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THREE–DIMENSIONAL SHIELDING EFFECTS ON CHARGED PARTICLE FLUENCES MEASURED IN THE P0006 EXPERIMENT OF LDEF *

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SUMMARY

Three-dimensional shielding effects on cosmic ray charged particle fluences were measured with plastic nuclear track detectors in the P0006 experiment on LDEF. The azimuthal and polar angle distributions of the galactic cosmic ray particles (mostly relativistic iron) were measured in the main stack and in four side stacks of the P0006 experiment, located on the west end of the LDEF satellite. A shadowing effect of the shielding of the LDEF satellite is found. Total fluence of stopping protons was measured as a function of the position in the main and side stacks of the P0006 experiment. Location dependence of total track density is explained by the three–dimensional shielding model of the P0006 stack. These results can be used to validate 3D mass model and transport code calculations and also for predictions of the outer radiation environment for the space station Freedom.

INTRODUCTION

Cosmic ray charged particles contribute to the health risk of crew members of manned flights and produce single event upsets (SEUs) in microelectronics in space. Risk estimations are usually based on measurements of the outer charged particle radiation environment and use three–dimensional mass

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models and computer transport codes to calculate inner radiation fields. Measurements of the inner radiation environment are also essential to validate transport codes and in some cases to provide direct data for risk estimation. Plastic nuclear track detectors (PNTDs) have been widely used to measure both outer (charge and energy spectra of galactic cosmic rays (GCRs) and trapped particles) and inner (LET–spectra, charge and energy spectra of secondary particles) charged particle radiation fields[1,2,3,4,5,6,7].

A series of PNTD stacks were exposed on the LDEF (Long Duration Exposure Facility) satellite and the ongoing analysis of these stacks makes the cosmic ray charged particle experiments performed on LDEF probably the most comprehensive and, as of today, the most important ever conducted with PNTDs. Unique features of the LDEF satellite make this even more reasonable. The long duration, almost six years in space, makes it possible to study low abundant cosmic rays and measure the high LET-tail with good statistical accuracy. The gravity–stabilized orientation gives the possibility of studying the directionality distribution of cosmic ray charged particles. Also, a detailed mass model of LDEF is available, which makes it possible to compare the inner radiation field and activation measurements with model calculations.

"Outer radiation field measurements" usually actually means "inner radiation field measurements", taking into account the shadowing effects of shielding. This shadowing effect and the contribution of secondary particles to the primary particle fluxes makes a strong difference in the inner and outer radiation fluxes. Hence the understanding of three–dimensional shielding effects on charged particle fluences is essential when interpreting experimental data measured at different locations on LDEF under different shielding distributions. In the present paper we present data of the measurement of galactic cosmic ray Fe particles and stopping trapped proton particles in the main and four side stacks of the P0006 experiment flown on LDEF. The contribution of the three–dimensional shielding effects to the observed anisotropy of Fe particles and to the position dependence of total track density is discussed.

EXPERIMENTS AND RESULTS

The P0006 Experiment

The P0006 experiment on LDEF is a complex experiment to measure the inner and to a certain extent the outer radiation field of cosmic rays. It consisted of activation materials, neutron detectors, thermoluminescent detectors and plastic nuclear track detectors to obtain different kinds of information about the inner radiation field.

The P0006 experiment was located in the F2 tray of LDEF on the west end and close to the space end of the satellite. Its experimental unit consisted of a main and four side stacks as shown in Figure 1. The main stack consisted of 9 sub–stacks of PNTDs, the planes of which were perpendicular to the east–west direction. The side stacks were attached to the four sides of the main stack with the normal vectors pointing out from the main stack into space with the approximate directions as follows: north–space (side stack A), north–Earth (side stack B), Earth–south (side stack C) and south–space (side stack D). (The orientation of the side stacks is assumptive in the sense that experimental results obtained are in agreement with and only

