TRAPPED IRON MEASURED ON LDEF

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SUMMARY

Heavy ions far below the cutoff energy were detected on the 28.5° inclination orbit of LDEF in a plastic track detector experiment. The Fe-group particles show a constant energy spectrum at $50 \leq E \leq 200$ MeV/nuc. The steep energy spectrum of Fe-particles at $20 \leq E \leq 50$ MeV/nuc and the arrival directions of these ions is consistent with a trapped component incident in the South Atlantic Anomaly at values of L=1.4-1.6.

INTRODUCTION

The objective of experiment M0002-2 was to register heavy cosmic ray nuclei with nuclear charge $Z \geq 3$ and to measure the chemical and energy spectra in the energy range from 20 to 1000 MeV/nuc. Two points of great interest were "geomagnetically forbidden" cosmic ray particles and heavy ions of the trapped radiation.

Early measurements at the orbit of Skylab (1) observed steeply falling spectra of nuclei with $Z \geq 8$ and $10 \leq E \leq 40$ MeV/nuc. The steep energy spectra were interpreted as evidence for energetic heavy nuclei in the inner radiation belt. Spacelab-1 measurements (2) reported the registration of oxygen ions in the South Atlantic Anomaly (SAA) and the TRIS data (3) also suggested a steeply falling trapped oxygen component. Finally, in a series of Cosmos flights, it could be proved that oxygen particles were trapped (4). "Geomagnetically forbidden" particles have energies less than the minimum cutoff value required for fully stripped ions to have access to a specific location inside the Earth's magnetic field. Transient magnetic field disturbances and partly ionized particles can produce such a "forbidden" component. SL-1 and SL-3 measurements have detected few iron and sub-iron particles at about 100 MeV/nuc which could only be explained by a strongly reduced ionization state (5,6). All cited experiments (as well as four individual experiments on LDEF) used passive visual track detectors for the registration of the heavy ions. These detectors provide an excellent spatial resolution for the arrival direction of the particles and they have registration thresholds that make the detector system almost insensitive to electrons and protons. No electrical power is needed for the particle registration; however, the detector does not provide information on the arrival time of the particle (special experiment operation (2) can overcome this).

All features of the three axis stabilized Long Duration Exposure Facility (LDEF) which stayed in a circular, 28.5° inclination orbit from April 1984 to January 1990 ($1.8 \cdot 10^8$ s), supported our investigation: a) the low inclination orbit provided a high geomagnetic shielding and thus low energy fully stripped heavy ions had no access to this orbit (the minimum required rigidity is about 3.5 GV); b) 80% of the mission was spent at an altitude greater than 444 km; c) the attitude stabilization provided a fixed orientation during SAA crossings; d) the extremely long-duration flight provided a unique collecting time covering the period of minimum solar modulation.

THE DETECTOR SYSTEM

CR-39 and Kodak CN plastic track detectors from Kiel were exposed on three different positions on LDEF. The Kiel experiment M0002 (on side-tray E6 with an aperture of 1000 cm^2) and two subunits of the Biostack experiment A0015 (DLR Cologne, on side-tray C2 and earth-tray G2, each with an aperture of 48 cm^2) covered an almost omnidirectional field of view. The detector arrangement under thermal covers equivalent to 14 mg/cm^2 is shown in Fig. 1 for the two different types of stacks. Scientific data were accumulated during the whole LDEF mission in latent tracks and revealed in the laboratory by means of chemical etching. After recovery small areas of experiment M0002 were exposed to 200 MeV/nuc Ar^{40} ions at the Saclay accelerator for a post-flight calibration.

