Short-term forecasting of solar energetic ions on board LISA

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***Abstract*. Solar energetic particles (SEPs) pose a hazard to manned and unmanned space missions. Moreover, in LISA (Laser Interferometer Space Antenna) and its precursor mission LISA Pathfinder (LISA-PF) the free-fall test-masses are charged by galactic and solar energetic particles. This process generates spurious forces on the test masses which appears as significant levels of 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. Contemporary observations of solar electrons, protons and helium nuclei on board LISA will allow us to forecast and investigate the characteristics of SEPs over small steps in longitude.**

***Keywords*: Sun: solar-terrestrial relations - Space interferometers**

I. INTRODUCTION

Incident galactic cosmic-ray (GCR) fluxes and solar event occurrence are related to the level of solar modulation. We have estimated the expected GCR incident fluxes and the number of solar events in the fluence range 10^6 to 10^{11} $protons/cm^2$ at the time of the LISA missions [1]. In this work we point out that solar electron detection on board each satellite of the LISA mission will allow us to forecast the appearance and intensity of large solar proton events at small steps in longitude. SEP forecasting will be used to optimize the test-mass discharging on LISA but, contemporary, important clues on solar physics will be obtained (see [1], [2], [3]). In a recent work by Posner [4] it was shown that up to one hour warning of upcoming solar energetic ions can be given with detection of relativistic electrons at 1 AU. LISA measurements will allow us to monitor and, consequently, to improve modeling of impulsive and gradual phases of strong solar events. SEP flux measurements at small steps in longitude on LISA will be compared to contemporary observations gathered near Earth or by any experiment devoted to solar physics operating at the time of this mission [3].

II. THE LISA MISSIONS

LISA is the first interferometric device devoted to the detection of gravitational waves in space in the frequency range 10^{-4} - 10^{-1} Hz. It consists of three spacecraft placed 5×10^6 km apart at the corners of an equilateral triangle. The formation center of mass lies on the ecliptic. Each spacecraft hosts two inertial sensors. Cubic gold-platinum test masses constitute the interferometer mirrors. Their position is detected with gold plated electrodes. Energetic solar and cosmic rays charging the test masses are one of the most important sources of noise for the experiment [5], [6]. Ultraviolet light beams will be used to discharge the proof masses ([7] and references therein).

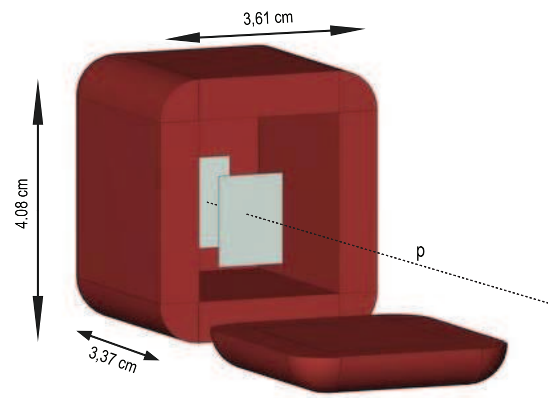

Fig. 1. LISA-PF radiation monitor set-up. Silicon wafers are sketched inside the shielding copper box. An incident proton trajectory is shown. Other details are reported in the text.

LISA will likely fly around 2018. The maximum mission duration is expected to be 10 years.

LISA-PF consists of one satellite hosting two test masses to be sent into orbit around L1 in 2011. LISA-PF target sensitivity is one order of magnitude smaller than LISA [8] . Data will be gathered for six months. Radiation detectors monitoring cosmic-ray and energetic solar particle fluxes will be placed on board both missions. Their design was finalized for LISA-PF only [9]. Two silicon wafers of 1.4 x 1.05 cm^2 area will be located in a telescopic arrangement at a distance of 2 cm. The geometrical factor of each silicon layer for an isotropic incidence is 9 cm^2 sr and for coincidence events is about one tenth of this. The silicon telescopes are placed 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) (see Fig. 1). This energy cutoff is similar to the minimum energy needed for the most abundant components of cosmic rays to penetrate the test masses [100 $MeV(/n)$]. No electron monitoring is allowed for on LISA-PF.

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

Very little is known about the solar particle energy spectrum evolution during strong solar events above 100 $MeV(/n)$.

We have simulated the LISA test-mass charging and radiation monitor performance at the occurrence of specific different intensity solar particle events [1], [5]. Radiation monitors designed for LISA-PF were considered. We have found that both the radiation monitor countrate and the 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. Radiation monitor data will be sent to ground every 614.4 s. SEP onset will be detected within this time resolution on LISA-PF. Optimization of test-mass discharging can be considered accordingly.

A work by Posner [4] has shown that during strong SEP events, relativistic electrons reach 1 AU always in advance with respect to non-relativistic ions. It was found that 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 early 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 on SOHO and GOES 8 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 time delays between relativistic electrons and non-relativistic protons of solar origin 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 Fig. 2 for minimum time delay determination. Maximum time delays of approximately 1 hour were estimated. Posner points out that only rarely is a major proton intensity increase observed after 2 or 3 hours from electron intensity increase.

