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SEP flux mapping with PHOEBUS

C. Grimani[1], G. Bagni[1], M. Fabi[1], A. Vicerè[1], L. Marconi[2], R. Stanga[3], L. Bosi[4], H. Vocca[4], H. Araújo[5], D. Shaul[5], T. Sumner[5], P. Wass[5], C. Boatella[6], A. Lobo[7], M. Chmeissani[8], I. Martinez[8]

[1] Università di Urbino and INFN Florence, Urbino, Italy
[2] Università di Pisa and INFN Florence, Pisa, Italy
[3] Università and INFN, Florence, Italy
[4] Università and INFN Perugia, Perugia, Italy
[5] Imperial College, London, UK
[6] IEEC, Barcelona, Spain
[7] ICE/CSIC and IEEC, Barcelona, Spain
[8] IFAE, Barcelona, Spain

E-mail: `cgrimani@fis.uniurb.it`

Abstract.
We report about PHOEBUS (PHysics Of Events BUrsted by the Sun): a proposal for solar physics and space weather investigation with LISA (Laser Interferometer Space Antenna). Galactic and solar cosmic-ray particles with energies larger than 100 MeV(/n) penetrate and charge the LISA test masses. Spurious forces occur between the test masses and the surrounding electrodes mimicking gravitational wave signals. This process constitutes one of the major sources of acceleration noise for LISA. Silicon particle detectors will be placed on board the LISA-PF and LISA missions to monitor the overall energetic incident cosmic-ray fluxes. These telescopes can be also used to carry out a map of shock accelerated Solar Energetic Particle (SEPs) fluxes associated with evolving Coronal Mass Ejections (CMEs) at different steps in longitude. We discuss the role of protons, helium nuclei, galactic heavy nuclei and solar ions. We aim to contribute to the COST724 (European CO-operation in the field of Scientific and Technical Research) action inside WG1/WP13000 developing appropriate simulations of the dynamics of CMEs by using space-based data and theoretical models.

1. Introduction
Galactic and solar energetic cosmic rays above 100 MeV(/n) deposit charge on the LISA test masses [1], [2], [3]. In particular, solar energetic particles have been found to constitute an important source of noise limiting the experiment sensitivity at low frequencies [2]. Solar phenomena occur randomly and therefore it has been recognized as necessary to place particle detectors on board in order to monitor real time incident fluxes on the test masses. In this paper we consider the radiation monitor developed for the LISA-PF mission [4].

We propose (PHOEBUS project [5], [6]) to use these particle detectors to study the dynamics of SEPs associated to evolving CMEs at various steps in longitude with LISA: 2 degrees among spacecraft, 20 degrees among LISA and experiments orbiting near Earth and, eventually, different intervals in longitude if data from other experiments in space will be available at the time of the LISA mission. These measurements are of interest to solar physics and space weather. In this work we estimate the expected particle telescope countrate due to incident protons and helium nuclei of galactic and solar origin. Charging of the LISA test masses due to gradual solar events of different intensities has been considered. Discrimination between galactic and solar protons and helium nuclei is also discussed. The present design of the front-end electronics of the particle detectors devoted to the LISA-PF mission does not allow us to monitor high Z particles [7]. We focus on the role of galactic heavy nuclei and ions of solar origin at the passage of SEPs associated to evolving CMEs.

2. LISA orbit characteristics

The LISA orbit is pictured in fig. 1. The spacecraft orbit the Sun 50×10^6 km behind the Earth placed at the corners of an equilateral triangle of 5×10^6 km side. The spacecraft of the LISA experiment present heliolatitudes off the ecliptic plane of less than 1^o and heliolongitudes varying between 19^o and 21^o with respect to Earth. Orbit details are summarized in Table 1.

