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OBSERVATION OF ENERGETIC TRAPPED OXYGEN IONS IN THE INNER MAGNETOSPHERE

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ABSTRACT

We report on a series of measurements of 5-30 MeV/nuc oxygen ions made with track detector stacks on Cosmos satellites. We find that the angular distributions during solar energetic particle events are isotropic, while solar-quiet times show highly anisotropic distributions suggestive of a trapped particle component. Detailed Monte Carlo simulations confirm this interpretation and allow us to separate the trapped and cosmic ray contributions to the quiet-time fluxes. Our data appear fully consistent with trapping of anomalous cosmic ray ions as the source of the trapped particles but inconsistent with radial diffusion from the outer radiation zone.

Introduction: Previous reports of excess oxygen flux at ~10 MeV/nuc in the inner magnetosphere (Mogro-Campero & Simpson 1970; Chan & Price 1975; Biswas & Durgaprasad 1980; Oschlies et al. 1989; Adams et al. 1991b) did not prove that the ions followed trapped particle trajectories. If trapped, these ions are of astrophysical interest. The anomalous component (AC) of cosmic rays comprises neutral interstellar atoms which have been swept into the heliosphere, become singly-ionized by the solar wind or solar UV (Fisk et al. 1974), and then accelerated to energies of ~10 MeV/nuc or greater (Pesses et al. 1981). Blake & Friesen (1977) noted that such particles can penetrate deeply into the magnetosphere and become stripped and stably trapped, with lifetimes ranging from hours to months. These trapped particles are thus a concentrated sample of interstellar matter directly available for study at Earth.

In 1986-89 CNO ions in the inner magnetosphere were measured ~10 times per year (Grigorov et al. 1988; 1989) using cellulose nitrate detector stacks flown for ~14 days on Cosmos satellites in nearly circular orbits at altitudes of 250-400 km and inclinations of 62°-82°. The detectors registered oxygen ions with energies of 5-30 MeV/nuc. The detectors recorded no timing information for individual nuclei but clearly showed the presence of trapped particles in the angular distributions of the tracks. Since the spacecraft were three-axis stabilized, the detectors always passed through the low-altitude radiation belts with the same attitude. Trapped particles thus arrived from characteristic directions and registered at characteristic angles. These same data, with angular cuts to exclude trapped particles, have been used to prove that AC oxygen ions are singly-ionized (Adams et al. 1991a and Paper SH 5.2.4).

Observations: The dip angle θ and azimuth angle ϕ in Fig. 1 specify a particle's arrival direction in the detector coordinate system. The polar diagrams of Fig. 2 display the distribution of arrival directions for two typical Cosmos exposures, one when solar energetic particles (SEPs) dominated the interplanetary particle fluxes (as indicated by IMP-8) and one during quiet-time. In the SEP exposure, particles come from around

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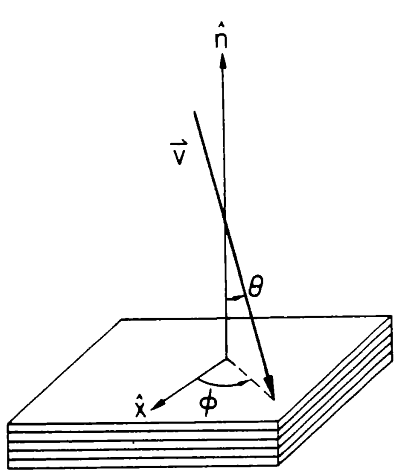

Fig. 1: Arrival direction angles. θ is the angle between the particle velocity vector **v** and the normal **n**. ϕ is between the projection of **v** onto the detector and a fixed direction **x**.

the zenith direction in a distribution which is isotropic, except for shadows caused by obstructions on the satellite and the solid Earth. During quiet-time, however, there are relatively few particles from around the zenith direction. The distribution is anisotropic, and a significant number of particles come from below the horizon.

The detectors were mounted in one of three possible locations on the satellite, corresponding to three different attitudes in passing through the radiation belts. Fig. 2 shows data from one of these attitudes. In Fig. 3, we show histograms of the azimuth ϕ from six different Cosmos exposures, including an SEP event and a quiet-time exposure in each attitude. The striking differences between SEP and quiet-time exposures are seen in all three cases. Apart from obstructions, the SEP distributions are flat. In the quiet-time exposures, the fluxes show strong azimuthal variation.

Monte Carlo Simulations: Figs. 2 and 3 strongly suggest a trapped particle component in the Cosmos data. To confirm this, we made detailed Monte Carlo simulations, as shown in Fig. 3. The SEP simulations ensure that the obstructions are well-understood. The quiet-time simulations show that trapped particles give a consistent view of the data, accounting for the differences among the detector attitudes.

To carry out simulations, we reconstructed the orbital trajectory of each flight on a second-by-second basis. At each location along the trajectory, the simulation sampled from a model of the incident flux to specify a particle's energy and velocity vector. The Monte Carlo program then accounted for obstructions, small detection inefficiencies, and the obliquity factor. For each flight, we simulated distributions of both cosmic rays and trapped particles. We then minimized χ^2 to fit the observed azimuth distribution to a linear combination of cosmic ray and trapped components.