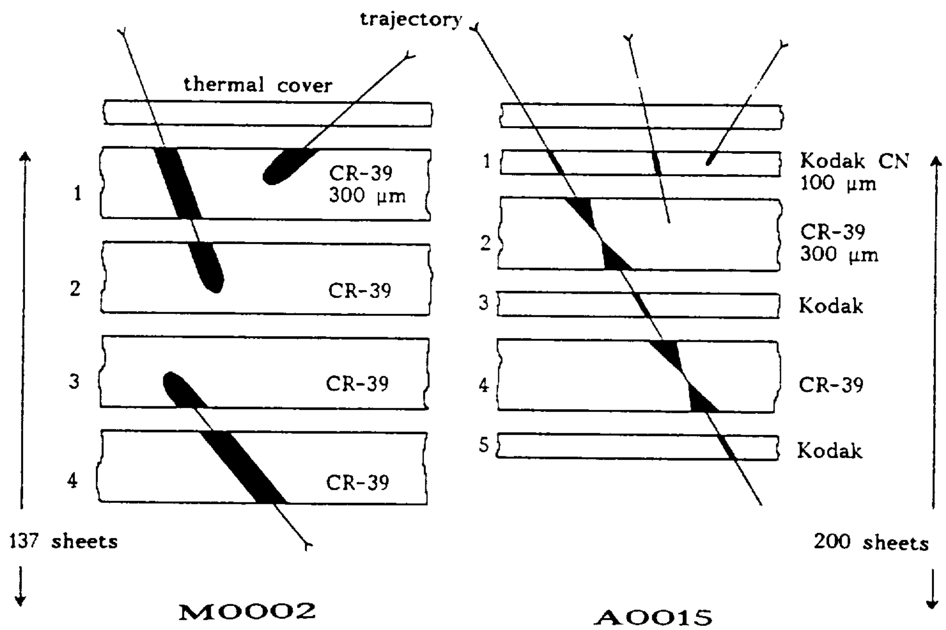

Fig. 1: Side view of the foil arrangement with track images after etching.

Etching of the CR-39 foils was performed at 70° C for 10 hours in 6n NaOH. This treatment was chosen in order to optimize the track size and minimize the number of background tracks (about $1.5\ 10^5$ very small etch pits per cm^2 on the topmost surface and $3.5\ 10^4$ small pits per cm^2 on other surfaces throughout the stack). The Kodak CN foils were etched for 2 hours in 6n NaOH at 50° C.

After etching, the detector foils were scanned and stopping particles were analysed by measuring the arrival direction with respect to the detector foil and the conelength (L) versus residual range (R) dependence. The inflight calibration of the detector response is based on the lack of tracks above the topmost band in the L-R plot (7) which is related to the sudden drop in the elemental abundances above charge Z=26. The edge is allocated to Fe ions and its presence shows that the detector sensitivity did not change seriously during the mission.

Fig. 2b shows the measured charge distribution of 53 particles arriving from unshielded space and stopping in M0002 (CR-39) on 300 cm^2 . The energy range is 50-250 MeV/nuc and the charge resolution deduced from the Fe peak is σ =1.0 charge units. A similar charge distribution was measured in CR-39 of the A0015 units for the same energy range. The low sensitivity of the CR-39 detector flown on LDEF (which is similar to the CR-39 response on SL-1) is due to the low oxygen concentration within the stack container and causes a decreasing registration probability for ions with decreasing nuclear charge. The response curve of the CR-39 on LDEF as a function of the restricted energy loss is:

$v_s/v_m - 1 = 0.025\ (REL/1000)^{2.6}$ (REL in MeV cm^2/g, ω_0=200 eV). Low energy particles are studied in the topmost three foils which show a slightly different response. The uncorrected, preliminary charge distribution of particles with E≤50 MeV/nuc is depicted in Fig. 2a (below Z=10 the registration probability is strongly decreased).

The calibration of the Kodak CN, integrated in the A0015 units, is in progress. The preliminary analysis indicates a higher sensitivity compared to the CR-39, and a high registration probability for nuclear charges Z≥ 6 is expected in these foils.

