

Short-term forecasting of solar energetic ions on board LISA

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Abstract. LISA (Laser Interferometer Space Antenna) and LISA Pathfinder (LISA-PF) free-falling test-masses are charged by galactic and solar energetic particles. This process generates spurious forces on the test masses which appear as noise in the experiments. It was shown that relativistic solar electron detection can be used for up-to-one-hour forecasting of incoming energetic ions at 1 AU. Warning of incoming solar energetic particle events could allow us to optimize the test-mass discharging. The current LISA-PF radiation monitor design needs to be upgraded if solar electron detection is to be implemented in LISA.

1. Solar relativistic electron and non-relativistic proton onset at 1 AU

Protons and helium nuclei constitute approximately 98% in composition of both galactic cosmic rays and solar particles. Electrons amount to about 1%. Electrons and ions with kinetic energies larger than a few MeV and 100 MeV($/n$), respectively, can penetrate the spacecraft material charging the LISA and LISA-PF test masses [1, 2]. Unfortunately, very little is known about solar particle energy spectrum evolution during strong solar events above 100 MeV($/n$).

Particle detectors will be placed onboard both LISA-PF and LISA missions to monitor the galactic and solar protons and helium nuclei incident on the spacecraft. The radiation monitors designed for LISA-PF consist of two silicon wafers of $1.4 \times 1.05 \text{ cm}^2$ area placed in a telescopic arrangement at a distance of 2 cm from each ones (figure 1) [3]. The geometrical factor of each silicon layer for an isotropic incidence is $9 \text{ cm}^2 \text{ sr}$ and for coincident events is about one tenth of that. The silicon telescopes are located inside a copper box of 6.4 mm thickness in order to limit the energy of protons and helium nuclei traversing these detectors to a few tens of MeV($/n$) (figure 2). This energy cutoff is similar to the minimum energy of the most abundant components of cosmic rays penetrating the test masses (100 MeV($/n$)) [4]. No electron monitoring will be carried out on LISA-PF. We have found that both radiation monitor countrate and charge deposited in the test masses vary by several orders of magnitude within a few tens of minutes at the occurrence of strong solar events [5]. The radiation monitor delivers data accumulated over periods of 614.4 s [3]. During this same period of time, all solar events

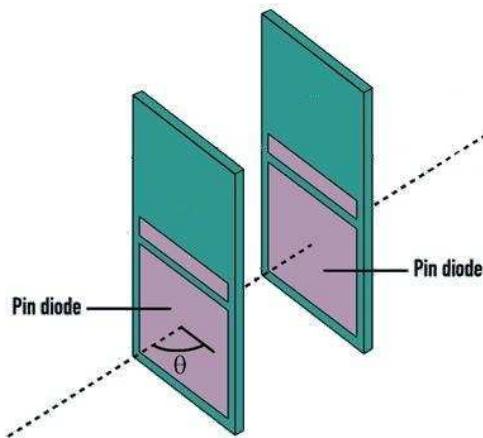


Figure 1. Sketch of silicon detectors of the LISA-PF radiation monitors.

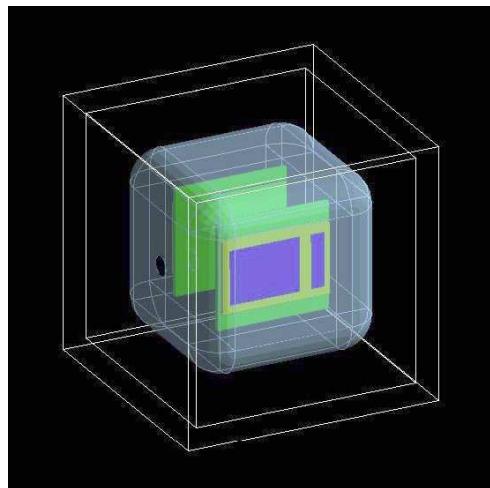


Figure 2. LISA-PF shielding copper box surrounding silicon wafers.

generating a proton flux larger than the statistical fluctuations of galactic cosmic rays will be detected. Optimization of test-mass discharging can be considered accordingly [6]. Work by Posner [7] has shown that during strong SEP events, relativistic electrons always reach 1 AU in advance of non-relativistic ions. It was found that the intensity increase of both electron and ion fluxes is similar and depends mainly on the magnetic longitude distance (magnetic connection) between spacecraft and flare. Correlations are found also between the early time profiles of electron intensity and increase with upcoming proton intensities. Electrons in the energy range 0.3-1.2 MeV and 31-50 MeV proton data from COSTEP [8] on SOHO [9] and GOES 8 [10] were studied in the Posner work. Events exceeding 10 pfu (proton flux units) above 10 MeV (fluxes above 10 MeV greater than 10 $protons/(cm^2 sr s)$) were considered for analysis.

