

Study of test-mass charging process in the LISA missions due to diffuse γ -rays

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Abstract. Gravitational inertial sensors will be placed on board the Laser Interferometer Space Antenna (LISA) and aboard its precursor mission LISA Pathfinder (LISA-PF) in order to detect low frequency gravitational waves in space. Free-floating test-masses (Au_7Pt_3 cubes) will be housed in inertial sensors for detecting possible laser signal variations induced by gravitational waves. Charging of the LISA test-masses due to exposure of the spacecraft to cosmic radiation and energetic solar particles will affect operation of gravitational inertial sensors. In this paper we report on the role of diffuse γ -rays in charging the LISA and LISA-PF test-masses with respect to protons and helium nuclei. The diffuse γ -ray flux in the Galaxy has been interpolated taking into account the outcomes of recent calculations. A comparison with γ -ray observations gathered by different experiments (COMPTEL and EGRET, Milagro, Whipple, HEGRA, TIBET) has been carried out. Simulations of the test-mass charging process have been performed by means of the FLUKA2006.3b package. Monte Carlo simulations of the interaction of cosmic particles with the LISA spacecraft indicate that the diffuse γ -ray contribution to the average steady-state test-mass charging rate and to the single-sided power spectrum of the charge rate noise is marginal with respect to that due to galactic cosmic-rays.

1. Introduction

The Laser Interferometer Space Antenna, in its Earth-like orbit around the Sun, will be affected by space environment disturbance. Solar energetic particles and galactic cosmic-rays (GCRs) with energies greater than $100 \text{ MeV}/n$ will be able to penetrate the apparatus charging the free-floating test-masses (TMs) which interact electromagnetically with surrounding conducting surfaces of the inertial sensors (ISs). This charging process simulates the effects of gravitational waves and limits the sensitivity of LISA to gravitational wave detection [1–7]. The precursor mission LISA Pathfinder, operating at the Earth-Sun L1 Lagrange point, will be similarly affected by this radiation environment noise. For this reason an UV discharge system is provided for both LISA and LISA-PF. This work concerns the role of diffuse γ -rays (undetected by on board radiation monitors) in charging the LISA and LISA-PF test-masses. Monte Carlo (MC) simulations of the TM charging process have been performed by means of the FLUKA2006.3b package [8, 9] taking into account a simplified geometry of the apparatus [4]. The average steady-state charging rate and the single-sided power spectrum of the charge rate noise induced

by diffuse γ -rays with respect to those due to GCR protons and helium nuclei are reported in this paper, while absolute values can be inferred from [1].

2. Diffuse galactic γ -ray spectrum

Observations of diffuse γ -ray flux in the Galaxy have been performed by different experiments as shown in Fig. 1: the COMPTEL and EGRET data are taken from [12,18]; the Milagro point is obtained from [13] with a conversion factor equal to 2.43 ± 0.55 as reported in [19]; other data points are upper limits set by Whipple [14], HEGRA [15,16] and TIBET [17]. EGRET observations reveal an excess above 1 GeV respect to the expected γ -ray spectrum calculated under the assumption that the locally observed cosmic-ray fluxes correspond to the GCR spectra. Recent calculation [10] have been performed assuming that GCR of energy below 100 TeV are accelerated by supernova remnant shock waves and that the shock compression ratio is supernova remnant age dependent. In [10] GCR proton and electron spectra have been obtained injecting the average source spectra (calculated from an ensemble of supernova remnants) in the Galaxy and using a 3-D convection-diffusion equation and the diffuse γ -ray spectrum has been produced by interaction of these GCRs with the interstellar medium and the interstellar radiation field. Results of model proposed in [10] are in agreement with the γ -ray experimental data at almost all energies except around 85 GeV (Fig. 1). We point out that averaged GCR spectra which reproduce the γ -ray experimental data so well result to be flatter than the GCR spectra observed locally (for a detailed discussion see [10]).

