THE MEAN CHARGE STATE OF SOLAR ENERGETIC OXYGEN IONS

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ABSTRACT

We report an attempt to measure the ionic charge state of solar energetic oxygen ions at energies of 8-20 MeV/nuc. This study is part of a cooperative project of the space agencies of the USA and the USSR, in which we compare data from cosmic ray experiments on IMP-8 and ISEE-3 outside the magnetosphere with data from a series of experiments on Cosmos satellites in low earth orbit. From these comparisons, we determine the orbit-averaged geomagnetic transmission of these particles, which can be related to the average ionic charge state. We present preliminary results on the three solar energetic particle events analyzed to date.

Introduction: The ionic charge states of solar energetic particles (SEPs) observed near 1 AU at E ~ 1 MeV/nuc provide a measure of the temperature of the plasma from which the ions were selected for acceleration. The mean charge states of eight elemental species have been measured by Luhn et al. (1985) for 12 large solar energetic particle (LSEP) events, and Mullan & Waldron (1986) have shown that these measurements imply a unique source temperature of ~$1\text{-}2\times10^6$ °K. At higher energies, SEP ions may have traversed a longer path during their acceleration. If SEP acceleration occurs in a sufficiently high density region, the integrated pathlength could be large enough for electron stripping to influence the mean charge state. The present upper limit on the pathlength of SEP H and He at ~50 MeV is < 30 mg/cm^2 (Mewaldt & Stone 1983). Measurements of the mean charge state of SEP ions at energies of ~10 MeV/nuc or higher are sensitive to pathlengths as small as ~10 μg/cm^2. In this paper we report the first attempt to measure mean charge state of SEP oxygen at energies of 8-20 MeV/nuc.

Observations: Starting in 1984 the composition and spectra of $Z\geq6$ ions have been 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-axis stabilized spacecraft fly in nearly circular orbits at 62°-82° inclination and altitudes of 200-400 km.

Simultaneous measurements were made outside the magnetosphere by instruments on IMP-8 and ISEE-3/ICE. The IMP-8 measurements were made by the Goddard Space Flight Center Very Low Energy Telescope (see McGuire et al. 1986 and references therein). The MPI/UMd Ultra-Low Energy Wide Angle Telescope on the ISEE-3/ICE spacecraft (Hovestadt et al. 1978) also provided data during 1985-86.

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We have surveyed daily-averaged proton and helium fluxes in four energy intervals from 1.4 to 12.5 MeV/nuc from the Caltech Electron/Isotope Spectrometer (Mewaldt et al. 1976) to identify LSEP events which occurred during Cosmos flights. We have selected three LSEP events that were simultaneously observed inside and outside the magnetosphere for our initial investigation. These events commenced on 25 April 1985, 4 February 1986, and 4 May 1989. Figure 1 shows the observations inside and outside the magnetosphere for the 25 April 1985 event.

Analysis and Results: The oxygen flux measured inside the magnetosphere during these events was much higher than typical quiet time levels. Adams et al. (1991b) have shown trapped heavy ions produce highly anisotropic angular distributions in the Cosmos detectors. In these exposures, however, the angular distributions are isotropic, which indicates that they are dominated by an exomagnetospheric source and contain no significant contamination from trapped oxygen ions. We therefore conclude that the Cosmos detectors are measuring the SEP oxygen flux that penetrates to the Cosmos orbit.

The oxygen fluxes measured outside the magnetosphere during these events were also elevated much above quiet time levels, indicating that these measurements are also dominated by SEPs. We have fit the observed spectra using the Ramaty-Lee model (Forman et al., 1986). The fit for the 25 April 1985 event is shown in Fig 1a. For the event of 4 February 1986 we found that, within statistics, a power law in kinetic energy was an equally good fit to the data. For comparison, Fig. 1 also shows fits to Galactic cosmic ray (GCR) and anomalous component (AC) spectra from quiet periods near the time of the 25 April 1985 event (Adams et al. 1991a). As shown, the GCR and AC contributions are typically small, and we make no corrections for their contributions to the observed fluxes.

To estimate the SEP oxygen flux at the orbit of the Cosmos satellite we calculated the geomagnetic cutoff along the Cosmos orbit to obtain an orbit-averaged transmission as a function of magnetic rigidity, following the method of Adams et al. (1983). This transmission function was then convolved with the fitted exomagnetospheric spectra to obtain the SEP spectra inside the magnetosphere. In calculating the magnetic rigidity of the SEP oxygen, we considered two possible ionic charge states, $Q = +1$ and $Q = +8$. The results are shown in Fig. 1b. Fig. 1b also shows the GCR and AC contributions to the Cosmos flux, which were transmitted to the Cosmos orbit, using $Q=+8$ and $Q=+1$, respectively.

