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Role of GCR positive and negative particles in charging the LISA-PF test masses in 2015

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Abstract. The LISA Pathfinder (LISA-PF) mission launch is scheduled during the second half of 2015. Galactic and solar ions with energies larger than 100 MeV/n and electrons above 10 MeV penetrate the spacecraft material and charge the gold-platinum test masses. This charging process generates spurious forces that, in some cases, may mimic the effects of genuine gravitational wave signals. A study of the test-mass charging due to galactic cosmic rays (GCRs) down to 1% in composition is reported here. The reliability of the results of this work is mainly limited by our capability to predict the energy spectra of GCRs in 2015. To this purpose, our model is applied to the expected PAMELA experiment proton data for the period January-March 2014 characterized by a positive polarity period and a level of solar modulation similar to those expected at the time of LISA-PF. The PAMELA observations will be available in the next few months. The comparison between our projections and measurements will provide valuable clues on the test-mass charging estimate uncertainty.

1. Introduction

Galactic cosmic rays (GCRs) are high energy particles reaching the Solar System from sources mostly distributed within the Milky Way. They consist approximately of 90% protons, 8% helium nuclei, 1% heavy nuclei and 1% electrons with energies ranging between 100 MeV and a few units $\times\ 10^{20}$ eV[1]. It is of primary importance for many experiments carried out in space to study the effects of the cosmic radiation in limiting or affecting the performance of on-board detectors.

LISA Pathfinder (LISA-PF) [2, 3] is the technology testing mission for eLISA [4], the first interferometer devoted to gravitational wave detection in space operating in the frequency interval 10^{-4}-1 Hz. LISA-PF consists of one satellite hosting inertial sensors with free-falling gold-platinum test masses. Electrodes allow for the determination of the positions of the test mass and the application of control forces where necessary. The LISA-PF spacecraft will be stationed in an orbit about the L1 Lagrange point for six months. Test-mass charging due to galactic and solar energetic particles (SEPs) [5, 6] with energies larger than 100 MeV/n represents one of the main sources of noise for the LISA-PF and eLISA missions in the lowest frequency interval [7]. The integral flux of protons and helium nuclei at energies larger than

[1] Deceased

the nominal cut-off energy of 70 MeV/n will be monitored with particle detectors placed on LISA-PF [8, 9]. This conservative choice was made in order not to underestimate the overall particle flux charging the test-masses in case of SEP event occurrence.

The LISA-PF test-mass charging due to the most abundant species of GCRs in 2015 is estimated here. Proper projections of GCR energy spectra at the time the mission will be in space are considered. We focus on the role of electrons that decrease the net charge deposited on the test masses while increase the shot noise. Uncertainties on the prediction of the GCR proton differential flux in 2015 can be tested by applying the model we use to the expected PAMELA experiment [10] observations between January and March 2014. This interval of time was characterized by the same condition of solar polarity and similar solar modulation level with respect to those expected in 2015. We recall that the solar polarity is called positive (negative) when the Global Solar Magnetic Field (GSMF) lines exit from the Sun North (South) Pole and that the solar polarity affects cosmic-ray observations near Earth up to 40% at 100 MeV(/n) [11].

2. Galactic cosmic ray proton and helium energy spectra in 2015

The LISA-PF mission will be sent into orbit during the descending phase of the solar cycle 24. A low level of solar modulation intensity is expected during the the second half of 2015. The minimum, average, and maximum sunspot predictions during this period are 29.9-54.1-78.4, respectively [12]. In 2015 the GSMF will present a positive polarity epoch. The symmetric model in the force-field approximation by Gleeson and Axford [13] allows for the estimation of the energy spectra of cosmic rays at a distance r from the Sun, at a time t by assuming time-independent interstellar intensities. A parameter Φ is defined that can be interpreted as the energy loss experienced by cosmic-ray particles approaching the Earth from infinity. The parameter Φ for protons and helium nuclei above rigidities of 100 MV (rigidity: particle momentum per unit charge) can be assumed equal to the solar modulation parameter ϕ characterizing the intensity of the solar modulation (see [14] for details). The Gleeson and Axford model appears in very good agreement with GCR observations gathered during positive polarity periods [15]. In [16, 17, 18] we have discussed the expected values of the solar modulation parameter in 2015 ranging between 350 MV/c and 800 MV/c. The energy spectra of GCR protons and nuclei can be interpolated accordingly to the following function [1]:

$$F(E) = A\ (E + b)^{-\alpha}\ E^{-\beta} \quad \text{Particles/(m}^2\text{ sr s GeV).} \tag{1}$$

The parameters A, b, α and β for the minimum and maximum projections of protons and helium nuclei in 2015 are reported in Table 1.

Table 1. Minimum (m) and maximum (M) projections for the energy spectra of the most abundant GCR particles in 2015.

Element	A_m	b_m	α_m	β_m	A_M	b_M	α_M	β_M
p	18000	1.54	3.67	0.88	18000	0.88	3.68	0.89
He	850	0.91	3.60	0.85	850	0.7	3.23	0.48

Proper ^{3}He and ^{4}He composition is taken into account in the following [6, 18].

In order to verify the reliability of our work, a prediction of the proton energy spectrum during the first four months of 2014 is carried out here. The PAMELA experiment collaboration is expected to publish the corresponding data in the near future. The observed average number of

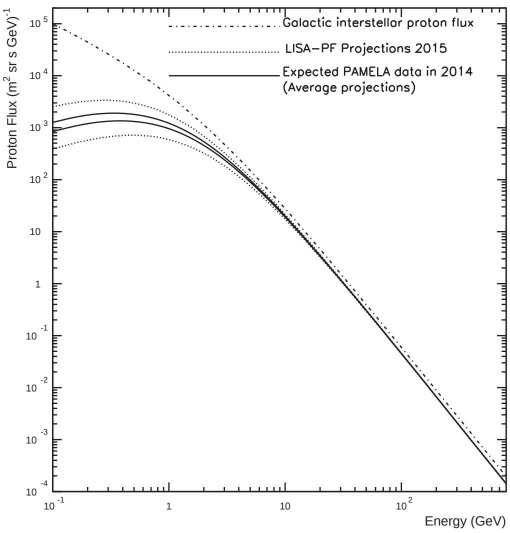

Figure 1. Minimum and maximum projections of the proton energy spectrum during the first 4 months in 2014 (continuous lines) and in 2015 (dotted lines). The dot-dashed line represents the proton spectrum at the interstellar medium [19].

sunspots between January and April 2014 was 71.2. Minimum, average and maximum sunspot projections for the same period are 42.4, 70.0, 97.6 [12], respectively, at the time of writing. Sunspot observations during the first four months of 2014 appear compatible with average sunspot projections for the same period. A similar number of sunspots was observed in 1971, 1972 and 1983, for instance. However, the solar modulation level appeared more intense for protons in 1983 during a period of negative polarity. In 1971-1972, characterized by a positive polarity epoch, the observed solar modulation parameter ranged between 500 MV/c and 600 MV/c [14]. By assuming that the solar modulation parameter varied in the same range of values during the first four months of 2014, minimum and maximum expected proton energy spectra measured by PAMELA would appear as reported in figure 1 (continuous lines). However, preliminary results for the proton differential flux in January 2014 (private communication from the PAMELA collaboration) are lower, close to our minimum projections for LISA-PF (bottom dotted curve in figure 1). We conclude that conservative (minimum and maximum rather than average) projections of GCR energy spectra should be considered even just before any mission launch.

3. LISA-PF test mass charging

We have carried out the simulation of the LISA-PF test-mass charging with the Fluka Fortran-based Monte Carlo package [20, 21]. GCR particles were propagated through the LISA-PF spacecraft by assuming an isotropic particle distribution. The same spacecraft geometry considered for a GEANT4 simulation [22] was imported in Fluka. It is worthwhile to point out that even if accurate, the geometry used in the simulation is an approximation of the actual mass distribution in the spacecraft. This approximation represents an additional source of uncertainty in the test-mass charging simulation results.