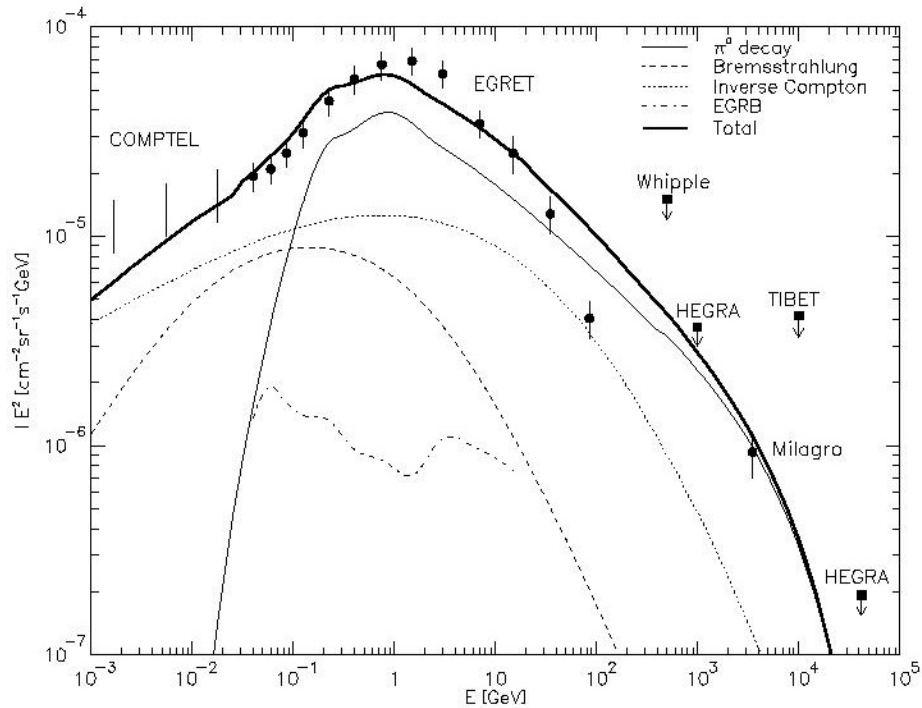


Figure 1. Averaged diffuse γ -ray spectrum in the Galaxy: results of calculation [10,11] are compared with experimental data points (COMPTEL and EGRET [12,18], Milagro [13,19]) and upper limits (Whipple [14], HEGRA [15,16] and TIBET [17]). Different model components have been taken into account in the total γ -ray spectrum computation: π^0 decay, bremsstrahlung and inverse Compton [10] and extragalactic diffuse γ -ray background (EGRB) taken from [18].

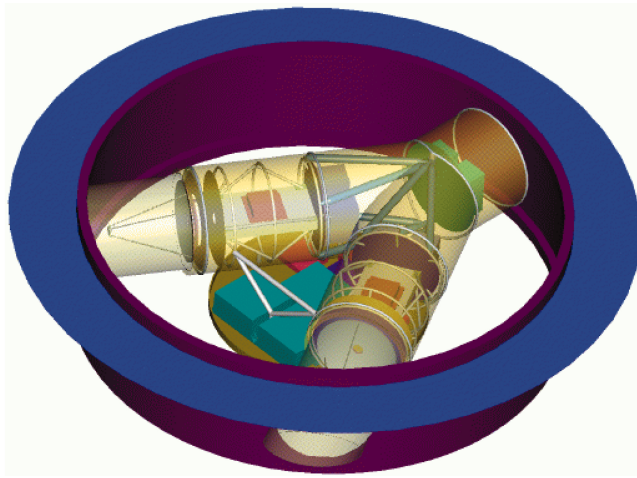


Figure 2. LISA carries identical science instruments on each of the three spacecraft. Like it is shown in this picture (from <http://lisa.jpl.nasa.gov/>), each spacecraft's instrument is made up of two optical assemblies and lasers, mounted on a disk-shaped radiator, housed inside a Y-shaped tubular structure that is supported by the spacecraft's cylindrical walls.