Following the Posner results, we estimated the minimum, average and maximum delay of non-relativistic protons with respect to relativistic electrons of solar origin in reaching 1 AU . Scatter-free particle propagation along the interplanetary magnetic field lines for a magnetically well connected event (pitch angle 0°; path=1.2 AU) was assumed in figure 3 for minimum time delay determination. Maximum time delays of approximately 1 h were estimated. Posner points

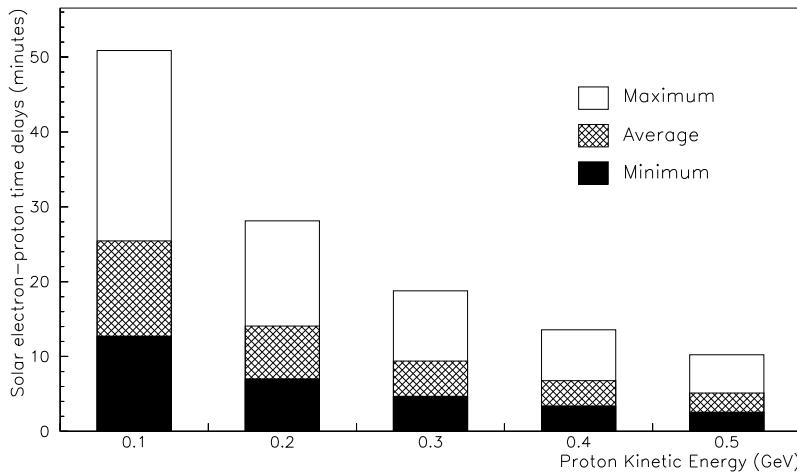


Figure 3. Minimum, average and maximum time delays between solar relativistic electrons and non-relativistic protons of different kinetic energies reaching 1 AU.

out that only rarely is a major proton intensity increase observed after 2 or 3 h following an electron intensity increase. As an example, the proton spectrum of a typical medium-strong event such as that dated 7 May 1978 (fluence between 10^6 and 10^7 protons/cm 2 above 30 MeV) is peaked at about 300 MeV at onset [5]. Therefore, according to figure 3, the time interval to be expected between solar relativistic electrons and non-relativistic protons reaching 1 AU ranges between 4 and 20 min. In other words, for a May 7th-like flare it will be possible to predict, within the above mentioned interval of time, a variation of the test-mass charging of 3 orders of magnitude from the moment solar protons reach the spacecraft and the peak of the event occurring in approximately 25 min [2]. Stronger events would result in higher test mass charging rates.

In figure 4 we have compared the expected electron and proton intensity increase versus time at the onset of a well connected event. Particle propagation along a path of 2 AU in the interplanetary magnetic field was assumed in figure 5. We point out that the increase of electron and proton intensities, $I(t)$, reported in arbitrary units in figures 4 and 5, at the beginning of a solar event, as a function of time (t) appears linear on a lin-log plot and therefore, it can be represented by the following expression:

$$I(t) = Ae^{\gamma t} \quad (1)$$

In figures 4 and 5 it can be seen that both electron and proton fluxes show a similar intensity increase. Sensitivity of an onboard monitor to large γ variations in electron intensity within a few minutes would allow us to issue a warning of incoming SEPs on LISA. In addition to the main connection distance effect influencing SEP onset at 1 AU, particle transport might play an important role. The interplanetary magnetic field sector structure affecting the onset of a few hundreds of keV electrons could reduce the accuracy of proton onset forecast. According to the Posner work (see figure 2 in [7]), this occurred in one case out of a sample of 65 well connected events.

In the rigidity (particle momentum per unit charge) range 0.3-300 MV, the mean free paths of electrons and protons are found to change by a factor of 20-50 from event to event [11], [12]. This corresponds to a maximum proton kinetic energy of 50 MeV.

