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Galactic cosmic-ray energy spectra and expected solar events at the time of future space missions

C Grimani[1,2], H M Araújo[3], M Fabi[1], A Lobo[4], I Mateos[4], D N A Shaul[3], T J Sumner[3] and P Wass[3]

[1] Dipartimento MFI, Università degli Studi di Urbino 'Carlo Bo', Urbino (PU), Italy
[2] INFN, Florence, Italy
[3] Imperial College, London, UK
[4] Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain

E-mail: catia.grimani@uniurb.it

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Abstract

Galactic cosmic-rays (GCRs) and solar energetic particles (SEPs) affect observations on board long-lived space missions. We developed a parameterization of proton and helium fluxes for various levels of solar modulation during opposite polarity periods. In addition to long-term variations (decades), short-term fluctuations (minutes to days) were considered as well. In particular, we focused on data from experiments carrying magnetic spectrometers in space. The shortest GCR variations we were able to study are of the order of hours. We point out that GCR variations and fluctuations are strongly energy dependent. The detector charging onboard space experiments is also energy dependent. The measurements of energy differential fluxes and their variations are needed in order to evaluate properly the performance of future space missions. We present here the projections for the GCR fluxes and solar events at the time of LISA (Laser Interferometer Space Antenna) Pathfinder (LISA-PF).

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1. Introduction

Solar activity level, drift of opposite charge particles in the global solar magnetic field (GSMF) and interplanetary processes affect cosmic-ray observations in the local interplanetary medium. Experiments devoted to cosmic-ray physics aim to infer from near-Earth measurements the interstellar spectra. In all other missions energetic particles might affect the performance of the onboard detectors. In LISA-PF and LISA, for example, solar and galactic proton and helium particles above 100 MeV per nucleon (MeV/n) limit the mission performance charging the onboard test masses (see for details [1, 2]). In particular, short-term galactic cosmic-ray (GCR) fluctuations generate spurious signals in the experiment band [3] and SEPs associated with strong solar events overcome the whole mission noise budget in the low frequency range (see for example [4]).

Predictions of future solar cycle amplitudes allow us to estimate the intensity of GCR and the number of expected solar events during the next decades. The sunspot number is the most widely used proxy for solar activity prediction. In this work we adopt the projections of the next solar cycle intensity based on the observed trend of the solar spot number during the first months of this year [5, 6]. According to these predictions, we estimate the GCR energy spectra and the number of solar events at the time of LISA-PF at the end of 2012. The number of solar events were estimated according to Nymmik's model [7, 8]. Details of the LISA-PF mission are reported in [9].

Part of this work was carried out earlier; however, an update was needed since the actual trend shown by the initial rise of the solar cycle 24 appears weaker than projections available up to 2008 [10].

Various theoretical models were proposed in the literature to take into account the effects of solar modulation and solar polarity on GCRs (see for example [11, 12]). At this time we prefer an empirical approach based on data gathered by experiments carrying magnetic spectrometers in space that must be used to calibrate theoretical models. Proton, helium and electron data were considered. The method was discussed accurately in [13]. Our predictions will be redundantly tested by cosmic-ray experiments in flight at the time of LISA-PF such as AMS [14] and by the onboard monitors of incident solar and galactic proton and helium nuclei above a few tens of MeV/n [15].

GCR short-term fluctuations are discussed here in addition to long-term variations. Among short-term fluctuations we include the 27 day variations related to the Sun rotation, Forbush decreases (see section 4.2) and variations of the order of hours. Cosmic-ray fluctuations could not be studied in smaller intervals of time. This limitation arises from the large statistical uncertainties affecting differential flux measurements carried out by experiments with small geometrical factors resulting from the use of magnetic spectrometers.

For completeness we add that studies of GCR fluctuations down to minutes were carried out, for example, by Starodubtsev *et al* [16] using ground neutron monitors.

2. Solar cycle 24 projections and observed initial rise

Predictions of a solar cycle include both amplitude and timing. Timing depends on the characteristics of the solar minimum. Due to the unusual long duration of the last solar minimum we presently expect the next maximum to occur in 2013. Present projections for the solar cycle 24 are reported in the right panel of figure 1 [5, 6]. Solar cycle 24 projections available up to 2008 according to Hathaway and Dikpati [10] appear in the left panel of figure 1. An extensive review of the solar cycle 24 projections is reported in [17]. Unfortunately, the majority of these predictions were very different from the actual trend shown by the first phase of the solar cycle 24. In particular, out of 54 predictions, only 4 reported a solar maximum to occur beyond 2012. Intensities ranging between 185 and less than 40 for the average annual sunspot number (R_{24}) were proposed. However, 78% of the whole sample of predictions indicated R_{24} above 100 at the maximum. In other words, almost the totality of predictions presented a solar cycle of medium–strong amplitude. Conversely, the anomalous long duration of the last solar minimum and the trend of the rise of the solar cycle 24 indicate approximately $R_{24} = 77 \pm 20$. We point out that a quite good projection was reported by Kontor [18] for both R_{24} (70 ± 17.5) and timing (2012.96). Moreover, Li *et al* [19] indicated an average annual

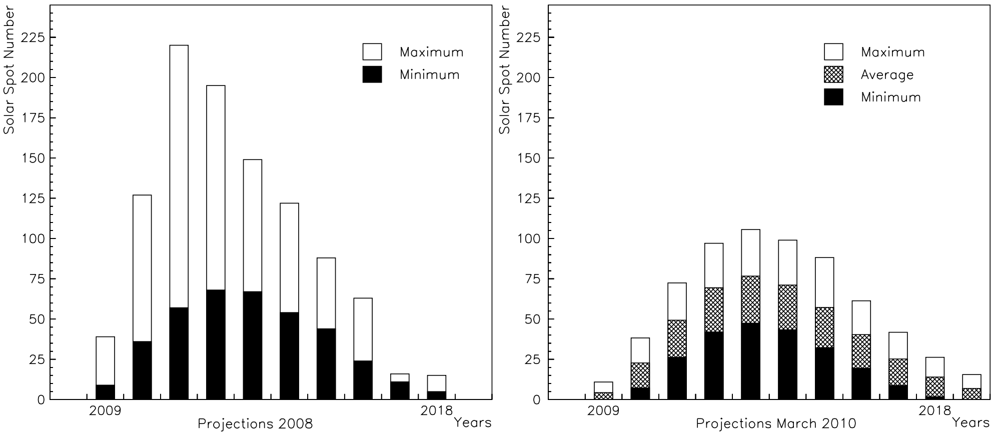

Figure 1. Predictions of the average annual sunspot number for the solar cycle 24: 2008 [10] and updated [5, 6] projections are compared.

sunspot number of 80 and the maximum to be reached in February 2013 (±8 months) in the case of a slow riser cycle.

3. Galactic cosmic-ray proton and helium energy spectra at the time of LISA-PF

Assuming that LISA-PF will be launched during the first quarter of 2012 and that about 3 months will be needed to reach its final orbit in L1, data will be taken during the second half of 2012, near the next solar maximum and possibly during the same negative polarity epoch we are presently experiencing. We recall that the GSMF polarity is positive (negative) when solar magnetic field lines are directed outward (inward) from the Sun's northern pole. GCR observations near Earth are affected by both solar activity level and solar polarity [20]. The effect of the solar modulation on GCRs during positive polarity periods is well represented by the symmetric model in the *force field* approximation by Gleeson and Axford [21]. This model (see equation (1)) allows us to estimate through an energy loss parameter, Φ, the fluxes of cosmic rays at a distance r from the Sun, at the time t ($J(r, E, t)$) assuming time-independent interstellar fluxes ($J(\infty, E + \Phi)$). In equation (1) E is the particle total energy and E_o is the rest mass. For proton and helium nuclei above rigidities (particle momentum per unit charge [22]) of 100 MV a modulation potential ϕ, given in units of MV, is such that $\Phi = |Z|e\phi$ corresponds to the average energy loss from the interstellar medium to a distance r from the Sun:

$$\frac{J(r, E, t)}{E^2 - E_0^2} = \frac{J(\infty, E + \Phi)}{(E + \Phi)^2 - E_0^2}. \qquad (1)$$