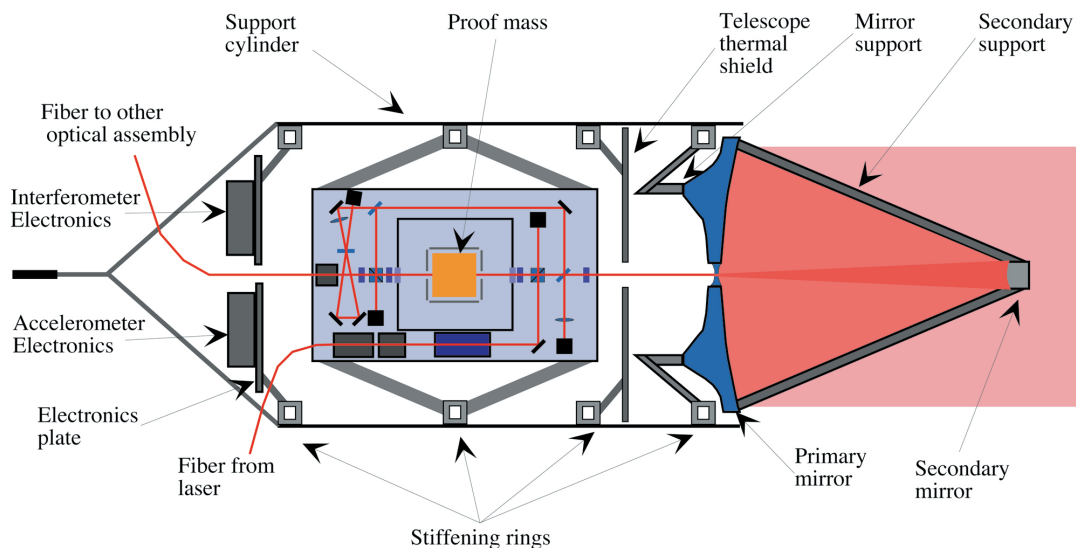


Figure 3. Optical assembly shown in detail (from <http://lisa.jpl.nasa.gov/>): here the TM is indicated as proof-mass.

3. FLUKA simulations

The LISA apparatus consists of an equilateral constellation of three spacecraft 5 million km apart. A gravitational wave will induce small variations in the laser signal as it runs along the space interposed between two free-floating TMs located aboard different spacecraft. In order to detect gravitational waves, each LISA module accommodates two interferometer telescopes mounted inside a Y-shaped payload structure (Fig. 2). Two free-floating TMs are housed in ISs located in optical benches (Fig. 3) mounted behind the telescopes. Each TM is a Au_7Pt_3 cube ($46\text{ mm} \times 46\text{ mm} \times 46\text{ mm}$) surrounded by electrodes lodged in a molybdenum housing and the assembly is accommodated in a titanium vacuum enclosure. This IS structure is the current design of the sensor aboard LISA-PF mission. In order to estimate the radiation environment noise, simulations of the LISA and LISA-PF TM charging process have been performed by means of the FLUKA2006.3b package [8, 9] taking into account a simplified geometry of the apparatus [4]. In carrying out MC simulation an isotropic primary flux has been generated uniformly on a spherical surface containing the whole apparatus and energies of primaries

have been sampled randomly in the interval $[E_{\min}, E_{\max}]$ following the given distribution of the primary flux $F(E)$. The MC timelines have been normalized on the basis of energy differential flux definition, that is taking into consideration the fact that N_0 primaries are generated in a time interval $[0, t]$ with $t = N_0 / (GF \cdot \int F dE)$, where GF is the geometrical factor ($GF = 4\pi^2 R^2$ for a spherical surface of radius R) and the flux integration is performed from E_{\min} up to E_{\max} . For each primary (event-by-event analysis), the MC model tracks all particles penetrated or produced inside the IS calculating the difference between those entering and leaving the TM. Taking into account that IS materials are thick enough, a threshold of 100 keV has been imposed for secondary particle production and transport inside the IS [8,9] .