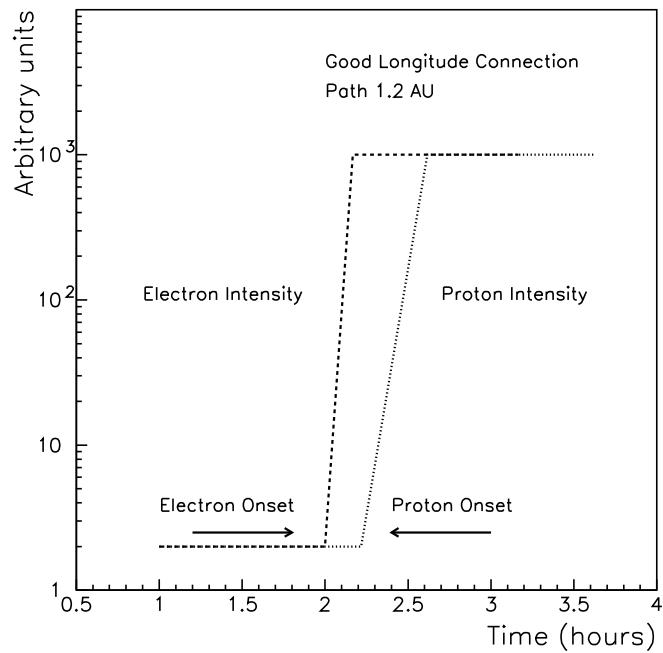


Figure 4. Expected time variation of the intensity of electron and proton fluxes at the onset of a solar event well connected to the spacecraft.

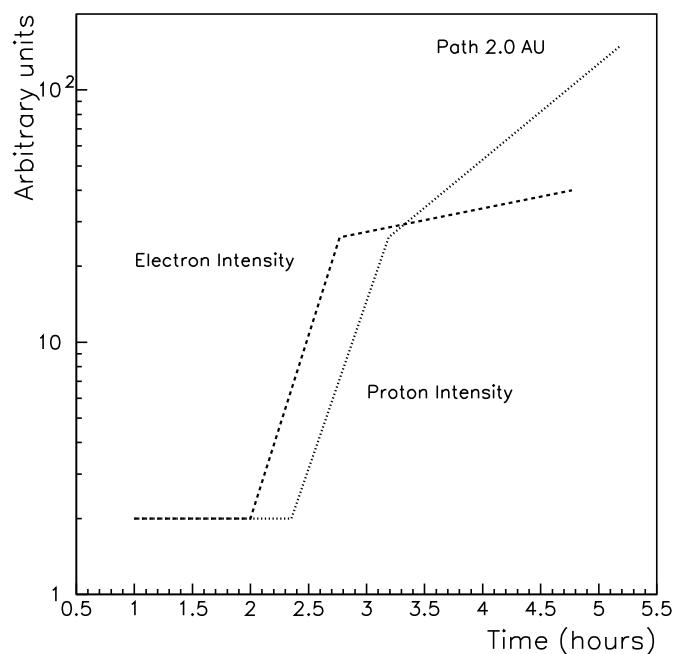


Figure 5. As figure 4, assuming particle paths of 2.0 AU instead of 1.2 AU.