Finally, we have attempted a measurement of the oxygen charge state. We fit the amplitude of the spectral model using the measurements outside the magnetosphere to obtain the best fit amplitude and the associated error. To minimize dependence on the Ramaty-Lee spectral model, we used only measurements in the same energy interval as those from Cosmos. Leaving the ionic charge state Q as a free parameter, the transmission function was used to fit the exomagnetospheric fluxes to the observed Cosmos fluxes. We found the best fit Q for each of the events. The weighted mean value, $\langle Q \rangle$, for the events of 25 April 1985 and 4 May 1989 is $\langle Q \rangle = 7.1 \pm 1.8$. This result is consistent with the average mean charge state of 7.00 ± 0.02 for oxygen with $0.54 < E < 2.64$ MeV/nuc reported by Luhn et al. (1985). The event of 4 February 1985 fit to $\langle Q \rangle = 4.3 \pm 1.5$. The observations of this event (Fig. 2), however, occurred during a very large magnetic storm (Solar-Geophysical Data, 1985), which may have suppressed the geomagnetic cutoff (Fluckiger et al. 1986) to give an apparently lower charge state.

Systematic errors: We have considered several sources of systematic error that could affect this measurement. The only significant errors are associated with our calculations of the geomagnetic cutoff. Unlike our studies of anomalous component oxygen (Adams et al. 1991a), where the rigidity of the O^{+1} ions was 1.3 - 3.1 GV, LSEP ions have rigidities of 0.31 - 0.44 GV, so our calculated transmission may be affected by errors in the cutoff.

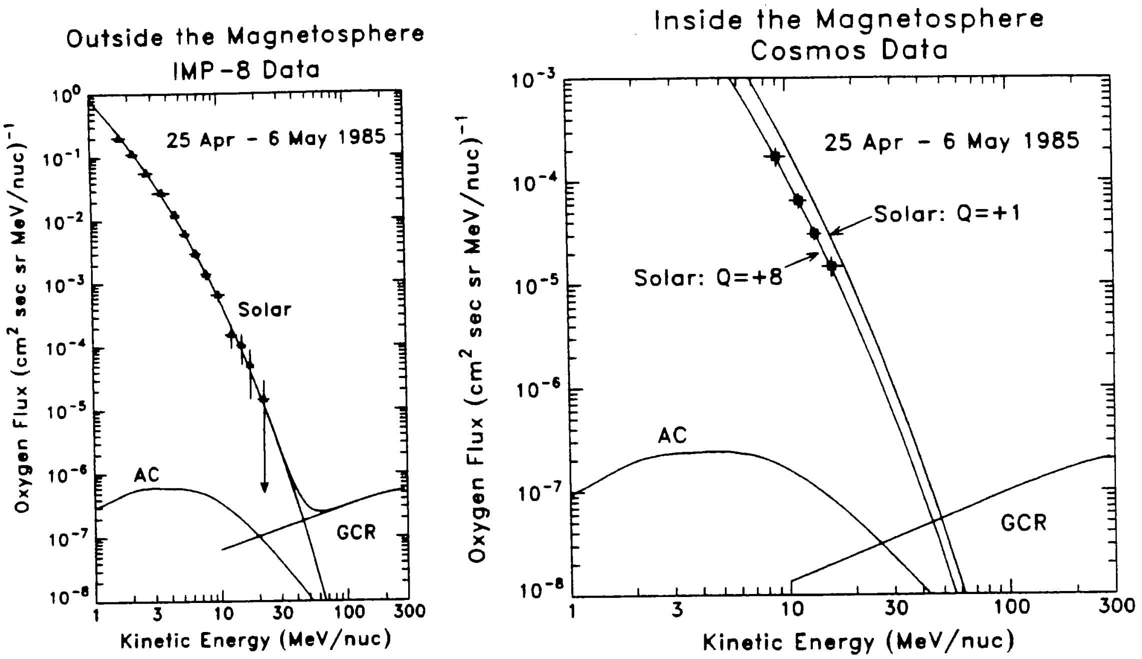

Fig. 1: Oxygen spectra measured simultaneously inside and outside the magnetosphere during the solar energetic particle event of 25 April 1985: (a) the spectrum measured at IMP 8 and fit with the Ramaty-Lee model. (b) The spectral fit is presented inside the magnetosphere for two assumed charge states and compared to Cosmos measurements.