The modulation potential can be correlated with both neutron monitor count rate [23] and solar spot number [24]. At the moment, the expected number of minimum, average and maximum average annual solar spots in 2012 are 42.03, 69.53 and 97.03, respectively, very similar to 2003 (40.18, 67.18 and 94.18, respectively [6]). The estimated solar modulation parameter in 2003 was 959 MV [25]. Moreover, the proton data trend observed by the BESS (balloon-borne experiment with a superconducting spectrometer [26]) experiment in 2002 and 2004 indicated a solar modulation parameter for protons of 1109 and 764 MV, respectively

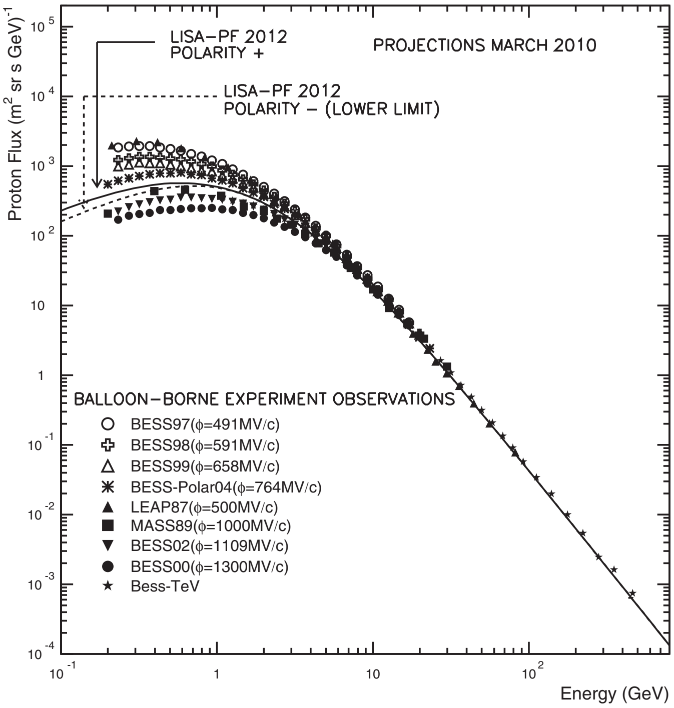

Figure 2. Estimated GCR proton energy spectra at the time of LISA-PF (2012).

Table 1. Proton (p) and helium (He) flux parameterization at the interstellar medium.

	A	P1	P2
p	$(1.94 \pm 0.13) \times 10^4$	0.70 ± 0.52	2.76 ± 0.03
He	$(7.10 \pm 0.56) \times 10^3$	0.50 ± 0.31	2.78 ± 0.03

(see figure 2). On the basis of these last two pieces of evidence we set to 950 MV the solar modulation parameter as a lower limit for the second half of 2012.

We use the model by Gleeson and Axford to estimate the particle energy spectra during a positive polarity epoch (continuous lines in figures 2 and 3 for proton and helium nuclei, respectively; references to data are reported in [13]).

Flux interpolation at the interstellar medium was gathered from [27] and reported in equation (2). The parameters for proton and helium fluxes appear in table 1. With β and R we indicate particle velocity and rigidity, respectively:

$$J(\infty, \beta, R) = A\beta^{P1}R^{-P2}. \tag{2}$$

The energy spectra during a negative polarity epoch were estimated according to [13] for near-solar-maximum conditions (dashed lines in figures 2 and 3). Presently, the Sun has a negative polarity. As pointed out in the previous section, a change of polarity from − to + is plausibly expected in 2013. Since at solar maximum a minor effect of solar polarity is observed on cosmic rays [28], we consider our estimated fluxes a lower limit at the time of LISA-PF.

