Scientific goals achievable with radiation monitor measurements on board gravitational wave interferometers in space

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Abstract. Cosmic rays and energetic solar particles constitute one of the most important sources of noise for future gravitational wave detectors in space. Radiation monitors were designed for the LISA Pathfinder (LISA-PF) mission. Similar devices were proposed to be placed on board LISA and ASTROD. These detectors are needed to monitor the flux of energetic particles penetrating mission spacecraft and inertial sensors. However, in addition to this primary use, radiation monitors on board space interferometers will carry out the first multipoint observation of solar energetic particles (SEPs) at small and large heliolongitude intervals and at very different distances from Earth with minor normalization errors. We illustrate the scientific goals that can be achieved in solar physics and space weather studies with these detectors. A comparison with present and future missions devoted to solar physics is presented.

1. Introduction

When the gravitational wave hunting moved from Earth to space, the problem of the control of the noise induced by the environment on the experiments changed completely. Free-floating metal test masses constitute the heart of the inertial sensors carried by interferometers in space [1, 2, 3]. Galactic and solar particles with energies larger than 100 MeV per nucleon (MeV/n) charge the test masses [4, 5, 6] and induce spurious forces that might mimic genuine gravitational wave signals [7].

ESA found as necessary to fly radiation monitors on LISA-PF [8], the technology test mission for LISA [2], the first interferometer devoted to the detection of low frequency gravitational waves in space. LISA-PF particle detectors will allow us to monitor the integral flux in energy of protons and helium nuclei (98% in composition of both galactic and solar particles) incident on the spacecraft. These in-situ measurements will help in evaluating the test-mass charging process. It was proposed to place particle detectors on the LISA and ASTROD [9] missions as well.

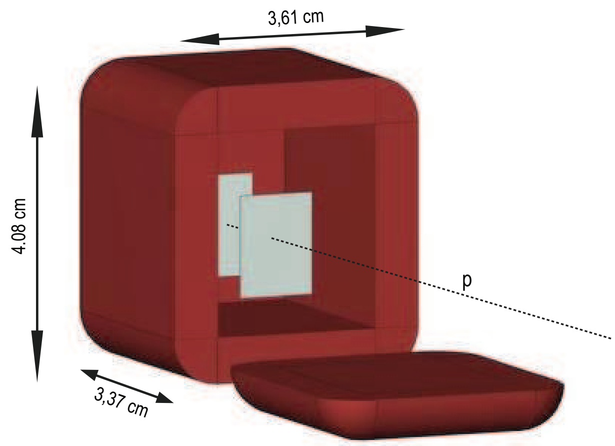

Figure 1. LISA-PF radiation monitor set-up. Silicon wafers are sketched inside the shielding copper box. An incident proton trajectory is shown. See text for details.

We show that radiation monitors on board space interferometers may provide important clues on solar physics and space weather investigations. We recall that by *space weather* we mean the conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life or health.

Measurements carried out with particle detectors on LISA and ASTROD would allow for the mapping of solar particles above 100 MeV/n at different steps in heliolongitude and at various distances from Sun and Earth. Identical instruments on board all spacecraft would carry out SEP observations with no systematic errors. Solar Sentinels [10] is the only proposed mission devoted to solar physics providing similar measurements but the Sentinel constellation will cover different distances from Earth and Sun and different intervals in heliolongitude compared to space interferometers as reported in Section 6. It would be possible to obtain a more complete representation of intense SEP event evolution if solar missions and space interferometers will be in orbit at the same time. We point out that a particular interest is devoted to the study of high energy solar particles before men return to the Moon and before the Mars exploration.

2. Radiation monitors on board space interferometers

The LISA-PF radiation monitors consist of two, 300 μm thick silicon wafers of 1.4 x 1.05 cm^2 area placed in a telescopic arrangement at a distance of 2 cm [11]. The silicon detectors are located inside a shielding, copper box (see figure 1). The box thickness of 6.4 mm prevents from detection protons and helium nuclei with energies smaller than 75 MeV/n for particle normal incidence [12]. This energy threshold was set, conservatively, slightly below the minimum energy needed to the most abundant components of cosmic rays to penetrate the spacecraft (100 MeV/n) in order not to underestimate the particle flux reaching the test masses.