Table 1. LISA spacecraft orbit characteristics

Distance from the Sun	149-152 $\times10^6$ km
	(0.9933 - 1.0133) AU
Latitude off the ecliptic	0.7^o - 1.0^o
Longitude difference with respect to Earth	19^o - 21^o

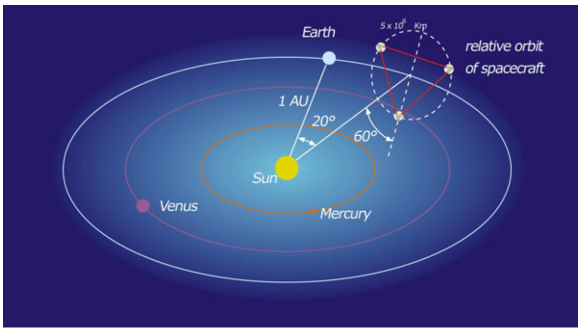

Figure 1. LISA spacecraft orbit with respect to Earth and Sun. http://lisa.jpl.nasa.gov/gallery.html

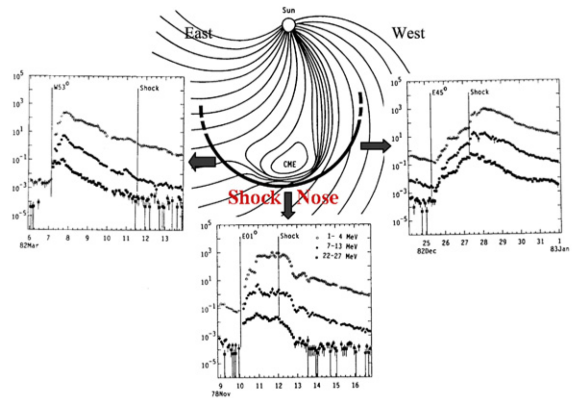

Figure 2. SEP fluxes observed at various longitudes [10].

3. Galactic and solar particles near the LISA orbit

Galactic cosmic-ray spectra near the LISA orbit have been discussed in [8], [3]. They consist approximately of 90% protons, 8% helium nuclei, 1% heavy nuclei and 1% electrons. A similar composition is observed for SEPs associated with gradual events. It must be stressed that galactic heavy particles are fully ionized while those of solar origin appear only partially ionized [9]. The latitude and longitude dependence of galactic and energetic solar particle fluxes associated to evolving CMEs has been discussed in [5] and references therein. We recall here that small latitude difference among spacecraft, while LISA orbits the Sun, does not cause relevant variations in incident galactic and solar particle fluxes. No major longitude dependence of galactic cosmic-ray fluxes is also expected. This is not the case for solar events. A supersonic emission of coronal mass produces a shock in the interplanetary medium. The Sun rotation affects the radial motion of the coronal mass. Time profiles of SEPs are affected by the evolution of the intersection point between the observer magnetic field line and the shock front. This point sweeps rapidly eastward across the shock at a rate of about 27^o-45^o day^{-1}. The maximum of the shock strength and particle acceleration occurs at the nose of the shock where the magnetic field lines are squeezed in front of the evolving CME itself. Conversely, at the shock flanks, the strength and the acceleration weaken. The SEP flux vary as a function of the intensity of the shock. Particle flux variations as a function of space and time above a few tens of MeV(/n) indicate the transit of SEPs associated with gradual events (see fig. 2).

4. LISA particle monitor characteristics

The LISA-PF particle monitors consist of two layers of silicon, 300 μm thick of dimensions 1.05×1.4 cm^2 arranged as shown in fig. 3 ([11]). The geometrical factor for isotropic incidence on one silicon telescope is 9.24 cm^2 sr while for both telescopes (events traversing both detectors, hereafter called coincidence events) is 0.87 cm^2 sr. The radiation monitor set-up used for the present simulation (FLUKA Monte Carlo program [12], [13]) is sketched in fig. 4. We have surrounded the silicon wafers by 2.2 cm of titanium corresponding to 10 g/cm^2 of matter for particle normal incidence. This constraint limits the energy of normally incident protons reaching the silicon detectors to 100 MeV: a cut-off energy similar to that of the lower energy particles penetrating the test masses. When the design of the particle monitor is finalized, we will adjust this constraint accordingly. It is worthwhile to stress that heavy nuclei of energies greater than a few hundreds of MeV/n will penetrate the silicon wafers. In fig. 4 non-interacting proton ionization energy losses in the radiation monitor are shown as coloured tracks.

The present design of the front-end electronics for the LISA-PF particle monitor allows us to store the overall particle countrate in each silicon detector up to a maximum of 10^8 particles/cm^2, while ionization energy losses are recorded for coincidence events only.