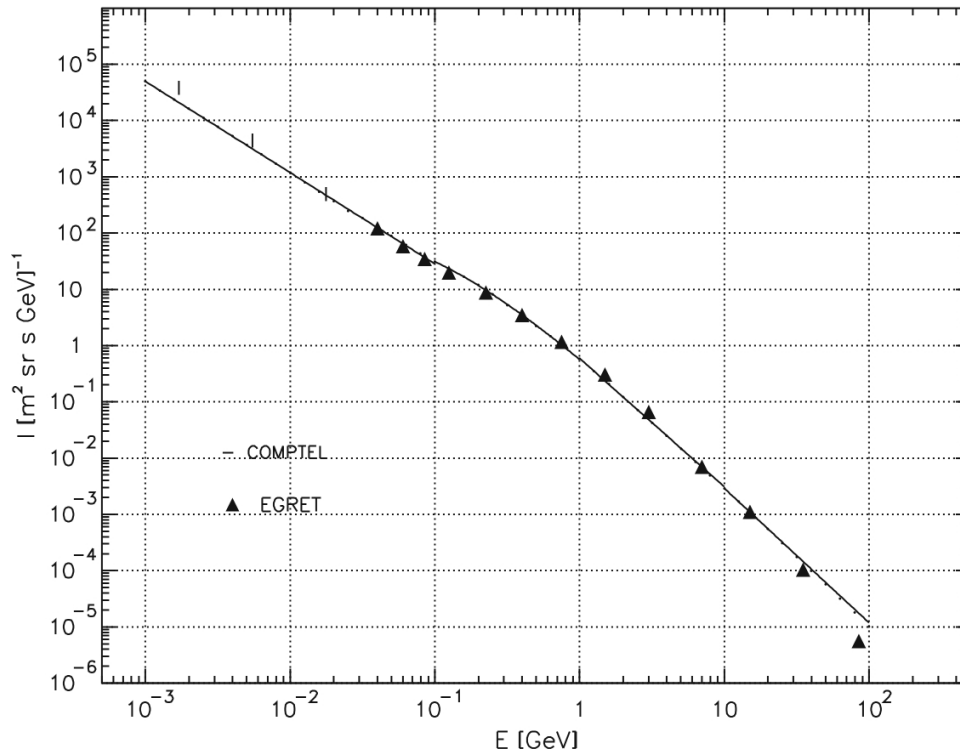


Figure 4. The diffuse γ -ray flux in the Galaxy in the energy interval 0.001 – 100 GeV has been interpolated taking into account the outcomes of calculations reported in [10] (dots). In this figure fit functions (unbroken lines) and experimental data points [12,18] are shown as well.

4. Simulation results

MC simulations have been performed for protons and ^4He nuclei (the two most abundant primary nuclei in GCRs) at the minimum of solar activity and for γ -rays. The adopted spectra for protons and ^4He nuclei have been chosen of the form $F = \alpha \cdot (E + \beta)^{-\delta} \cdot E^\sigma$ where E is the kinetic energy in GeV/(n) ranging in the interval 0.1 – 100 GeV/(n) and the differential flux F is in $\text{m}^{-2}\text{sr}^{-1}\text{s}^{-1}(\text{GeV}/n)^{-1}$ [5]. From a fit of experimental data it results: $\alpha = 18000$, $\beta = 1.09$, $\delta = 3.66$, $\sigma = 0.87$ for protons and $\alpha = 850$, $\beta = 0.99$, $\delta = 3.10$, $\sigma = 0.35$ for ^4He nuclei [6,7]. We point out that GCR protons and ^4He nuclei with energies below 100 MeV/(n) are not able to penetrate the shielding overlying the TM. For γ -rays the energy E has been sampled randomly in the interval 0.001 – 100 GeV following a distribution (Fig. 4) interpolated taking into account the outcomes of calculations reported in [10]. The corresponding γ -ray differential flux fit functions are reported in Tab. 1. During each run, the total exposure time was 600 s for

protons and ^4He nuclei and 6000 s for γ -rays. We point out that only primaries with energies below 100 GeV(/n) have been considered since events with energies above 100 GeV(/n) are extremely rare for both GCRs and γ -rays.

