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Solar Energetic Particle Observations with the PAMELA Experiment

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Despite the progress made over the past decades, the physical mechanisms underlying the origin of solar energetic particles (SEPs) are still debated. The largest uncertainties concern the most energetic ($\gtrsim$500 MeV) SEP events, which are difficult to characterize due to the relatively few and indirect observations such as those made by neutron monitors. The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment has recently offered a unique opportunity to study SEPs with energies between 80 MeV and few GeV, including their energy spectra, composition and pitch angle distributions. In particular, PAMELA has measured for the first time with good accuracy the spectral features at moderate and high energies for 26 SEP events occurring between 2006 December and 2014 September, providing important constraints for current SEP models. Reported spectral shapes exhibit a high-energy rollover that can be attributed to particles escaping the shock region during acceleration, as a consequence of its limited extension and lifetime. PAMELA observations also allow the relationship between low-energy SEPs detected by in-situ spacecraft and the high-energy SEPs registered by the worldwide network of neutron monitors during the rare ground-level enhancements (GLEs) to be investigated. No qualitative distinction between the spectra of GLE and non-GLE events was observed, suggesting that GLEs are not a separate class, but rather are a subset of a continuous distribution of SEP events that are more intense at high energies. In this work we combine data from PAMELA and other near-Earth spacecraft in order to determine the SEP spectral shapes at 1 AU from tens of keV to a few GeV.

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1. Introduction

Solar energetic particle (SEP) events are a major space weather phenomenon affecting the near-Earth environment and constraining human activities in space, with significant hazards for robotic and manned missions. The problem is exacerbated during high-energy SEP events, when enhanced radiation risks occur for high-altitude aircraft (see, e.g., [1]). In particular, the most energetic ($\gtrsim$500 MeV) SEP events induce atmospheric showers whose secondary products can be detected by ground-based detectors such as neutron monitors (NMs), muon hodoscopes, and ionization chambers, during the so-called "ground-level enhancements" (GLEs). Apart from the relevant space weather implications, GLE-like events are of special interest since they are associated with the most efficient particle acceleration mechanisms occurring at the Sun.

The origin of SEPs is commonly attributed to a mixture of processes related to solar flares and coronal mass ejections (CMEs), though there is still debate regarding the relative importance of these contributions, and large uncertainties affect the modeling of both acceleration and transport mechanisms which determine the SEP properties observed at 1 AU (see, e.g., [2]). In particular, high-energy particles in large SEP events are believed to be accelerated mostly at CME-driven shock waves. According to the diffusive shock acceleration (DSA) scenario, particles can be scattered by magnetic turbulence back and forth across the shock multiple times, achieving efficient acceleration. It has been suggested that the maximum particle energy may be determined by several concomitant factors, including the shock speed, geometry and age (e.g., [3, 4]), the coronal magnetic field strength and configuration (e.g., [5]), and the presence of seed particle populations (e.g., [6, 7, 8]). In particular, recent studies have shown that the most energetic particles originate very close to the Sun ($<$2 R_s), where the magnetic field is stronger and thus the acceleration is more efficient. This is corroborated by observations of type-II radio bursts produced by electrons accelerated by shocks, which commence at higher frequencies for the most energetic particle events [9]. Since both the shock speed and the magnetic field strength decrease with increasing heliocentric distances, the maximum acceleration energy reduces with time as the shock propagates out into the interplanetary space [10, 11].

The DSA ideally predicts power-law energy spectra whose slope is controlled by the shock compression ratio. However, changes in the acceleration efficiency arise from a number of factors, including the three-dimensional curvature and size of the shock front, the limited acceleration time scales, and the vanishing power in the magnetic field wave spectrum with the heliocentric distance (causing the diffusion coefficient to increase rapidly), each contributing to releasing particles from the shock and terminating acceleration [12, 13, 14, 15]. As a consequence, the spectra are expected to be modulated at high-energies by an exponential cutoff reflecting the limits of particle acceleration. It has been argued that the SEP spectral breaks observed at 1 AU typically occurring at energies between few and tens of MeV/n are indicative of these effects (see e.g., [16, 17, 18]), although interplanetary transport may also play a relevant role [19, 20]. However, the characterization of high-energy SEPs has been plagued by the relatively few observations, that were often influenced by selection biases, instrument thresholds, and incomplete coverage. In particular, observations of SEPs with energies above a few hundred MeV have been relegated to the rare[1] GLE

[1] Only 72 GLEs were registered in the past 77 years (`http://www.nmdb.eu/`), with two – associated with the 2012 May 17 and 2017 September 10 events – occurring during solar cycle 24.