In simulating SEP's and quiet-time cosmic rays, the flux was assumed to be isotropic except for directions below the Earth's horizon, where the flux was set to zero. Particle energies were sampled from orbit-averaged spectra (see Paper SH 5.2.4).

To simulate trapped particles, we constructed a simple model based on the fact that trapped ions are observable at Cosmos altitudes only near their mirror points in the South Atlantic Anomaly (SAA). Both AC trapping (Blake & Friesen 1977) and radial diffusion of outer zone ions (Panasyuk 1984) predict that trapped oxygen ions of these energies should be found primarily at $L > 2$. The simulations therefore restricted the trapped flux to the portion of the SAA at $2 < L < 3$. Within this region, the intensity and spectrum of the trapped particles were assumed to be the same everywhere. To approximate the local pitch angle distribution, the angle between the local magnetic field (IGRF85; Barraclough et al. 1987) and the particle's velocity vector was sampled from a Gaussian distribution centered at 90° and with standard deviation 6°. Trapped particle energies were sampled from a relatively flat spectrum, as suggested both by AC trapping (Blake 1990) and by radial diffusion (Spjeldvick & Fritz 1978).

To check the assumed geomagnetic distribution of trapped particles, we also ran simulations in which trapped oxygen particles were assumed throughout the SAA or only at $1.2 < L < 1.5$ (where the trapped proton flux is most intense). In these cases the simulated azimuth distributions gave significantly poorer agreement with the data.

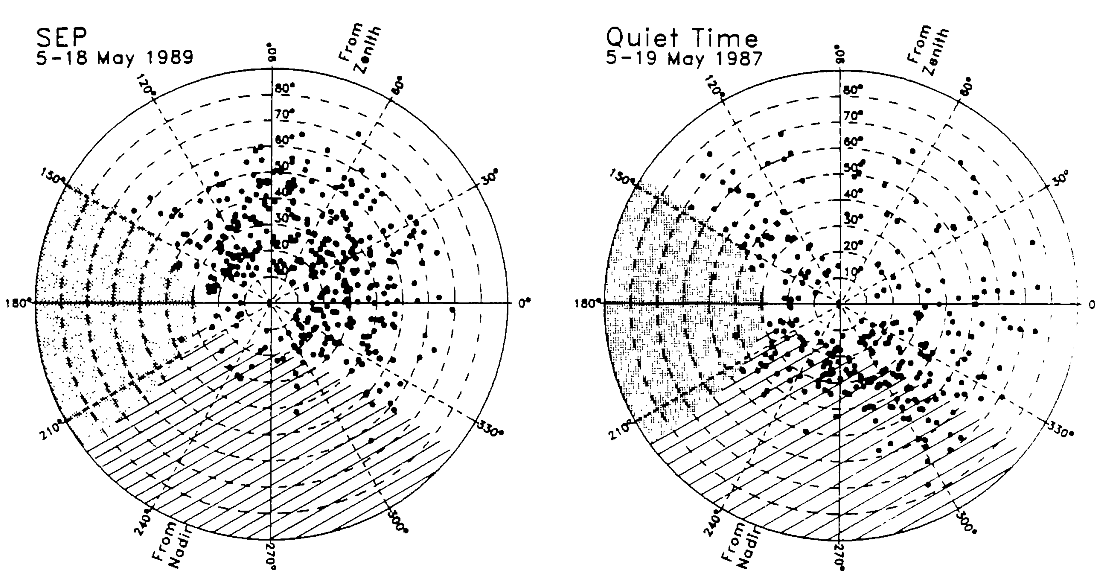

Fig. 2: Observed arrival directions in a SEP-dominated (left) and in a quiet-time (right) exposure. Each point represents a single particle, with θ and ϕ plotted as the radial and azimuthal coordinates, respectively. The locations of zenith and nadir are noted. The shaded area shows directions blocked by an obstruction on the satellite. The hatched area shows directions from below the Earth's horizon.