The proton flux of a typical medium-strong event such as that dated May 7th 1978 (fluence between 10^6 and 10^7 $protons/cm^2$ above 30 MeV) is peaked at about 300 MeV at the onset. Therefore, according to Fig. 2, the time delay to be expected between solar relativistic electrons and protons reaching 1 AU is ranging between 4 and 20 minutes.

IV. Solar electron and proton intensity variations at 1 AU

In Fig. 3 we have shown 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 Fig. 4.

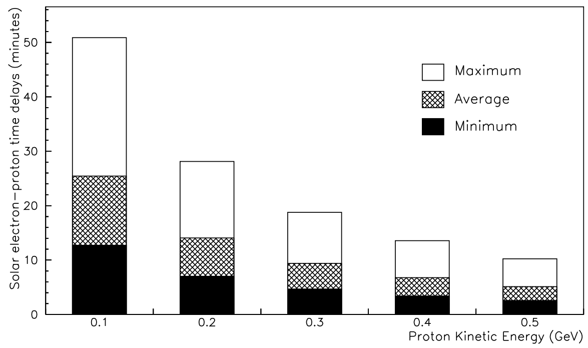

Fig. 2. Minimum, average and maximum time delays between solar relativistic electrons and protons of different kinetic energies reaching 1 AU.

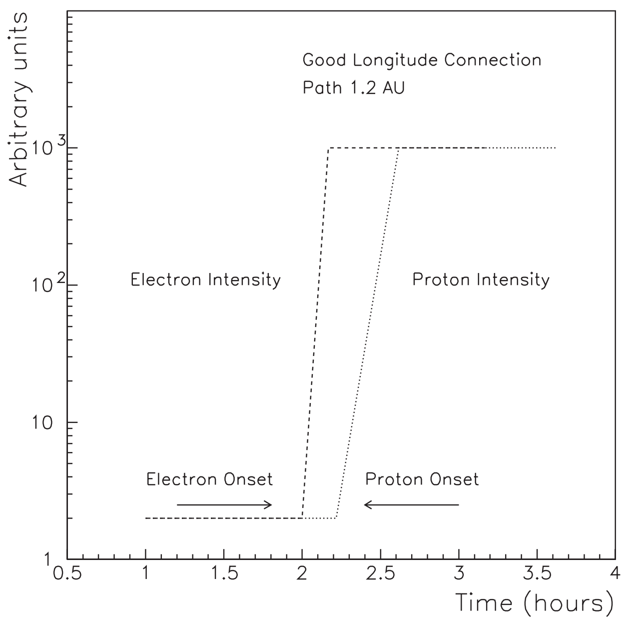

Fig. 3. Expected time intensity variation of electron and proton fluxes at the onset of a solar event well connected to the spacecraft.

We point out that the increase of electron and proton intensities, I(t), reported in arbitrary units in Figs. 3 and 4, at the occurrence of a solar event versus 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 Figs. 3 and 4 it can be noticed that both electron and proton fluxes show similar intensity increase. The detection of large γ variations for solar electron intensities within few minutes will allow us to issue a warning of incoming SEPs on LISA.

It is worthwhile to recall that 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 might compromise the capability to forecast proton onset.

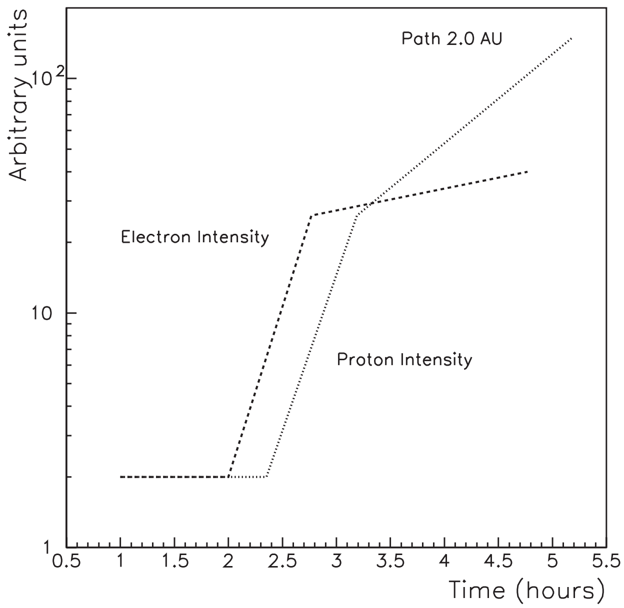

Fig. 4. Same as 3 assuming particle paths in the interplanetary medium of 2.0 AU.