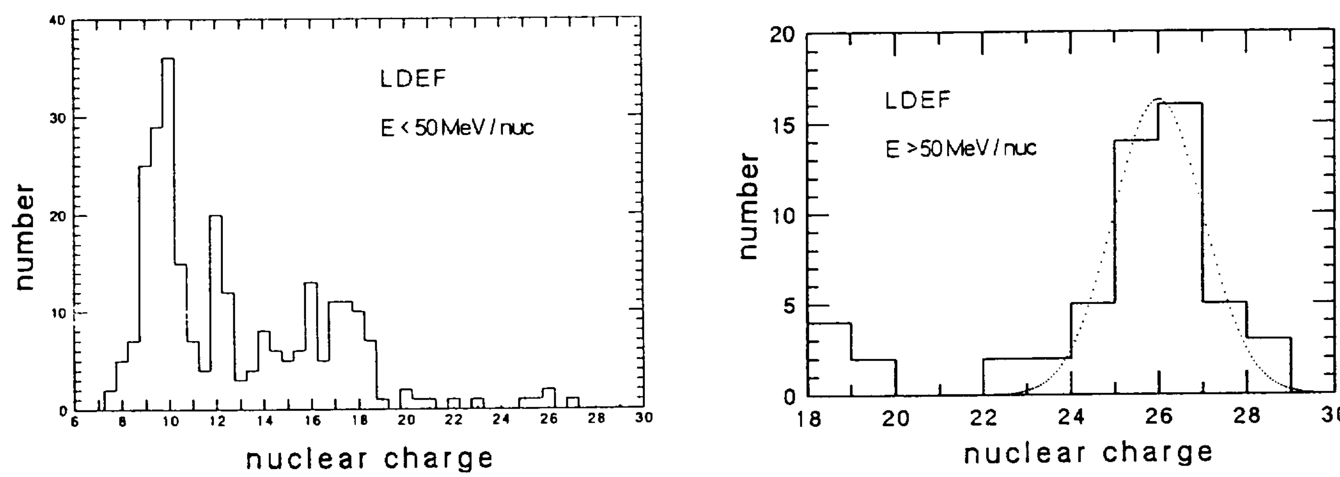

Fig. 2: Measured charge distribution in M0002: a) preliminary spectrum for E≤50 MeV/nuc, b) set of 53 tracks with energies E≥50 MeV/nuc used for the response calibration.

PARTICLE ENERGY SPECTRA

Mission and field of view averaged energy spectra for selected particle groups are shown in Fig. 3. The measurement for Z>6 was calculated from preliminary measurements in Kodak CN; the Ar and Fe results were obtained on 300 cm^2 CR-39 in M0002. The striking feature for the Fe-group is the steeply falling spectrum below 50 MeV/nuc and the plateau up to 200 MeV/nuc where our flux measurement is in agreement with the results of M0001 (Adams et al., these proceedings). The flux of the Ar-group particles at energies above 50 MeV/nuc was not analysed; however, it is less than the Fe flux at these energies. Preliminary flux calculations for Ne-group particles around 20 MeV/nuc yielded similar flux values and almost the same slope as depicted for Ar. All detected particles have energies well below the cutoff value for the LDEF orbit, assuming fully stripped nuclei.

