (see below).

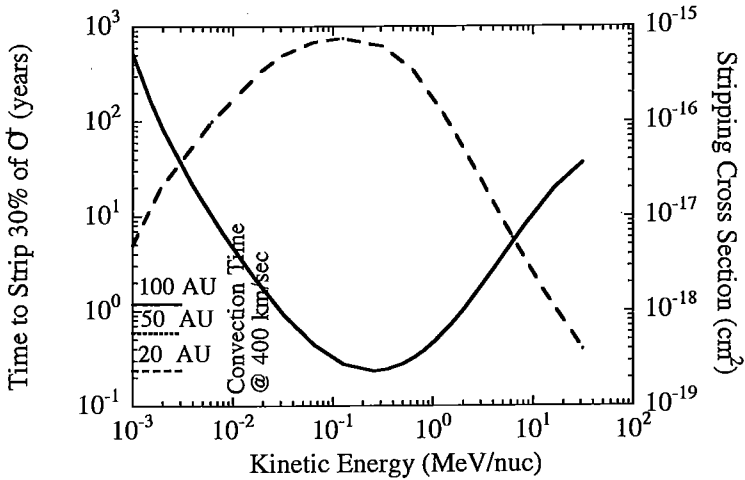


Figure 25. Charge exchange time scales for stripping 30 % of O^+ (solid line, left scale) and stripping cross section from Spjeldvik (1979) (dashed line, right scale). Also shown are the convection time scales for a 400 km/s solar wind.

It has been shown that acceleration at the quasi-perpendicular termination shock could also provide the necessary short time scale of the order of ~ 1 year (Jokipii, 1992). A recent detailed two-dimensional model calculation for the acceleration of ACR oxygen, including acceleration at the termination shock and charge exchange losses (Jokipii, 1996) is in reasonable good agreement with the observations of singly charged oxygen ions dominating below ~ 20 MeV/nuc. Above this energy the model also shows the dominance of the higher charge states, although with a somewhat larger mean ionic charge than observed (see also Section 7). This is possibly due to uncertainties in the oxygen charge exchange cross sections, which are not all well known.

The sharp drop of the abundance of singly ionized oxygen at ~ 20 MeV/nuc, however, is well reproduced by the model. This drop can also be qualitatively understood in terms of the characteristic energy, E_{\max} , the particles can gain at the termination shock:

$$E_{\max} = \max q \quad (13)$$

where $\max \sim 240$ MV, and q is the ionic charge of the ion (e.g. Jokipii and Giacalone, 1998). Equation (13) shows that for singly charged ions the characteristic maximum energy is 240 MeV, i.e. the characteristic energy per nucleon will be ordered by mass. Thus, for ACR N, O, and Ne the highest characteristic energy per nucleon can be expected for singly ionized ACR nitrogen, the lowest for neon with oxygen being in between. The observed variation of $E_{50\%}$, i.e. the constant value of $E_{50\%}$ (~ 350 MeV, see above) is in good agreement with this expectation. The precise value of the energy where the abundance of singly ionized ACR ions drops off depends, however, on an interplay between the acceleration and propagation

processes in the heliosphere. The presently available data on the ionic charge composition provide the basis for future more detailed comparisons of the ACR charge composition with model calculations.