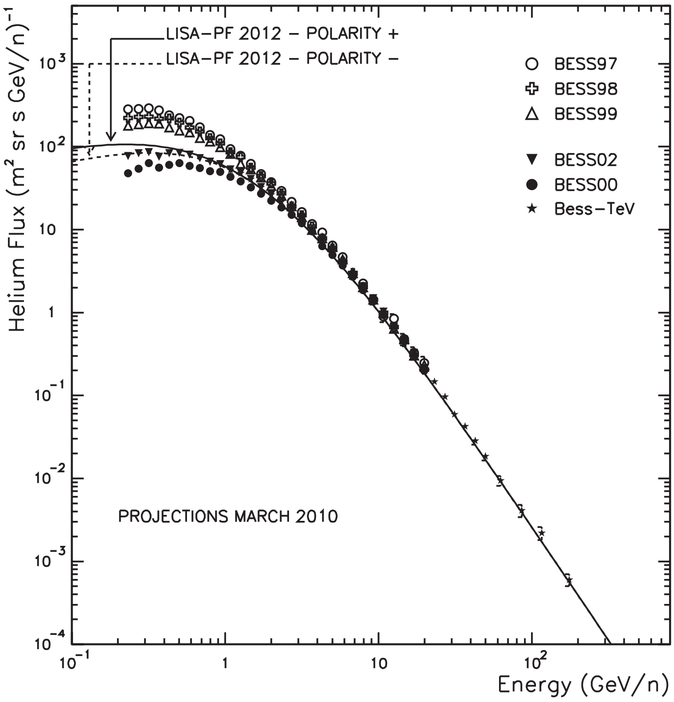

Figure 3. Same as figure 2 for helium nuclei.

Table 2. Proton and helium flux parameterization at 1 AU at the time of LISA-PF assuming a positive solar polarity.

Particle fluxes	A	B	α	γ
p	18000	1.50	3.90	1.10
He	850	1.30	3.23	0.48

The particle differential flux interpolation function we use at 1 AU is [29]

$$F(E) = A(E + B)^{-\alpha} E^{\gamma} \text{ Particles}/(m^2 srs \text{ GeV}). \tag{3}$$

The parameters in equation (3) for proton and helium nucleus flux interpolation are reported in table 2.

4. Galactic cosmic-ray short-term variations and fluctuations

4.1. 27-day variations

The Sun is a massive sphere of plasma and gas rotating at different rates depending on the heliolatitudes. The equator and near-equatorial regions of the Sun rotate with a period of about 25–26 days: the Sun's sideral rotation period. For an observer at the Earth this periodicity equals about 27–28 days due to the orbital motion of the Earth. This is called the Sun's sinodic period of rotation. At the poles the Sun rotates with a period of about 36 days. The distribution of active regions and coronal holes on the Sun generates a solar wind asymmetric velocity distribution with respect to heliolongitude and heliolatitude. Since the Sun rotation depends

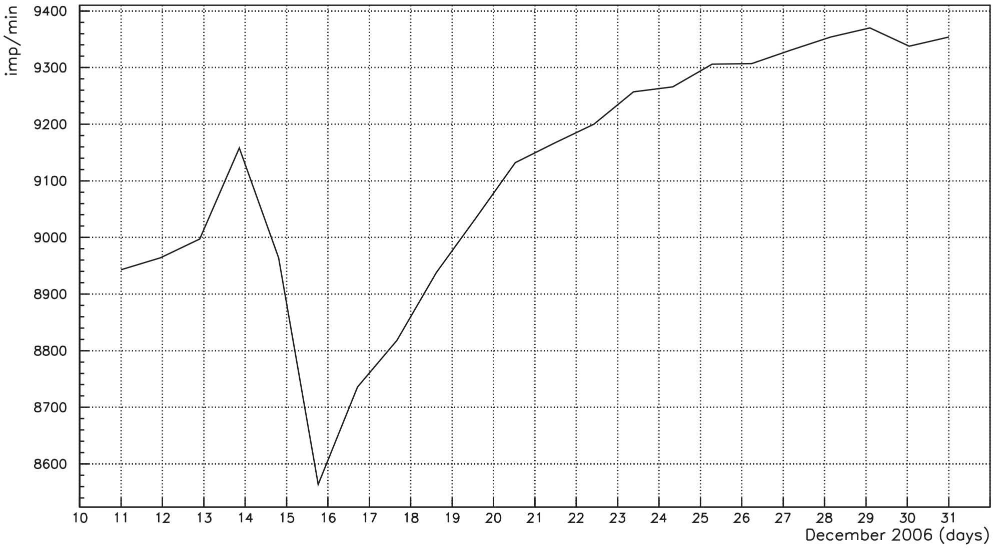

Figure 4. Moscow neutron monitor counting rate in December 2006 [32]. A Forbush decrease occurred on 15 December. We recall that the neutron monitor count rate (*Y*-axis label) is expressed in neutron impulses per minute.

on the reference system of the observer, these recurrent variations are called 27 day variations of GCR intensity [30].

