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LISA and LISA-like mission test-mass charging for gamma-ray burst detection

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ABSTRACT

Cubic gold-platinum test-masses (TMs) play the role of free-falling geodesic reference and interferometer end mirrors of the future Laser Interferometer Space Antenna (LISA) observatory for low-frequency gravitational wave detection in space. A similar arrangement has been proposed for the Chinese missions Taiji and TianQin and for the LISA follow-on missions such as ALIA and BBO. The TMs are charged by high-energy particles and photons. The deposited charge couples with stray electric fields surrounding the TMs thus inducing spurious forces that limit the sensitivity of the mission mainly at low frequencies. The TM charging was measured in space in 2016-2017 with LISA Pathfinder (LPF), meant for the testing of the LISA instrumentation. Unfortunately, during the time LPF remained in orbit, no solar energetic particle events or major astrophysical phenomena were observed. We aim at estimating the LISA TM charging attributable to long, short gamma-ray bursts (GRBs) and magnetar flares in comparison to that of charged particles of galactic and solar origin. The contribution of these major astrophysical phenomena to the LISA TM charging is discussed here for the first time. The results found here can be extended to LISA-like missions. The response of the radiation monitors hosted on the three LISA S/C is also evaluated. We show that long, intense extragalactic GRBs and galactic magnetar flares at kpc distances can be detected and monitored through a sudden change from positive to negative charging of the TMs and an increase of the TM charging noise. This is a unique signature since both galactic and solar particles charge positively the LISA TMs. This peculiar behavior of the TM charging would allow monitoring the whole dynamics of GRBs. The suggestion reported in the literature, about the detection of long GRBs and gravitational waves from the same sources, in principle, may apply to LISA and other LISA-like missions since the increase of the TM charging noise during these extreme transient phenomena is estimated to remain below the mission sensitivity while particle detectors are expected to saturate.

1. Introduction

LISA (Laser Interferometer Space Antenna) is the European Space Agency mission designed to be the first interferometer for gravitational wave (GW) detection in space in the frequency range 10^{-4}-10^{-1} Hz (Amaro-Seoane et al., 2017; Colpi et al., 2024). LISA will consist of three spacecraft (S/C) placed in an equilateral triangular formation with the center of mass on the ecliptic. The three LISA S/C will trail Earth at 50 million km distance. Each S/C will carry two cubic gold-platinum test masses (TMs) of approximately 2 kg mass (Jennrich, 2009). The TMs constitute both references of geodesic motion and end mirrors of the interferometer. The launch of LISA is scheduled in 2035 and the minimum mission lifetime is expected to be 6 years (Colpi et al., 2024).

The charges deposited on the TMs by galactic, solar particles and photons with energies high enough to penetrate about 16 g cm^{-2} of LISA S/C and instrument material (Vidano et al., 2022) generate spurious Coulomb and magnetic forces between the TMs and surrounding electrode housing (EH, Armano et al., 2023). The corresponding acceleration of the TMs limits the mission sensitivity mainly below 1 mHz (Vocca et al., 2005). In order to control these forces, that increase with the charge deposited on the TMs, a periodic discharging with ultraviolet light beams will be carried out on each LISA S/C (Inchauspé et al., 2020).

The measurement of the TM charging due to galactic cosmic rays (GCRs) was carried out in 2016-2017 (Armano et al., 2017, 2023) during the declining part of the solar cycle 24 with the LISA Pathfinder

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(LPF, Armano et al., 2016, 2018) mission, meant for the testing of the instrumentation that will be placed on board LISA. No solar energetic particle (SEP) events were observed with LPF in 2016-2017 above the GCR background.

LISA Pathfinder pre-launch Monte Carlo simulations dedicated to the estimate of the net and effective charging (charging noise) of the TMs during the mission operations (Grimani et al., 2004; Vocca et al., 2004; Araújo et al., 2005; Grimani et al., 2005; Vocca et al., 2005; Wass et al., 2005; Grimani et al., 2015) were carried out with both FLUKA (Battistoni et al., 2014; Böhlen et al., 2014) and Geant4 (Agostinelli et al., 2003; Allison et al., 2006, 2016) toolkits for galactic and solar particles. These two sets of simulations resulted in excellent agreement when the same input particle fluxes were considered (Grimani et al., 2015). In an early-day paper (Finetti et al., 2009), we also discussed the LPF TM charging associated with the diffuse gamma rays in comparison to GCRs an SEPs. We found that diffuse photons were not giving any relevant contribution to the TM charging.

The comparison of Monte Carlo simulations and LPF measurements carried out in April 2016 (Armano et al., 2017), in particular, showed that the net charging was in agreement with the simulations, while the charging noise appeared to be higher by a factor of 3-4 (Araújo et al., 2005; Grimani et al., 2015). It is worthwhile to recall that the net charging is given by the algebraic sum of the charges deposited on the TMs while to the charging noise contribute both positively and negatively charged particles.

Several possibilities were explored to determine the origin of the large charging noise observed on board LPF. It was evaluated that any cause associated with the satellite geometry and incident particle fluxes would have generated a disagreement between observations and simulations common to both net and effective charging. Conversely, the experimental evidence was suggesting that a large number of particles (typically electrons) with the same charge were both entering and escaping the TMs thus increasing the charging noise without contributing to the net charging.

