THE ASTROPHYSICAL JOURNAL, 466:L43–L46, 1996 July 20

EVIDENCE FOR MULTIPLY CHARGED ANOMALOUS COSMIC RAYS

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Received 1996 March 27; accepted 1996 May 14

ABSTRACT

New measurements from the *SAMPEX* spacecraft show that most anomalous cosmic ray (ACR) oxygen nuclei with energies above 20 MeV nucleon^{-1} are multiply ionized, with ionic charge states of $Q = 2$, $Q = 3$, and probably higher. This new result contrasts with lower energies, at which most ACRs are singly charged. The observed abundance of multiply charged ions agrees with estimates of the fraction of singly charged ACRs that undergo electron stripping during acceleration if the timescale for acceleration to 10 MeV nucleon^{-1} is ∼1 yr. The existence of multiply charged ACRs helps explain their acceleration to high energies, and it has implications for several other studies.

Subject headings: cosmic rays — interplanetary medium — solar wind

1. INTRODUCTION

During the early 1970s, a new energetic particle component was discovered when anomalous enhancements were observed in the quiet-time energy spectra of He, N, O, and Ne with ∼5–50 MeV nucleon^{-1} (see review in Klecker 1995). The accepted explanation for these anomalous cosmic rays (ACRs) (Fisk, Kozlovsky, & Ramaty 1974) is that they originate from interstellar neutral atoms that have been swept into the heliosphere and ionized by solar UV or charge exchange with the solar wind to become solar wind pickup ions. The pickup ions are then convected into the outer heliosphere and accelerated to tens of MeV per nucleon, probably at the solar wind termination shock (Pesses, Jokipii, & Eichler 1981).

A fundamental prediction of the above theory is that ACRs should be singly charged, unlike Galactic cosmic rays (GCRs) or solar energetic particles. There is abundant evidence that the bulk of ACRs with ∼10 MeV nucleon^{-1} have an ionic charge state of $Q = 1$. Following several indirect tests of this prediction (e.g., Klecker et al. 1980; Cummings, Stone, & Webber 1984), Adams et al. (1991) found $Q = 0.9^{+0.3}_{-0.2}$ for 5–11 MeV nucleon^{-1} ACR oxygen by comparing orbit-averaged fluxes inside the magnetosphere with interplanetary fluxes. A more direct approach traces individual particle trajectories back through the geomagnetic field to place limits on the charge state (Oschlies, Beaujean, & Enge 1989; Singh et al. 1991), and recently, Klecker et al. (1995), using the Heavy Ion Large Telescope sensor on *SAMPEX*, found that more than 90% of 8–16 MeV nucleon^{-1} ACR oxygen is singly charged.

Another *SAMPEX* study (Mewaldt et al. 1996) used Earth's field to filter ACRs from GCRs and found that the spectra of ACR N, O, and Ne all extend to above 70 MeV nucleon^{-1}, several times the characteristic "maximum" energy expected for diffusive shock-drift acceleration at the termination shock (Jokipii 1990). To explain how ACRs could attain such high energies, Mewaldt et al. (1996) suggested that the highest energy ACRs may be multiply charged, in which case this acceleration process achieves greater energy per nucleon. In this Letter, we test the hypothesis that the highest energy ACRs have $Q > 1$.

2. OBSERVATIONS AND INTERPRETATION

The observations were made with the Mass Spectrometer Telescope (MAST) on the polar-orbiting *SAMPEX* satellite from 1992 July 7 to 1995 February 18. MAST measures the charge, mass, kinetic energy, and trajectory of incident ions, including oxygen from ∼16 to ∼160 MeV nucleon^{-1}. The measured kinetic energy versus invariant latitude (λ) for quiet-time oxygen events is shown in Figure 1, based on 865 days of data with daily average 8–15 MeV nucleon^{-1} helium fluxes of less than 4 (m^2 sr s)$^{-1}$. Invariant latitude is defined by $\cos^2 \lambda = 1/L$, where L is the McIlwain L-parameter (see, e.g., Roederer 1970). The approximate geomagnetic cutoffs for vertically incident O^+, O^{+2}, O^{+3}, O^{+4}, and O^{+8}, shown in Figure 1, are based on a modified Størmer dipole theory, described below.

