APPENDIX N

Linear Energy Transfer (LET) Spectra of Cosmic Radiation in Low Earth Orbit

by

T.A. Parnell and J.W. Watts, Jr.
LINEAR ENERGY TRANSFER (LET) SPECTRA OF COSMIC RADIATION IN LOW EARTH ORBIT

A. B. AKOPOVA,* N. V. MAGRADOZ,* V. E. DUDKIN†, E. E. KOVALEV,† Y. V. POTAPOV †, E. V. BENTON ‡, A. L. FRANK‡, E. R. BENTON‡, T. A. PARNELL‡ and J. W. WATTS§


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Abstract—Integral linear energy transfer (LET) spectra of cosmic radiation (CR) particles were measured on five Cosmos series spacecraft in low Earth orbit (LEO). Particular emphasis is placed on results of the Cosmos 1887 biosatellite which carried a set of joint U.S.S.R.-U.S.A. radiation experiments involving passive detectors that included thermoluminescent detectors (TLDs), plastic nuclear track detectors (PNTDs), fission foils, nuclear photo-emulsions, etc. which were located both inside and outside the spacecraft. Measured LET spectra are compared with those theoretically calculated. Results show that there is some dependence of LET spectra on orbital parameters. The results are used to estimate the CR quality factor (QF) for the Cosmos 1887 mission.

INTRODUCTION

The integral linear energy transfer (LET) spectra are important for characterizing cosmic radiation (CR) because they can be used to estimate the absorbed and equivalent particle dose and to evaluate the respective quality factors. Earlier, the integral LET distributions were measured in the following works: Petrov et al. (1975), Benton (1983, 1986), and Akopova et al. (1985, 1986, 1987, 1988). As a rule, these investigations used passive detectors (plates, emulsions) which permitted measurements in a restricted LET interval. In some investigations (e.g. Akopova et al., 1987, 1988; Heinrich, 1977; Heinrich and Baer, 1984), the LET distributions were calculated as a function of shielding. In all of these theoretical studies, only the galactic cosmic ray particles were regarded as sources of cosmic radiation.

This paper presents the results of a recent experimental and calculational study carried out by the authors. Particular attention was paid to comparing results obtained by various experimental techniques, and to finding the laws which govern the dependence of the forms of the integral LET distributions on orbital parameters. Measurements were taken in free space (behind very thin shielding), and inside the spacecraft where the mean thickness of the shielding of detectors reached tens of g cm⁻². The contribution of trapped protons and electrons is also taken into account in the theoretical calculations.

EXPERIMENTAL TECHNIQUES

The use of LET spectral data is necessary for appraising the radiation environment inside spacecraft. Previous measurements were made on board Cosmos 782, 936, and 1129 using an electron spectrometer, nuclear emulsions, and plastic detectors. These results have been presented by Benton (1986) together with dosimetric measurements and LET spectra obtained on board some of the U.S. Shuttle flights.

The current work presents the results obtained on board five Cosmos-type satellites using two types of detectors, namely, nuclear photo-emulsions (NPE) and solid state nuclear track detectors (SSNTDs). The NPE assemblies containing 200 μm thick BR- and BYa-type emulsions wrapped with light-tight paper and aluminized Lavsan were placed either in instrument modules outside the spacecraft or inside the spacecraft. After exposure and recovery, each layer of emulsion assembly was treated by the selective-development technique which makes it possible to control the NPE layer threshold sensitivity in a broad interval of LET (see Akopova et al., 1983). The emulsion threshold sensitivity control is based on the introduction of Br⁻ ions into an exposed emulsion layer by diffusion. The Br⁻ ions emanated from BR-type layers (emitters) glued to either of the surfaces of the exposed layer that had been irradiated beforehand with blue–violet light. The Br⁻ ion generation and diffusion from the emitters to the exposed...
layers gives rise to a negative bromine barrier around the latent image centers, thereby increasing the induction periods of developing centers. The ability of the centers to be developed depends, then, upon the ratio of the height of the barrier restricting the arrival of electrons at the centers to the depth of the potential well in which the electrons are captured. Thus, controlling the NPE threshold sensitivity is based on different degrees of dispersion of the latent image centers produced by particles with different LET values. The threshold sensitivity of the exposed layer permits only those particle tracks to be developed for which the LET is at least equal to some threshold LET value. Therefore, the technique of finding the planar fluence of the particles with LET ≥ LETthreshold does not require the track parameters to be measured but is reduced to counting the number of the tracks traversing a particular section of an NPE surface. Calibration of the technique was achieved by exposing NPEs to particle beams of well-defined LETs.

We used BYa-type emulsion which permits the integral LET spectra to be measured within an interval from 12 to ~10^6 MeV cm^-2 of biological tissue (water), with the lower limit (~12 MeV cm^-2) being defined by the effective sensitivity of the BYa-type emulsion. To obtain a complete LET distribution, we sometimes used the relativistic BR-type emulsion, thereby making it possible (to within a large microscope scanning error) to find the planar fluence of cosmic radiation particles at small LET values (the LET of relativistic protons in tissue is equal to some 2.0 MeV cm^-2). The error in counting these tracks at LETthreshold = 2.0 MeV cm^-2 increases (i) due to a high track exposure of the detectors (the satellite flights lasted, as a rule, for more than 10 days) and (ii) because the operator can easily overlook tracks of relativistic protons (low grain densities).