Recently, several simulation works have been published by our and other groups with an improved estimate of the LPF TM charging including the propagation of electrons down to a few eV energies (Grimani et al., 2022; Taioli et al., 2023; Wass et al., 2023). In Wass et al. (2023), the proton and electron kinetic emission below 100 eV was added to the Geant4-Opt.4 Physics list. It is worthwhile to recall that Geant4-Opt.4 uses the standard electromagnetic physics.[1]

A toolkit for the LISA TM charging, FLUKA/LEI, was also developed at the University of Urbino to take into account the electron and positron propagation below 1 keV (Villani et al., 2020; Grimani et al., 2021; Villani et al., 2024), not allowed by FLUKA. A paper on a new Geant4 v11 simulation is also in preparation.[2]

Here we focus, for the first time, on the role of the most extreme bursts of hard X rays and gamma rays lasting from milliseconds to several minutes reaching the solar system from distances up to the observable Universe (Zhang et al., 2012). The effects of large magnetar flares of galactic and extragalactic origin are also considered (Ajello et al., 2021; Bissaldi et al., 2021). These extreme astrophysical phenomena are rare and were not observed in 2016-2017 during the LPF mission through a sudden variation of the TM charging or through a large increase of the energy released in the radiation monitor hosted on board the satellite (Canizares et al., 2011). However, this may be the case for longer duration missions like LISA and the other future interferometers carrying TMs equal or similar to those hosted on board LISA. Among these future missions we mention the Chinese Taiji and TianQin, supposed to be launched just before or at the same time of LISA (Gong et al., 2021). Taiji consists of a triangular constellation of satellites placed at 3×10^6 km with the center of mass on the ecliptic preceding Earth by 50×10^6 km while LISA will most likely trail Earth at the same distance. The TM charging of Taiji is discussed in Han et al. (2024). TianQin is also an interferometer made of a triangular formation of satellites with an arm of 10^5 km supposed to orbit around Earth (Luo et al., 2016). Among the successors of LISA, there is the Big Bang Observer (BBO), consisting of four LISA-like constellations in orbit around the Sun at 1 AU (Cutler and Holz, 2009) and the Advanced Laser Interferometer (ALIA) with shorter arms with respect to LISA (Crowder and Cornish, 2005). The overall elapsed time of the future space interferometers will be plausibly of tens of years, therefore observations may be possible. The occurrence of major astrophysical phenomena would result in a sudden acceleration of the TMs. The origin of glitches in the TM acceleration during LPF are described in Armano et al. (2022). However, differently from any other kind of glitch, the sudden acceleration of the TMs due to astrophysical phenomena, would be detected by both radiation monitors and test-mass charging.

As a matter of fact, a new and sophisticated radiation monitor has been designed for the three LISA S/C (Mazzanti et al., 2023). This detector, is meant to monitor the variations of GCRs and SEPs above 70 MeV and to measure the proton and helium fluxes below 400 MeV/n. The same may also reveal unexpected increases of released energy associated with gamma-ray bursts (GRBs) and magnetar flares. While this instrument may play a primary role in detecting the onset of these events by maintaining the energy readout every 4-6 seconds, it is also expected to saturate during the most intense events as similar instruments dedicated to the detection of GRBs do. For instance, during the GRB 221009 both Fermi Large Area Telescope (LAT) and NaI detectors of the Gamma-ray Burst Monitor (GBM) saturated. In particular, no LAT data were available in the intervals of time 220-240 and 260-270 s (Stern and Tkachev, 2023).

Conversely, we show that the monitoring of the test-mass charging constitutes a unique method to study the evolution of the most intense astrophysical transients by allowing us to observe *in situ* GRBs. The possibility to correlate GRB and GW detection from the same sources within 1 Mpc was proposed by Suwa and Murase (2009). The association between a long GRB and a supernova was established with the GRB 980425 occurred at 40 Mpc distance (Daigne and Mochkovitch, 2004).

In Section 2 we report the main characteristics of short, long GRBs and magnetar flares. The photon energy spectra associated with these phenomena are presented. In Section 3 the simulations of the net and effective TM charging during selected long, short GRBs and magnetar flares is compared to that ascribable to GCRs and SEPs. In Section 4 the possibility to detect intense GRBs with the LISA radiation monitors is discussed. In Section 5 the GRB detectability through the TM charging is evaluated and the associated noise is estimated and compared to the mission sensitivity. We point out that while no GWs are expected to be observed with LISA from magnetar flares, the same may be detected by Earth interferometers. Moreover, these observations contribute to space weather investigations in the absence of solar activity.

2. Gamma-ray bursts and magnetar flares

Gamma-ray bursts were discovered on July 2, 1967 with the Vela satellite (Schilling, 2002). Multi-wavelength, broadband photon spectra are observed during GRBs. These events are usually classified as short or long on the basis of the interval of time during which an instrument observes between 5% and 95% of gamma ray-hard X rays total fluence (T_{90}, Mazets et al., 1981). Short GRBs are those characterized by T_{90} smaller than 2 s while long ones are those with T_{90} greater than 2 s (Kouveliotou et al., 1993). This classification is generally accepted, although it is worthwhile to point out that sometimes conflicting clues on T_{90} can be provided by different instruments. This is, for instance, the case of the GRB 210217A that was classified by the Swift Burst Alert Telescope as a long one with $T_{90} = 3.76$ s and by the Fermi GBM as a

1 https://geant4.web.cern.ch/docs/#physics-list-guide.

2 This work is carried out within the scope of the activities of the ESA contract No. 4000133571/20/NL/CRS "Test Mass Charging Toolkit and LPF Lessons Learned".

short one with a duration of 1.024 s. As a matter of fact, the event resulted ambiguous presenting properties of both short and long GRBs (Dimple et al., 2022).

Long GRBs are associated with core collapse of massive stars. The collapsar model concerns the formation of a black hole from the collapse of a massive star (MacFadyen, 2001). Conversely, mergers of neutron stars or of a black hole and a neutron star are supposed to be at the origin of short GRBs (D'Avanzo, 2015).

Gamma-ray bursts are characterized by a prompt, intense phase lasting from tens of milliseconds to several hours when gamma-ray radiation is observed and by a longer duration emission at larger wavelengths. The second phase, named "afterglow", is characterized by a duration from tens of seconds to a few days, and begins after tens of seconds from the prompt phase (Xin et al., 2023).

Magnetar flares are the most bright phenomena in our Galaxy and constitute a special class of short GRBs. Magnetars are young ($<10^5$ years), isolated, ultramagnetized neutron stars (10^{13} - 10^{15} G) with typical periods of 5-12 s. Contrarily to GRBs that are of extragalactic origin, magnetar flares can be either of extragalactic or galactic origin. A relativistic outflow, associated with the giant flare, interacts with gas and produces shock waves that accelerate electrons to very high energies. The first recorded giant magnetar flare dates back to March 5, 1979, generated from the soft gamma repeater (SGR) 0525-66 (total energy $\simeq 6\times10^{44}$ erg, Fenimore et al., 1996) in the Large Magellanic Cloud at 55 kpc from the Solar System (Kazanas, 1988). The second event, associated with the SGR 1900+14 at 12.5 kpc from the solar system, was recorded on August 27, 1998 (Feroci et al., 2001). Another giant flare was observed on December 27, 2004 from the SGR 1806-20 located at 8.7 kpc from Earth (Palmer et al., 2005). All confirmed events have been observed in the Local Group of galaxies. Due to the small number of observed events the actual rate of occurrence of these observations is poorly known. However, on time scales of LISA, LISA-like and LISA follow-on missions, a few observations are plausibly expected from known sources or new ones. Despite being rare, the scientific interest of these events and their impact on the biosphere is of great relevance.

In Grimani (2016) we estimated that the number density of young and middle-aged pulsars within 1 kpc from the solar system is 33 pulsars kpc^{-3}. Magnetars are approximately one order of magnitude fewer (Grimani, 2015, and references therein). Therefore, in principle, magnetar flaring may also occur in the Milky Way within 1 kpc from the Solar System. Giant flares from magnetars have typical durations from 0.1 to 1 s and peak in the hard X ray-soft gamma ray band.

Gamma ray bursts and magnetar flares have a deep impact on space weather (Inan et al., 2007) and sensitive LISA-like missions. For the future space interferometers would be important to follow *in situ*, with the measurement of the TM charging, the effects of the whole evolution of strong GRBs and magnetar flares, while dedicated instruments may saturate (Stern and Tkachev, 2023). Suwa and Murase (2009) have shown that, in principle, the detection of GWs from collapsars within 1 Mpc with LISA is possible. The intensity of detectable events would decrease with decreasing distance. As a matter of fact, all processes generating short, long gamma-ray bursts and magnetar flares are also supposed to be sources of GWs. Both resonant bar (Modestino and Pizzella, 2011) and Advanced LIGO (Abbott et al., 2019) experiments carried out a search for GW signals from magnetar bursts. The EXPLORER and NAUTILUS data were analyzed for GW short signal search on December 27, 2004 at the time of the giant flare of the SGR 1806-20. No statistical excess was found to claim between electromagnetic and GW signals. Advanced LIGO carried out a search for GW signals from the same magnetar, on February 11, February 25 and March 4, 2017, and from the GRB 170304A thought to be associated with another magnetar burst. Also in these analyses, no evidence of GW signals was found. Advanced LIGO set upper bounds on the total dimensionless strain between 150 Hz and 1550 Hz. Upper bounds on the isotropic GW energy has been set accordingly.

In the following we study the classes of GRBs and magnetar flares that will be detectable with LISA-like interferometers through a sudden variation of the test-mass charging and radiation monitor measurements, with respect to observations associated with the GCR background and SEP event occurrence. We also focus on the events that, in principle, may be correlated with GW detection in the LISA frequency band if the associated TM charging noise will remain below the interferometer sensitivity.

2.1. Selected photon events as case studies for the LISA test-mass charging

2.1.1. Short gamma-ray bursts

In order to study the effects of short GRBs on the LISA TMs we have simulated the bright GRB 181222 detected by Fermi/GBM at 20:11:37.438 UT on December 22, 2018 (Albert et al., 2022). The photon energy spectrum is reported in Fig. 1 as a dot-dashed line. The duration of the event was of 1.1 s, the peak was reached after 0.5 s.[3] No measurements of redshift for this event are available. A class M solar flare (continuous line) is reported for comparison (Grigis, 2004; Benz, 2017).

2.1.2. Long gamma-ray bursts

On October 9, 2022 several telescopes observed the most intense long GRB ever detected (GRB 221009A, Cao et al., 2023; O'Connor et al., 2023). The estimated distance was 583 Mpc. The prompt phase lasted more than 600 s before the transition to the afterglow phase. The prompt emission onset was recorded at 13:16:59.99 UTC. The spectrum at the peak of the prompt phase between 225 s and 233 s is reported as the top dotted line in Fig. 1. The afterglow phase is disregarded here since the photon flux was several orders of magnitude smaller with respect to that of the prompt phase even though photons up to TeV energies were recorded by the HESS experiment (Aharonian et al., 2012).

Another weaker long GRB observed in January 1999 (GRB 990123, bottom dotted line) is also shown for comparison (Briggs et al., 1999).

2.1.3. Magnetar flares

We consider here the effects that magnetar flares may have on the LISA TMs in case of the detection of an event like that of March 5, 1979 or of such an event occurred within 1 kpc from the solar system.

The SGR 0526-66, from which originated the flare, is located in the Large Magellanic Cloud at 55 kpc from the Solar System (Kazanas, 1988). The March 5, 1979 flare showed an initial spike that contained half of the energy and 90% of the photons with energies ranging from 30 keV to 2 MeV (bottom dashed line in Fig. 1). The intensity of the spike was about 1.5×10^{-3} erg cm^{-2} s^{-1} and 10^4 photons cm^{-2} s^{-1}. The peak emission lasted 0.2 s and was hundred times brighter than the subsequent pulsations. After the spike the source pulsation with 8 s periodicity was observed for at least 200 s. Sinusoidal pulses with a pulse/subpulse structure revealed a magnetar origin (Fenimore et al., 1996). The top dashed line in Fig. 1 represents the extrapolation of the March 5 event in case the location of the magnetar was at 1 kpc distance from the Solar System.

It is interesting to notice that the solar and the magnetar flare show a similar trend even though the magnetar flare peaks at higher energies.

3. LISA Pathfinder net and effective test-mass charging for LISA

The LISA and LPF TM net (λ_{net}) and effective (λ_{eff}) charging rate are defined below (Grimani et al., 2022):

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

[3] https://gcn.gsfc.nasa.gov/other/181222B.gcn3.

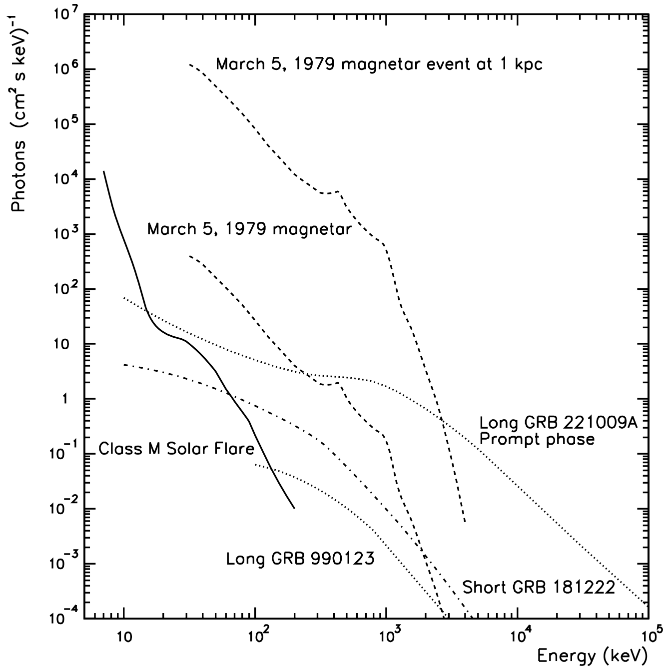

Fig. 1. Photon energy spectra associated with short (dot-dashed line), long GRBs (top and bottom dotted lines) and magnetar flares observed during the March 5, 1979 event (bottom dashed line) and during the same event in case of occurrence at 1 kpc from the Solar System (top dashed line). For comparison we have shown a class M flare from the Sun (continuous line).

Table 1
Net and effective TM charging measured with LPF on April, 20-23 2016 (Armano et al., 2017).

	Test mass 1	Test mass 2
Net charge (e^+ s^{-1})	$+22.9 \pm 1.7$	$+24.5 \pm 2.1$
Effective charging (e s^{-1})	1060 ± 90	1360 ± 130

$$\lambda_{eff} = \sum_{j=-\infty}^{+\infty} j^2 \lambda_j \quad s^{-1}, \tag{2}$$

where j represents the net charge deposited by single incident particles or photons and λ_j is the rate of occurrence of these events. Positive and negative charges cancel out in the net charging computation while both positive and negative net deposited charges contribute to the effective charging.

3.1. LISA Pathfinder test-mass charging during the mission operations

The TM net and effective chargings were measured on board the LPF satellite on April 20-23, 2016 during the declining phase of the solar cycle 24. The results are reported in Table 1 (Armano et al., 2017).

The Monte Carlo simulations of the TM charging carried out with FLUKA right before the LPF mission launch and reported in Grimani et al. (2015) indicated that incident protons and nuclei, electrons and photons do not give any relevant contribution to the TM charging below 100 MeV/n, 20 MeV and 100 keV, respectively. In the same work we showed that intervals for net and effective charging associated with the GCRs at the beginning of 2016 were 15-38 positive charges per second and 172-312 charges per second, respectively. By comparing the observations reported in Table 1 with these simulation outcomes, it was concluded that the measured net charging was in the middle of the range of simulation predictions, while the measured effective charging was 3-4 times larger than expected. Any possible cause of the mismatch had to be plausibly associated with particles with the same charge sign entering and escaping the TMs thus contributing to the noise without contributing to the net charging. Very low-energy electrons produced at the separation surfaces between EH and TMs, not included in the simulations, were the most plausible candidates (Araújo et al., 2005).

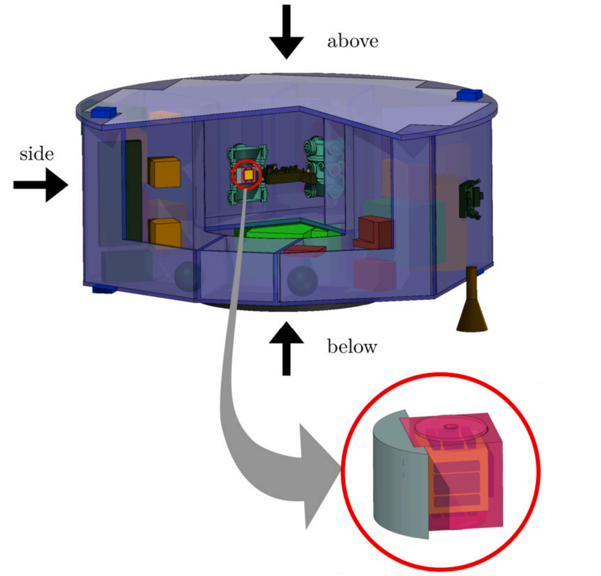

Fig. 2. LPF combinatorial geometry model built with Flair for Fluka. The top plate has been removed in order to show the internal components. The magnified image of the TM and EH is shown in the circle. The arrows in the figure indicate possible incidence directions of photons on the S/C (refer to Table 4 and Table 5).

Electrons and positrons, as the smallest mass charged particles, propagate at keV energies over typical pathlengths of microns in solid materials. FLUKA stops the propagation of e^- and e^+ to 1 keV energy to limit the computation time. In the majority of applications the lack of propagation of these particles below 1 keV does not impact on the results. Unfortunately, this is not the case for the LPF and LISA missions since the potential difference between the TMs and surrounding EH is of the order of 1 V and the presence of low-energy electrons strongly affects the TM charging process (Taioli et al., 2023).

When the propagation of electrons and positrons is extended to energies below 1 keV for e^- and e^+ the ionization energy losses, kinetic emission and quantum diffraction must be properly considered (Villani et al., 2020; Grimani et al., 2021; Villani et al., 2021; Taioli et al., 2023; Villani et al., 2024).

3.2. The FLUKA/LEI Monte Carlo tool

The LPF S/C geometry was built in FLUKA with the Flair interface (Vlachoudis, 2009, see Fig. 2).

The final geometry and material distribution of the LISA S/C is not yet available. However, from a preliminary design it is plausible to assume that the material grammage of the LISA and LPF S/C are similar. The LISA TMs are supposed to be surrounded by approximately 16 g cm^{-2} of S/C and instrument materials (Vidano et al., 2022; Taioli et al., 2023), while an average of 13.8 g cm^{-2} surrounded the LPF TMs (Grimani et al., 2022). We study here the effects of GRBs on the LPF TM charging to obtain precious clues for LISA.

The electron and positron production and propagation from keV energies down to the limit of their quantum wave-like behavior have been taken into account in a new Monte Carlo program written in Fortran 95 and Mathematica, LEI (from *Low-Energy Ionization*), that allows us to include the effects of very low-energy electromagnetic processes (Villani et al., 2020; Grimani et al., 2021; Villani et al., 2024) in the LPF TM charging simulations in addition to FLUKA. When these low-energy processes are included in the simulations, the computation time increases dramatically. As a result, LEI has been activated in the outer 150 nm

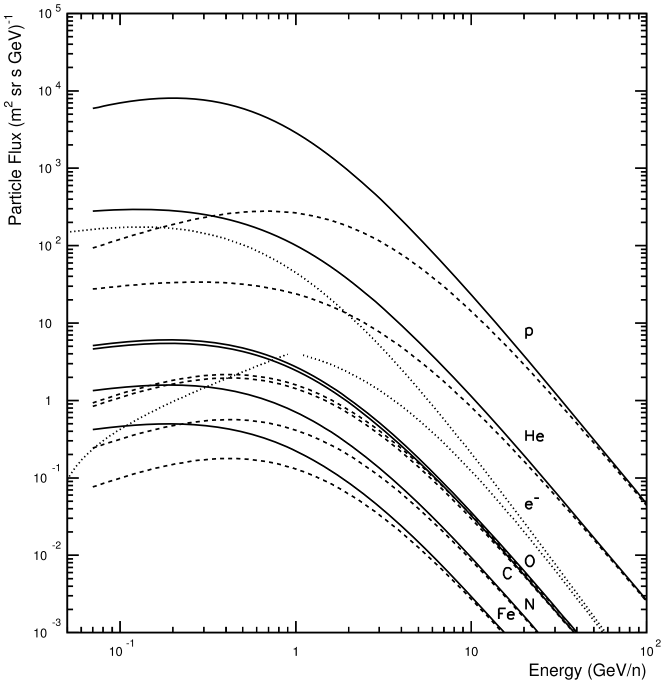

Fig. 3. Cosmic-ray nucleus energy spectra at solar minimum (continuous lines) and maximum (dashed line). From top to bottom: protons (p), helium (He), oxygen (O), carbon (C), nitrogen (N) and iron (Fe) are shown. The top and bottom dotted lines represent the minimum and maximum electron energy spectra.

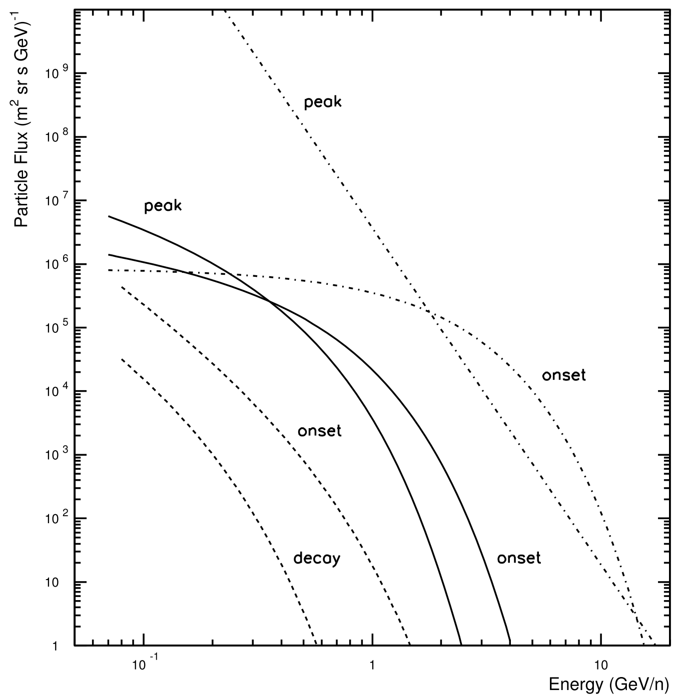

Fig. 4. Solar energetic particle event evolution for the events dated February 23, 1956 (dot-dashed line), December 13, 2006 (continuous line), December 14, 2006 (dashed lines). Different phases of the events are indicated.

of the gold-plated layers of the TMs and EH. The thickness of these layers was chosen as a compromise between increasing computing time and the aim to include in the simulations all the electrons and positrons contributing to the TM net and effective charging.

All particles incident on the gold layers obtained with the FLUKA Monte Carlo outcomes constitute the input data for the Monte Carlo LEI that allows us to simulate electron and positron low-energy electromagnetic processes down to 12 eV when the quantum diffraction (see Villani et al., 2020; Grimani et al., 2021; Villani et al., 2021, 2024, for details) is also activated.

Particles incident on the EH and TM gold plated layers are propagated at 1 nm steps, while the electrons produced within the slab are propagated at 1 angstrom steps. When the FLUKA/LEI simulations are over, all charged particles deposited into the TMs by each incident particle are counted and the net and effective chargings are estimated.

3.3. LISA test-mass charging at solar minimum, maximum and during solar energetic particle events with FLUKA/LEI

In order to investigate the possibility of using the LISA TM charging for GRB and magnetar flare detection, the Monte Carlo simulation outcomes during these events must be compared to the charging associated with GCRs at solar minimum and maximum and during SEP events. In Figs. 3 and 4 we show the GCR and SEP energy spectra used for the simulations.

The estimated TM charging associated with the GCR and SEP fluxes shown above (see also Grimani et al., 2022) is reported in Tables 2 and 3, respectively. The three SEP events of different intensity at the onset, at the peak and during the decay phase were originally presented in Vashenyuk et al. (2007); Adriani et al. (2011) and studied in detail in Grimani et al. (2013). During SEP events the increase of the net and effective charging can be small, of the order of that associated with GCRs as in the case of the event dated December 14, 2006 or larger by several orders of magnitude as in the case of the SEP event dated February 23, 1956. It is possible to notice that the FLUKA/LEI tool has allowed us to find a better match with the LPF observations with GCRs with respect to early simulations. We point out once more that these improved results have been obtained after including the low-energy electromagnetic physics processes (<1 keV) in the simulations. Unfortunately, no SEP events were observed during LPF for the time the mission remained in orbit.

3.4. LISA test-mass charging associated with short, long gamma-ray bursts and magnetar flares

In this section, we report the test-mass charging during the GRBs and magnetar flares considered in Section 2.1 as case studies. The simulation results, presented in Table 4, must be compared with the background charging associated with GCRs. Different incidence directions of photons on the S/C have been considered (for the meaning of above, below and side refer to Fig. 2).

The estimate of the LISA TM charging with FLUKA and with FLUKA/LEI are presented separately to stress the importance of including the propagation of low-energy electrons. The first thing to notice is that photons induce a negative charge on the LPF/LISA TMs. Any abrupt change of the TM net charging from positive to negative and a sudden increase of the charging noise would reveal the detection of a GRB or of a magnetar flare. This is an opposite scenario with respect to the TM charging associated with GCRs and SEPs. It is possible to notice that the GRB 221009A, or also an event one order of magnitude weaker, would generate a sudden charging noise increase and a change in the net charging that can be observed at both solar minimum and maximum. Since the estimated uncertainties on the net and effective TM charging measurements are of the order of 10% over periods larger than 200 s (Armano et al., 2017, 2023), the signal-to-noise (S/N) ratio for astrophysical phenomena detection is set above the GCR background. However, the S/N ratio estimate is difficult to be set for the net charging due to the change of charging sign from positive, with GCRs only, to negative during GRB and magnetar flare events. Conversely, the effective charging would suddenly increase with respect to the background value. The S/N ratio for the effective charging at both solar minimum and maximum is reported in Table 4. From Table 5 it

Table 2
Average FLUKA/LEI LPF TM charging at solar minimum and solar maximum.

Primary particle	Solar Minimum Net charging (e^+ s^{-1})	Solar Minimum Effective charging (e s^{-1})	Solar Maximum Net charging (e^+ s^{-1})	Solar Maximum Effective charging (e s^{-1})
Protons	50.4	937.9	5.30	316.6
^{4}He	5.8	182.5	0.28	108.9
^{3}He	2.9	90.5	0.07	54.0
Nitrogen	-0.1	11.3	0.02	6.4
Carbon	0.4	31.9	0.08	19.6
Oxygen	0.5	80.6	0.13	34.0
Iron	0.1	27.5	-0.04	26.5
Electrons	-7.8	167.8	-1.2	53.6
Total	52.2	1530.0	4.64	619.6

Table 3
Average FLUKA/LEI LPF TM charging during the evolution of SEP events.

