THE MEAN CHARGE STATE OF ANOMALOUS COSMIC RAY OXYGEN

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ABSTRACT

The ionic charge state of anomalous cosmic ray oxygen has been determined by comparing measurements obtained inside the magnetosphere on a series of Cosmos satellite flights with simultaneous observations outside the magnetosphere from IMP-8 and ICE. We find a mean charge state $<Q>=0.9^{+0.3}_{-0.2}$ for ~10 MeV/nuc anomalous oxygen, consistent with the model of Fisk, Kozlovsky, and Ramaty in which anomalous cosmic rays originate from the neutral component of the local interstellar medium (ISM). This same approach gives $<Q>=+7$ for solar energetic oxygen ions.

Introduction: Following the discovery of enhancements in the low-energy spectra of cosmic ray He, N, and O, Fisk, Kozlovsky, & Ramaty (1974) proposed that this "anomalous component" (AC) comprises interstellar neutral atoms that have been swept into the heliosphere, ionized by the solar wind or solar UV, and then accelerated to energies of ~10 MeV/nuc, probably at the solar wind termination shock (Pesses et al. 1981). (For a review, see Webber (1989) and McKibben (1987).) Presently available evidence on composition (e.g. Cummings & Stone 1990) favors this model, but Fisk (1979) noted that the clear test is to confirm the singly-charged ionization state, Q=+1.

There have been numerous attempts to determine Q from its response to solar modulation. (Cummings et al. 1984; McDonald et al. 1988; Garcia-Munoz et al. 1990.) A less model-dependent approach is to infer Q from the AC's transmission through Earth's magnetic field, based on the difference in rigidity between Q=+1 and Q=+8 at the same energy. This approach has shown evidence for Q=+1 (Grigorov et al. 1988; Oschlies et al. 1989; Singh et al. 1991; Marenny et al. 1990; Adams et al. 1991b), but these previous results have been complicated by trapped heavy ions, low AC fluxes, and the lack of simultaneous measurements outside the magnetosphere. Here we remove these difficulties: we compare simultaneous measurements outside the magnetosphere with an extensive series of quiet time oxygen measurements in which trapped particles have been excluded (Grigorov et al. 1988, 1990; Adams et al. 1991c). A brief report of this work has recently been published (Adams et al. 1991a).

Observations: In 1984-88 the composition and spectra of $Z \geq 6$ ions were measured inside the magnetosphere approximately ten times per year using cellulose nitrate track detector stacks on ~14 day Cosmos satellite flights (Grigorov et al. 1988). These 3-

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axis stabilized spacecraft flew in nearly circular orbits at 62°-82° inclination and altitudes of 200-400 km.

Most measurements outside the magnetosphere come from three instruments on IMP-8. Quiet-time measurements of oxygen at 5-28 MeV/nuc were provided by the Caltech Electron/Isotope Spectrometer (Mewaldt et al. 1976), which also provided H and He spectra to select quiet periods. The Goddard Space Flight Center Very Low Energy Telescope provided oxygen spectra during solar energetic particle (SEP) events (see McGuire et al. 1986 and references therein). The University of Chicago instrument (Garcia-Munoz et al. 1977) provided quiet-time spectra of 30-200 MeV/nuc helium and oxygen nuclei. In addition, the MPI/UMd Ultra-Low Energy Wide Angle Telescope on the ISEE-3/ICE spacecraft (Hovestadt et al. 1978) provided quiet-time oxygen spectra for 0.6-12 MeV/nuc during 1985-86.

Analysis and Results: Eighteen time periods in 1985-88 were identified as quiet, in which the fluxes of 1.4-12.5 MeV/nuc H and He were <3 times the minimum levels for that year and the flux of 7-12.5 MeV protons <10 times minimum levels. The interplanetary 5-28 MeV/nuc O and the C/O ratios also show that these periods were dominated by the AC.

Grigorov et al. (1990) have shown that the anisotropic distribution of tracks in the Cosmos detectors in quiet periods is consistent with two sources: (1) ions trapped in Earth's magnetic field; and (2) ions coming directly from outside the magnetosphere. They also showed that these sources can be separated by angular cuts, as confirmed with detailed Monte Carlo simulations (Adams et al. 1991c). For this work, we used only tracks within angular limits in which the flux is isotropic and free of trapped ions.