The second technique for finding the LET distributions is based on the use of SSNTDs of the CR-39, CN, and polycarbonate type, whose effective LET thresholds of track detection are 40, 1000, and 2250 MeV cm^-2 in water, respectively. CN and Lexan were used in earlier measurements (the ASTP, Skylab, and Apollo 17 missions). During later flights, including the 24 initial flights of the U.S. Shuttle, use was made of SSNTDs of the CR-39, polycarbonate, and polystyrene types which were subjected after the flights to the standard NaOH etching with 6.25 N at 70°C. Preliminary scanning showed that the density of the tracks detected in polycarbonate and polystyrene was very low compared with that of CR-39. The method for using SSNTD to find the LET spectra is described in detail by Henke and Benton (1974).

**RESULTS AND DISCUSSION**

In Fig. 1 are shown the results of LET spectra measurements by the NPE method. The NPE assemblies were placed in external instrument modules on spacecraft with different orbital parameters (see Table 1). For these external assemblies, the shielding thickness may be considered not to exceed ~1.0 g cm^-2. The shielding of the detectors by the satellite bodies and by the Earth and the geometry of the exposures were approximately the same for all of the flights.

The integral LET spectra shown in Fig. 1 have been obtained mainly with the BYa-type emulsions, so the distribution ranged from 12 to 1.5 × 10^6 MeV cm^-2 of tissue. From Fig. 1 it is seen that the values of the integral spectrum at the lower LET values were

![Fig. 1. The experimental LET spectra obtained from different satellites of the Cosmos series at δ ≤ 1.0 g cm^-2 by the NPE method.](image)

<table>
<thead>
<tr>
<th>Cosmos series satellite</th>
<th>Exposure time</th>
<th>Apogee/ perigee (km)</th>
<th>Orbital inclination</th>
<th>Solar activity period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1129</td>
<td>Sep. 25-Oct. 10, 1979</td>
<td>406/226</td>
<td>62.8°</td>
<td>max</td>
</tr>
<tr>
<td>1371</td>
<td>Jun. 11-Jun. 26, 1984</td>
<td>420/355</td>
<td>70°</td>
<td>min</td>
</tr>
<tr>
<td>1600</td>
<td>Sep. 27-Oct. 10, 1984</td>
<td>420/354</td>
<td>70°</td>
<td>min</td>
</tr>
<tr>
<td>1757</td>
<td>Jun. 11-Jun. 19, 1986</td>
<td>252/189</td>
<td>92.3°</td>
<td>min</td>
</tr>
<tr>
<td>1887</td>
<td>Sep. 39-Oct. 12, 1987</td>
<td>406/224</td>
<td>62.8°</td>
<td>min</td>
</tr>
</tbody>
</table>
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obtained using the relativistic Bp-type emulsion on board Cosmos 1571 and 1757 only. In order to make the presentation of data clear, the experimental points have been unified by a solid line of the approximate form \( x \cdot L^{-1} \), where \( L \) is LET in tissue, \( x \) and \( \beta \) are constants.

The following preliminary conclusions may be drawn from the curves presented in Fig. 1:

1. Experimental values of the integral LET distributions are very close to each other for the satellites with similar orbital parameters (Cosmos 1129 and 1887, Cosmos 1571 and 1600);
2. Effects of solar activity are insignificant (the values of the spectra obtained from Cosmos 1129 and 1887 are alike);
3. Slopes of the integral spectra obtained from satellites differing in orbit inclination, \( i \), are similar to each other (the spectral index \( \beta \) of all three spectra for the LET ranging from 10 to 100 MeV cm\(^{-1}\) of tissue is the same within deviations of \( \pm 15\% \));
4. Values of the LET spectra seem to rise with increasing orbit inclination at \( i \geq 60^\circ \);
5. The integral LET spectrum obtained from Cosmos 1757 is higher than all the other spectra despite the fact that the particular orbit was 1.5 times lower in altitude than the other orbits.

A preliminary conclusion may be drawn from comparing these results with the results of Benton (1983): in the case of highly inclined orbits (\( i > 60^\circ \)) the absolute flux values of the LET spectra and, hence, of the absorbed and equivalent doses, depend more strongly on the orbit inclination (\( i \)) than on altitude (\( h \)), whereas in the case of low inclination orbits (\( i < 60^\circ \)) their flux values depend more strongly on altitude than on orbit inclination. Further measurements in high inclination orbits are needed for verification.

The observation can be understood by considering how the various contributions to LET vary with orbital altitude and inclination. Above 60° inclination at low altitudes galactic cosmic rays dominate the LET. The GCR is not strongly modulated by altitude at the altitudes considered, but is modulated by the rigidity cut-off, which is a function of geomagnetic latitude. For lower inclination orbits, trapped particles are more important. Trapped particles are strongly modulated with altitude, but not so strongly modulated with inclination.