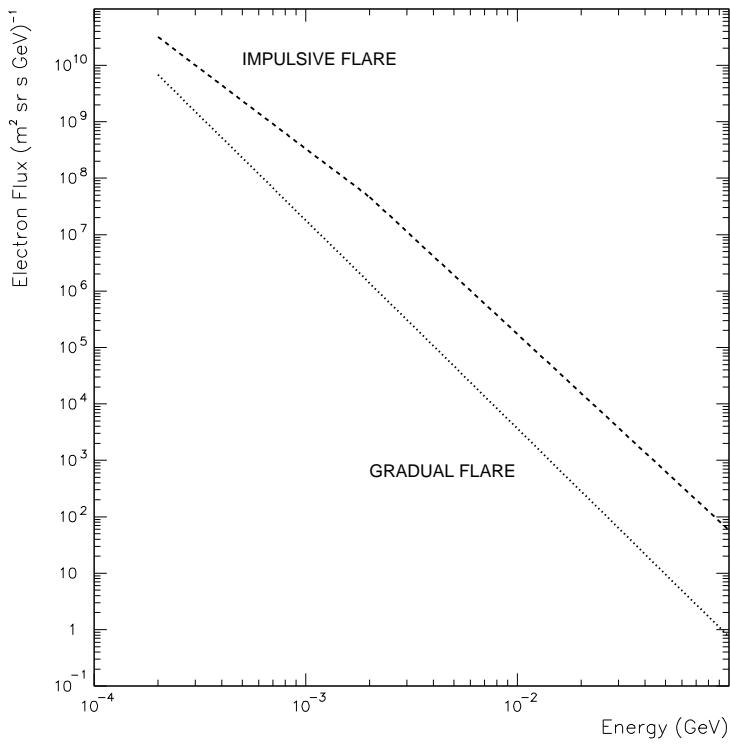


Figure 6. Interpolated solar electron fluxes associated with the November 3rd (dotted line) and September 7th 1973 (dashed line) solar flares. The measurement trend was extrapolated to 100 MeV.

The order of magnitude of the mean free path variations is close to the scatter of rise parameters of 1 MV electrons and 100 MV protons about the regression curve with magnetic connection distance [7].

The onset times of relativistic electrons are related to the coronal mass ejection (CME) speed for events occurring outside the fast propagation region (25° - 90° range of the angular connection) corresponding to approximately 57% of the events [13]. In particular, the delay time between electron onset and flare is close to the time of CME propagation to the observer's magnetic field line [14]. Interplanetary shocks accelerate only small amounts of electrons, therefore, solar electron detection cannot be used to forecast interplanetary shock transit. However, interplanetary shocks do not accelerate ions above 30 MeV/n and therefore LISA-PF and LISA are not affected by interplanetary acceleration.

2. Solar electron detection requirements on LISA

It is well known that only a subset of solar events generate particles above 100 MeV(/n). SEP forecasting on LISA should be addressed to these events only. To this purpose, we suggest monitoring electron intensity variations for particle energies above a few hundreds of keV on board LISA. This choice is due to the fact that only during the strongest events a relevant electron flux is generated above these energies. Unfortunately, we will not be able to discriminate between strong pure impulsive events which accelerate protons and nuclei below a few tens of

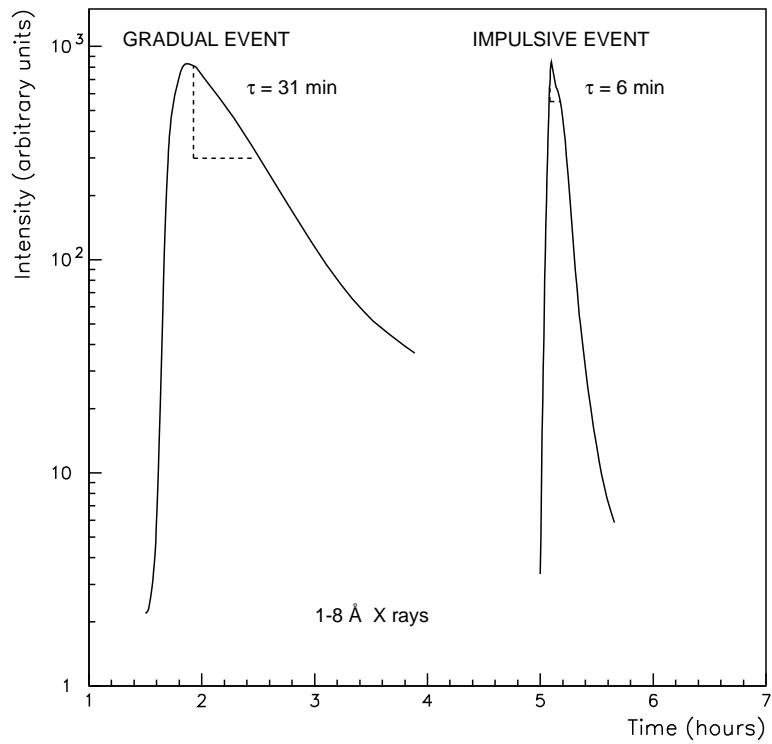


Figure 7. X-ray intensity near peak for typical gradual and impulsive events.

MeV, and gradual events. Relevant electron fluxes up to tens of MeV are associated with both kind of events. The main difference is that electron spectra observed for impulsive events present a double power-law slope, breaking at a few MeV, while gradual events present electron spectra modeled by a single power law, up to tens of MeV [15]. Examples of the two types of spectra are presented in figure 6.