February 23, 1956		
	Net charging (e^+ s^{-1})	Effective charging (e s^{-1})
Onset	8870	73730
Peak	1.3×10^8	1.3×10^8
December 13, 2006		
	Net charge (e^+ s^{-1})	Effective charging (e s^{-1})
Onset	2425	5695
Peak	1123	2360
December 14, 2006		
	Net charge (e^+ s^{-1})	Effective charging (e s^{-1})
Onset	88.7	141.3
Decay	3.3	4.9

is possible to notice that only rare extreme SEP events (that differently from GRBs would be associated with a positive charging of the TMs over typical periods of days) may generate a large increase of the charging noise at level of the intense astrophysical phenomena considered here. It is worthwhile to point out that the increased charging noise during astrophysical phenomena would not be large enough to limit the LISA sensitivity. The measurement of the charging noise with GCRs carried out during the time LPF remained in orbit appears in Figure 3 of Castelli (2020). The associated TM acceleration noise was observed to range between 2×10^{-16} and 2×10^{-15} m s^{-2} $Hz^{-1/2}$ for frequencies in the interval 10^{-5}-10^{-4} Hz. This was between one and two orders of magnitude below the LPF sensitivity, similar to that expected for LISA. Since the spectral density of the charging shot noise (S) is proportional to the square root of the λ_{eff} and to the charge, which makes this charging noise ($S=(2e^2\ \lambda_{eff})^{1/2}$ e s^{-1} $Hz^{-1/2c}$) proportional to the force noise, it can be concluded that an increase of the λ_{eff} between a factor of four through a factor of ten, would produce a noise that remains below the sensitivity curve for GW signal detection in the LISA band as it is shown in Table 5. A huge magnetar flare with a typical duration of 0.2 s at a few kpc distance would be also detectable, the TM charging must be properly estimated from the results reported in Table 4 in charges per second, according to the actual duration of the event and distance from the source.

4. LISA radiation monitor detection of gamma-ray bursts

In the following, we evaluate if the detection of GRBs and magnetar flares on board LISA with radiation monitors is also feasible. The design of this instrument is reported in Mazzanti et al. (2023). The radiation monitor will consist of four active scintillator layers of 3 mm thickness and three tungsten passive material layers of 1 cm, 2 cm and 4 cm thickness, respectively. Coincidence among the sensitive layers is allowed for proton and helium spectra measurements. A copper box, approximately 6 mm thick, surrounds the sensitive part of the instrument. This arrangement, as in LPF, will allow to stop protons and nuclei below 70 MeV/n. A slightly lower energy threshold than 100 MeV is considered in order not to underestimate the flux of hadrons contributing to the TM charging.

The radiation monitor is supposed to provide the variations of the overall galactic and solar proton and helium fluxes and to measure the differential fluxes of these particles up to 400 MeV/n. The nominal dynamic range of the scintillators goes from 400 keV to 5 MeV.

A simple Monte Carlo simulation has been carried out to estimate if GRBs may actually release in the scintillators enough energy to be detected or to saturate the electronics.

The test-mass charging already indicated which kind of events may be detected below several g cm^{-2} of material. Therefore, we proceeded by simulating the two strongest events: the long GRB dated October 9, 2022 and the March 5th magnetar flare at 1 kpc distance. In Table 6 we have reported the energy released in the scintillator planes of the detector by considering several incidence directions of the photons on the instrument (from above, from below or from side with reference to Figure 1 in Mazzanti et al. (2023)). We conclude that the particle detector would saturate during these events for any period of integration larger than 1 second as expected. The onset and duration of the events, however, would be detected. As it was recalled above, a major increase of the energy released in the scintillators of the radiation monitor can be associated with GRBs or SEP events. The two kind of events can be distinguished mainly on the basis of the duration ranging from seconds-hours in the case of GRBs to days for SEP events. Moreover, the negative net charging due to GRBs would reduce the large positive charging of the TMs due to SEPs and make feasible the detection of GRBs also during medium-strong SEP events.

5. Multimessenger astrophysics with LISA test-mass charging

In the previous Sections we have found that intense to extreme long GRBs charge negatively the LISA TMs well above the GCR background. This unique signature may be associated with GWs detected in the LISA band from the same source of the long GRB in a similar manner of the GW170817 event detected by LIGO and Virgo (Abbott et al., 2017b) that was associated with the coalescence of two neutron stars from which the Fermi GBM and the International Gamma-Ray Astrophysics Laboratory detected the short GRB 170817A at +1.74±0.05 s with respect to GW170817 (Abbott et al., 2017a). These observations allowed the authors to constrain the difference between speed of light and speed of GWs, the violations to the Lorentz invariance, the test on the equivalence principle and the Shapiro delay between gravitational and electromagnetic radiation. In principle, with the detection of a long GRB and GWs on board LISA we may be able to discriminate between different models of the central engine of the source of long GRBs powered by neutrino annihilation or magnetic fields. Gravitational wave emission is expected from both mechanisms. Suwa and Murase (2009,

Table 4
LISA Pathfinder test-mass charging during long (GRB 990123 and GRB 221009A), short (GRB 181222) GRBs and magnetar flaring (March 5, 1979 event) from the Large Magellanic Cloud and in our Galaxy at 1 kpc distance. The S/N ratio for the TM effective charging is calculated during the considered astrophysical phenomena.