Figures 2 and 3 present the integral LET spectra obtained from Cosmos 1887 by the NPE and SSNTD methods. The respective values for the external assemblies are shown in Fig. 2, while the data obtained inside the satellite are presented in Fig. 3. The two figures also show the calculated results obtained by the method described in Akopov et al. (1987) behind shielding thickness \( \delta = 1.0 \) g cm\(^{-1}\) (Fig. 2) and \( \delta = 1.0, 10.0, \) and \( 20.0 \) g cm\(^{-1}\) (Fig. 3). The calculations were made for the Cosmos 1887 orbit parameters. The number of histories is \( 10^8 \).

A method for calculating the integral LET spectrum of galactic cosmic ray particles is described in Akopov et al. (1987). Our work is the first to include both the galactic cosmic ray particles and the radiation belt protons in the region of the South Atlantic Anomaly (SAA). The LET distributions from the protons were determined from the energy spectra of radiation belt protons calculated using the Sawyer

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**Fig. 2.** The experimental and calculated integral LET spectra obtained from Cosmos 1887 (outside the satellite).

**Fig. 3.** The experimental and calculated integral LET spectra obtained from Cosmos 1887 (inside the satellite).
and Vette (1976) AP8MIN trapped proton environment. Figures 2 and 3 present the total calculated LET distributions (the histograms).

The following preliminary conclusions may be drawn from analyzing the curves presented in Figs 2 and 3:

1. The experimental results obtained by the NPE and SSNTD methods are similar in the region where the LET spectra overlap, thereby indicating that both methods may be used in studies of this type. The best agreement between the experiments was obtained from measurements made inside the spacecraft (Fig. 3);

2. The experimental and calculated data are also in satisfactory agreement with each other. The fact that the experimental and calculated curves shown in Fig. 3 are about the same at \( \Delta = 10.0 \, \text{g cm}^{-2} \) seems to imply that the mean thickness of the shielding of the detectors was close to \( \sim 10.0 \, \text{g cm}^{-2} \);

3. It should be noted that the calculated and experimental data disagree at small shielding thicknesses (\( \Delta \leq 1.0 \, \text{g cm}^{-2} \)), especially for the lower LET values (Fig. 2). As shown by a relevant analysis, \( 85-95\% \) of the spectrum at the LET values from \( 10 \) to \( 100 \, \text{MeV cm}^{-2} \) of tissue is due to the radiation belt protons (on assumption of the isotropic proton distribution in the SAA). The trapped proton calculations therefore seem to be less consistent with the experiment than the GCR calculations. However, the experimental points are scanty in the given LET range, a fact that should be taken into account in further studies;

4. The results of calculating the integral LET spectra from galactic cosmic ray particles behind shielding from \( 0 \) to \( 50 \, \text{g cm}^{-2} \) were previously done by Heinrich (1977) and Heinrich and Baer (1984), where the following two main conclusions were reached, namely, (i) the spectral slopes change at \( \sim 10 \, \text{MeV cm}^{-2} \) for all shielding thicknesses and (ii) the spectral slope angle is independent of the LET for \( \Delta > 10 \, \text{MeV cm}^{-2} \) and depends upon the latter (with thickness) for \( \Delta < 10 \, \text{MeV cm}^{-2} \). Our studies have confirmed the first conclusion completely. Our calculations have shown that the slope angles of the LET spectra are alike in the range of LET \( \Delta > 10 \, \text{MeV cm}^{-2} \) where the value of the spectrum is defined solely by the galactic cosmic ray particles (mainly, by Fe nuclei). The contribution of radiation belt protons to the total integral LET distribution decreases with increasing shielding thickness. The opposing dependencies lead to the near-independence of the slope angle of the total GCR and proton distributions on shielding for shielding thicknesses up to at least \( 20 \, \text{g cm}^{-2} \), for LET \( \leq 10 \, \text{MeV cm}^{-2} \).

We have used our experimental and calculated LET distribution data to estimate the mean quality factor (QF) in the Cosmos 1887 orbit behind shieldings of \( 1.0 \) and \( 10 \, \text{g cm}^{-2} \). This applies to particles having LET in tissue from \( 2.0 \) to \( 10 \, \text{MeV cm}^{-2} \). We used the AE8MIN environment (Teague and Vette, 1972) to calculate the doses from the radiation belt electrons in the Cosmos 1887 orbit behind a \( 1.0 \, \text{g cm}^{-2} \) shielding. In the case of a \( 10 \, \text{g cm}^{-2} \) shielding, the electrons were neglected because of their small contribution to the total dose. We have found their QF to be \( 1.3 \pm 0.2 \) and \( 1.7 \pm 0.2 \) at \( 1.0 \) and \( 10 \, \text{g cm}^{-2} \), respectively. These values are in good agreement with the calculated and experimental data published elsewhere (Kovalev et al., 1979; Curtis et al., 1986).

In future studies, particular attention should be paid to detection of spectra at small LET values. In addition, knowing the distribution of the spacecraft shielding is extremely important, as this information will allow a more correct comparison between the calculated and experimental data.

REFERENCES


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