Previous *SAMPEX* studies identified a population of N, O, and Ne ions near $\lambda = 45°$ originating from ACRs that have become trapped in the inner radiation belt. Selesnick et al. (1995) found that trapped ACRs with 16–50 MeV nucleon^{-1} have pitch angles of 60°–120° and are bounded in latitude by the requirement for adiabatic motion, characterized by $\epsilon Q < 1$ (dashed line in Fig. 1). Here $\epsilon = 3\mathcal{R}/(LR_{\rm E}B_0)$, where $\mathcal{R}$ is magnetic rigidity, $R_{\rm E}$ is Earth's radius, and B_0 is the equatorial magnetic field strength. Using these properties, we have excluded trapped ACRs from Figure 1 and this analysis.

From the observation of a single particle at a given latitude, it is possible only to determine an upper limit on its charge state because lower charge state particles also have access to that latitude. However, it is also possible to estimate the distribution of charge states in a particle population from their latitude distribution. The extent to which ACRs penetrate the geomagnetic field is evident in Figure 1. At low energies ($E < 30$ MeV nucleon^{-1}), ACR oxygen is observed at latitudes down to the O^+ cutoff. However, above 30 MeV nucleon^{-1} there are only three events observed at latitudes

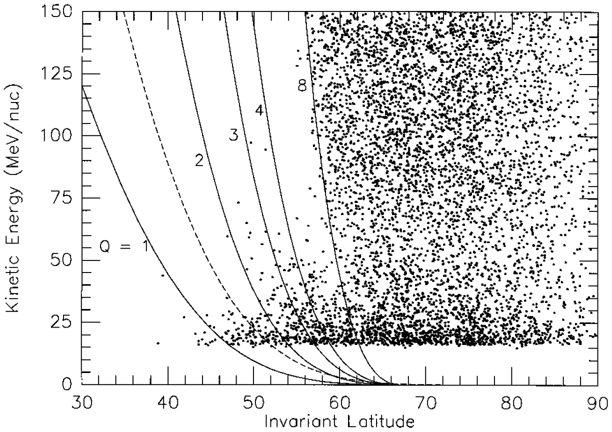

FIG. 1.—Measured energy per nucleon vs. invariant latitude for quiet-time oxygen events. Also shown are calculated vertical geomagnetic cutoffs for O^{+}, O^{+2}, O^{+3}, O^{+4}, and O^{+8} and the upper boundary for trapped ACRs (*dashed line*).

below the O^{+2} cutoff, compared to more than 30 between the O^{+2} and O^{+3} cutoffs.

Oxygen latitude distributions are shown in four energy intervals in Figure 2. To determine the distributions expected from a given charge state, we have used the Størmer theory for the cutoff in a dipole magnetic field with some empirical adjustments. A particle is assumed to have access if its rigidity is greater than the cutoff rigidity, given by

$$\mathcal{R}_c = \frac{C_s(\cos^4 \Lambda - \cos^4 \Lambda_o)}{R^2[1 + (1 - \sin\theta \cos\phi \cos^3 \Lambda)^{1/2}]^2}\,. \tag{1}$$

Here $C_s = 57.9$ MV is Earth's dipole moment converted to a rigidity, θ and ϕ are the trajectory zenith and azimuth angles, respectively (azimuth measured from east to north), and Λ and R are the magnetic latitude and equivalent radius from the dipole center, respectively (see, e.g., Roederer 1970). To account for the open polar cap, $\mathcal{R}_c$ includes an empirical offset, $\Lambda_o = 67° + D_{\rm st}/16.5$ (where $D_{\rm st}$ is a geomagnetic activity index), derived from solar particle observations (Leske et al. 1995). Included in Figure 2 are fits to the latitude distributions for (1) a mixture of only O^{+8} GCRs and O^{+} ACRs and (2) a mixture of O^{+}, O^{+2}, O^{+3}, and O^{+8}. In each energy interval, the charge state abundances were varied to obtain the best fit to all latitude bins above the O^{+} cutoff. It is clear that singly charged ACRs alone cannot account for the observations, particularly above 30 MeV nucleon^{-1}. Table 1 summarizes the reduced χ^2 for fits with maximum ACR charge states ranging from O^{+} to O^{+4}. In all but the lowest energy interval, the fits are significantly better when O^{+2} and O^{+3} are included. From 40 to 54 MeV nucleon^{-1}, O^{+3} is found to be the most abundant charge state, consistent with the improvement in the reduced χ^2 in Table 1. The need for O^{+4} in addition to O^{+2} and O^{+3} is not established.

TABLE 1

GOODNESS OF CHARGE STATE FITS

INCLUDED CHARGE STATES	REDUCED χ^2 (MeV nucleon^{-1} bins)			
	16–22	22–30	30–40	40–54
1, 8	1.79	1.66	3.38	2.45
1, 2, 8..................	1.87	0.83	0.93	1.35
1, 2, 3, 8...............	1.89	0.80	0.79	0.99
1, 2, 3, 4, 8	1.99	0.84	0.82	1.03

These results were checked with a Monte Carlo approach in which particle trajectories were traced backward by numerical integration through a geomagnetic field model that combined the 1992 International Geomagnetic Reference Field internal field with the Tsyganenko (1989) external field, modified to account for variations in geomagnetic activity (Boberg et al. 1995). Although this approach yields cutoffs ~2° higher than the modified Størmer cutoffs, the resulting fraction of multiply charged ACRs is similar. We present here the results of the Størmer approach, which agrees better with the observed GCR cutoffs and yields better overall fits.

Because the relative charge state abundances are subject to uncertainties in the geomagnetic cutoffs, we have combined the best-fit abundances of all $Q > 1$ species into a single quantity. The resulting energy spectra of $Q = 1$ and $Q > 1$ ACRs, along with their sum, are shown in Figure 3. Integrating these, we find that multiply charged ions account for ~50%–60% of ACRs above 16 MeV nucleon^{-1} and more than 95% of ACRs with energies greater than 30 MeV nucleon^{-1}. Extrapolating to lower energies using typical ACR spectral shapes (see below), we estimate that at 1 AU multiply charged ACRs constitute ~20% of the integral flux of ACRs above 1 MeV nucleon^{-1}.

3. DISCUSSION

It may seem surprising that such a large fraction of high-energy ACRs are multiply charged in light of their origin as pickup ions and the previous verifications that most ACRs are singly charged. However, these previous studies were either at lower energy or were not sufficiently precise to identify multiply charged ACRs. The presence of multiply charged ACRs implies either that the source population contains a large fraction of multiply charged pickup ions or that many ACRs are stripped of additional electrons during their acceleration. The first possibility is unlikely because the abundance of pickup He^{+2} is only ~2% of He^{+}, with the abundance of

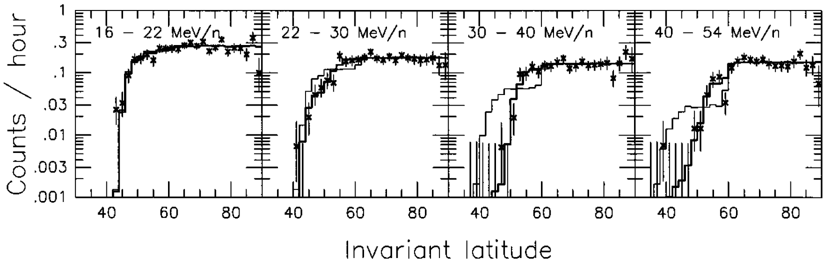

FIG. 2.—Measured latitude distributions of oxygen events in four energy intervals, along with fits to the distributions including charge states of $Q = 1$ and 8 (*light traces*) and $Q = 1$, 2, 3, and 8 (*dark traces*).

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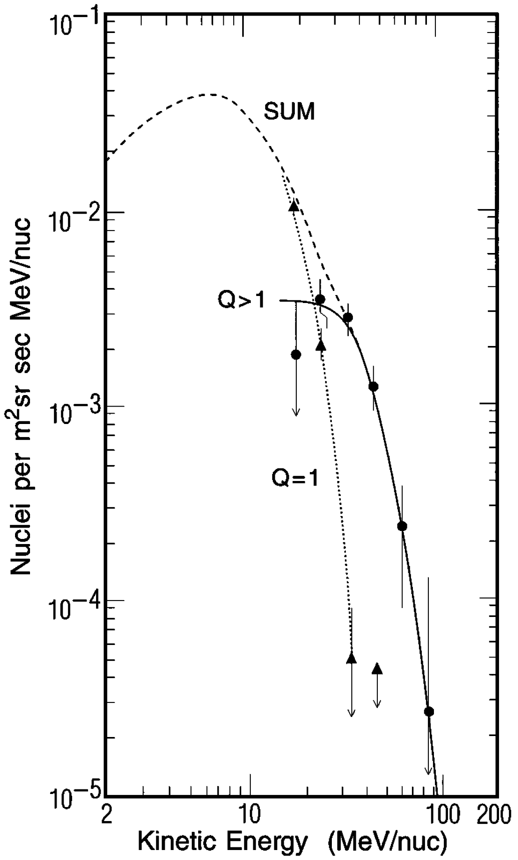