Table 1. Fit functions of the γ -ray distribution used for MC simulations: the γ -ray energy E is in GeV and the γ -ray differential flux F is in $m^{-2}sr^{-1}s^{-1}GeV^{-1}$.

Energy interval	Fit function	Parameter values
0.001 GeV – 0.1 GeV	$F = \alpha \cdot E^{-\beta}$	$\alpha = 0.67730; \beta = 1.6214$
0.1 GeV – 1 GeV	$F = \alpha \cdot (E + \sigma)^{-\beta}$	$\alpha = 0.68316; \sigma = 0.085615; \beta = 2.2654$
1 GeV – 10 GeV	$F = \alpha \cdot E^{-\beta}$	$\alpha = 0.58984; \beta = 2.2810$
10 GeV – 100 GeV	$F = \alpha \cdot E^{-\beta}$	$\alpha = 0.70851; \beta = 2.3888$

In MC simulations, the average TM charging rate R has been calculated by using the following formula:

$$R = \sum_q (qe k_q)$$

where e is the elementary charge equal to the absolute value of the electron charge, qe is the total charge generated in the TM for a single primary impinging on the apparatus (event-by-event analysis) and k_q is the rate of events which generate a total charge equal qe in the TM during the exposure to primary flux. Since the charging process causes stochastic fluctuations, the single-sided spectral density of the shot noise S_R associated with the charging current has been evaluated by considering the stochastic nature of the process (Poisson distribution)

$$S_R = \sqrt{\sum_q [2(qe)^2 k_q]}$$

We remind that taking into account time-dependent fluctuations of the total charge $Q(t)$ accumulated by the TM at the time t , at a given frequency f the single-sided spectral density of the noise due to charge fluctuations $S_Q(f)$ is given by

$$S_Q(f) = \frac{S_R}{2\pi f}$$

From MC simulations a negative charging rate induced by diffuse γ -rays has been predicted while a positive charging rate has been obtained for both GCR protons and ^4He nuclei. The negative charging rate for γ -rays is due to the fact that the number of secondary electrons stopped inside the TM is higher than that of secondary positrons, while for GCR protons and ^4He nuclei the charging process is mainly from direct primary stopping in the TM. Moreover, from MC simulations the average steady-state charging rate induced by diffuse γ -rays R_γ with respect to that due to GCR protons R_p and that caused by ^4He nuclei R_α resulted $R_\gamma/R_p = -0.5 \cdot 10^{-3}$ and $R_\gamma/R_\alpha = -3.4 \cdot 10^{-3}$ (the minus signs in the two charging rate ratios are due to the negative charging induced by diffuse γ -rays with respect to the positive one due to GCRs) and for the single-sided power spectrum of the charge rate noise related to diffuse γ -rays S_{R_γ} with respect to that caused by GCR protons S_{R_p} and that due to ^4He nuclei S_{R_α} we obtained $S_{R_\gamma}/S_{R_p} = 7.5 \cdot 10^{-2}$ and $S_{R_\gamma}/S_{R_\alpha} = 27.6 \cdot 10^{-2}$.

5. Conclusions

MC simulations of the interaction of cosmic particles with the LISA spacecraft indicate that the contribution to the average steady-state TM charging rate due to diffuse γ -rays is marginal with respect to that caused by GCRs. Moreover, in MC simulations the negative charging rate for γ -rays results from the fact that the number of secondary electrons stopped inside the TM is higher than that of secondary positrons, while for GCR protons and ^4He nuclei the charging process is mainly from direct primary stopping in the TM (positive charging rate).

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