It is not feasible to measure differential particle fluxes on LISA, therefore this separation will not be possible. However, simultaneous observations of solar events on other experiments devoted to solar physics, monitoring X-ray and γ -ray fluxes, might help in discriminating between pure impulsive and gradual events within 10 min from occurrence (see [13] and references therein). It was shown that X-ray events can be classified into two classes: gradual and impulsive, by considering the duration of 1.8 Å emission. If the time interval (τ) when the peak intensity decreases by a factor 1/e is >10 min (≤ 10 min) the event is gradual (impulsive). In figure 7 the trend of X-ray intensity associated with gradual and impulsive events are shown.

Solar events reaching Earth and near Earth detectors, such as LISA, are mostly generated in the western hemisphere because of the interplanetary magnetic field topology. Impulsive events with heliographic longitude $<-30^\circ$ never produce SEPs reaching Earth. Electrons in the MeV range can be detected more than 80° from the flare longitude. However, these events are not associated with SEPs and they can be identified since the electron peak intensities are small and decrease with increasing connection angle [16]. Conversely, SEPs associated with gradual events presenting heliographic longitudes ranging between -120° and $+180^\circ$ are observed. False warnings would be issued on LISA only for those strong impulsive events generating electrons

detected on each spacecraft within the 10 min needed to discriminate between impulsive and gradual events through X-ray observations. In the work by Laurenza et al. [13], SEP events analyzed were those exceeding 10 pfu above 10 MeV , as in the work by Posner. These authors find that 7% is the fraction of impulsive events of the whole sample of impulsive and gradual events for which it was possible to determine the heliographic longitude.

Electron intensity read-out would be necessary every minute at most on board LISA. The best connected events (up to 20 degrees) are expected to present very sharp electron onsets, of the order of 4 min. A dead-time in e^- intensity read-out larger than 4-5 min would prevent us from detecting in advance the most intense solar events. In case a SEP event occurs after other intense events, we expect a maximum uncertainty of 10 min in proton onset prediction. We have shown that [5] at the onset of a medium-strong solar event the incident proton flux increases of approximately one order of magnitude in about ten minutes. In the same interval of time, this variation can be detected above the statistical fluctuations associated with a previous event.

3. Detector characteristics for solar electrons on board LISA

Multi-layer solid-state detectors a few hundreds μm thick can be used for solar electron, proton and helium nucleus identification. Active anticoincidence shielding would be required around solid state detectors to identify charged particles. Fast-pulse-height analysis would be necessary for electron and ion separation [6]. X-rays would be absorbed in the shielding material, the anticoincidence would in any case avoid contamination of Compton electrons produced inside the detector. Total weight and power consumption can be limited to below a few kilograms and 2 W , respectively (similar to the EPHIN [17] sensor on SOHO). A geometrical factor of a few cm^2sr is required.

The detector aperture should point in the direction of the nominal interplanetary magnetic field at 1 AU , 45° west of the spacecraft-Sun line. Spacecraft rotation would probably require pointing the particle detector in the spacecraft-Sun line in order to maintain, on average, a good particle detection.

4. LISA dead-time reduction

SEP forecasting could help in better matching test-mass charging [1] and discharging rates on LISA [6]. Consequently, an electron monitor would allow for mission noise and, possibly, dead time reduction [2].

As an example, in Vocca et al. [18] it was shown that the 7 May 1978 medium-strong solar event would have increased the test-mass charging of 1 order of magnitude every 15 min during the first hour after the onset, limiting the LISA sensitivity in the low frequency range soon after the onset. During solar events of similar or larger intensity, the test-mass discharging is expected to increase with respect to solar quiet time, in order to allow for reliable data analysis. We point out that during solar maximum periods the occurrence of strong solar events might amount to up to a fraction of 20% of the mission time. Solar events of fluence larger than $10^9 \text{ protons/cm}^2$ might damage the radiation monitors, preventing us from further solar event prediction. The probability of occurrence of solar events as a function of intensity is reported in [5].

5. Conclusions

We have shown that solar electron detection on board LISA would allow us for short-term forecasting of incoming energetic ions of solar origin. Basically all events magnetically well connected to the spacecraft will be detected. A maximum issue of false warnings of 7% was estimated. Optimization of test mass discharging and experiment dead-time reduction might be consequently achieved. Minor modifications with respect to the LISA-PF radiation monitor design would be required in order to obtain a major experiment performance improvement.

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