The May 17, 2012 solar event: back-tracing analysis and flux reconstruction with PAMELA

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Abstract. The PAMELA space experiment is providing first direct observations of Solar Energetic Particles (SEPs) with energies from about 80 MeV to several GeV in near-Earth orbit, bridging the low energy measurements by other spacecrafts and the Ground Level Enhancement (GLE) data by the worldwide network of neutron monitors. