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LISA test-mass charging process due to cosmic-ray nuclei and electrons

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Abstract
Solar energetic particles and galactic cosmic rays with energies larger than 100 MeV cause progressive charging of the LISA experiment test masses. Consequently, Coulomb forces occur between the test masses and the surrounding conducting surfaces generating spurious signals that might be mistaken for gravitational wave signals. We have parametrized the energy spectra of galactic cosmic-ray nuclei and electrons near the LISA orbit in order to evaluate their role in the test-mass charging relative to the most abundant proton component. This work has been carried out using the FLUKA Monte Carlo program.

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1. Introduction

The LISA test-mass charging process due to incident galactic and solar cosmic rays affects the acceleration noise of the experiment (see, e.g., Araújo *et al* (2003), Vocca *et al* (2004)). In order to estimate this phenomenon correctly, the galactic and solar cosmic-ray spectra near the experiment orbit have to be determined and propagated through the instrument. Cosmic-ray spectra of the most abundant components of cosmic rays (p, He, C, O) have been reported in Grimani *et al* (2004). In this work we discriminate between ^{3}He and ^{4}He fluxes at both solar minimum and solar maximum. We report the parametrization of rare primary cosmic-ray nucleus and electron fluxes as well. In particular, we have considered those nuclear components constituting at least 10% of the oxygen bulk at solar minimum. Although some

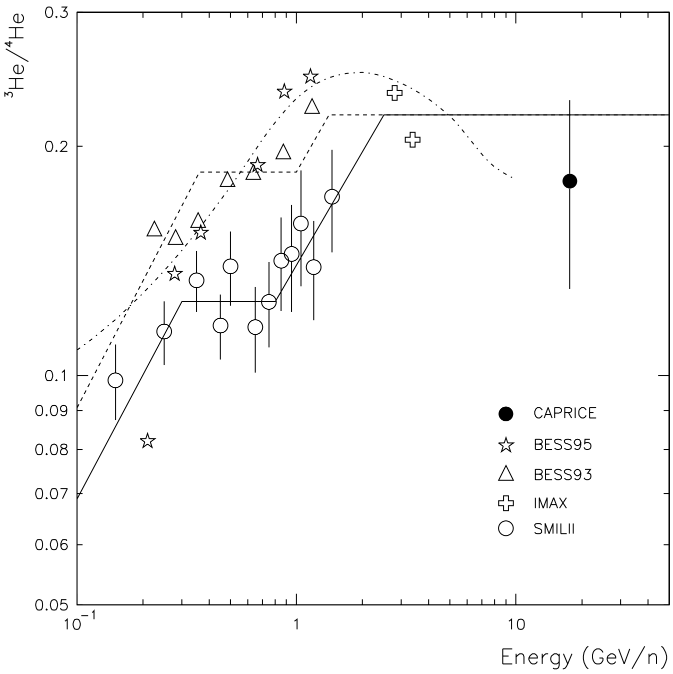

Figure 1. ^{3}He/^{4}He ratio measurements. Error bars compatible with the size of the data points have not been shown. The dashed and continuous lines represent simple best fits of the data at solar minimum and maximum, respectively. The dot-dashed line corresponds to the prediction of the leaky box model as reported in Wang *et al* (2002) where a modulation parameter of 0.6 GeV/*c* (average solar modulation) has been assumed.

of these components represent less than 1% of the content of cosmic rays, we conclude that their role in the test-mass charging is worth a separate investigation with respect to protons. Particle species contributing less than 1% to the net charging process have been disregarded.

2. ^{3}He and ^{4}He

The cosmic-ray helium flux at the top of the atmosphere includes ^{3}He and ^{4}He nuclei. A compilation of ^{3}He data published before 1997 is reported in Seo *et al* (1997). More recent data are presented in Wang *et al* (2002), Myers *et al* (2003) (BESS experiment) and Mocchiutti *et al* (2003) (WiZard experiment). The BESS balloon-borne detector has been flown annually from Lynn Lake, Manitoba, Canada since 1993.

Data reported in figure 1 range in the energy interval between 100 MeV/n and about 18 GeV/n. The ^{3}He/^{4}He ratio seems to increase from 0.1 to 0.2 up to about 1 GeV/n at solar minimum (BESS93–BESS95). The few available data points above 3 GeV/n do not show any clear trend. The increase of the ^{3}He/^{4}He ratio near earth is predicted up to a few GeV by theoretical models of cosmic-ray propagation in the interstellar medium when the solar modulation is taken into account. Conversely, the ratio is supposed to decrease above 3 GeV/n. In figure 1 we have reported the predictions of the leaky box model for an average solar modulation as a dot-dashed line according to Wang *et al* (2002). Note that the ^{3}He/^{4}He ratio at 1 GeV/n is approximately 0.22 at solar minimum (BESS95—Seo *et al* 1997), while at solar maximum drops to only 0.16–0.18 (SMILI-I experiment (1989)—Beatty *et al* 1993).

Table 1. $^3He/^4He$ ratio parametrization at solar minimum, $C(m)$. The energy (E) is measured in GeV/n.

	$0.10 \leqslant E \leqslant 0.36$	$0.36 \leqslant E \leqslant 1.00$	$1.00 \leqslant E \leqslant 1.40$	$E > 1.40$
$C(m)$	$0.335 \times E^{0.569}$	0.187	$0.187 \times E^{0.491}$	0.22

Table 2. $^3He/^4He$ ratio parametrization at solar maximum, $C(M)$.The energy (E) is measured in GeV/n.

	$0.10 \leqslant E \leqslant 0.30$	$0.30 \leqslant E \leqslant 0.80$	$0.80 \leqslant E \leqslant 2.50$	$E > 2.50$
$C(M)$	$0.239 \times E^{0.538}$	0.125	$0.140 \times E^{0.496}$	0.22

Table 3. Cosmic-ray abundances at 1 AU near solar minimum (Simpson 1983).

Element	Z	Abundance (% with respect to oxygen)
N	7	28
Ne	10	16
Mg	12	20
Si	14	14
Fe	26	9

On the basis of the data reported in the above mentioned papers, if we call C the $^3He/^4He$ ratio, the ^3He and ^4He fluxes can be obtained from the overall ^{3+4}He flux (Grimani *et al* 2004) according to the following expressions:

$$F(^3\mathrm{He}) = C/(1+C)F(^{3+4}\mathrm{He}) \tag{1}$$

$$F(^4\mathrm{He}) = 1/(1+C)F(^{3+4}\mathrm{He}) \tag{2}$$

The factor C, reported in tables 1 and 2 at solar minimum $C(m)$ and solar maximum, $C(M)$, has been determined by parametrizing data as shown in figure 1.

Since the data do not allow us to discriminate among different cosmic-ray propagation models in the interstellar medium, we have assumed the $^3He/^4He$ ratio to be constant above 3 GeV/n. This assumption can be considered reasonable for the purpose of the LISA test-mass charging process simulation.

3. Heavy nuclei

A complete review of data on cosmic-ray elemental and isotopic composition has been published by Simpson (1983). More recently, Stephens and Streitmatter (2001) have determined the source, local galactic and solar corona nucleus abundances by comparing the world observations on heavy nucleus fluxes gathered near solar minimum with the results of a simple leaky box model. Recent measurements have also been presented in Labrador *et al* (2003).

In view of the measurements reported in the above papers, by taking into account the abundances near Earth and the charge of each nuclear species (see table 3), we decided to include in the simulation, besides C and O also the N, Ne, Mg, Si and Fe.

Even if experimental data reported by Stephens and Streitmatter (2001) are all gathered near solar minimum, different experimental observations are widely scattered (mainly for N). By assuming the same parametrization function used for p, He, C and O (Grimani *et al* 2004):

$$F(E) = A(E+B)^{-\alpha}E^{\beta} \text{ particles m}^{-2}\text{ sr}^{-1}\text{ s}^{-1}\text{ (GeV/n)}^{-1} \tag{3}$$

Table 4. Parametrization of the primary cosmic-ray fluxes at solar minimum (A_m, B_m, α_m, β_m) and solar maximum (A_M, B_M, α_M, β_M).

	A_m	B_m	α_m	β_m	A_M	B_M	α_M	β_M
He	850	0.99	3.10	0.35	850	1.25	3.80	0.85
C	23	0.95	3.00	0.29	23	1.22	3.40	0.69
O	21	0.95	3.00	0.32	21	1.22	3.40	0.72
N	5.9	0.95	3.00	0.32	–	–	–	–
Ne	3.4	0.95	3.00	0.32	–	–	–	–
Mg	4.2	0.95	3.00	0.32	–	–	–	–
Si	2.9	0.95	3.00	0.32	–	–	–	–
Fe	1.9	0.95	3.00	0.32	–	–	–	–

a good approximation was found by using the same parameters obtained for oxygen, after normalizing the parameter A to reproduce the abundances reported in table 3.

The parameters for each nuclear species are reported in table 4. No parametrization is reported for heavy nuclei at solar maximum since each nuclear species contributes less than 1% to the net charging process of the test masses.

4. Electrons

A recent compilation of electron flux measurements has been reported in Grimani *et al* (2002). Electrons and positrons are rare $Z = 1$ particles in cosmic rays, therefore only the use of magnetic spectrometers in the last 20 years has allowed a reliable identification of these particles (Grimani 2004). Positrons constitute about 10^{-3} of the proton content and therefore their contribution to the LISA test-mass charging can be disregarded.

Only a few measurements are available for e^- below 1 GeV and at different levels of solar modulation. Consequently, it is preferable to model instead of fitting the e^- spectrum in our simulations. Theoretical predictions of the electron fluxes by Moskalenko and Strong (1998) and Stephens (2001a, 2001b) have been recently published. Both calculations are compatible with the electron data while a better agreement is shown by the Stephens calculations with the positron measurements (Grimani *et al* 2002).

In figure 2 we have reported the calculated electron flux according to Stephens (2001a, 2001b). The continuous line corresponds to the interstellar electron flux. In order to include the solar modulation effect near the ecliptic plane, a modulation parameter ϕ of 400 MeV/c (low solar modulation, dashed line), 550 MeV/c (average solar modulation, dot-dashed line) and 1200 MeV/c (high solar modulation, dotted line) has been considered. It is interesting to note that the data of Golden *et al* (1984), extrapolated at the interstellar medium, are in a very good agreement with the calculations (continuous line). The computation captures the trend of the Caprice data gathered near solar minimum (Boezio *et al* 2000) as well. The AMS data (Alcaraz *et al* 2000) show a trend below 2 GeV that disagrees with other measurements and is hard to account for on the basis of the solar modulation effect only.

5. Charge rate induced in the LISA test masses by nuclei and electrons

A preliminary study of the LISA test-mass charging rate due to nuclei and electrons has been carried out by using the FLUKA Monte Carlo program (Fassó *et al* 2000). In the FLUKA program nuclear interactions of heavy nuclei are included. Moreover, transportation

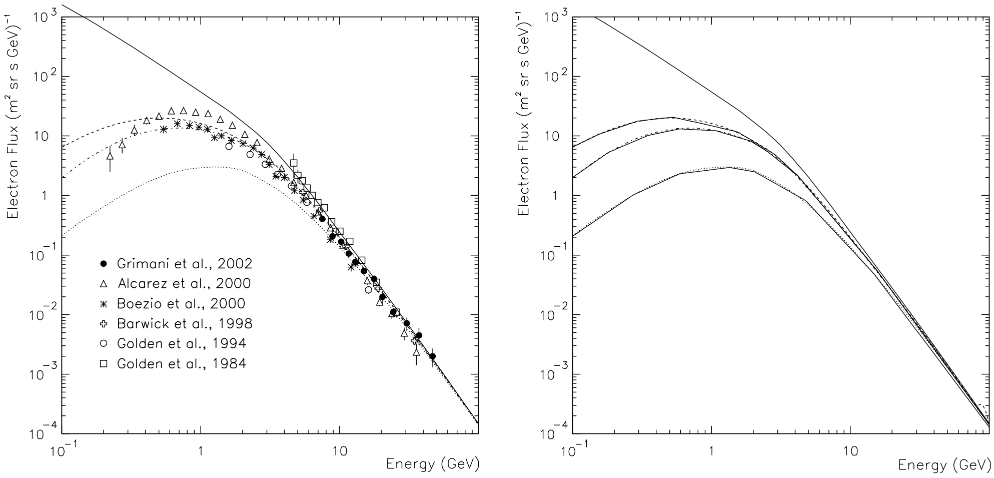

Figure 2. Left panel: electron flux measurements and predictions. The continuous line represents the electron flux at the interstellar medium. The dashed, dot-dashed and dotted curves represent the electron flux estimated by using a modulation parameter of 400 MeV/*c*, 550 MeV/*c* and 1200 MeV/*c*, respectively, near the ecliptic plane according to Stephens (2001a, 2001b). Right panel: Power-law parametrization of the electron fluxes in different energy intervals as used for the simulation.