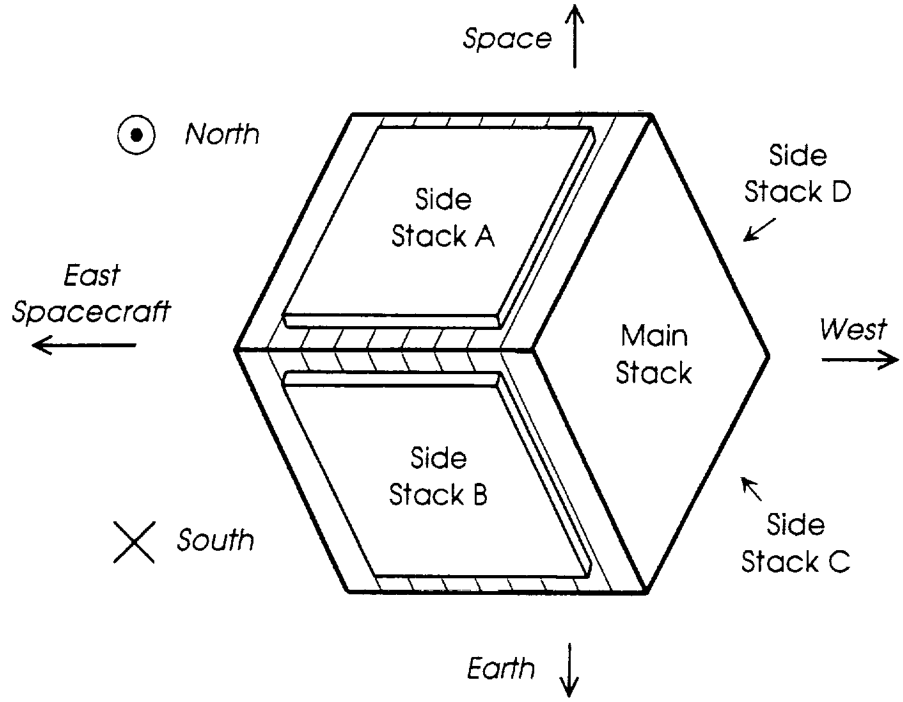

Figure 1: The P0006 experimental block on the LDEF satellite.

with this assumption. Unfortunately it was not possible to confirm the orientation of the side stacks from the data available about the disassembly of the LDEF satellite.)

The P0006 experimental block was placed in a sealed aluminum canister with 1 atmosphere normal air inside. In the surrounding of the P0006 experiment there were 4 other canisters of the P0004 corn seed experiment representing a significant amount of shielding from those directions.

Measurement of Relativistic Fe Particles

Two layers of CR-39 PNTDs were selected from the center of the main stack (6.5 g/cm^2 shielding from the top of the canister) and from the side stacks (1.3 g/cm^2 shielding) for scanning and measuring. The central area of each layer was scanned for tracks in coincidence at the adjacent surfaces. Track pairs were further investigated as to whether they have corresponding tracks on the top surface of the top layer and on the bottom surface of the bottom layer (4–surface tracks). Comparing the size of the tracks at all four surfaces to each other we found that the size of the tracks did not change within experimental errors which means that these tracks were produced by high energy particles. Comparing the differential LET–spectra of 4–surface tracks found in LDEF samples to a differential LET–spectra of 4–surface tracks found in a sample flown on a shuttle flight with similar altitude and inclination to LDEF, we found that practically all 4–surface tracks measured in LDEF samples must be produced by relativistic energy Fe particles. In the case of the sample from the shuttle flight other galactic cosmic ray particles are also included in the differential LET–spectra and the peak of the relativistic Fe particles can clearly be seen because of the