FIG. 3.—Measured energy spectra of singly and multiply charged ACRs, along with their sum (*dashed line*). The $Q > 1$ spectrum is the sum of the best-fit abundances of O^{+2}, O^{+3}, and O^{+4}. Smooth lines have been drawn through the points to guide the eye. Below 16 MeV nucleon^{-1}, the summed spectrum was estimated from other measurements (Mewaldt et al. 1993; Hasebe et al. 1994; Cummings et al. 1995).

multiply charged pickup oxygen expected to be much less (Geiss, Gloeckler, & von Steiger 1995).

To evaluate electron stripping during ACR acceleration, we use the model of Jokipii (1992), who estimated a minimum time of ~0.5 yr to accelerate O^+ to 10 MeV nucleon^{-1} at the termination shock (see also Klecker 1995). For a mean free path that is independent of rigidity, a reasonable approximation below ~1 GV (Palmer 1982), the acceleration time is proportional to rigidity. Using cross sections for stripping O^+ (Spjeldvik 1979) in an assumed neutral H density of 0.1 cm^{-3}, we have evaluated the fraction of ions stripped to various charge states. These fractions are shown in Figure 4 for an acceleration rate that achieves 10 MeV nucleon^{-1} in 1 yr. Note that, by 15 MeV nucleon^{-1}, ~30% of the O^+ is stripped to O^{+2}, O^{+3}, or O^{+4}, with most of the stripping occurring at energies of ~0.1–1 MeV nucleon^{-1}, where the cross sections are largest. It had previously been assumed that most stripping occurs at higher energies (Jokipii 1992; Klecker 1995). Similar results, with somewhat less stripping for a 1 yr timescale, are obtained for an acceleration time proportional to energy. Slower acceleration rates produce proportionally more multiply charged ACRs, but the acceleration timescale must be less than the ~1.5 yr timescale for adiabatic deceleration in the outer heliosphere (Jokipii 1992; Klecker 1995).

It was pointed out by Mewaldt et al. (1996) that the presence of multiply charged ions would help explain the acceleration of ACRs to energies greater than 50 MeV nucleon^{-1}. According to Jokipii (1990), the "maximum" energy gain ΔE by an ion with electrical charge Qe at a quasi-perpendicular shock is $\Delta E \approx Qe\Delta\phi$, where $\Delta\phi$ is the electrostatic potential gained in drifting along the shock face. He found $\Delta\phi \approx 240$ MV for the termination shock, corresponding to ~15 MeV nucleon^{-1} for O^+, beyond which the O^+ spectrum should steepen significantly. This implies that singly charged ACRs that lose electrons as they are accelerated will gain additional energy, particularly if they are lost at low energy. The data in Figures 1 and 3 support a picture in which higher charge ions gain more energy, and we regard this as strong support for the diffusive shock-drift acceleration model (Jokipii 1990).

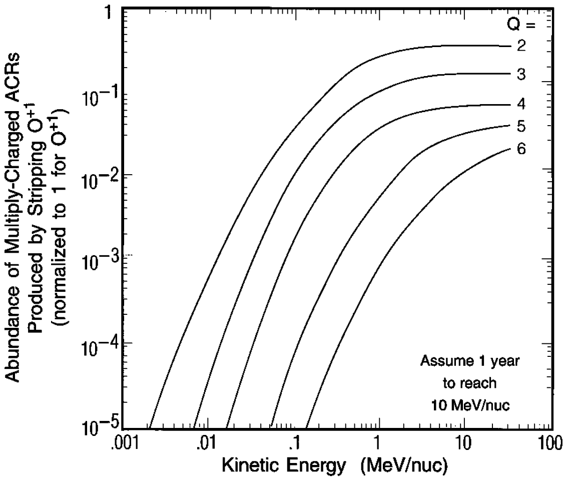

FIG. 4.—Calculated fraction of ACR oxygen with $Q = 2$–6 (normalized to 1 for O^+) produced by stripping singly charged ACRs during their acceleration. The acceleration time was assumed to be proportional to rigidity, with 1 yr required to reach 10 MeV nucleon^{-1}.

