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ABSTRACT

We report on the development of a method of measuring the mean ionic charge states of solar energetic ions and apply it to carbon and oxygen ions at energies of 8-20 MeV/nuc. These measurements are made by comparing simultaneous flux measurements inside and outside the magnetosphere to determine the geomagnetic transmission and using this result to find the mean ionic charge state that gives the measured transmission. The key to this method is to determine the dependence of the geomagnetic cutoff transmission function on the mean ionic charge states of the ions. We explore the dependence of the transmission on the choice of methods for calculating the geomagnetic cutoff.

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 /1/ for 12 large SEP events, and these measurements /2/ are consistent with a source temperature of ~1-2x10^6 °K.

We explore here a different method /3/ to measure mean ionic charge states which gives results at higher energies. Not only could this new method give independent measurements, it could reveal energy dependence in the mean ionic charge state in certain kinds of events. These are the motivations for developing this new technique.

The current paradigm for acceleration of SEP's /4/ envisions different mechanisms in impulsive and gradual events. While SEP acceleration in gradual events is thought to occur far above the sun, in the very low densities of the outer corona and the interplanetary medium, this is not thought to be the case for the impulsive events. The evidence is that in impulsive events, SEP ions are accelerated near the flare site where the electron density is $>10^8$ e/cm^2, /5/. In such a case the mean ionic charge state may be energy dependent. If, for example, the more energetic ions spend longer near the flare site gaining their energy, they may pass through enough matter for electron stripping to influence the mean charge state. The present upper limit /6/ on the pathlength of SEP H and He at ~50 MeV is < 30 mg/cm^2. 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.

The key to the success of the new method is a reliable method of computing the geomagnetic cutoff transmission function. In our initial investigation of this method, we found that a quiet time cutoff calculation seemed to work for two of the three SEP events analyzed. It appeared to fail for the third event which occurred at the time of a very large magnetic storm /3/. In this paper we explore a ray tracing method /8/ based on the Tsyganenko Model of the earth's field /9/.

Measurements of Differential Energy Spectra

Starting in 1984 the composition and spectra of $6 \lesssim Z \lesssim 10$ ions have been measured inside the magnetosphere approximately ten times per year using cellulose nitrate track detector stacks on ~14 day Cosmos satellite flights /10/. 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 /11/ and references therein). The MPI/UMd Ultra-Low Energy Wide Angle Telescope on the ISEE-3/ICE spacecraft /12/ also provided data during 1985-86.

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 /13/ to identify SEP events which occurred during Cosmos flights. We have identified eight SEP events that were simultaneously observed inside and outside the magnetosphere and appear to be large enough for our investigation. Figure 1 shows the observations inside and outside the magnetosphere for one of these events, the event of 4 February 1986.

Analysis and Results

The analysis used here followed the method described in /3/ except that we used the ray tracing method based on the Tsyganenko Model /9/. The Tsyganenko model describes the contribution to the earth's magnetic field from currents flowing in the magnetosphere. It provides descriptions of the magnetosphere during both quiet periods and magnetic storms of various sizes indexed by the Kp index.

We have used this model to calculate the geomagnetic cutoff transmission function for the SEP event of 4 February, 1986. We calculated the transmission for each value of Kp and combined them weighting each according to the time spent at that Kp level and the intensity of the flare as measured with $7 \lesssim E \lesssim 12.5$ MeV/nuc helium flux measured by the Caltech instrument on IMP-8. Figure 1 shows the flux inside the magnetosphere estimated quiet-time cutoffs and assuming the SEP oxygen ions have charge states of +1 and +8 (the upper and lower spectra). The spectrum in the middle was obtained by accounting for the geomagnetic cutoff suppression from the magnetic storm activity and assuming that the ionic charge state was +8.

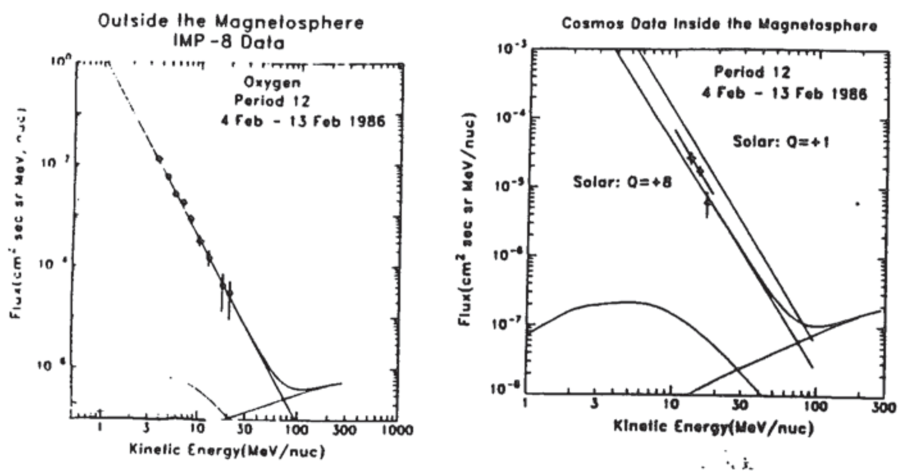

Figure 1: Oxygen spectra measured simultaneously inside and outside the magnetosphere during the solar energetic particle event of 4 February 1986: (a) the spectrum measured at IMP 8 and fit with a power law in kinetic energy. (b) The spectral fit is presented inside the magnetosphere for two assumed charge states and compared to Cosmos measurements. The calculated spectra that bracket the two lower energy data points are obtained from a quiet-time calculation of the geomagnetic cutoff function buy assuming charge states of +1 and +8 for the SEP oxygen. The line passing through these data points was obtained by accounting for geomagnetic cutoff suppression as explained in the text.

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. While we have found a way of accounting for geomagnetic cutoff suppression at high altitudes due to geomagnetic storms, the only way to be sure of our calculated transmission function is to measure it. We plan to use data from the NOAA-I and GOES satellites to measure the geomagnetic cutoff, thus determining any systematic error in the calculated cutoffs. With these cross checks, we should be able to obtain reliable measurements of the charge state of carbon and oxygen ions in SEPs.

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