During quiet periods the relative composition in the Cosmos data is C/O = 0.04±0.02, N/O = 0.12±0.04 and (Z>8)/O = 0.35±0.08. Note that the C/O ratio is small compared to SEP's (C/O ~0.5), Galactic cosmic rays (GCR's) (C/O ~1), and cosmic ray albedo, (C/O > 1). These sources thus make only a very limited contribution to the measured oxygen fluxes. The observed Cosmos composition is typical of the AC (Gloeckler 1979; Mewaldt et al. 1984) and agrees with the IMP-8 measurements.

For each of 18 quiet periods the average Cosmos spectrum was compared with that from IMP-8 and (during 1985-86) from ICE using an orbit-averaged geomagnetic transmission function calculated for each Cosmos flight (Adams et al. 1983). Typically, the transmission probability for ~10 MeV/nuc oxygen varied from 0.13 (for Q=+8) to 0.4 (for Q=+1). We also examined the Dst index to make sure that there was no significant geomagnetic activity during the exposures.

Fig. 1 shows the temporal variation of quiet-time oxygen fluxes measured by IMP-8 and Cosmos. The Cosmos data have been corrected to outside the magnetosphere assuming Q=+1. Fig. 1 also includes the counting rate of the Mt. Washington neutron monitor (Lockwood 1988) shifted forward 54 days, taken to the 30th power, and suitably normalized, a representation that correlates well with the AC flux (Mewaldt 1990). The correlation of the IMP-8, Cosmos, and neutron monitor data confirms that the IMP-8 and Cosmos fluxes were both dominated by the AC and that the observed variation is due to solar modulation.

The oxygen flux contains contributions from at least three sources: (1) the GCR component, (2) the AC; and (3) the low energy component (LEC) of solar (or perhaps interplanetary) origin. The GCR component was determined by fitting IMP-8 GCR spectra and extrapolating to lower energies. This component was typically 5-10% of the observed oxygen flux at 10 MeV/nuc. The LEC oxygen flux for each period was estimated by fitting a single spectral form to the IMP-8 H and He spectra and scaling by an O/He ratio of 0.015 (Cook et al. 1984; Mason 1987). The LEC contribution at 10 MeV/nuc amounted to as much as 10% in a few cases. A model AC spectral form was obtained by fitting the IMP-8 oxygen summed over quiet periods in 1985-88.

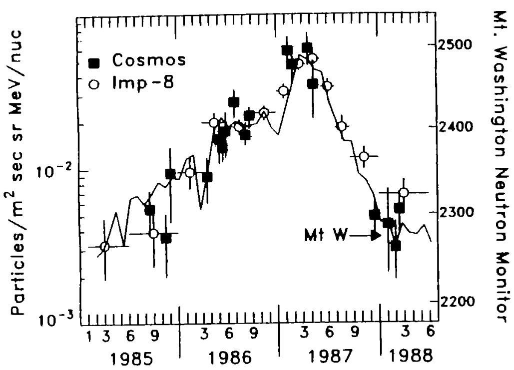

Fig. 1: Time history of quiet-time oxygen fluxes measured on IMP-8 at 5-11 MeV/nuc and on Cosmos satellites at 8-12 MeV/nuc and corrected for geomagnetic transmission assuming <Q>=+1. No corrections have been made for the different energy intervals or for GCR and solar contributions. The curve shows the Mt. Washington neutron monitor counting rate (right-hand scale), shifted and scaled. (See text.)

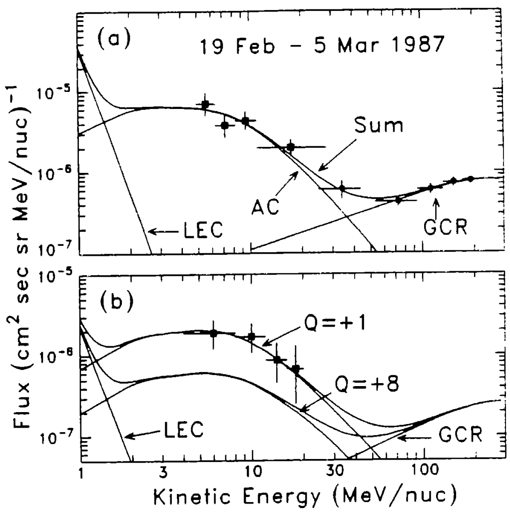

Fig. 2: The oxygen spectra measured simultaneously inside and outside the magnetosphere during one quiet period near solar minimum. (a) the oxygen spectrum measured outside and deconvolved into solar, anomalous, and GCR components; (b) the measured spectrum inside compared with the transmitted components. The transmitted AC is presented for two possible charge states.