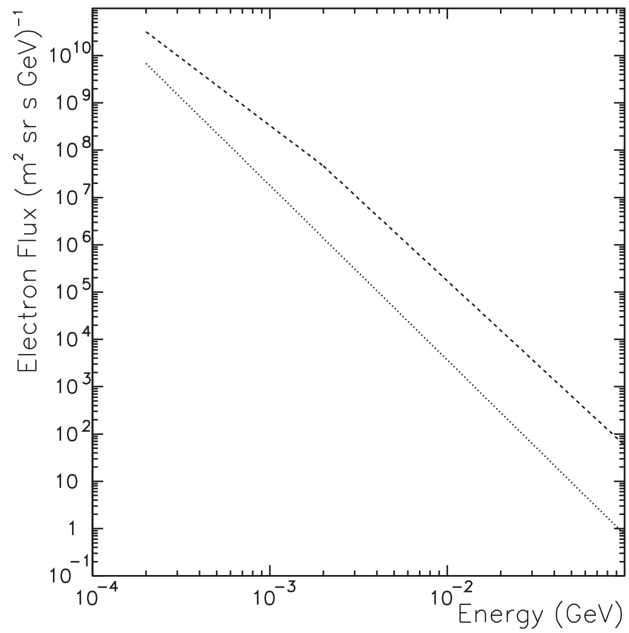

Fig. 5. Interpolated solar electron fluxes associated with the November 3rd (dotted line) and September 7th 1973 (dashed line) solar flares. Measurement trend was extrapolated to 100 MeV.

Moreover, mean free paths versus rigidities of electrons and protons are found to change by a factor of 20 from event to event for particle rigidities (particle momentum per unit charge) in the range 0.3-300 MV [10] (maximum proton kinetic energy 50 MeV and therefore below the range of interest of LISA). 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. The onset times of relativistic electrons are related to coronal mass ejection (CME) speed for events occurring outside the fast propagation region (25° - 90° range of the angular connection). In particular, the delay time between flare and electron onset is close to the time of the CME propagation to the observer magnetic field line [11]. However, these interplanetary phenomena do not affect the onset of intense SEP events well connected to the spacecraft that could be always forecast on LISA via solar electron detection.

V. 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 to monitor electron time intensity variations above a few hundreds of keV on board LISA. This choice is due to the fact that only during the most strong events a relevant electron flux is generated above these energies. Unfortunately, we will not be able to discriminate between strong pure impulsive events, accelerating protons and nuclei below a few tens of 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 in correspondence with impulsive events present a double power-law slope with a breaking at a few MeV, while gradual events present electron spectra modeled by single power laws up to tens of MeV [12]. Examples are presented in Fig. 5. It is no feasible to measure differential particle fluxes on LISA, therefore this separation won't be allowed. 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 minutes from occurrence ([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 $\mathring{A}$ emission. If the time interval when the peak intensity decreases by a factor 1/e is $>$10 minutes ($\leq$10 minutes) the event is gradual (impulsive).

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 $<-30°$ never produce SEPs reaching Earth. Electrons in the MeV range can be detected at more than $80°$ from the flare longitude. However, these events are not associated with SEPs and they can be recognized since the peak electron intensities are small and decrease more and more with increasing connection angle [14]. Conversely, SEP events associated with gradual events presenting heliographic longitudes ranging between $-120°$ to $+180°$ are observed. False warnings would be issued on LISA only for those strong impulsive events generating electrons detected on each spacecraft within the 10 minutes needed to discriminate impulsive and gradual events through X-ray observations. In the work by Laurenza et al. [13] the SEP events were considered those exceeding 10 pfu above 10 MeV, analogously to the work by Posner. These authors find that the fraction of impulsive events is 7$\%$ of the whole sample of impulsive and gradual events for which it was possible to determine the heliographic longitude.

Electron intensity variation read-out would be necessary every minute at the most on board LISA. The best connected events (up to 20 degrees) are expected to present very sharp electron onset of the order of 4 minutes. A larger dead-time for e^- intensity read-out would prevent us from detecting in advance most intense events.

Additional maximum uncertainty of 10 minutes in proton onset recognition should be considered if SEP occurrence is found after other intense events.

VI. Detector characteristics for solar electrons on board LISA

Multi-layer solid-state detectors a few hundreds of 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 [2]. 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 below a few kilograms and 2 W, respectively. Typical geometrical factor of a few cm^2 sr 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 to point the particle detector in the spacecraft-Sun line in order to maintain, on average, a good particle detection.

VII. LISA dead-time reduction

SEP forecasting could help in matching test-mass charging and discharging rates on LISA. Consequently, an electron monitor would allow for noise reduction and experiment live-time extension. As an example, in [6] it was shown that the May 7th 1978 medium-strong solar event would have limited the LISA sensitivity in the low frequency range soon after the onset. During solar events of similar or larger intensity only a proper discharging of the test masses allows for reliable data analysis. We point out that during solar maximum periods the rate of strong solar events might lead up to a fraction of 20% mission dead time.

VIII. Conclusions

We have shown that solar electron measurements on board LISA would allow us to forecast incoming solar ions up to one hour in advance. Well connected events approximately 5 minutes in advance. More in general, LISA would make possible to monitor the dynamics of both impulsive and gradual phases of solar events within two degrees in longitude at 1 AU. An improvement of the experiment performance and precious clues on solar physics will be provided by particle detection on board LISA.

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