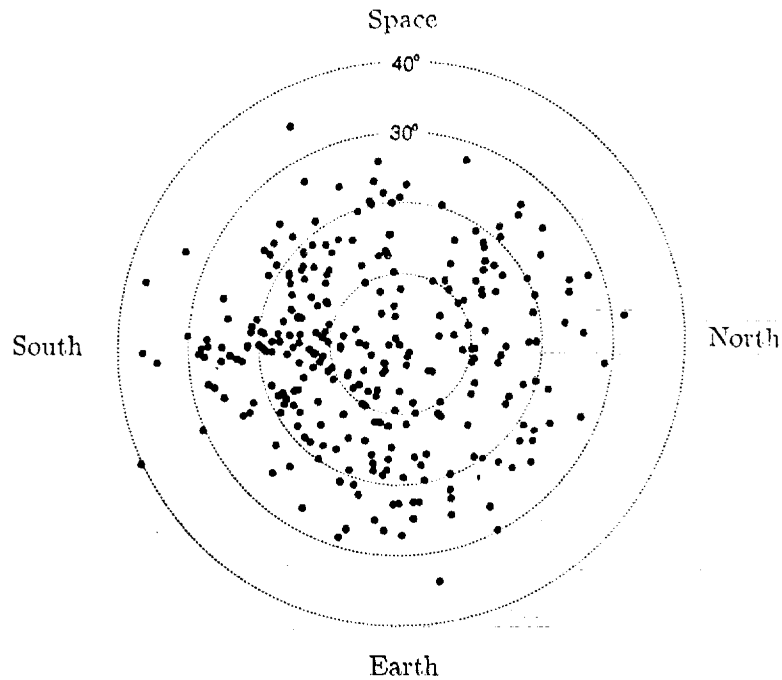

Figure 2: Arriving directions of GCR Fe particles with relativistic energies looking to the west direction from the center of the P0006 experiment on LDEF. Particles with dip angle greater than 40° could not be measured because of the critical angle cut–off of the detector.

relatively high abundance of these particles to the neighboring elements. Lighter than iron relativistic particles could not be seen in the case of the LDEF samples because of the short etching time needed.

300 particles in the main stack and 100 particles in each side stack were identified as relativistic galactic cosmic ray Fe particles in the present experiment. The azimuthal and dip angle distributions of the particles were measured. Since the moving direction along the particle trajectory could not be measured we assumed that all the particles measured arrived from the west direction and moved toward the east direction. Experimental data in the side stacks are consistent with this assumption.

Figure 2 shows from which directions 300 GCR Fe particles arrived to the center of the main stack of the P0006 experiment. No particles could be detected with dip angle (measured from the normal of the detector layer) greater than about 40° because of the dip angle cut–off of the detector. Scanning efficiency close to the cut–off dip angle was also significantly less than 100% due to the difficulty of finding corresponding tracks on the first and fourth surfaces of the CR-39 doublet. Figure 2 shows that arriving directions of particles from the west are very isotropic with some extra particles coming from the south-west, parallel with the Earth's surface.

In Figure 3, empty circles show the arriving directions; filled circles show the leaving directions of 100 particles in each side stack. The shielding of the LDEF satellite is the east side and the shielding of the P0004 canisters are at the center of the graphs. It seems that these large (about 40–150 g/cm^2) shieldings

