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GEOMAGNETICALLY TRAPPED ANOMALOUS COSMIC RAYS AT SOLAR MINIMUM

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ABSTRACT

The geomagnetically trapped anomalous cosmic rays have been monitored continuously by instrumentation on the SAMPEX satellite since its launch in mid-1992. With the approach of solar minimum the intensity has been increasing along with that of the interplanetary anomalous cosmic ray source. We compare the time variations of the two components using data from the MAST instrument, describe improved measurements of the spatial distribution of the trapped component, and discuss implications for the trapping and lifetime of the trapped component.

INTRODUCTION

The geomagnetically trapped anomalous cosmic rays (ACRs) have been described in detail only during a relatively short part of the solar cycle (Selesnick et al., 1995a,b), but the interplanetary ACRs, which are the direct source of the trapped component, are known to vary substantially in intensity during the 11 year cycle (e.g. Mewaldt et al., 1993). The extent to which time variations in the trapped ACRs match those of the interplanetary ACRs depends on the lifetime of the trapped particles, a parameter that has not yet been determined experimentally. Therefore, it is of interest to measure the time dependence of the trapped ACRs over a complete solar cycle. Data from the MAST instrument on the SAMPEX satellite now cover the time period from mid-1992 to early-1997 during which the sunspot number has varied from high to low. In addition to providing measurements of the trapped ACRs over nearly half a solar cycle, these data also substantially improve the statistical accuracy for determining other characteristics of this radiation belt component.

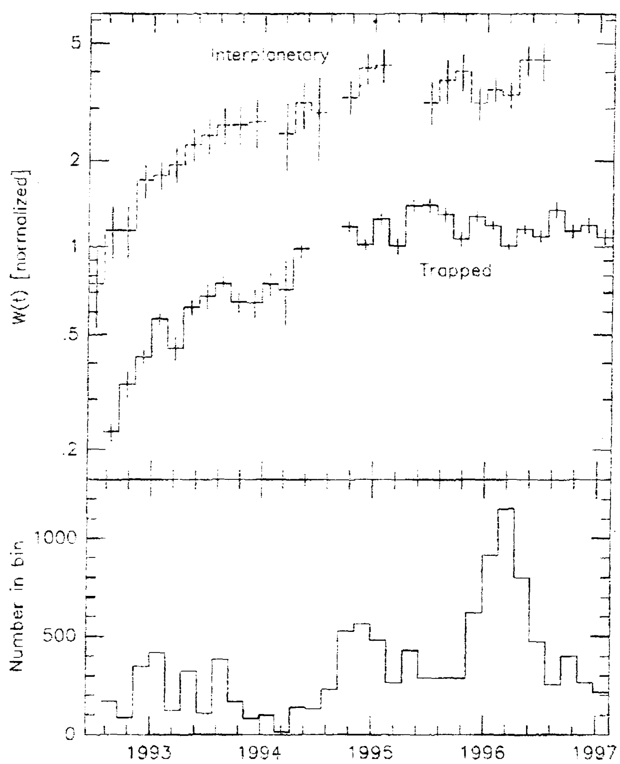

Fig. 1: (top) Trapped ACR O intensity (solid histogram) normalized to an average of 1 *and interplanetary ACR O intensity (dashed histogram) versus time labeled at the beginning of each year. The interplanetary O, from invariant latitudes* $\Lambda > 60°$*, has units of* $(cm^2\ sr\ s\ MeV/nucleon)^{-1}$ *for* 17 *to* 31 *MeV/nucleon and is multiplied by* 3×10^6*. (bottom) Number of trapped O ions collected in each* 52 *day time bin.*

DATA ANALYSIS

The analysis technique is the same as the one we have used before (see Selesnick et al., [1995a] for details), and is dictated by the low data collection rate of ~1 to 10 particles per day. The MAST trapped ACR oxygen data are binned in kinetic energy per nucleon E, pitch angle α_1, L shell, and time t. The intensity is assumed to be uniform in each bin and to be a separable function $j_1(E, \alpha_1, L, t) = U(E, L)V(\alpha_1)W(t)$. The three functions U, V, and W are determined by an iterative technique taking into account the MAST geometry and the varying satellite position and orientation. The subscript 1 indicates that the intensity and pitch angle are evaluated at a common dipole radius $R = 1.3$ which is near the maximum altitude reached by SAMPEX in its orbits over the South Atlantic region where the data were collected. The local pitch angles α are readily converted to α_1, thus providing a reference location for compiling the pitch angle distribution.

