Spectral shape of solar particle events at energies above 100 MeV/n

C Grimani1,2, M Fabi1, N Finetti2,3, M Laurenza1, M Storini4
1DiSBeF, Università degli Studi di Urbino “Carlo Bo”, Urbino (PU), Italy
2Istituto Nazionale di Fisica Nucleare, Florence, Italy
3Dipartimento di Fisica, Università degli Studi dell’Aquila, L’Aquila, Italy
4Institute for Space Astrophysics and Planetology, INAF, Rome, Italy
E-mail: catia.grimani@uniurb.it

Abstract. High energy particles of galactic and solar origin crossing a spacecraft affect experiment performance in space. At time scales of tens of minutes, galactic cosmic-ray (GCR) energy fluxes vary of a few percent at most. Conversely, solar energetic particle (SEP) fluxes may vary of several orders of magnitude during the same periods of time. In order to study accurately the effects of the incident solar particles on future space experiments, a good knowledge of particle energy distribution during the whole duration of SEP events is necessary. We report here the parameterization of proton and helium energy spectra observed during SEP events of different intensity at energies above 100 MeV/n. We benefit of both data inferred at the top of the atmosphere from ground neutron monitor observations and recent measurements gathered by the PAMELA cosmic-ray experiment carrying a magnetic spectrometer in space.

1. Introduction

Large solar energetic particle (SEP) events pose serious radiation hazard for manned and unmanned space flights. We recall that 100 MeV/n is, typically, the minimum energy of protons and ions being able to cross spacecraft materials and astronaut suits. 100 MeV/n is also the minimum energy needed to galactic and solar particles to penetrate the LISA-PF [1] spacecraft and charge the experiment free-floating test masses [2, 3, 4] inducing spurious forces that might mimic genuine gravitational wave signals [5]. LISA-PF is the technology test-mission for the LISA/NGO program [6] for low-frequency gravitational wave detection in space. LISA-PF represents also a fundamental step forward for all future space interferometers such as ASTROD [7] and DECIGO [8]. In order to estimate the LISA-PF charging process, we focus here on the characteristics of solar energetic proton and helium energy spectra at energies > 100 MeV/n during the evolution of SEP events of different intensities. In a recent work [9], we have estimated the number of SEP events with an intensity larger than 10^6 protons/cm^2 at energies above 30 MeV [10, 11] expected to occur during the six months of LISA-PF data taking in 2015. Two events with integral fluences ranging between 10^6 protons/cm^2 and 10^8 protons/cm^2 are expected even if the occurrence of stronger events cannot be excluded. SEP events with these characteristics will overcome the expected GCR overall flux in 2015 [9] at energies larger than 100 MeV.

We benefit here of data measured in space or extrapolated at the top of the atmosphere on the basis of neutron monitor measurements. In particular, we report on the interpolation of proton
Figure 1. Expected GCR proton and helium nucleus energy spectra in 2015 [9]. The helium spectrum was scaled down by a factor of 10 in the figure. Top continuous curves 1 and 2 represent the proton energy spectra during the prompt phase and the peak for the event dated February 23rd 1956 [13], respectively. Dot-dashed curves 3 and 4 have the same meaning for the event dated December 13th 2006 [12]. The dotted curve is the peak proton energy spectrum for the event dated December 14th 2006 [12].

and helium energy spectra of the SEP event dated December 13th 2006 and proton energy spectra of the event dated December 14th 2006, both observed by the PAMELA experiment [12]. For comparison we studied the trend of the intense SEP event dated February 23rd 1956 [13].

2. GCR and SEP energy spectra

GCR proton and helium nucleus energy spectra expected in 2015 are reported in figure 1. In the same figure we have shown the prompt phases and peak fluxes associated to the evolution of SEP events of different intensities.

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 [14] integral proton intensities of about $10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at energies larger than 500 GeV were suggested for the 29 September 1989, 15 June 1991 and 12 October 1981 ground level events. The most energetic particles (energies larger than 1 GeV) arrive with a delay of only a few tens of minutes after the visual recognition of the flare. Lower energy particles appear later according to the dispersion velocity effect while the high energy particles tend to 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.

Attempts to parameterize the rigidity ($R = \frac{pc}{Ze}$; particle momentum per unit charge) and energy spectra of solar energetic protons were carried out by many authors. Several spectral laws have been proposed, such as power law, soft exponential, power law modulated by an exponential, broken power law (e.g. [15, 16, 17]). For instance, Mottl and Nymmik [18] found
that at energies > 30 MeV integral SEP spectra are power-law functions of particle momentum. Vashenyuk et al. [13] found for 12 strong SEP events, including that dated February 23rd 1956, an exponential trend for the prompt component and a power-law spectrum for the delayed component in kinetic energy. Indeed, it is important to underline that the spectral characteristics can evolve during the event [19], also as a consequence of propagation effects. Laurenza et al. [17] have introduced the Shannon’s differential entropy as a proxy to study the SEP spectrum evolution; they have shown the continuous evolution of the SEP event spectral shape and remarked strong spectral changes in different phases of a SEP event.