The dynamic range (50 keV - 5 MeV) permits to monitor the fluxes of protons and helium nuclei [7].

5. Galactic and solar proton and helium nucleus identification in the silicon detectors

In fig. 5 we have reported the expected countrate generated by coincidence protons (yellow bars) and helium nuclei (blue bars). The count-rates associated with the galactic particle flux at solar maximum (M), at solar minimum (m) [8], and that due to solar particle fluxes, related to solar flares of different intensities, have been estimated. The latter are estimated as a function of time. In particular, we have indicated by f1 the peak flux of the June 21st 1980 solar flare [14], while fluxes f1-f5 of the May 7th 1978 solar flare are reported in fig. 3 of [6] and the fluxes f1-f3 of the September 29th 1989 solar flare have been shown in [5]. Helium count-rates have been obtained as 10% of the proton count-rates (upper limit). One may notice that the transit of solar flares of various intensities causes variations of the particle detector countrate for coincident events from a fraction of particle per second due to galactic cosmic rays to a few hundreds of particles per second depending on the solar flare intensity. In fig. 6 we have reported the expected variation of the proton countrate on each silicon wafer at the transit of two medium solar events from west (dot-dashed line) and from center-east (solid line) [5]. A different trend versus time is observed for the two classes of events. In figs. 7 and 8 we have shown the ionization energy loss distributions in one silicon wafer due to coincidence galactic protons at solar minimum and due to the proton flux at the peak of the September 29th 1989 solar flare, respectively. The peaks of the two distributions differ by approximately a factor of four. An analogous scenario is observed in figs. 9 and 10 for ionization energy losses due to helium nuclei.

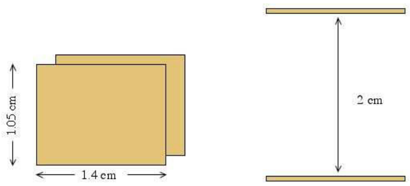

Figure 3. Geometrical characteristics of the silicon telescopes.

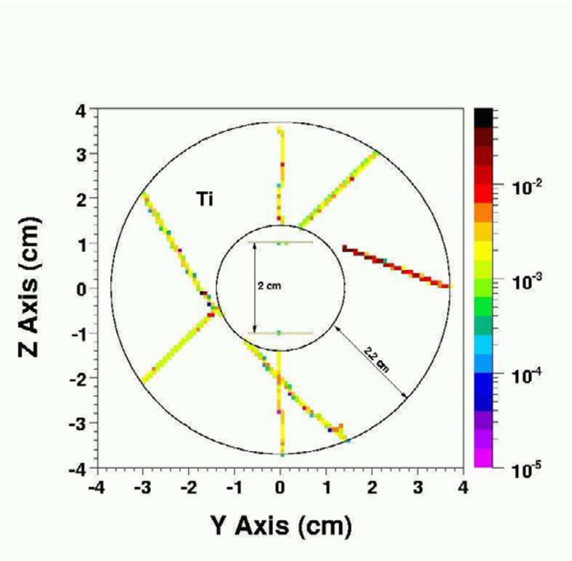

Figure 4. Set-up of the particle monitors used in the FLUKA simulation: 2.2 cm of titanium surround the two layers of silicon wafers. Coloured tracks indicate energy losses of non-interacting protons in GeV units.

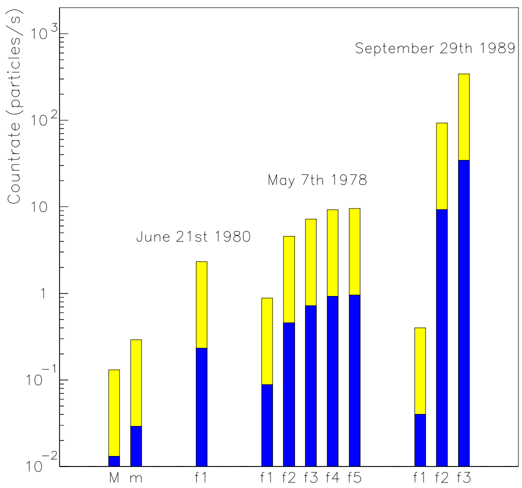

Figure 5. Expected countrate generated by protons (yellow bars) and helium nuclei (blue bars) of galactic and solar origin. See text for details.