Time Dependence

The normalized time dependence of the intensity $W(t)$ is shown in Figure 1 with the interplanetary ACR intensity also measured by MAST. The data rate, shown in the lower plot, varies substantially due to changes in the satellite orientation and instrument performance. The rise in both the trapped and interplanetary ACR intensities prior to mid-1994, followed by nearly constant levels, is representative of the solar cycle dependence and similar in appearance to the cosmic ray modulation during the cycle that occurred 22 years earlier (Mewaldt et al., 1993). The similarity in the time dependencies of the trapped and interplanetary ACRs over a time scale of several years is consistent with the relatively short trapped ACR lifetimes expected for the low altitude (~600 km) SAMPEX observations. The lifetimes are discussed further below.

Pitch Angle Distribution

The normalized pitch angle distribution $V(\alpha_1)$ is shown in Figure 2. This is similar to the previous result (Selesnick et al, 1995a), with the trapped component clearly separated from the untrapped particles in the two loss cones at $\alpha_1 \lesssim 60°$ and $\alpha_1 \gtrsim 120°$. The statistical accuracy is improved due to the longer collection period and the intensity minimum near $\alpha_1 = 90°$ is now clearly significant. The shape of the pitch angle distribution has not changed significantly during the data collection period (a reanalysis of the earlier data with improved pitch angle calculations has improved our measurement of the intensities near $\alpha_1 = 90°$). A possible interpretation of the minimum near $\alpha_1 = 90°$ is that the product of the trapped particle source rate and lifetime

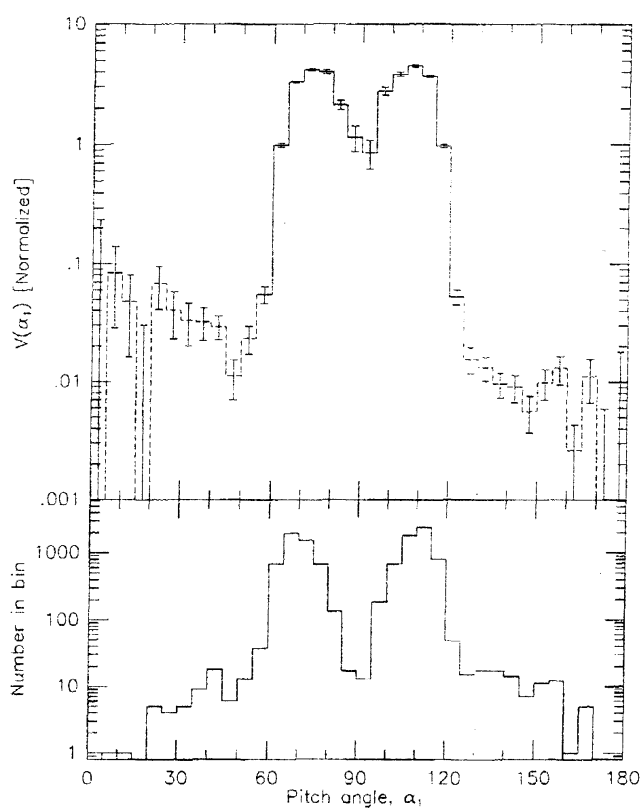

Fig. 2: (top) Oxygen pitch angle distribution for $R = 1.3$ normalized at $\alpha_1 = 90°$. The loss cone particles (dashed lines) were not included in the trapped ACR intensities. (bottom) Number of O ions collected in each 5° pitch angle bin.