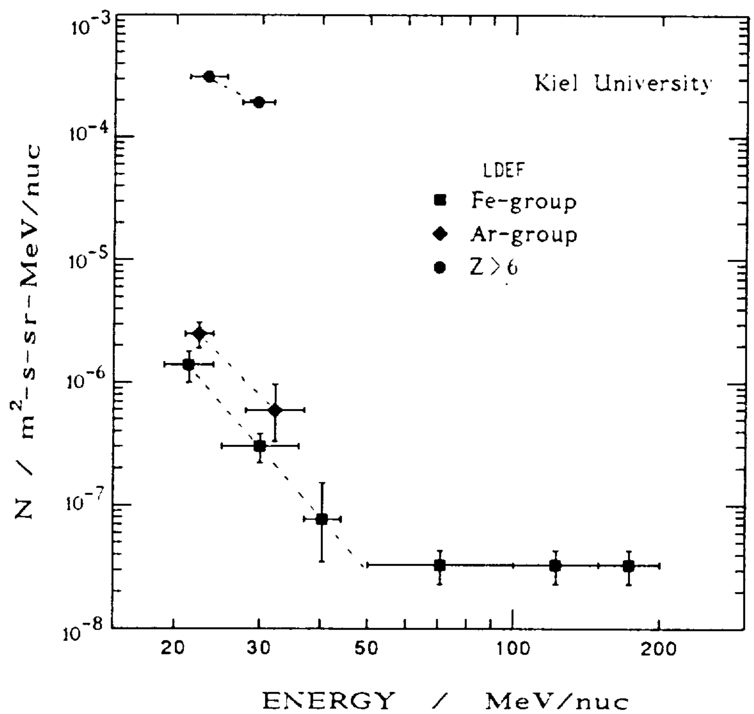

Fig. 3: LDEF mission averaged fluxes for selected charge groups.

PARTICLE ARRIVAL DIRECTIONS

Based on the good spatial resolution of visual track detectors, the arrival directions of the particles were measured with respect to the detector foils. Because LDEF maintained a constant attitude during the mission, the SAA crossings occurred with a known orientation. Thus the trapped heavy ions arrive at characteristic angles, thereby making them distinguishable from other particles.

The particle group Z>6 of Fig. 3, penetrating the topmost Kodak CN foil of A0015 on tray C2 (E≥10 MeV/nuc), has arrival directions as shown in Fig. 4. This highly anisotropic distribution shows the characteristics of a cylindrical geometry. Fig. 5 shows angular distributions from tray E6 for particle groups taken from Fig. 2a (E≤50 MeV/nuc). Again the distributions show the characteristics of a cylindrical geometry but less pronounced. The indicated geographic directions are given as a reference assuming that the LDEF velocity vector is pointing to the east (valid at 28.5° latitude).

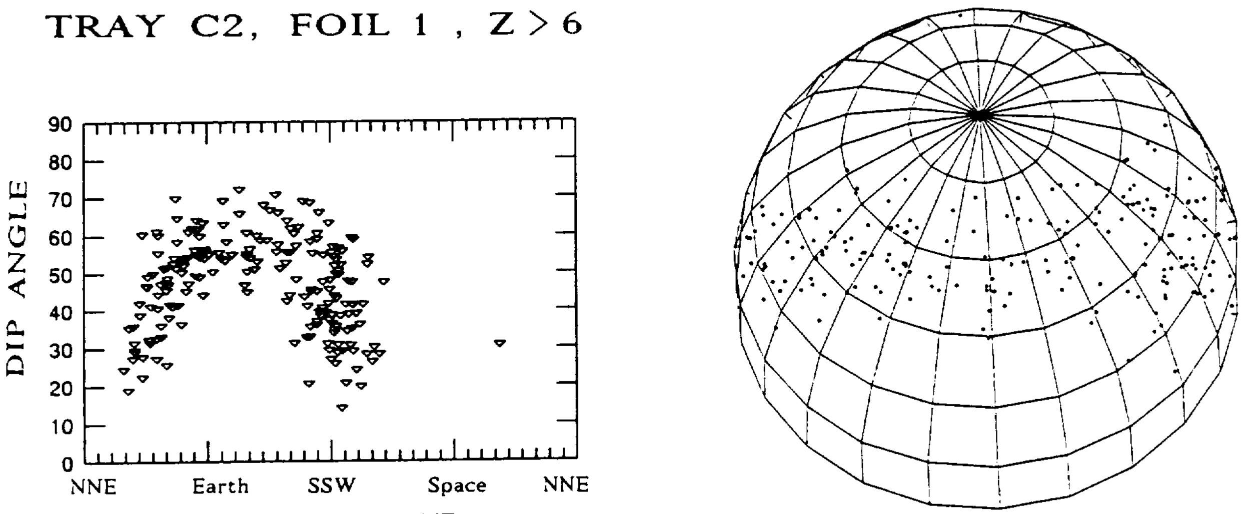

Fig. 4: Arrival directions for particles on tray C2 (Z>6, E>10 MeV/nuc); the pole in the 3D-plot indicates 90° dip angle (vertical incidence).