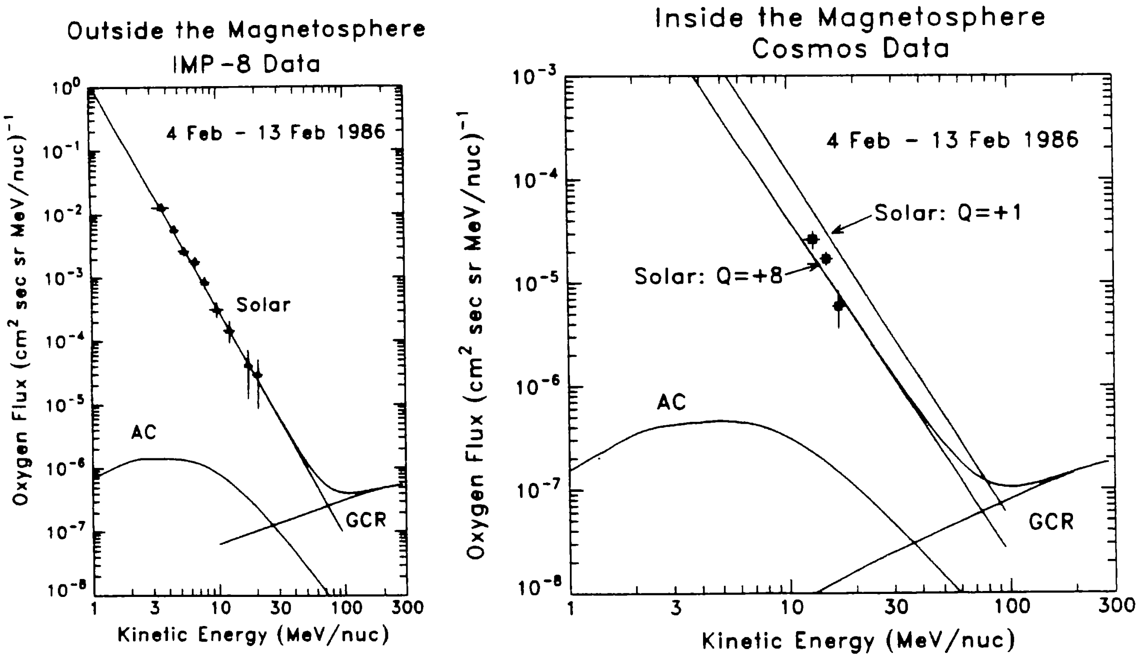

Fig. 2: Oxygen spectra measured simultaneously inside and outside the magnetosphere during the solar energetic particle event of 4 February 1986: (a) the spectrum measured at IMP 8 and fit with a power law in kinetic energy. (b) The spectral fit is presented inside the magnetosphere for two assumed charge states and compared to Cosmos measurements.

At rigidities ≥ 2 GV, observed cutoffs are in agreement with calculations (Smart 1975). At lower rigidities, however, there have been several reports of cutoffs below the calculated values (eg. Seo et al. 1991). These reports are based on relatively short duration observations in a particular geomagnetic location, and it is unclear how they apply to our observations, which are averaged over ~14 days and around the Earth. To estimate the effect of a systematic error in the calculated cutoff, we repeated our analysis with reduced cutoffs. Extrapolating from the observations of Seo et al. (1991), we systematically reduced the cutoffs all around the world in both hemispheres, in the following way:

$$P_t = P_c[1-.225(2-P_c)] \quad \text{for } P_c < 2$$
$$P_t = P_c \qquad\qquad\qquad \text{for } P_c \geq 2,$$

where P_t and P_c are the true and calculated cutoffs, respectively, in units of GV/c.

For 8.9 MeV/nuc oxygen ions with Q=+7, the increase in the transmission function that results from this assumed systematic error in the cutoff is enough to make Q appear to be +4.6. The consistency of our result for the 25 April 1985 and 4 May 1989 events with that of Luhn et al. suggests that any systematic error in the calculated cutoff is probably not as large as assumed above, but the possibility of some systematic cannot be ruled out.

As previously noted, cutoff suppression due to geomagnetic storms appears to affect our results. In such periods the transmission must be measured.

Future Plans: We have Cosmos and IMP-8 observations of several more large flares including two that are larger than the 25 April 1985 event. These observations include carbon as well as oxygen spectra. Also the Cosmos track detector stacks from the 25 April 1985 and 4 May 1989 events contain additional, un-analyzed data that could improve the accuracy of these measurements. We also plan to use data from the NOAA-I and GOES satellites to measure the geomagnetic cutoff, thus removing the uncertainty in the calculated cutoffs. With these improvements, we should be able to obtain useful measurements of the charge state of carbon and oxygen ions in LSEPs.

Acknowledgements: We thank NASA and IKI for sponsoring this study. We thank D. I. Kozlov for the Cosmos flights. This work is supported in part by NASA contracts NAG8-678, NAG5-706, W-17,358; NASA grants NAG5-728, NGR 05-002-160, NAGW-1990; and NSF grant ATM-90-23414.

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