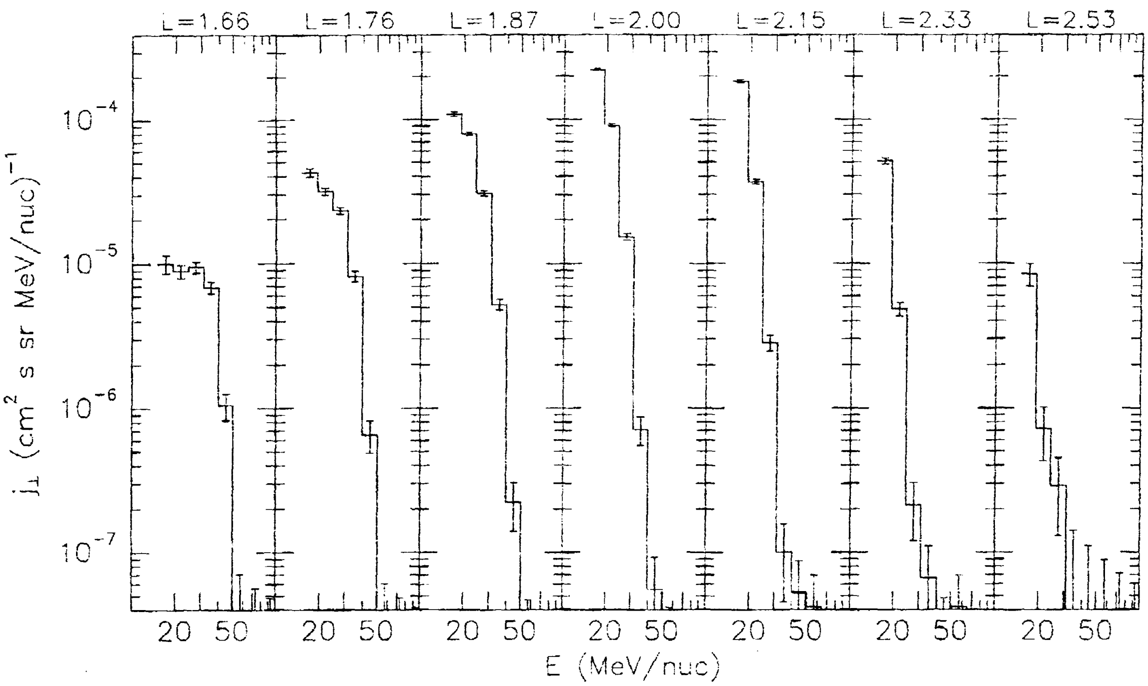

Fig. 3: Average energy spectra of trapped O for 90° pitch angles at $R = 1.3$. The data were divided into bins of 2° invariant latitude and the L shell at the center of each bin is shown above the corresponding spectrum.

is a decreasing function of the mirror point altitude. This would be true if the incoming ACRs are stripped of electrons in a multi-step process, so that the source rate is proportional to the atmospheric density raised to the power of the number of steps while the lifetime is directly proportional to the atmospheric density. A model of the drift averaged atmospheric densities (Selesnick and Mewaldt, 1996) shows that the density ratio between $\alpha_1 = 70°$ and 90° varies from ~10 to 30 during the solar cycle. Comparing this with the corresponding intensity ratio of ~4 gives an average number of steps in the stripping process of ~1.5. An alternative explanation of the density minimum is that it is due only to the dependence of the lifetimes on α_1. The same atmospheric model gives lifetimes for 30 MeV/nucleon O nuclei in solar-cycle average conditions of 0.4 years at $\alpha_1 = 70°$ and 8 years at $\alpha_1 = 90°$, so that the intensities near $\alpha_1 = 90°$ are a longer term average and may be lower than those at $\alpha_1 = 70°$ at solar minimum. However, the lack of time dependence in the depth of the intensity minimum may rule out this second interpretation and favor the first one. Quantitative modeling will be required to confirm this conclusion.