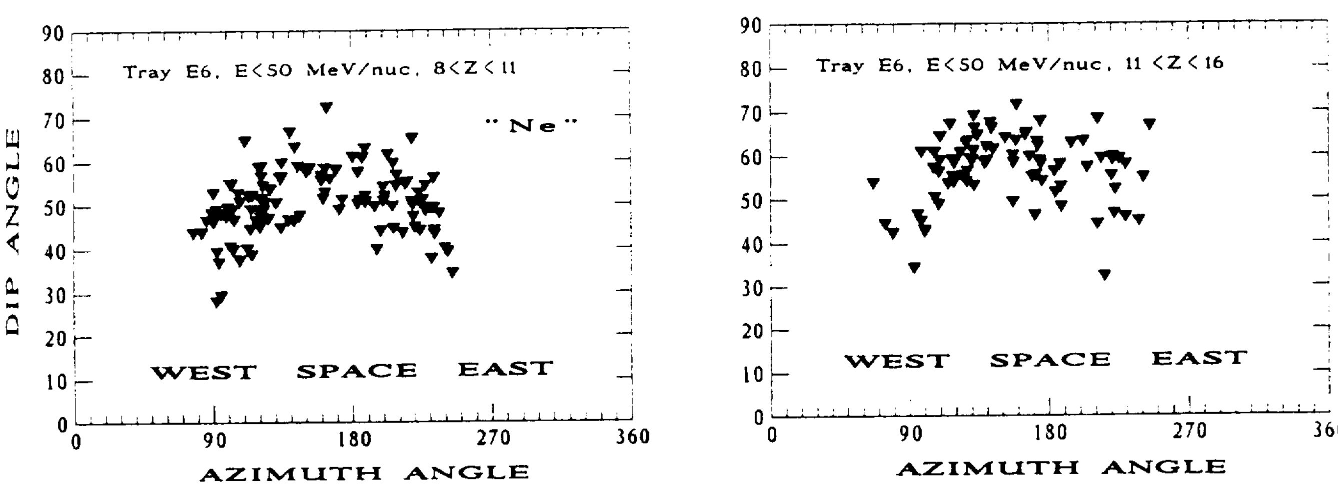

Fig. 5: Arrival directions for particles with E<50 MeV/nuc on tray E6 Azimuth and Dip angles are referred to the detector foil.

The arrival directions of three particle groups are studied in more detail combining measurements on trays E6, C2 and G2 (note the different aperture size). Fig. 6 shows Ar and Fe ions below 50 MeV/nuc; Fig. 7 shows Fe above 50 MeV/nuc (see energy spectra in Fig. 3). The arrival directions in Figs. 6 and 7 are given relative to a plane which is perpendicular to the local vertical with an azimuth angle referring to the LDEF velocity vector (pointing to the East at 28.5° latitude). The dotted lines define a dip angle of 20° with respect to the detector surface at the three positions (for the earth tray this line is nearly congruent with the shadow of the solid earth).

Although the change of the registration efficiency within the individual fields of view is not yet corrected, one can conclude that up to 200 MeV/nuc the arrival directions show a similar structure (which is discussed in the following chapter), whereas above 200 MeV/nuc all particles arrive from western directions without a pronounced structure. If these particles enter from outside the magnetosphere this distribution can be explained by the fact that the region of the lowest cutoff is the western horizon.