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data registered by ground-based instruments, which are affected by large uncertainties related to a number of assumptions needed to model SEP spectral shapes and angular distributions accounting for the cosmic-ray interactions with the terrestrial magnetosphere and atmosphere.

2. The PAMELA experiment

Such difficulties have been recently overcome by the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) space mission. The instrument, launched into a low-Earth orbit (70° inclination, 350-610 km altitude[2]) on board the Resurs-DK1 satellite on 2006 June 15, consisted of a magnetic spectrometer equipped with a microstrip silicon tracking system, a time-of-flight system shielded by an anticoincidence system, an electromagnetic calorimeter and a neutron detector. Thanks to its superior observational capabilities, PAMELA has provided a major improvement in the investigation of high-energy SEP events in terms of energy spectra, composition and pitch angle distributions [21, 22, 23, 24, 25, 26]. In addition, PAMELA data have been used to cross-calibrate the proton detectors on board the Geostationary Operational Environmental Satellites (GOES), significantly enhancing the reliability of the spectroscopic measurements [27]. The derived "effective" energies were used to obtain the high-energy spectra during the intervals when PAMELA was not acquiring data or after the mission was terminated in 2016 [26, 28].

2.1 SEP observations

Bruno et al. [25] made accurate measurements of the spectra of 26 SEP events between 2006 December and 2014 September in the energy range spanning from 80 MeV to a few GeV, encompassing the low-energy data from previous space-based instruments and the sporadic NM observations during the GLEs. All detected events were associated with full halo CMEs and ≥M-class flares with few exceptions. In addition, all were accompanied by long-duration type-II and type-III radio bursts. In particular, the measured type-II emission ranges from metric to decameter-hectometric wavelengths for most events, suggesting that the shocks accelerating particles formed close to the Sun [9]. Taking advantage of calibrated GOES data [27], the analyzed SEP sample was subsequently extended to other high-energy events occurring in solar cycle 24 [26], including the 2017 September 10 GLE [28].

The source locations of the 14 most energetic events, based on PAMELA and GOES-13/15 data, are displayed in Figure 1. While most events were concentrated on the western visible hemisphere of the Sun or just behind the West limb, consistent with magnetic connectivity arguments, the 2014 February 25 and the 2014 September 1 events were located close to and behind the East limb, respectively, demonstrating that poorly connected events can contribute to the high-energy SEP flux measured at Earth. These events were characterized by significantly longer durations than the well-connected events, suggesting that processes such as cross-field diffusion and co-rotation with the Sun delayed their arrival and extended their duration at Earth.

2.2 Spectral analysis

PAMELA observations show that the high-energy SEP spectra are well described by a power law modulated by an exponential cutoff, according to the functional form introduced by Ellison &

[2] In 2010 the satellite was moved to an approximately circular orbit at an altitude of ∼580 km.

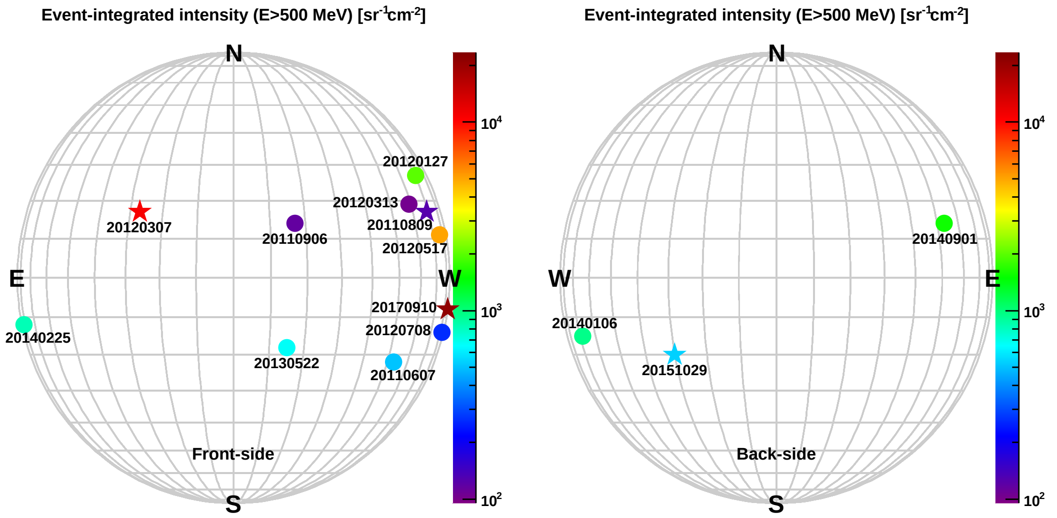

Figure 1: Heliographic locations of flares associated with the 14 most energetic SEP events during solar cycle 24. The color code gives the event-integrated intensity above 500 MeV. The circles are the events measured by PAMELA [25]; the stars are based on calibrated GOES-13/15 data [26, 28] according to [27].

Ramaty [12] (hereafter referred as "E-R" function):

$$\Phi_{E-R}(E) = A\ (E/E_s)^{-\gamma}\ exp\,(-E/E_r)\,, \tag{2.1}$$

where γ is the spectral index and E_r is the "rollover" energy, ranging from several tens to some hundreds of MeV; the scaling energy E_s is fixed to the PAMELA detection threshold for protons (80 MeV). Assuming that interplanetary transport effects are negligible, which may not be the case as discussed below, in the framework of DSA the power law can be interpreted in terms of the shock compression ratio of the shock, while the cutoff energy is a reflection of the limits of the acceleration process (see Section 1).

As example, Figure 2 reports the event-integrated intensity spectra measured by PAMELA during the 2012 January 27 (left panel) and the 2012 May 17 (right panel) SEP events. The solid and the dashed lines are the fits performed by using the E-R function and a simple power-law function, respectively. In both cases, the former is found to better reproduce the data; the corresponding E_r values are marked by the arrows. The 2012 January 27 sub-GLE[3] event, associated with a X1.7 flare and a 2541 km/s space speed CME (`https://cdaw.gsfc.nasa.gov/CME_list/halo/`), originated at relatively high heliographic latitudes (N27W71)[4]. Indeed, it can be speculated that a GLE might have been observed if the source eruption was located at better-connected latitudes [29]. The resulting spectrum is rather soft (γ~3.4±0.1), with a ~480±111 MeV rollover energy. The 2012 May 17 event was linked to an M5.1 flare (located at N11W76) and a 1596 km/s space speed CME. Despite the relatively less powerful parent eruption, it was both longitudinally and latitudinally well-connected to Earth, resulting in the first GLE of solar cycle 24. In

[3] According to convention, a SEP event is counted as a GLE if at least two independent NMs – including a near sea level station – have registered a simultaneous statistically significant increase related to the SEP arrival. Analogously, events unambiguously detected only by the high-altitude South Pole NMs can be classified as "sub-GLEs".

[4] The solar equator inclination to the ecliptic (B0 angle) was also unfavorable (-5.6°), so the final latitude was ~N33.

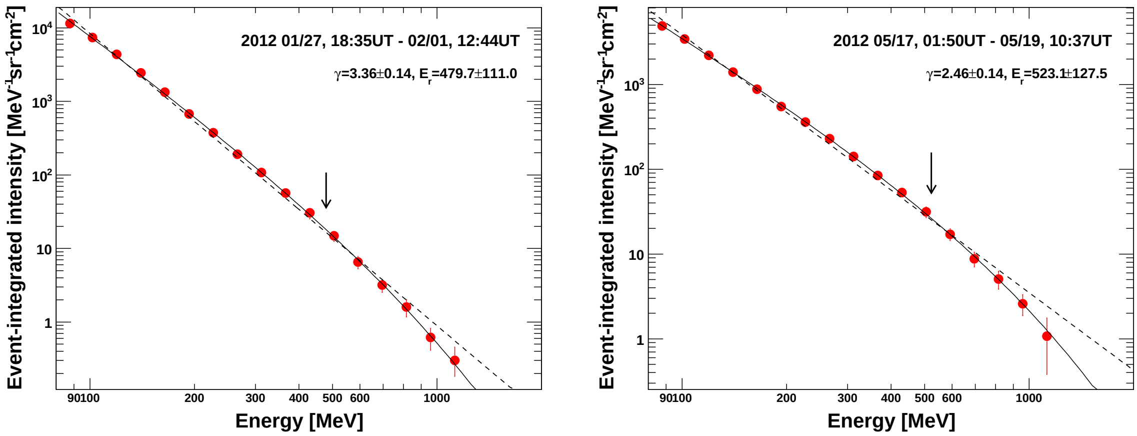

Figure 2: 2012 January 27 (left) and 2012 May 17 (right) SEP event-integrated intensity spectra measured by PAMELA [25]. The solid lines are the fits performed by using the E-R function (Equation 2.1); corresponding parameters are also reported along with the integration intervals. The downward pointing arrows mark the rollover energies. For comparison, the dashed lines denote the fits with a simple power-law model.