Energy Spectra

Energy spectra $U(E, L)$ for the trapped ACR O are shown for the various L shell bins in Figure 3. They represent the average perpendicular intensity $j_\perp$ at $R = 1.3$ because of the normalizations chosen for V and W. They are consistent with previous results and have better statistical accuracy. The average trapped ACR intensities at $\alpha_1 = 90°$ have not changed significantly, but those at higher and lower pitch angles have increased as shown by the change in the pitch angle distribution discussed above. Recent results showing that the interplanetary ACRs are multiply ionized at high energies (Mewaldt et al., 1996; Selesnick et al., 1997) can explain the relatively soft trapped ACR energy spectra if only the singly ionized interplanetary ACRs can undergo a sufficient change in ionization state to become trapped.

Trapping Limit

A parameter that has been used to describe the particle trapping boundary is the adiabaticity parameter $\epsilon = 3\mathcal{R}/(LaB_0)$, where $\mathcal{R}$ is rigidity or momentum per charge, a is the Earth radius, and B_0 is the equatorial magnetic field for a given L shell. Because the charge state Q of the particles is not known we calculate ϵQ, the distribution of which is shown for trapped N, O, and Ne in Figure 4. Earlier results in this format suggested that the three elements were trapped at a common charge state because the upper limits of the data were at common ϵQ values. However, with improved statistical accuracy, particularly for the Ne, we now see that this is not true. Instead, the data appear to be more consistent with the elements being fully stripped of electrons at initial trapping. Model curves representing the assumptions of common and fully stripped initial charge states, based on simple assumptions about the trapping process (Selesnick et al., 1995a), are shown in the figure for comparison with the data. If the fully stripped assumption is correct then the data now appear to be consistent with a trapping limit of $\epsilon = 0.11$, although more detailed models are clearly required to accurately describe the spatial distributions.

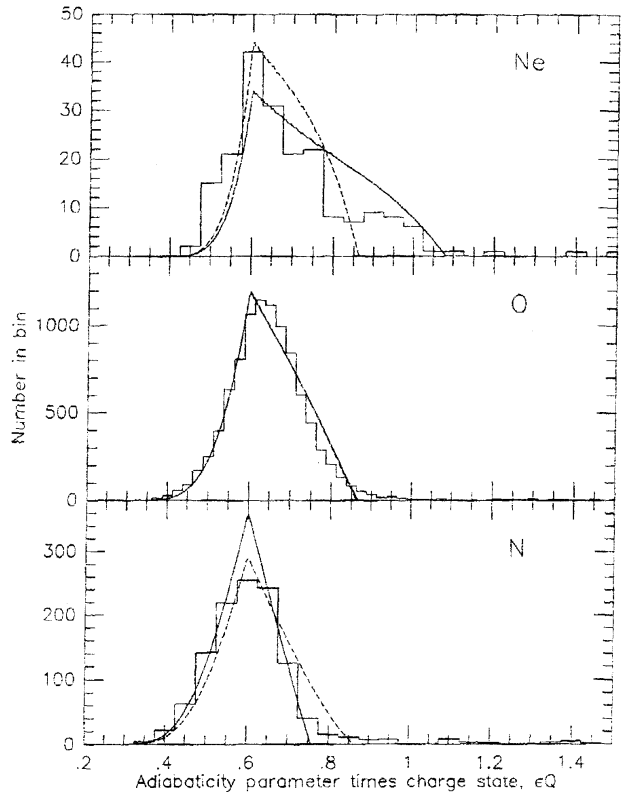

Fig. 4: Histograms of ϵQ for trapped ACR N, O, and Ne. Model fits are based on the assumptions of common initial charge states (dashed curves) and fully stripped initial charge states (solid curves).

ACKNOWLEDGEMENTS

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