Event	FLUKA charging Net charging (e s^{-1})	FLUKA charging Effective charging (e s^{-1})	FLUKA/LEI charging Net charging (e s^{-1})	FLUKA/LEI charging Effective charging (e s^{-1})	Effective charging S/N (e s^{-1}) Solar minimum	Effective charging S/N (e s^{-1}) Solar maximum
GRB 990123 (above)	≈ 0	1	≈ 0	3	< 1	< 1
GRB 990123 (below)	≈ 0	≈ 0	≈ 0	2	< 1	< 1
GRB 990123 (side)	≈ 0	≈ 0	≈ 0	≈ 0	< 1	< 1
GRB 181222 (above)	+2	4	+2	10	< 1	< 1
GRB 181222 (below)	≈ 0	1	≈ 0	5	< 1	< 1
GRB 181222 (side)	≈ 0	≈ 0	+1	1	< 1	< 1
GRB 221009A (above)	-523	4526	-1520	9661	6.3	15.6
GRB 221009A (below)	-946	8813	-3326	18776	12.3	30.3
GRB 221009A (side)	-474	5266	-1633	11174	7.3	18.0
March 5, 1979 (above)	-7	61	-4	105	< 1	< 1
March 5, 1979 (below)	-14	38	-45	87	< 1	< 1
March 5, 1979 (side)	-7	7	-7	8	< 1	< 1
March 5, 1979 1 kpc (above)	- 60044	113467	- 103267	229133	149.8	369.8
March 5, 1979 1 kpc (below)	- 18222	150222	- 131089	410111	268.0	661.9
March 5, 1979 1 kpc (side)	≈ 0	9354	-10000	18165	11.9	29.3

Table 5
Charging shot noise spectral density associated with GCRs at solar minimum, maximum, and during selected SEP events in comparison to the charging shot noise ascribable to the GRB 221009A and the March 5, 1979 magnetar flare in case of occurrence at 1 kpc distance.

	Effective charging (e s^{-1})	Charging shot noise spectra density (e s^{-1} $Hz^{-1/2}$)
GCR_{min}	1530	55
GCR_{max}	620	32
SEP February 23, 1956 (onset)	73730	384
SEP February 23, 1956 (peak)	1.3×10^8	16125
SEP December 13, 2006 (onset)	5695	107
SEP December 13, 2006 (peak)	2360	69
SEP December 14, 2006 (onset)	141	17
SEP December 14, 2006 (decay)	5	3
GRB 221009A (above)	9661	139
GRB 221009A (below)	18776	194
GRB 221009A (side)	11174	150
March 5, 1979 (1 kpc, above)	229133	677
March 5, 1979 (1 kpc, below)	410111	906
March 5, 1979 (1 kpc, side)	18165	191

Table 6
Energy released in the LISA radiation monitors by intense, long GRBs and nearby magnetar flares.

Event	Direction	Scintillator 1 (MeV/s)	Scintillator 3 (MeV/s)	Scintillator 3 (MeV/s)	Scintillator 4 (MeV/s)
GRB 221009	Above	154	155	28	1
	Below	2	3	13	316
	Side	193	279	280	175
March 5, 1979 1 kpc	Above	33229	1471	302	12
	Below	7	23	108	47120
	Side	30352	31779	31802	29783

and references therein) have shown that neutrino-induced GWs would be detectable by LISA up to 1 Mpc distance and by BBO up to 100 Mpc if the central engine of the collapsar is powered by neutrinos. We are aware that the probability of detecting a GRB within 1 Mpc is negligible, since detected GRBs are located beyond tens of Mpc distance. On the other hand, before observation, the expected rate of occurrence of the GRB 221009 was estimated to be one every ten thousands years. As a matter of fact, the actual probability of observing these events is poorly known and even if none of them will be observed with LISA, it is definitely plausible that detections will be carried out with other future space interferometers carrying TMs similar to those of LISA.

These observations would open the window to *in situ* multimessenger astrophysics on board space interferometers. Moreover, the multiple observations of the long GRBs, with a typical time delay of 8 s among the three LISA S/C, will help in constraining the position of the source in case radiation monitors on board LISA would allow for energy deposits countrate every 4 s and by possibly correlating the timing of TM charging on board LISA and the Chinese missions, if they will be contemporaneously in space. The TM charging could be measured over intervals of time larger than 4 seconds since the overall TM charging would be dominated by the effects of major astrophysical phenomena with respect to the GCR background. Even though the GW signal from magnetar flaring is expected above tens of Hz (Macquet et al., 2021), and therefore, well beyond the LISA sensitivity band, the monitoring of magnetar flares will provide precious clues on space weather investigations also aimed at evaluating the impact on space missions, when the majority of silicon detectors would saturate.

6. Summary and conclusions

In this work we have studied the feasibility of detecting extragalactic GRBs and galactic magnetar flares with both LISA TMs due to a change from positive to negative charging and radiation monitors on board the three LISA S/C. The TM charging and the particle detector performance during GRBs and magnetar flares have been studied with the FLUKA/LEI Monte Carlo program. We have demonstrated the importance to follow the paths of very low-energy electrons in the gap between EH and TMs, to correctly take into account the role of these particles in the TM charging. The detection of intense long GRBs such as the event dated October 9, 2022 and nearby magnetar flares is feasible in the absence of SEP events and also during SEP medium-strong events. The outcomes of our work apply to LISA and to the future LISA follow-on and LISA-like missions. The LISA-like mission S/C constellations would also allow to infer the direction of long GRBs by monitoring the TM charging and with appropriate minimum data taking rate from particle detectors. This is a proposal for the first multimessenger detection of astrophysical phenomena on board LISA-like interferometers. The magnetar flaring may also generate GWs, in the sensitivity band of Earth interferometers. Magnetar flare detection remains of paramount importance for mission environment monitoring and space weather investigations.

CRediT authorship contribution statement

Catia Grimani: Writing – original draft, Supervision, Formal analysis, Conceptualization. **Mattia Villani:** Software, Methodology, Formal analysis. **Michele Fabi:** Software. **Federico Sabbatini:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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