Alania *et al* [31] showed that the larger amplitudes of the 27 day variations of the GCR intensity and anisotropy are observed during periods of minimum solar activity and positive polarity. In particular, they found that the amplitudes of the 27 day intensity variations present a power-law spectrum in rigidity ($A_{27} = \mathrm{b}R^{-\delta}$). This spectrum appears hard ($\delta = 0.54 \pm 0.11$) during positive polarity periods and soft ($\delta = 0.95 \pm 0.12$) during negative polarity epochs. From the data reported by Alania *et al* we have inferred that A_{27} varies between 6% at 0.445 GV (0.1 GeV for protons) and 1.2% at 10 GV at solar minimum during positive polarity epochs while goes down to 4% at 0.445 GV and 0.2% at 10 GV during negative polarity periods. GCR anisotropy is smaller than 0.06% (0.03%) during positive (negative) polarity periods.

The 27 day variations were not found to depend on the tilt angles of the heliospheric current sheets according to neutron monitor data.

4.2. *Forbush decreases*

Forbush decreases were discovered by Forbush in 1937. A Forbush decrease is a worldwide drop of the observed GCR intensity occurring within tens of minutes to hours followed by a gradual recovery to the previous average intensity within many hours or days. Forbush decreases can be divided into two classes: sporadic (transient) and recurrent. The sporadic Forbush decreases generate GCR intensity drop lasting 1–2 days then present gradual recovery in, on average, 5–10 days (an example is reported in figure 4 [32]). The sporadic Forbush decreases of the GCR intensity are associated with major solar flares. These Forbush decreases can be caused by (1) shock and ejecta, (2) shock only, or (3) ejecta only [33]. Sporadic Forbush decreases generate drops of the order of 5–10% at 10 GV rigidity. The recurrent Forbush effects (with amplitudes < 3–4% at the rigidity of 10 GV) are associated with the corotating

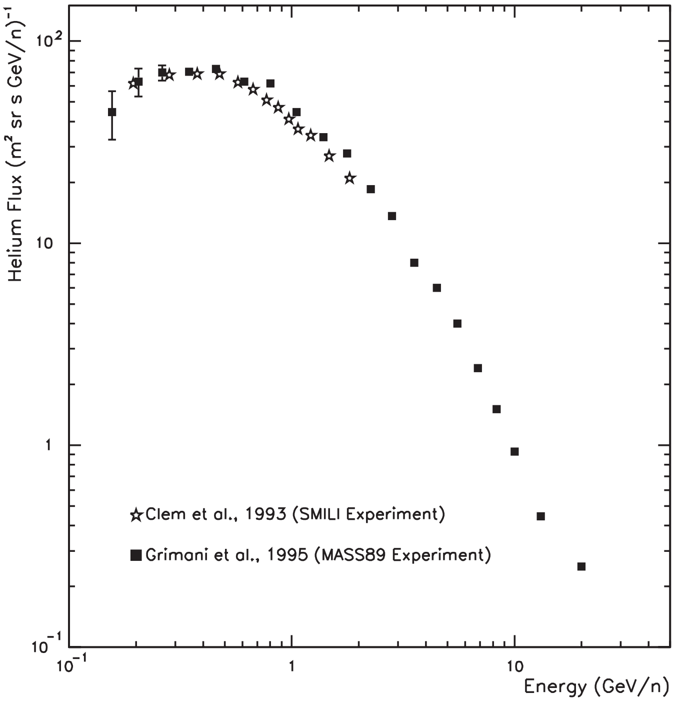

Figure 5. Helium flux measurements carried out by the SMILI and MASS89 experiments on 1 and 5 September 1989, respectively. A Forbush decrease started on 4 September. Normalization problems can be observed between the two experiments since above 1 GeV the SMILI flux assumes smaller values with respect to those of MASS89.

interaction regions in the interplanetary space. Recurrent Forbush effect has approximately symmetric time profile: the GCR intensity decreases gradually during 5–7 days and recoveries last approximately the same time.