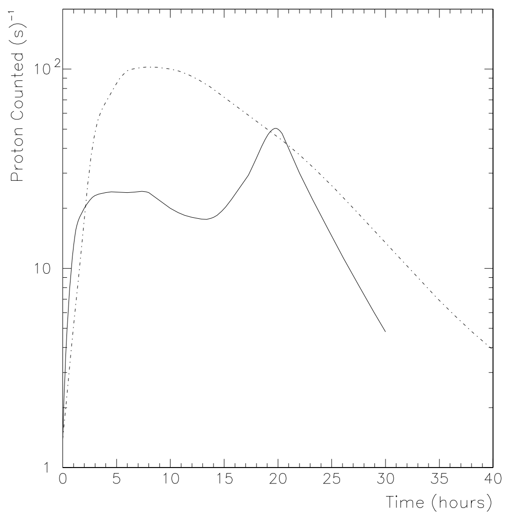

Figure 6. Estimated countrate variation on each silicon detector due to energetic protons associated to a western (dot-dashed line) or to a central-eastern event (solid line).

6. Galactic nucleus and solar ion identification in silicon detectors

In the previous paragraph we have shown how the particle monitors on board the LISA-PF mission will allow us to map energetic proton and helium flux variations at the transit of SEPs

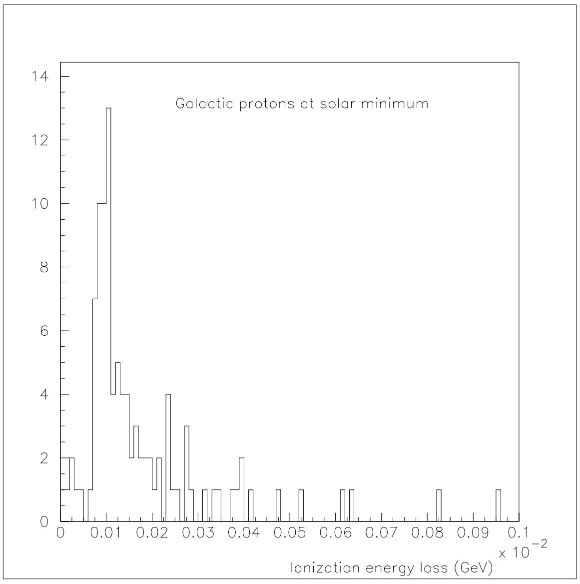

Figure 7. Ionization energy loss distribution in one silicon layer for coincidence galactic protons at solar minimum.

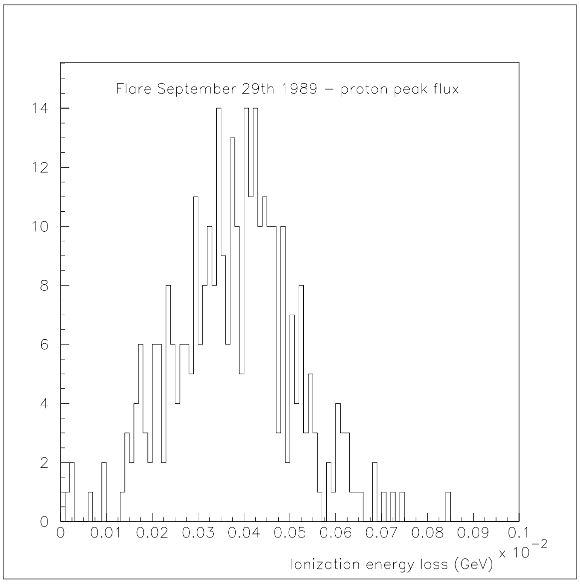

Figure 8. Ionization energy loss distribution in one silicon layer for coincidence protons at the peak of the September 29th 1989 solar flare.