To illustrate the energy spectra of multiply charged ACRs expected from electron stripping, we use a generic shape based on the O^+ spectrum in Figure 3, extrapolated to lower energies. Cummings et al. (1984) showed that the energy of the peak intensity of various ACR species near 1 AU scaled as $(A/Q)^{-0.91}$ in 1978 while the intensity due to acceleration and solar modulation effects scaled as $(A/Q)^{1.29}$, where they assumed $Q = 1$ for ACRs. For source abundances, we use the composition at 3 MeV nucleon^{-1} in Figure 4, an energy that is small compared to the MAST energy range. The resulting spectra, shown in Figure 5, illustrate the expected acceleration of multiply charged ACRs to higher energies. In this example, 56% of ACRs with energies above 16 MeV nucleon^{-1} are multiply charged, in close agreement with the observations. This empirically based example illustrates how ACRs can attain high energies. It also indicates that electron stripping during acceleration can account for the observed charge state composition with an acceleration rate consistent with theoretical limits on acceleration at the termination shock and with expected rates of energy loss. Jokipii (1996) presents a more complete calculation that includes electron stripping within a self-consistent acceleration and transport model.

The dominance of multiply charged ACRs at high energy can also explain why trapped ACRs have a steeper energy spectrum than interplanetary ACRs (Selesnick et al. 1995) and why the trapped ACR spectrum extends only to ~50 MeV nucleon^{-1}, much less than the interplanetary spectrum. To be

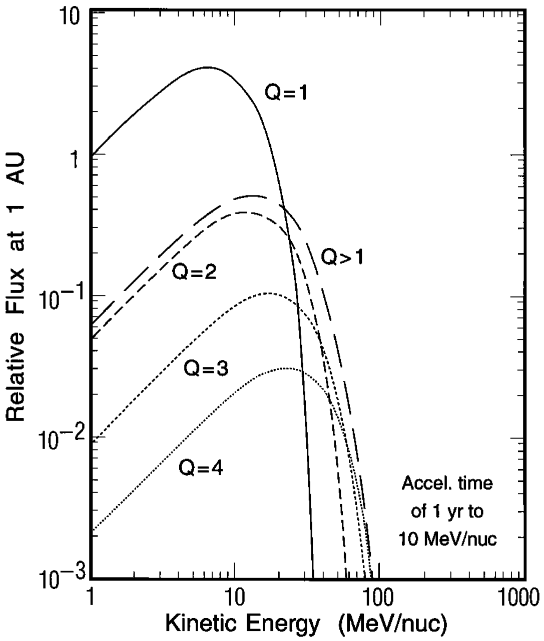

FIG. 5.—Illustration of the energy spectra of ACR oxygen with various charge states that would result from further acceleration of O^{+2}, O^{+3}, and O^{+4} produced by stripping O^{+} during its acceleration up to 3 MeV nucleon^{-1} (see Fig. 4).

trapped by the Blake & Friesen (1977) mechanism, interplanetary ions must have access to invariant latitudes below the $\epsilon Q = 1$ line in Figure 1. Since only singly charged oxygen can reach this region, trapped ACRs are derived from only ACR O^{+} and not from multiply charged ACRs that dominate at higher energy.

The results presented here imply that there will also be contributions of multiply charged ACRs to other species (He, C, N, Ne, and Ar), which may affect spectral shapes. Indeed, we obtain similar fractions of multiply charged ACRs for high-energy N and Ne, with lower statistical accuracy. Multiply charged ions should be relatively more abundant in the outer heliosphere because they are affected more by solar modulation processes.

In summary, we find that ACR charge states are much more complex than previously assumed. Calculations indicate that multiply charged ACRs are produced at low energies (<1 MeV nucleon^{-1}) during the acceleration process, providing a "clock" that is consistent with a timescale of ~ 1 yr for acceleration at the termination shock. Multiply charged ACRs will have implications for studies of ACRs throughout the heliosphere.

This work was supported by NASA under grants NAS5-30704 and NAGW-1919. We appreciate discussions with J. R. Jokipii, B. Klecker, and A. C. Cummings.

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