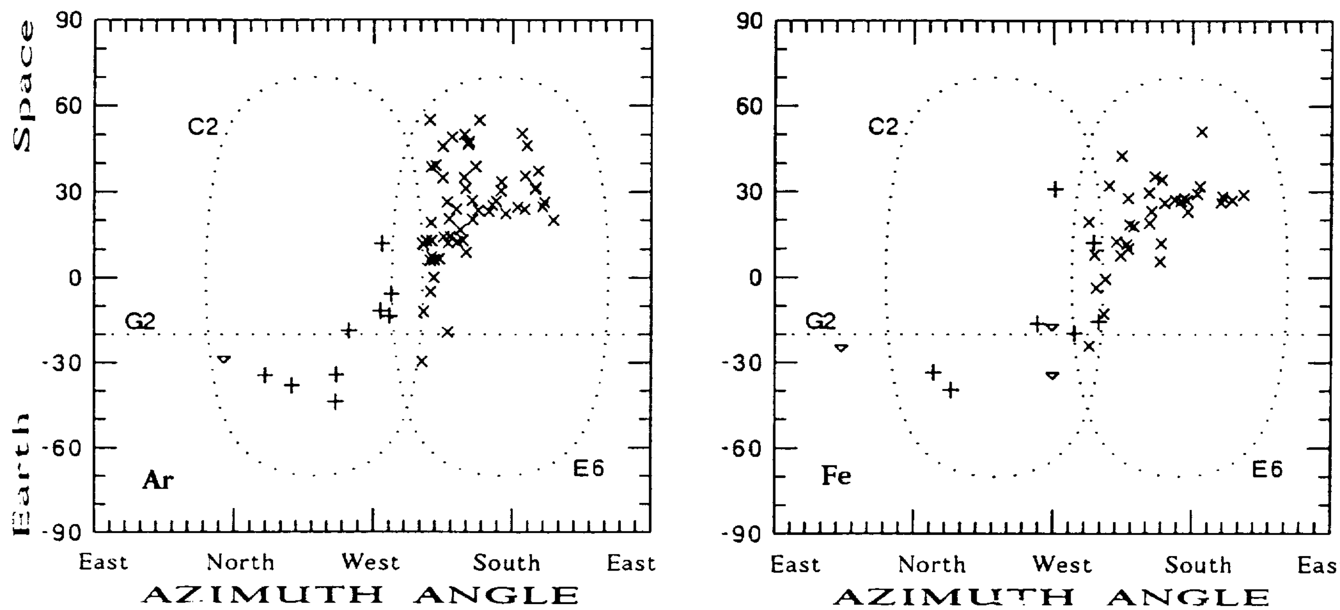

Fig. 6: Arrival direction of Ar- (l) and Fe-group (r) particles with E≤ 50 MeV/nuc.