of low-energy nuclear fragments is carried out by taking into account ionization energy losses, multiple scattering, evaporation, fission and gamma de-excitation. Delta rays are simulated down to 1 MeV energy.

The cosmic-ray nucleus spectra, parametrized as reported in table 4, have been propagated through the LISA spacecraft. In order to evaluate the role of nuclei and electrons with respect to protons the same simplified geometry reported in Vocca *et al* (2004) has been used.

Cosmic rays traverse about 13 g cm^{-2} of matter before reaching the test mass, a gold cube of 4.6 cm side located at the centre of the geometry.

The LISA test-mass net (λ_{net}) and effective (λ_{eff}) charge rates due to ^{3}He, ^{4}He, heavy nuclei and electrons are reported in table 5 as a fraction of those generated by protons at both solar minimum and maximum. We recall that for the net charge rate estimate, opposite charged particles cancel out, while for the effective charge rate they do not (see Weber *et al* (2003)). In particular, λ_{eff} indicates the charging rate of particles with charge one needed to generate the observed shot noise and it is one of the parameters used to estimate the test-mass acceleration due to the charging (see, e.g., Vocca *et al* (2004)).

No absolute values of the charge rates have been reported since no actual spacecraft geometry was used for the simulation. While absolute values of the test-mass charge deposit are geometry dependent, this is not the case for the relative role of each particle species in the test-mass charging process. For absolute charge rate values see Araújo *et al* (2005). The present work is still at a preliminary stage. As a next step we plan to include the actual spacecraft geometry in the Monte Carlo in order to obtain the absolute values of the charge rates. We recall that nuclear species contributing less than 1% of protons have been neglected. Neon was not studied since proper cross sections for this nuclide were missing.

On inspecting table 5 one concludes that the nucleonic component of the cosmic rays impinging on the LISA test masses accounts for a fraction of the charging rate which is about 25% of that due to the incident protons, while the electron effect is two orders of magnitude smaller than the proton contribution both at solar minimum and solar maximum.

Table 5. Net and effective charge rate induced in the LISA test masses by nuclei and electrons at solar minimum (λ^m_{net}, λ^m_{eff}) and maximum (λ^M_{net}, λ^M_{eff}). The results are reported as fractions of the charge rate induced by galactic protons ($\lambda_{net,p}$, $\lambda_{eff,p}$). λ_{net} is meant in e^+/s for nuclei and in e^-/s for electrons (λ_{eff} in e/s).

Element	λ^m_{net} (% $\lambda^m_{net,p}$)	λ^m_{eff} (% $\lambda^m_{eff,p}$)	λ^M_{net} (% $\lambda^M_{net,p}$)	λ^M_{eff} (% $\lambda^M_{eff,p}$)
^{3}He	2.3	1.4	2.1	–
^{4}He	15.2	9.2	14.2	1.9
C	2.4	9.3	4.6	5.5
N	1.1	2.1	–	–
O	3.2	13.8	4.6	7.8
Mg	–	–	–	–
Si	–	–	–	–
Fe	–	–	–	–
e^-	1.4	6.0	–	5.0
Subtotal	22.8	41.8	25.5	20.2

6. Conclusions

The LISA experiment test-mass charging rates due to galactic nuclei and electrons as a fraction of those due to protons at solar minimum and maximum have been studied with the FLUKA Monte Carlo program. A simplified spacecraft geometry has been considered. We have found that nuclei, including helium, contribute about 25% of the protons at solar minimum and solar maximum in the test-mass charging process. Electrons contribute about 1% of the total under all solar modulation conditions. We plan to double check these results on the actual geometry of the experiment spacecraft.

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