3. Parameterization of SEP events of different intensities
We have interpolated the energy spectra, $F(E)$, of solar protons associated with the evolution of SEP events dated February 23rd 1956, December 13th 2006 and December 14th 2006. Helium nucleus energy spectra were studied for the event dated December 13th 2006. Other SEP events will be presented at the Conference.

We considered the following interpolation functions:

$$F(E) = A e^{-\frac{E}{E_0}} \text{ Particles (m}^2 \text{ sr s GeV)}^{-1}$$  \hspace{1cm} (1)

$$F(E) = A E^{-\gamma} \text{ Particles (m}^2 \text{ sr s GeV)}^{-1}$$  \hspace{1cm} (2)

$$F(E) = A e^{-\frac{E}{E_0}} E^{-\gamma} \text{ Particles (m}^2 \text{ sr s GeV)}^{-1}.$$  \hspace{1cm} (3)

Results are reported in Table 1.

4. Conclusions
Particles of both galactic and solar origin with energies larger than 100 MeV/n penetrate spacecraft and astronaut suits. As a case-study, we aim to estimate the charging process of metal free-floating test-masses on board interferometers devoted to the detection of low-frequency gravitational waves in space. This charging process is strongly dependent on the solar particle energy. We have interpolated the energy spectra of solar protons and helium nuclei associated with the evolution of events of different intensities at energies > 100 MeV/n. In particular, we have focused on the characteristics of the events dated December 13th 2006 and December 14th 2006 measured by the PAMELA experiment using a magnetic spectrometer in space. These events present fluences similar to those expected to occur in 2015 at the time of LISA-PF data taking. We have found that for both proton and helium nuclei the SEP event onset is better represented by an exponential trend. Other phases of the events show a trend consistent with a power-law trend modulated by an exponential or a pure power-law trend.

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Table 1. Interpolation of energetic solar particle spectra observed during the evolution of the SEP events dated February 23rd 1956, December 13th 2006 and December 14th 2006.

| Event                  | Protons Particles (m$^2$ sr s GeV)$^{-1}$ | Helium Particles (m$^2$ sr s GeV)$^{-1}$ |
|------------------------|-------------------------------------------|------------------------------------------|
| February 23rd 1956     |                                            |                                          |
| 0400 UT                | 850880 e$^{-\frac{E}{0.72}}$ E$^{-0.51}$   | 51079 e$^{-\frac{E}{1.11}}$ E$^{-1.77}$   |
| 0430 UT                | 3688100 E$^{-5.30}$                         |                                          |
| 0500 UT                | 1026400 E$^{-5.24}$                         |                                          |
| 0600 UT                | 2954200 E$^{-4.56}$                         |                                          |
| December 13th 2006     |                                            |                                          |
| 0318-0349 UT           | 4469000 e$^{-\frac{E}{0.66}}$ E$^{-0.51}$ | 51079 e$^{-\frac{E}{1.11}}$ E$^{-1.77}$   |
| 0349-0433 UT           | 5530000 e$^{-\frac{E}{0.71}}$ E$^{-1.02}$ | 1122 e$^{-\frac{E}{0.66}}$ E$^{-1.77}$   |
| 0433-0459 UT           | 1203800 e$^{-\frac{E}{2.27}}$ E$^{-1.95}$ | 3117 e$^{-\frac{E}{0.71}}$ E$^{-1.58}$   |
| 0818-0917 UT           | 1057 E$^{-3.60}$                            | 675 e$^{-\frac{E}{0.71}}$ E$^{-1.72}$   |
| 1650-2235 UT           | 58718 e$^{-\frac{E}{0.612}}$ E$^{-0.37}$  |                                          |
| December 14th-15th 2006|                                            |                                          |
| 2305-0235 UT           | 1155 e$^{-\frac{E}{0.72}}$ E$^{-2.48}$    |                                          |
| 0305-0455 UT           | 463 e$^{-\frac{E}{0.72}}$ E$^{-2.68}$     |                                          |
| 0525-0630 UT           | 23005 e$^{-\frac{E}{0.66}}$ E$^{-1.13}$   |                                          |
| 0750-0800 UT           | 400900 e$^{-\frac{E}{0.74}}$ E$^{-0.95}$  |                                          |
| 1540-1930 UT           | 15909 e$^{-\frac{E}{0.66}}$ E$^{-0.96}$   |                                          |
| 1930-2335 UT           | 435 e$^{-\frac{E}{0.619}}$ E$^{-2.10}$    |                                          |

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