this case, the event-integrated intensities are smaller at low energies and the spectrum is harder ($\gamma \sim 2.5 \pm 0.1$), with a similar rollover energy ($E_r \sim 523 \pm 127$ MeV). The same functional form was found to successfully reproduce all the SEP event spectra measured by PAMELA with adequate statistical precision [25]. In particular, the absence of qualitative differences between GLE and non-GLE events suggests that GLEs are not a separate class of SEP events but they rather are the extreme end of a continuous spectral distribution (see Figure 12 in [25]).

In the scenario of DSA, the spectral rollovers are attributed to particles escaping the shock region during acceleration due to effects mostly related to the limited extension and lifetime of the shock (see Section 1). The event-integrated intensities were found to be well correlated with rollover energies, with the spectra of the most energetic events exhibiting the highest cutoffs; the reported correlation improves with increasing proton energy. As predicted by the theory, the more efficient the shock acceleration is, the greater the overall SEP intensity and the hardness of the spectrum. In addition, we found that higher rollover energy values tend to be associated with higher type-II burst starting frequencies, suggesting a lower shock formation height [9].

It should be emphasized that the high-energy rollovers identified for the first time by PAMELA represent a distinct spectral feature with respect to the breaks previously reported at much lower energies (few/tens of MeV/n) in the spectra of H-Fe nuclei (e.g., [18] and references therein). While such low-energy spectral breaks, that decrease in energy with the ion charge-to-mass ratio, were predicted to originate from DSA at near-Sun [16, 17], there are alternative interpretations based on interplanetary transport effects [19, 20]. The spectral shapes below a few hundred MeV have been typically fitted with the double-power-law empirical function introduced by Band et al. [30]:

$$\Phi_{Band}(E) = \begin{cases} A\ E^{-\gamma_a}\ exp\left(-E/E_0\right) & \text{for } E < (\gamma_b - \gamma_a)\ E_0, \\ A\ E^{-\gamma_b}\ \left[(\gamma_b - \gamma_a)\ E_0\right]^{(\gamma_b - \gamma_a)}\ exp\left(\gamma_a - \gamma_b\right) & \text{for } E > (\gamma_b - \gamma_a)\ E_0, \end{cases} \tag{2.2}$$

originally developed to fit gamma-ray burst spectra. It provides a smooth transition between two spectral regions characterized by different slopes (γ_a and γ_b); the transition energy is given by

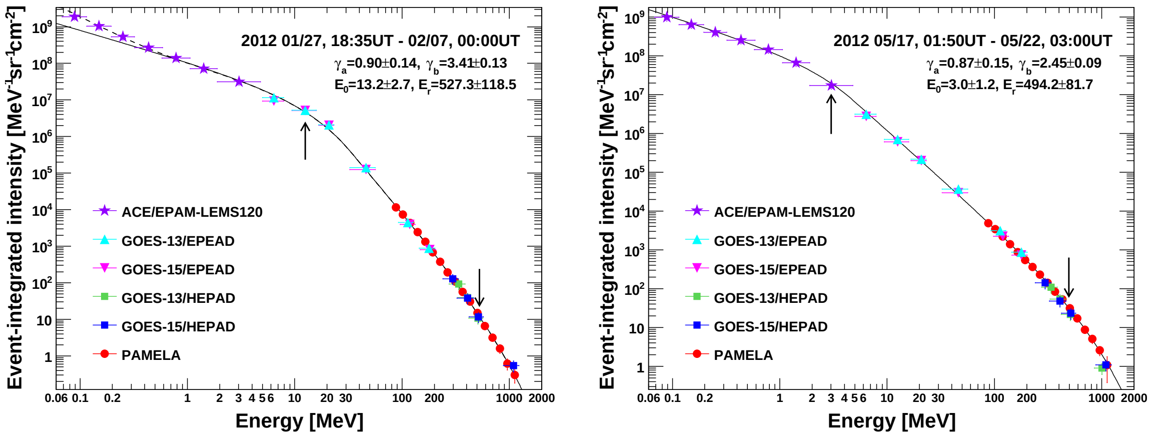

Figure 3: 2012 January 27 (left) and 2012 May 17 (right) SEP event-integrated intensity spectra measured by near-Earth spacecraft. The solid lines are the fits performed by using the combined functional form (Equation 3.1); corresponding parameters are reported along with the integration intervals. The upward and downward pointing arrows mark the break and the rollover energies, respectively. The dashed line in the left panel accounts for a low-energy component from a previous SEP event.