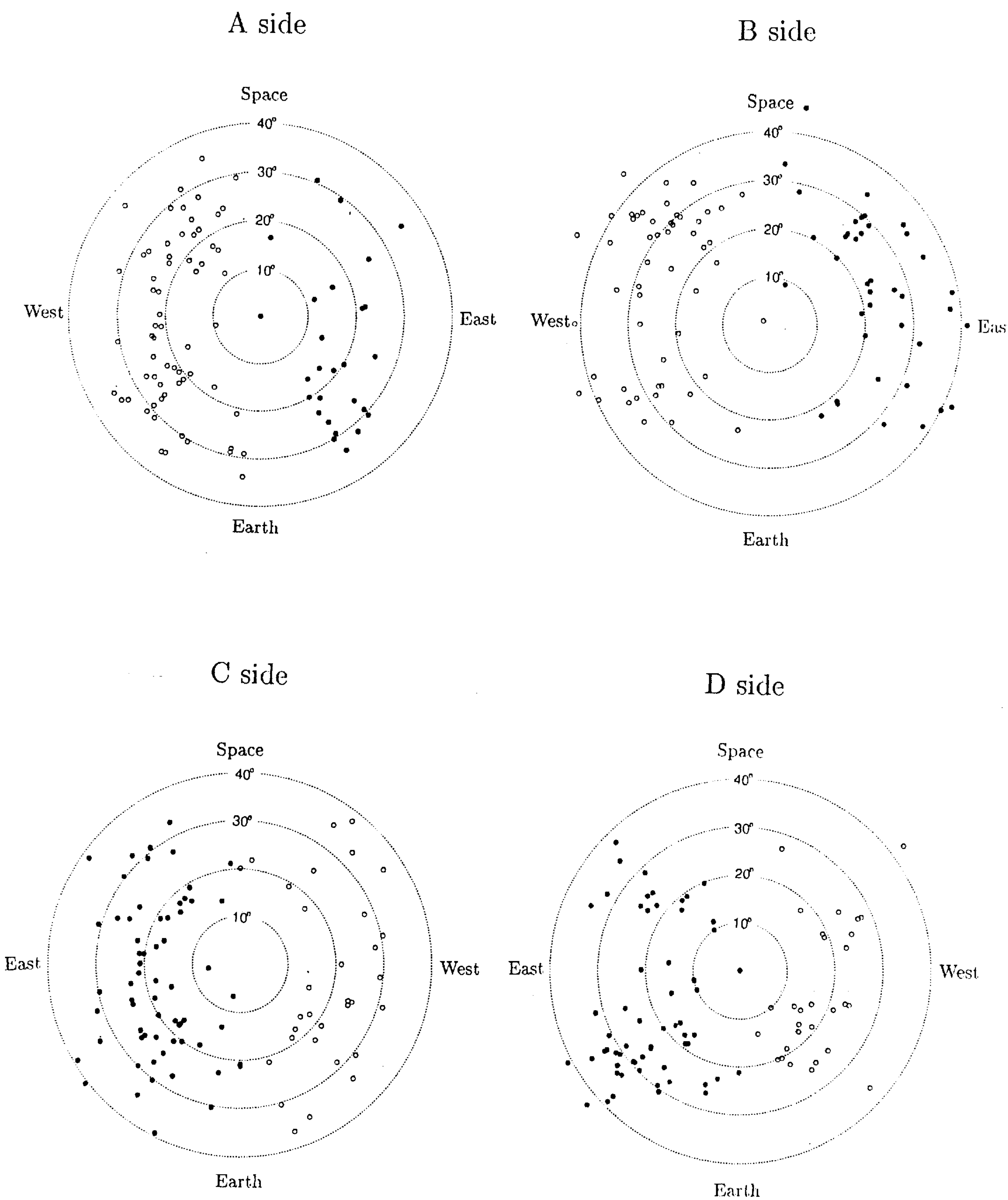

Figure 3: Arriving directions of GCR Fe particles with relativistic energies in the side stacks of the P0006 experiment.

can absorb relativistic Fe particles and only a very few percent can penetrate them. However, some anisotropy of the GCR Fe particles cannot be related to shielding effects, hence we believe there is an anisotropy in the flux of the primary GCR Fe particles.

Total Track Density Measurements

We have measured two–dimensional total track density profiles in each side stack using an image analyzer. The image analyzer was able to pick up tracks darker than a certain brightness threshold and having contrast high enough to detect edges. Track size criteria were also applied in the counting. Overlapping tracks were separated by the software with very high efficiency. Total track density measurements were also performed by manual scanning and counting and the results were used to calibrate the automatic system. A reasonably good agreement between manual and automatic scanning has been established.

Total track density in CR-39 consists of tracks of different particles. At low shielding, such as the case for the side stacks, a large contribution is due to stopping primary trapped protons. A significant contribution is due to secondary stopping particles and recoils and also from GCR Fe particles. At higher shielding depths, these particles dominate the total track density as the high flux of low energy trapped protons is absorbed in the shielding.

On the other hand, not all of the particles can be detected by CR-39. A stopping proton can be detected with very high efficiency if the particle stops in the upper layer of the detector, which has a thickness comparable with the layer removed by the chemical etching of the detector. This thickness was about 8–10 μm in our samples. The critical angle for the detection of a proton in this case is about 70° measured from the normal of the detector surface. This critical angle decreases rapidly with the residual range of the proton if the particle stopped below the post–etched surface which, we found, is usually the case for proton tracks. A detailed detection efficiency calculation is in progress taking into account a variable track etch rate ratio model for stopping particles. Internal calibration will also be performed using tracks of stopping proton particles.

Detection efficiency for other than proton particles is almost 100% if the particle stops in the removed layer, which means that CR-39 can detect practically all heavy recoils that have a part of their trajectories in the removed layer thickness. Relativistic Fe particles, on the other hand, are detected only from a small field angle around the normal of the detector with a critical angle of about 40°.