We have estimated the average test-mass net (λ_{net}) and effective (λ_{eff}) charging generated by GCR proton and helium nuclei at the time of LISA-PF data taking. The net charging rate is represented by the following equation:

$$\lambda_{net} = \sum_{j=-\infty}^{+\infty} j\lambda_j \quad \mathrm{e\ s}^{-1} \tag{2}$$

where j represents the amplitude of charging released by single events and λ_j is the rate of occurrence of these events. Positive and negative charges cancel out in the net charging computation while both contribute to the effective charging rate defined below:

$$\lambda_{eff} = \sum_{j=-\infty}^{+\infty} j^2\lambda_j \quad \mathrm{e\ s}^{-1}. \tag{3}$$

The effective charging rate represents the charging of single charges that would generate the same observed shot noise. The spectral density of the charging shot noise is expressed in terms of effective charging rate:

$$S = \sqrt{2e^2\lambda_{eff}} \quad \mathrm{e\ s}^{-1}\ \mathrm{Hz}^{-1/2}. \tag{4}$$

The charging fluctuations at frequency f are represented by:

$$S_Q(f) = \frac{S}{2\pi f} = \frac{\sqrt{2e^2\lambda_{eff}}}{2\pi f} \quad \mathrm{e\ Hz}^{-1/2}. \tag{5}$$

In each considered case study for test-mass charging simulation, we propagated more than $2{\times}10^6$ primary particles through the LISA-PF spacecraft. This choice allows for the optimization of the computing time by limiting the uncertainty on the λ_{net} and λ_{eff} below 5% and 2%, respectively. In Table 2 we have reported the net and effective charging generated by GCRs when minimum (m) and maximum (M) projections are considered for each particle species.

Table 2. Net and effective test-mass charging of the LISA-PF test masses for the minimum (m) and maximum (M) projections of proton and helium nucleus energy spectra in 2015.

Element	λ_{net}^m e^+/s	λ_{eff}^m e/s	λ_{net}^M e^+/s	λ_{eff}^M e/s
p	14.1	168.9	32.5	295.5
^{3}He	0.22	0.92	1.9	5.6
^{4}He	0.81	1.9	3.8	10.7

4. The role of interplanetary electrons in charging the LISA-PF test masses

Electrons constitute a minor fraction in composition of the primary cosmic radiation ($e^-/p \simeq 10^{-2}$; $e^-/He \simeq 10^{-1}$). However, as low-mass, highly penetrating particles, the LISA-PF test-mass charging due to e^- must be properly taken into account.

The interplanetary absolute fluxes of electrons during minimum and maximum solar activity periods under both conditions of solar polarity were estimated in [23]. In the same work it was shown that electrons of solar origin associated with solar energetic particle events play a negligible role in charging the LISA-PF test masses. Analogous results were found for electrons produced in the magnetosphere of Jupiter. Conversely, our simulation work indicated that primary and secondary galactic electrons reduce the net charging of protons by 12% (55%) at solar minimum (maximum) during positive polarity periods. During negative polarity epochs galactic e^- were found to match 16% (65%) the positive charge released by protons at solar minimum (maximum). Finally, the effective charging due to galactic electrons was found 22%-23%(38%) of that of protons at solar minimum (maximum) during both polarity epochs.

Under the solar modulation level expected in 2015 electrons could match 50% of the absolute charge released in the test masses by protons while they may increase by about 30% the effective test-mass charging.

As a final remark, we recall that in case particle monitors with solar electron detection capabilities will be flown on eLISA, it will be possible to short-term forecast intense SEP events observed on eLISA (for a detailed discussion see [23, 24]). These improvements of particle detector performance would help in optimizing the test-mass discharging process and possibly, extending the mission lifetime.

5. Conclusions

The role of the most abundant components of GCRs in contributing to the net and effective charging of the LISA-PF test masses was considered here. In 2015 electrons are expected to match 50% of the positive charge released by protons and to contribute to approximately 30% of the proton effective charging.

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