$(\gamma_b - \gamma_a)\, E_0$, where E_0 is the break energy. We note that the "Band" function reduces to a single power-law extending the spectrum to infinite energies, but this is inconsistent both with the idea that shock acceleration is limited in time and space, and with the experimental results provided by PAMELA.

3. SEP event spectra in an extended energy range

In this section, the PAMELA data are combined with lower energy SEP observations from other near-Earth spacecraft. In general, spectral features observed at different energies may arise from particle acceleration in different locations (e.g., the flare region, corona or interplanetary space), so the spectral shapes may exhibit the combined signatures of several dynamic processes that may be complex to disentangle. Furthermore, the morphology and the evolution of SEP events are strongly influenced by the magnetic connection to sources, and by interplanetary transport effects and transient/corotating solar wind disturbances, which significantly complicate the interpretation of data. As a consequence, it is challenging to model the SEP spectral shape over a wide energy range with a simple functional form. An attempt to reproduce both the low-energy break and the high-energy rollover in the SEP spectra is provided by the "combined" function [28]:

$$\Phi_{tot}(E) = \Phi_{Band}(E)\; exp\,(-E/E_r)\,, \tag{3.1}$$

that gives a double-power-law function modulated by an exponential cutoff.

As example, Figure 3 shows the event-integrated intensity spectra measured by near-Earth spacecraft during the 2012 January 27 (left panel) and the 2012 May 17 (right panel) SEP events in the energy interval ranging from 70 keV to ~1.3 GeV. The datasets used include the observations of the Low Energy Magnetic Spectrometer-120 (LEMS-120) of the Electron, Proton, and Alpha Monitor (EPAM) instrument on board the Advanced Composition Explorer (ACE), the Energetic

Proton, Electron, and Alpha Detectors[5] (EPEADs) and the High Energy Proton and Alpha Detectors (HEPADs) on board GOES-13/15, and PAMELA. The GOES data points are based on the calibrations by [31] and [27] for proton energies below and above 80 MeV, respectively; the horizontal errors bars denote the corresponding "effective" ranges. The solid lines are the fits performed by using the combined functional form; the corresponding break and rollover energies are marked by the upward and downward pointing arrows, respectively. The spectrum of the 2012 January 27 event includes a low-energy component from the previous SEP event on January 23 (dashed line). The spectral shapes are significantly different, with the 2012 May 17 event spectrum characterized by a much smaller break energy (E_0∼3±1 MeV vs ∼13±3 MeV) resulting in a smaller spectral index at higher energies (γ_b∼2.4±0.1 vs ∼3.4±0.1), that may be consistent with the better magnetic connectivity to the source. However, several factors including the prevailing interplanetary conditions complicate such arguments based on simple assumptions for the connectivity [28, 32].

4. Summary

The PAMELA experiment has provided the first direct measurements of the energy spectra of SEP events up to a few GeV, offering important constraints for particle acceleration models. 26 SEP events with a proton energy in excess of 80 MeV were detected between 2006 December and 2014 September [25]. Taking advantage of cross-calibrated GOES data [27], the analyzed SEP sample has been extended to other high-energy events occurring in solar cycle 24 [26, 28]. Measured spectra exhibit a high-energy rollover that can be attributed to the limits of DSA. However, further work is required to explore the relative influences of acceleration and transport processes. No qualitative distinction between the spectra of GLE and non-GLE events was observed, suggesting that GLEs are not a separate class, but are a subset of a continuous distribution of SEP events that are more intense at high energies. Furthermore, the SEP spectra at 1 AU were reconstructed over a wide energy range by combining observations by PAMELA and other near-Earth spacecraft. Such spectra will allow the relationship between low- and high-energy spectral features to be investigated, and enable a clearer view of the SEP origin and propagation mechanisms.

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