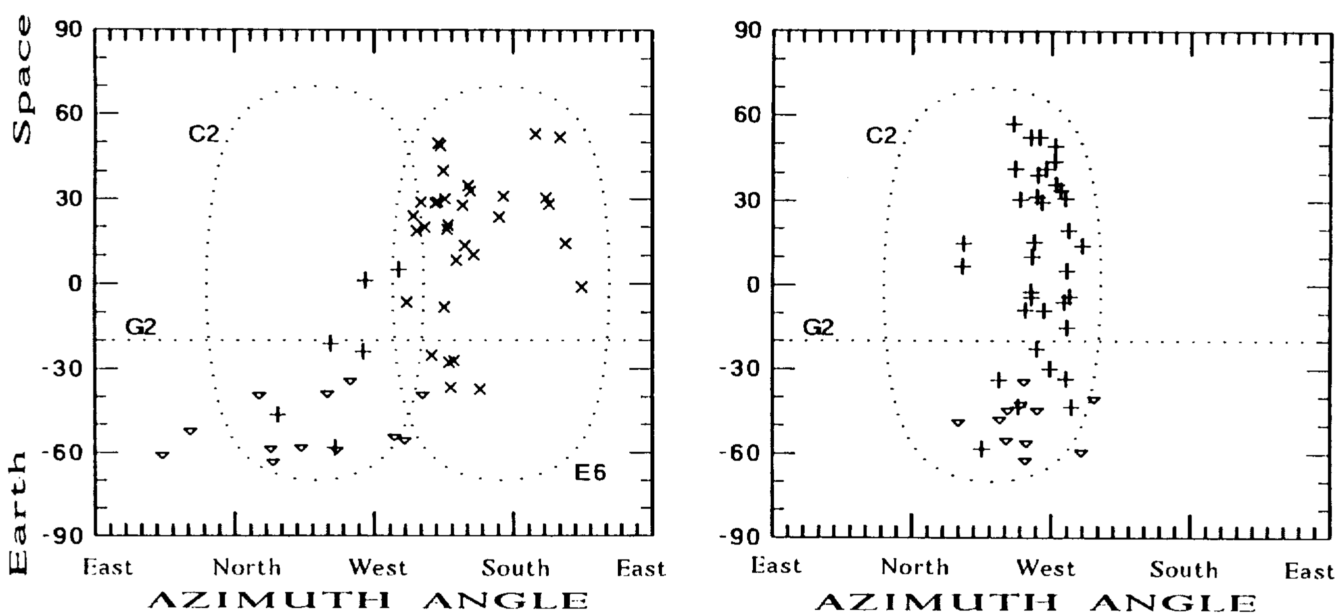

Fig. 7: Arrival direction of Fe-group particles: 50-200 MeV/nuc (left) and 200-400 MeV/nuc. (right, E6 omitted due to limited statistics).

SIMULATION OF TRAPPED PARTICLE ARRIVAL DIRECTIONS

The steep energy spectra below 50 MeV/nuc and the arrival direction distribution are interpreted as evidence for a trapped particle component. To check this interpretation, a Monte-Carlo simulation for the detection of trapped particles (Z>6, Ar and Fe) on the LDEF orbit during SAA crossings was calculated.

As our passive detector system cannot provide the time and orbital position of the particle impact, a geographical region for the particle detection had to be assumed. The basic flux contour lines were adopted from SAA proton measurements at 400 km which

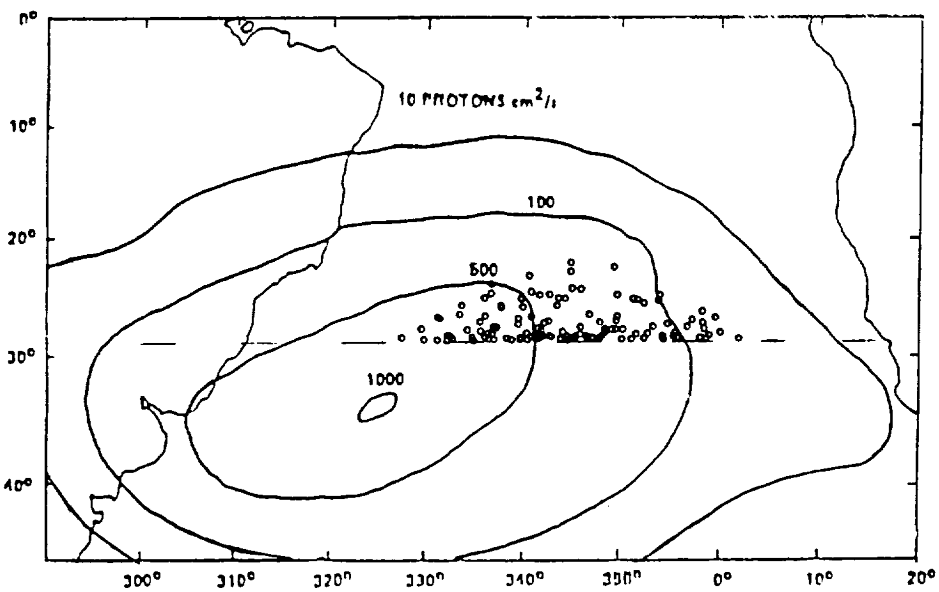

Fig. 8: Monte-Carlo simulation of the geographical distribution for the impact of trapped heavy ions on LDEF (proton contour lines from Watts et al., ref.8).

show a peak flux at 34° S and 35° W. The lateral size of the detection region was assumed to be ±21° longitude and ±13° latitude. Taking random distributed equator crossings of the LDEF orbit (due to the long flight duration), the longitudinal position of the detection region was changed to fit the Monte-Carlo simulation to the measurement.