Forbush effects on the 27 day variation of the GCR intensity are currently unknown.

Forbush decreases affect high energy GCR more than all other short-term variations and fluctuations. A detailed study of the LISA-PF test-mass charging variation during a Forbush decrease is in preparation. GCR energy differential flux measurements during Forbush decreases were carried out, for example, by the SMILI [34], MASS89 [35] and PAMELA [36] experiments. SMILI and MASS89 are balloon-borne experiments flown from Saskatchwan (Canada) soon before (1 September) and during (5 September) the Forbush decrease dated 4 September 1989, respectively. Unfortunately, even if these last two experiments show a low energy modulation of the helium nucleus spectrum due to the Forbush decrease, evident normalization problems between the two experiments do not actually present the possibility of studying accurately the energy dependence of the decrease (see figure 5). This was not the case for the event dated 15 December 2006. The dynamics of the whole event was observed by PAMELA. This satellite experiment, launched on 15 June 2006, is devoted to antimatter search in cosmic rays. Preliminary results were presented by the PAMELA collaboration at the last August European Cosmic-Ray Symposium in Turku (Finland) [37]. In figure 4, the Moscow neutron monitor counting rate represents the trend of the GCR intensity in December 2006. In figure 6, we have reported the variations of GCR proton flux in different energy intervals (0.4–1 GeV, 1–5 GeV, 5–20 GeV) during the same period as measured by PAMELA. It appears

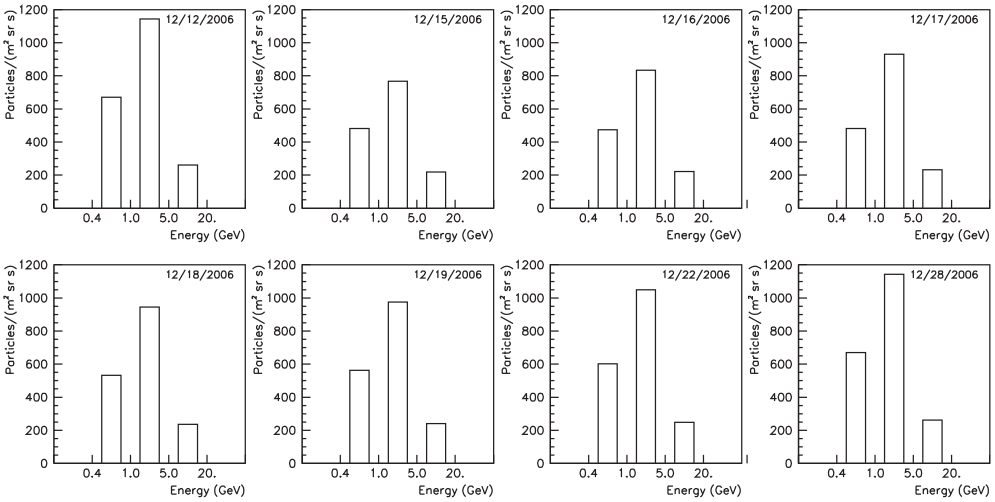

Figure 6. GCR integral proton flux observed by PAMELA in various energy intervals between 12 and 28 December 2006 [37].

that the Forbush decrease is softened by solar particles below 1 GeV while an intensity drop of up to 30% is observed between 1 and 5 GeV. Some reduction of the flux is found above 10 GeV.