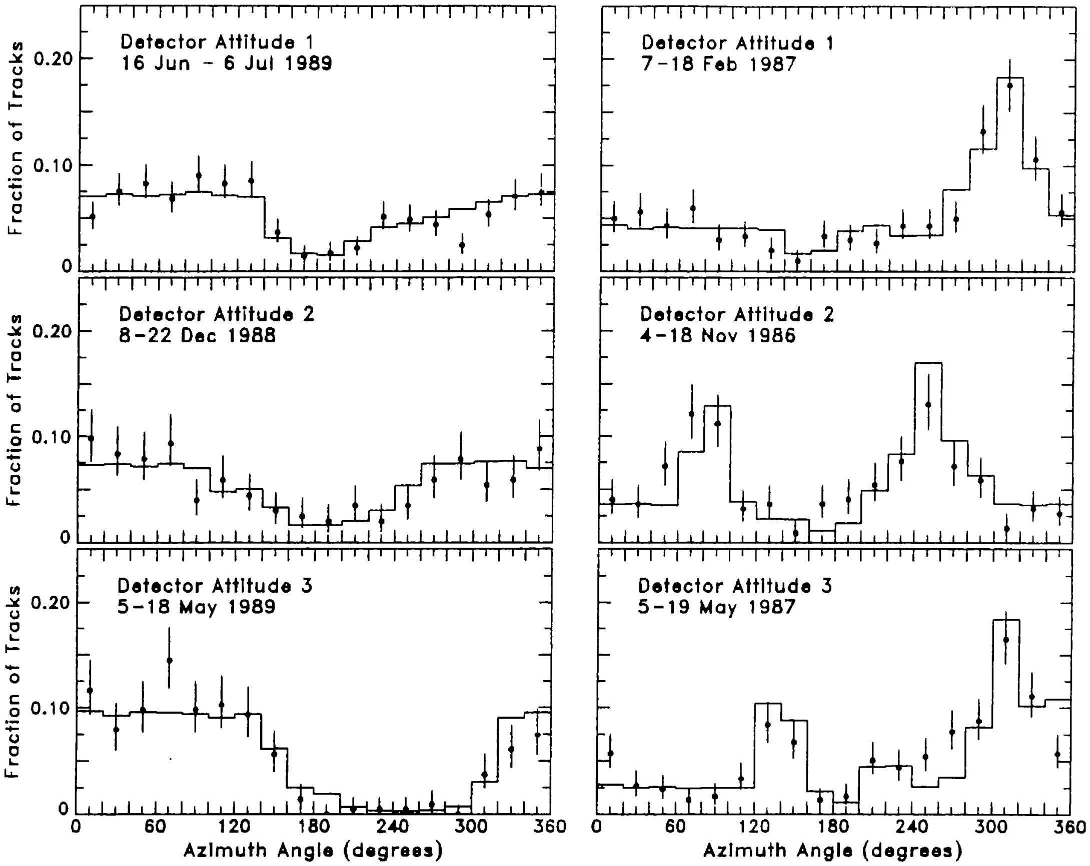

Fig. 3: Histograms of the azimuth angle ϕ for SEPs (left) and quiet-times (right) for three different detector attitudes. The points are the Cosmos data with statistical error bars, and the solid lines are the Monte Carlo simulations. Statistical errors on the simulations are negligible.

The agreement between the data and simulations in Fig. 3 is generally good. We also compared observed and simulated distributions of dip angles and particle ranges in the detector and checked the correlations among the θ, ϕ, and range observables. In all cases there was satisfactory agreement with the data.

Origin of the Trapped Particles: One possible origin for these particles is trapping of anomalous cosmic ray ions (Blake & Friesen 1977). All of our observations, including geomagnetic location, spectrum, composition, and temporal variation, appear consistent with this explanation. A second possible origin is radial diffusion from the outer radiation belt. This explanation appears inconsistent with the data in two ways. First, classical radial diffusion theory cannot account for acceleration of ionospheric ions to the energies observed here. Outer zone ions with the necessary initial energies must therefore be of solar wind or (more likely) of SEP origin. For these sources, the C/O ratio is typically ~0.5. The observed C/O ratio in the Cosmos data, however, is only a few percent, consistent with the observed composition of the AC. It is difficult to understand how radial diffusion could produce such a large change in the particle composition. Second, the trapped flux is variable and anticorrelated with solar activity. Fig. 4 compares the time history of the observed trapped oxygen flux with IMP-8 interplanetary measurements of the AC oxygen flux. The temporal variations are very similar, and both the AC and the trapped flux reached their peaks near solar minimum. Because radial diffusion is promoted by large magnetic storms caused by solar flares, it is unclear why a trapped flux from this process would peak at solar minimum.

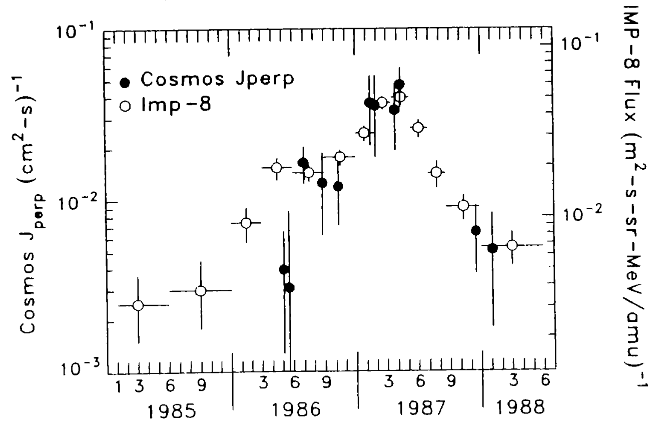

Fig. 4: Time history of the Cosmos trapped flux Jperp near the mirror points (left-hand scale) and the quiet-time 5-11 MeV/nuc oxygen flux (right-hand scale) from the Caltech Electron/Isotope Spectrometer on IMP-8 (uncorrected for small Galactic and solar contributions).

Conclusions: In summary, the Cosmos data, when compared with our simulated angular distributions, clearly demonstrate the presence of trapped energetic oxygen ions in the inner magnetosphere. The characteristics of this trapped component are fully consistent with originating from the anomalous component of cosmic rays.

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