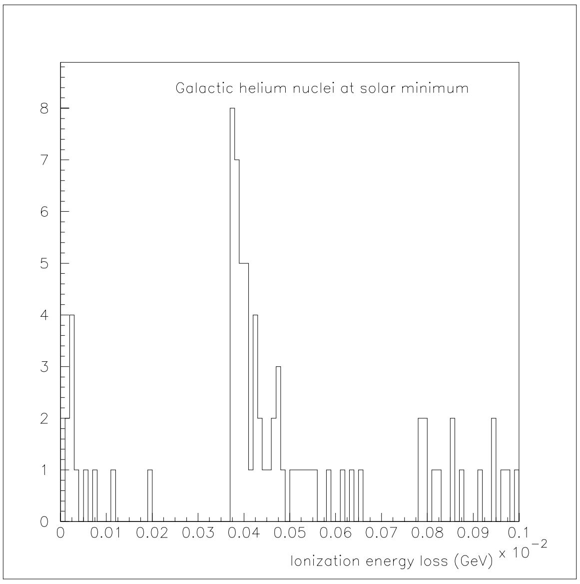

Figure 9. Ionization energy loss distribution in one silicon layer for coincidence galactic helium nuclei at solar minimum.

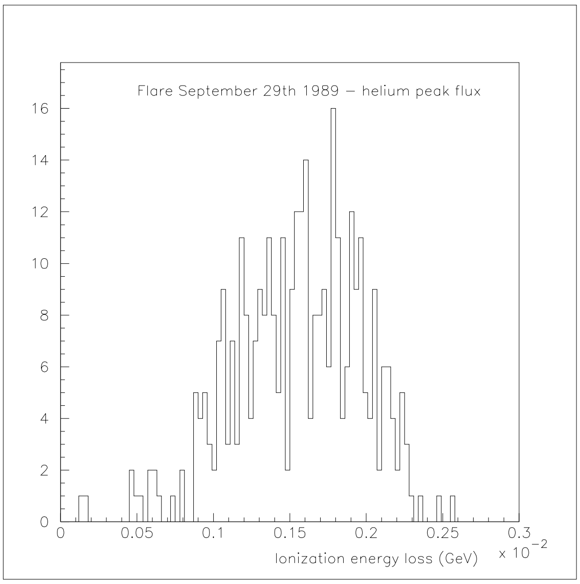

Figure 10. Ionization energy loss distribution in one silicon layer for coincidence helium nuclei at the peak of the September 29th 1989 solar flare.

associated with evolving CMEs. It might be important to extend the dynamic range of the silicon detector front-end electronics for the LISA experiment in order to monitor the fluxes of heavy particles. Galactic heavy nuclei are responsible for about 10% of the total charge released in the LISA test masses [3]. It is plausible to assume that a similar fraction of test mass charging is caused by solar heavy ions. Heavy particles appear only partially ionized in solar gradual events. Oxygen, for example, is found with a charge status of 5-7 while iron ions have been observed with charges ranging between 11 and 19 with an average value of 14±2 [9]. Even though limited data is available in the literature, above a few MeV/n, solar events of different intensities are expected to have differing heavy particle composition [15]. Small intensity events are characterized by proton and helium nucleus integral fluxes similar to those of galactic origin and therefore their passage can be hardly detected [14]. The composition monitoring of heavy particles could represent a valuable cross-check. Carbon and oxygen ion fluxes in medium-strong events are expected to be of the same order of magnitude as the galactic fluxes [8], [16]. Their ionization status is such that ionization energy losses in the silicon wafers are compatible with those of galactic carbon and oxygen nuclei. An overall enhancement of approximately a factor of two of these events will be recorded during the transit of SEPs. A similar increase due to solar iron ions will appear for events with charges close to 14, corresponding to galactic silicon nuclei.

7. Conclusions

It will be necessary to include particle monitors on each of the three LISA spacecraft, to minimise the effect of disturbances associated with test-mass charging. In addition to this primary task, these monitors offer the possibility of mapping the transit of solar energetic proton and helium nucleus fluxes, with energies in excess of the particle monitor threshold, over the three spacecraft array. By comparing these measurements with data gathered simultaneously, by other experiments orbiting near the Earth or elsewhere in space, we will be able to study the characteristics of energetic particles, associated with the dynamics of CMEs, at various steps in longitude. These data would be an invaluable contribution to the COST724 action, in improving models of evolving CMEs.

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