These three spectral forms were used to deconvolve the exomagnetospheric oxygen spectra for each period, with the AC amplitude as the only free parameter. During the 1986-87 solar minimum period the AC was near its peak intensity at 1 AU and was well measured. Fig. 2a shows an example of the deconvolution in 1987. In 1985 and 1988 the AC was less intense and therefore less well defined.

The three components were separately transmitted to Cosmos inside the magnetosphere. We assumed Q=+8 for the GCR and mean charge state <Q>=+7 for the LEC (based on the mean charge state of SEP oxygen (Luhn et al. 1984)). For AC oxygen we considered both <Q>=+1 and +8. Fig. 2b compares simultaneous Cosmos data with these estimates. <Q>=+1 is consistent with the data; <Q>=+8 is not.

For each period we subtracted the estimated GCR and LEC contributions from the Cosmos and IMP-8 spectra. We then corrected the Cosmos flux to outside the magnetosphere using <Q>=+1 and <Q>=+8. Fig. 3 compares the Cosmos and IMP-8 AC fluxes. There is good agreement when <Q>=+1 is assumed. The data are inconsistent if <Q>=+8. The weighted mean of the best fit <Q> from the 18 periods is $\langle Q\rangle=0.9^{+0.2}_{-0.1}$. Systematic error in <Q> is estimated to be $\pm$ 0.2 charge units, primarily due to uncertainty in the IMP-8 measurements. Combining statistical and systematic errors in quadrature gives $\langle Q\rangle=0.9^{+0.3}_{-0.2}$.

To test our method we checked the oxygen charge state during three SEP events. These results are presented in Paper SH 5.2.2 of these Proceedings. In all cases the SEP spectra were consistent with <Q>=+7 (Luhn et al. 1984) but inconsistent with <Q>=+1.

Conclusions: We have made a detailed comparison of simultaneous measurements of oxygen fluxes inside and outside the magnetosphere from 18 quiet-time periods during

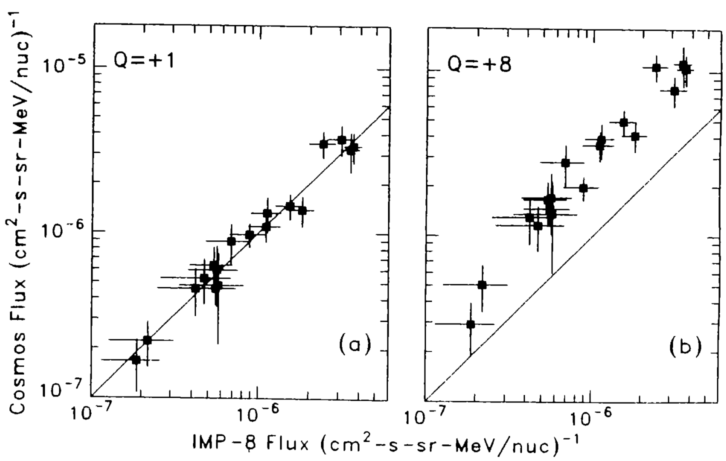

Fig. 3: Correlation plot of the AC oxygen fluxes on IMP-8 and on Cosmos, with Cosmos fluxes corrected to outside the magnetosphere assuming $\langle Q \rangle = +1$ (Panel a) or $\langle Q \rangle = +8$ (Panel b). The diagonal lines indicate agreement between the measurements.

1985-88. This comparison gives $\langle Q \rangle = 0.9^{+0.3}_{-0.2}$ for the mean charge state of anomalous component oxygen. These measurements and all other available data indicate that anomalous cosmic rays originate from the neutral ISM.

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