Ionization energy losses for particles traversing both silicon wafers (coincidence mode) and counts on each silicon layer will be measured by on board LISA-PF radiation monitors [11]. Below 100 MeV/n the radiation monitor geometrical acceptance decreases rapidly with increasing incidence angle. Above 100 MeV/n the geometrical factor is energy independent and equal to 9 cm^2 sr for particle isotropic incidence on each silicon layer. In coincidence mode the geometrical factor is about one tenth of this value. The radiation monitor data will be stored over periods of 614.4 seconds and then sent to the on board computer in the form of histograms. The maximum detectable countrate is 6500 counts/s, corresponding to a SEP event integrated fluence of the order of 10^8 protons/cm^2. In coincidence mode up to 5000 energy deposits per second can be stored in the histogram. Only extreme SEP events might lead to bin saturation.

Neither electron nor heavy ion monitoring will be carried out on LISA-PF. The possibility to modify the LISA-PF radiation monitors for LISA in order to include solar electron detection for SEP event forecasting was presented in [13]. It was also recently proposed to place radiation monitors on board the ASTROD missions. SEP detection on board ASTROD would add an extra topic of solar physics to the scientific goals of this experiment already including detection of solar g-modes and the measurement of the solar Lense-Thirring effect to 10 parts per million [9].

3. Interplanetary medium characteristics

The Sun flings 10^6 tons of fully ionized plasma from the corona out into the space every second. This material constitutes the solar wind. Solar wind particles (mainly electrons and protons) travel at supersonic speeds of 200-800 km/s. Near the Earth the solar wind plasma has a density ranging between 0.4 and 100 particles/cm^3 with an average value of 6 particles/cm^3. Typical particle energies range between 0.5 and 3 keV [14]. The expanding solar wind drags also the solar magnetic field outward, forming what is called the interplanetary magnetic field. Although the solar wind moves out almost radially from the Sun, both solar wind and magnetic field are twisted into a spiral by the Sun rotation. At the orbit of the Earth the angle between the field lines and the radial is about 45^o. The value of the interplanetary magnetic field ranges between 0.2 and 80 nT with an average value of 6 nT. Sectors (typically four) with alternating inward and outward directed magnetic fields can be identified. In addition to the solar wind which blows continuously, much more energetic electrons and protons (solar energetic particles with energies larger than 1 MeV) generated by impulsive or gradual solar flares can reach the Earth. Short duration events are more properly indicated as solar flares while long duration events are thought to be associated with coronal mass ejections (CMEs). CMEs are believed to be caused by sudden disruptions in the Sun's magnetic field. Magnetic field lines are supposed to stretch until they break. Large CMEs may contain 1000 tons of matter presenting speeds at the Earth of up to 2000 km/s. It has to be stressed that only 1-2% of CMEs (fast CMEs driven shocks) produce SEPs. Finally, the interplanetary medium is filled by interplanetary and galactic cosmic rays (GCR) consisting of 90% of protons, 8% of helium nuclei, 1% of heavy nuclei and 1% of electrons. The energy range of GCR varies between 100 MeV/n and beyond 10^{20} eV. Both GCRs and solar particles show latitude, longitude and distance from the Sun dependence. The magnitude of galactic cosmic-ray gradients varies from 10% per AU at one AU to 4% per AU at five AU.

An accurate study of cosmic-ray variations and fluctuations and solar event occurrence is mandatory to evaluate the performance of missions like LISA and ASTROD. In [15] we have discussed the capability of the LISA-PF radiation detectors to monitor the solar event evolution above the minimum and maximum GCR background expected in 2014.