Trapped protons are expected to have a strong directionality. In the case of the P0006 stack they are expected to arrive from the west direction, mostly parallel with the Earth's surface and with the surfaces of the CR-39 layers in the side stacks. It means that the track density of stopping primary trapped protons is expected to decrease with the depth in the main stack as the low energy trapped protons and their secondaries are absorbed in it. The secondaries of the high energy trapped protons, however, are not expected to show strong shielding effects because they can penetrate the whole stack with approximately constant interaction cross sections. Hence, a strong location dependence of total track density is expected at low shieldings and some relatively smooth track density profiles at higher protected areas.

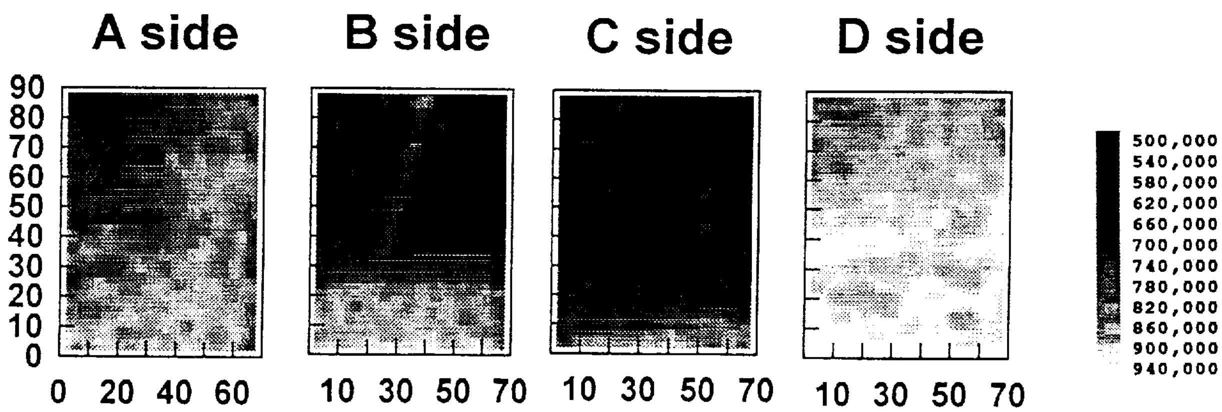

Figure 4: 2D total track density profiles in CR-39 from the side stacks of P0006. Bottom edges of the layers are the space side edges.

Figure 4 shows some preliminary 2D total track density profiles measured in the side stack CR-39 samples. The total track density varied between 0.6 and 1.3 million tracks/cm^2. Side stacks A and D had significantly higher track densities than side stacks B and C facing toward the Earth. On the side stacks facing toward space the side stack D has higher track density than side stack A, indicating more particles from the south–west than from the north–west direction. This observation is in good agreement with the Al activation measurements around the LDEF satellite which also show a maximum in the south-west direction.

On each sample the track density is highest at the space edge of the sample and decreases toward the LDEF satellite. This is especially demonstrated on side stacks B and C. The sudden drop of track density moving from the space edge toward the satellite probably reflects the absorption of low energy trapped protons arriving from the west–space direction and slowing down as they penetrate the main stack. The dominance of the trapped protons from the west–south–space direction is also suggested by the relatively uniform track density on the side stack D which has practically no shielding from this direction.

CONCLUSIONS

It is demonstrated that the three–dimensional shielding effect has to be taken into account when cosmic ray charged particle fluences are measured under different shielding conditions. The shadowing effect of the LDEF satellite on the relativistic GCR Fe particles was found. Additional observed anisotropy in the fluence of these particles is assumed due to the anisotropic directional distribution of the particles which has to be explained by propagation codes.

The variation of total track density as a result of self shielding of the P0006 stack was also observed. The strong location dependence of the track density was found to be in good agreement with the anisotropic trapped proton environment and 3D geometrical considerations of the P0006 experimental block.

These experiments clearly indicate the need for detailed mass model calculations together with which they may provide an excellent opportunity to validate model calculations and help update flux data of the outer radiation environment.

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