4.3. Hourly and daily GCR fluctuations

Short-term GCR fluctuations observed near the Earth are affected by solar-terrestrial relations. However, the balloon-borne BESS-Polar I experiment, flown from Antarctica from 13 through 21 December 2004 [38], detected galactic proton differential flux variations correlated with the solar activity. Shortly before the BESS-Polar I flight an interplanetary coronal mass ejection or a magnetic cloud reached Earth and on 14 December the count rate of the Bartol South Pole neutron monitor started to recover gradually. The GCR intensity recovery was softened by a high-speed stream in the solar wind reaching the Earth between 16 and 17 December. Short-term GCR variations depend on the characteristics of each interplanetary process; however, the BESS-Polar I data provide precious clues on these intensity variations as a function of the energy. The proton flux was measured by BESS-Polar I experiment in 4 h time intervals normalized to the flight average flux in the energy ranges 0.29–0.54 GeV, 0.54–1 GeV, 1–3.4 GeV and 3.4–10 GeV. While diurnal variations do not allow us to give any meaningful explanation to the fluctuations of individual data points [38], a continuous recovery of the low energy differential flux was observed in agreement with the Bartol South Pole neutron monitor trend modulated by the Sun activity. In particular, between 200 MeV and 1 GeV the proton spectrum varies between −5% and +3% with respect to the average value during the whole flight. Between 1 and 10 GeV the variations appear reduced and consistent with statistical uncertainties [39].

5. Updated estimate of the number of solar events at the time of LISA-PF

Nymmik [7, 8] has found that the SEP fluence distribution follows a power-law trend with an exponential decrease for large fluences. This model applies to solar proton fluences ranging

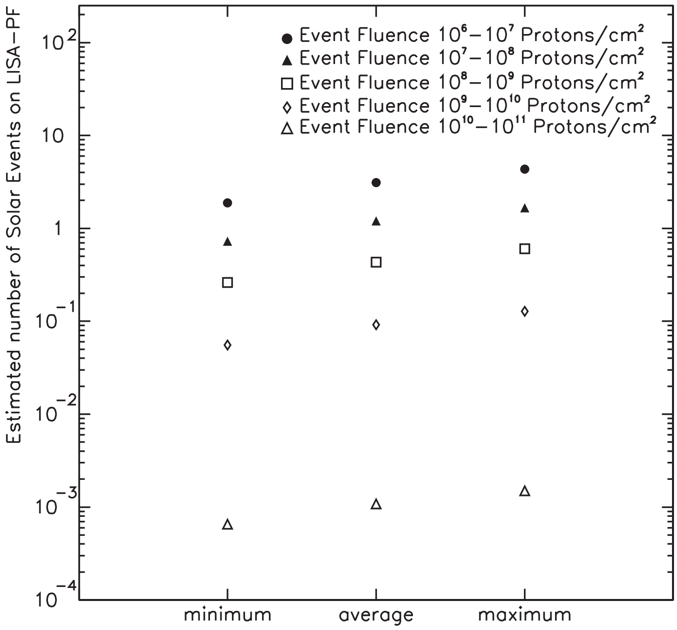

Figure 7. Estimated number of solar events per interval of fluence in 2012.

between 10^6 and 10^{11} protons cm^{-2} for particle energies above 30 MeV. The Nymmik results were inferred from the analysis of the spacecraft IMP-7 and 8 measurements of SEP events during the solar cycles 20–22 and from proton fluxes estimated on the basis of radionuclide observations in lunar rocks generated in the last few million years. Nymmik's model offers the possibility of predicting solar events in terms of energy range and of particle peak fluxes instead of fluence only (for a review of other models see [40, 41] and references therein).

The number of SEP events in individual intervals of fluence during the 6 months of the expected LISA-PF data taking were estimated according to the March 2010 projections of the number of solar spots reported in figure 1 (see [20] for details).

We have found a minimum, average and maximum number of solar events in 2012 of 2.92, 4.83 and 6.73, respectively. Half of these are expected in 6 months. The number of events estimated to occur in 2012 per interval of fluence appear in figure 7.

6. Conclusions

The most recent projections of the solar cycle 24 allow us to estimate the GCR fluxes at the time of future space missions. In addition to long-term variations, short-term fluctuations were considered. In particular, we found that Forbush decreases generate intensity drops up to 30% in individual energy intervals. Other short-term variations cause maximum variations of a few per cent at most. We have also estimated the number of solar events with fluences larger than 10^6 protons cm^{-2} expected during the second half of 2012. This number ranges between 1.5 and 3.4, well below previous expectations. This might mean that no events or, at least, no events with fluences equal or larger than 10^7 protons cm^{-2} might occur at the time of LISA-PF data taking. We point out that 10^7 protons cm^{-2} is the intensity of events generating a noise larger than the whole LISA budget at low frequencies (at the peak).

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