Cosmic rays of planetary origin and solar particles below 100 MeV/n play no role on board space interferometers being stopped by the spacecraft material.

4. SEP energy spectra

Pure impulsive or gradual events are rare. On short time scales of the order of the duration of the event at one AU, the particle fluxes rise over a period of 1/2-1 day with a slow decay of about a few days. A strong increase after a first decay phase is found in the largest events and is due to a series of CMEs and shocks. The majority of solar proton events occurs during years 5-8 of the solar cycle [16]. It has to be underscored that in most cases SEPs present energies smaller than 10 GeV even if observations of particles with energies as high as 50 GeV and more have been reported. In particular, in Karpov, Miroshnichenko and Vashenyuk [17] integral proton intensities of about 10^{-5} cm^{-2} s^{-1} sr^{-1} at energies larger than 500 GeV were found for the 29 September 1989, 15 June 1991 and 12 October 1981 ground level events. Often impulsive-flare events cluster in or behind a CME that magnetic field lines connect to an observer. In these cases, a particle velocity dispersion is observed since particles arrive in inverse order to their velocity. The energy content in impulsive events appears to lie below 1 MeV [18]. Particles from a large, magnetically well connected gradual event associated with a CME-driven shock also show velocity dispersion early in the event but present identical time profiles that last for several days late in the event. The most energetic particles (energies larger than 1 GeV) arrive with a delay of only a few minutes after the visual recognition of the flare. Lower energy particles appear in increasing numbers while the high energy particles fade away. The dynamics of SEP events magnetically well connected to the observer is also characterized by a strong anisotropy at the onset while late in the event solar energetic particles show a smaller anisotropy. The proton flux dynamics associated with the solar medium-strong gradual event dated May 7th 1978 was reported, for example, by Grieder [19]. Recently, a satellite experiment for cosmic-ray antimatter detection, PAMELA, measured the proton and helium differential fluxes associated with the evolution of the solar event dated December 13th 2006 [20].

Attempts to parameterize the rigidity (R=pc/Ze; particle momentum per unit charge) spectra of solar energetic protons were reported by Grieder ([19] and references therein):

$$J(R,t) = I_o(t)e^{-\frac{R}{G(t)}} \tag{1}$$

where G ranges between 40 MV and 400 MV and I_o between 2 and 1000 protons cm^{-2} sr^{-1} s^{-1}. Energy spectra with an exponential trend were reported also by Vashenyuk, Balabin and Miroshinchenko [21] for the strongest event ever recorded dated February 23rd 1956. In order to show how intense the solar proton flux can be at a few hundreds of MeV, in figure 2 we have compared the proton peak flux associated with the February 23rd 1956 event with the galactic proton flux expected in 2014 at the time of LISA-PF [15].

SEP production and acceleration processes are still matter of discussion and investigation and the relative role of flaring phase and shock acceleration in large, strong SEP events remains, in general, to be understood due to the different characteristics of individual events.

5. Space interferometer radiation monitor contribution to solar physics and space weather forecasting

In addition to the main role of noise monitoring, particle detectors placed on board missions for gravitational wave detection in space may provide precious clues on solar physics for space weather applications. In order to better study and model solar energetic proton fluxes that affect manned and unmanned space missions and life on Earth, multipoint, inner heliospheric SEP observations are needed. We recall that cosmic rays and solar particles with energies larger than 100 MeV/n penetrate spacecraft and astronaut suits. A crew on the surface of the Moon exposed to the August 1972 flare during the Apollo program would have gotten really sick or worse as in the case of the giant flare dated September 1859. Unfortunately, because of the difficulty to separate galactic cosmic rays from solar particles above 100 MeV/n and since only the strongest solar events generate particles at these energies, the majority of experiments intended for solar physics do not allow for high energy particle discrimination from lower energy ones. Consequently, very few data are available in the literature on very energetic solar particles. These data are naturally provided by cosmic-ray experiments carrying magnetic spectrometers in space. The PAMELA experiment, in orbit since June 15th 2006 during the very long lasting solar minimum, did not detect many events. This mission is supposed to end before the next solar

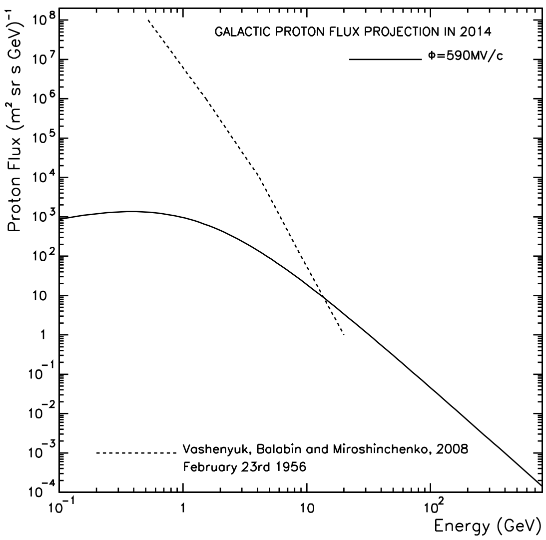

Figure 2. Comparison of the galactic proton spectrum expected in 2014 (solid line) with the proton peak flux associated with a 'worst case' SEP event such as that dated February 23rd 1956 (dashed line).

maximum. The Alpha Magnetic Spectrometer [22], launched in the summer 2011 is supposed to take data for the next ten years.

LISA and ASTROD experiments are natural multipoint observatories for cosmic and solar particles. The LISA mission [2] consists of three spacecraft located at the vertices of an equilateral triangle inclined at 60 degrees on the ecliptic. The details of this mission are still under discussion, however the arm of the interferometer might range between 1 and 5 million km. This means that the three LISA spacecraft will cover 0.4-2 degrees in heliolongitude. The orbit will be heliocentric. The LISA spacecraft constellation will slowly drift away from Earth. The distance from Earth will not exceed 50 million km in 4 years and 65 million km in 6 years. The mission lifetime is supposed to be 6 years.

In other words LISA would allow for a contemporary observation of SEP events at small (0.4-2 degrees in heliolongitude between LISA spacecraft) and increasing longitude interval ranging between 0 and 26 degrees with respect to experiments devoted to solar physics taking data near Earth during the mission whole lifetime. LISA would play the role of a sentinel for the detection of SEPs magnetically well connected to this mission and associated with CMEs emitted in the Earth direction.

The european-chinese ASTROD program consists of three missions: ASTROD I [9], ASTROD II (or ASTROD) [23] and ASTROD III (or Super-ASTROD) [24]. ASTROD I is one-spacecraft, interplanetary mission in solar orbit. The maximum distance from Earth that will be reached by the spacecraft is 1.7 million km. The most optimistic launch date is 2017. ASTROD II will consist of three spacecraft allowing for probing primordial gravitational waves below the LISA bandwidth. For the third phase, the mission ASTROD III is supposed to be characterized by larger orbits to map the outer solar system and to probe the primordial gravitational waves at frequencies below the ASTROD II bandwidth. The ASTROD spacecraft would orbit at different distances and heliolongitude intervals with respect to LISA.

LISA-PF consists of one spacecraft stationed in a Lissajous orbit around Lagrangian point

L1 at 1.5 million km from Earth. The satellite is supposed to spin with a period of six months. The same period of time is needed to the spacecraft to move on its orbit. Data will be taken for six months during the second half of 2014.

Space interferometers are supposed to be in orbit for years detecting solar events at very different intervals in heliolongitude and distances from Earth for at least two solar cycles.

Tens of medium-strong SEP events are estimated to be detected by LISA on the basis of the predictions we have carried out for LISA-PF [15].

The role of solar physics with and for LISA was described also in [25].

6. Future missions devoted to solar physics allowing for SEP measurements

STEREO [26] is the first multispacecraft observatory aiming to study the Sun and the nature of its CMEs. Launched on October 25th 2006 from Cape Canaveral (Florida), STEREO consists of two nearly identical observatories in heliocentric orbit (one moving ahead of the Earth and one moving behind). Electron and proton observations will be carried out on board STEREO but only below 4 MeV and 100 MeV, respectively.

On October 4th 2011 ESA selected Solar Orbiter [27] as a class M mission for implementation and launch in 2017 within the Cosmic Vision program (2015-2025). The cruise phase to the Sun should last approximately three years. The mission lifetime is supposed to be seven years. Solar Orbiter will have an elliptical heliocentric orbit with perihelion as low as 0.28 AU and with increasing inclination up to more than 25^o with respect to the solar equator. This mission aims to answer fundamental questions such as how the Sun creates and controls the inner heliosphere. The Sun's magnetised atmosphere, the properties and dynamics of solar wind and solar energetic particle fluxes will be monitored by the onboard instrumentation. In particular, the Energetic Particle Detector (EPD) is devoted to the observation of particles in the energy range 2 keV/n-200 MeV/n.

Solar Sentinels [10] is a mission devoted to solar physics that will carry out multipoint, inner heliospheric, in-situ observations meant to discover, understand and model initiation, propagation and solar connections of those energetic phenomena dangerous to humans for space explorations and life on Earth. Solar Sentinels were designed to investigate high-energy solar particle generation and propagation processes but also to study CME origin, evolution and interactions, to characterize the interplanetary environment and finally to allow for the development of forecasting capabilities for Earth, Mars and for spacecraft transit. Solar Sentinels consist of a constellation of four identical spacecraft stationed between Venus and Mercury allowing for solar wind ion and electron composition measurements and solar energetic electron, proton and ion observations up to 10 MeV, 500 MeV/n and 100 MeV/n, respectively, associated with strong SEP events. A near-Earth sentinel, a single probe orbiting near Earth will carry a coronagraph for observing the Sun's faint corona where CMEs get started. The farside sentinel is another single probe meant to watch the farside of the Sun. Together with the other spacecraft, this sentinel would provide a complete picture of the Sun including the area not visible from Earth. Solar Sentinels might be launched within the solar cycle 24. Solar Orbiter and Solar Sentinels constitute the Heliophysical Explorers (HELEX): a joint science and technological effort of NASA and ESA (NASA/TM-2008-214159).

Finally, Solar Probe Plus [28] is the NASA mission supposed to reach the solar corona appoaching the Sun as close as 9.5 solar radii (8.5 solar radii above the Sun's surface). Solar Probe Plus will sample the near-Sun environment, improving our knowledge and understanding of coronal heating and the origin and evolution of the solar wind. Solar energetic particles will be studied in-situ where they are energized. Measurements of composition and energy spectra of ions extending from energies through about 100 MeV/n will be carried out. Solar Probe Plus will provide complementary observations with respect to the missions described above and with respect to radiation monitors on board space interferometers to complete the scenario of the most hazardous solar events and solar particle acceleration and propagation in the interplanetary medium. The Solar Probe Plus launch date is expected in July 2018.

7. Conclusions

Radiation monitors placed on interferometers for gravitational wave detection in space are primarily used to estimate test-mass charging and experiment overall noise. However, they may also provide precious clues on solar physics and space weather investigations before manned missions will return to the Moon and before the beginning of the Mars exploration. We have shown that particle detectors on board the LISA and ASTROD missions would allow for contemporary observations of solar particles above 100 MeV/n at small and large steps in heliolongitude (between a fraction of a degree and tens of degrees) and at various distances from the Sun with identical detectors avoiding systematic errors. SEP observations gathered by radiation monitors on space interferometers and by future solar experiments like Solar Orbiter, Solar Sentinels and Solar Probe Plus are expected to clarify the role of flares and CMEs in accelerating solar particles up to very high energies.

Acknowledgements

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