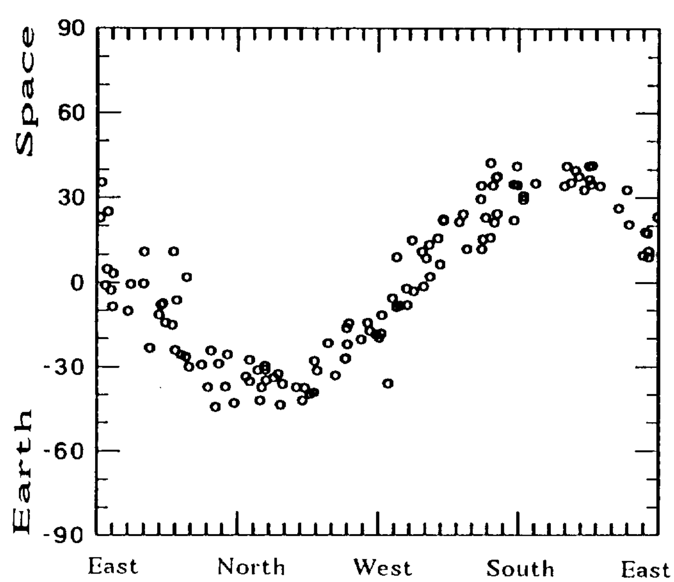

Fig. 9: Simulated arrival directions of trapped heavy ions relative to a horizontal plane (the indicated geographical directions are valid at 28.5° S).

The best fit was achieved when the region was centered at 15° West, yielding the simulated geographical detection distribution shown in Fig. 8. The resulting arrival direction distribution on a horizontal plane on LDEF (Fig. 9) was calculated for 90° pitch angles in the 1985 IGRF field model.

DISCUSSION

All detected particles have energies well below the cut-off value for fully stripped ions to have access to the LDEF orbit. From the energy spectrum and the angular distribution we conclude that two different populations were detected on LDEF.

At energies E>100 MeV/nuc, most of the Fe particles (up to now only these ions were analysed at Kiel above 50 MeV/nuc) seem to originate from outside the magnetosphere. They have to be partly ionized with $Q/Z < 0.5$ to reach the LDEF orbit. Exact transmission calculations are in progress (taking into account disturbed magnetic conditions) in order to study the origin of these particles. The analysis of M0001 (A.J.Tylka et al., these proceedings) has shown that the features of the Fe data above 200 MeV/nuc can be explained by solar energetic particles from the October 1989 events.

At energies E≤50 MeV/nuc, the features of the detected particles and the Monte-Carlo simulation suggest the registration of a trapped component mirroring at L=1.4-1.6 in the South Atlantic Anomaly. Energy spectra and measured arrival direction distributions of all analysed charge groups on trays E6, C2 and G2 (Z>6 on C2 only) are in agreement with this assumption.

The origin and trapping mechanism of these particles are not clearly identified. Calculations for trapped anomalous cosmic rays (9) predict our results for Argon. However, the detection of trapped anomalous Oxygen and Ne on the LDEF orbit is not predicted in this calculation, and the remaining detected ions are not part of the anomalous component. The comparison of the elemental composition in Fig. 2a with the Galileo results for heavy ions in the October 1989 SEP events (10) indicates that part of the low energy particles on LDEF may originate from these solar events (as well as the Fe component at higher energy, see A.J.Tylka et al., M0001, these proceedings).

The energy spectra of Fig. 3 were calculated as mission time averages for an isotropic flux. However, the angular distributions indicate a highly anisotropic flux and the time intervall of registration may be significantly less than the mission time. Only a small part (1-2%) of the mission time was spent close to the SAA, and the life time of trapped heavy ions originating from SEP events is not considered. In addition, the flux of the trapped anomalous component shows a strong temporal variation correlated with the solar activity cycle (4). Future analysis will take this into consideration.

ACKNOWLEDGEMENTS

We greatly thank B. Filz (AFGL, Bedford, MA) for his invitation to participate in experiment M0002 and G. Reitz (DLR Köln) for the integration of our detector foils in experiment A0015. We thank L. Clark (NASA LaRC, Hampton, VA) for his support during the design phase and the integration at Langley. This work was financially supported by BMFT under grant QV 297 and by DARA under grant OS 9001.

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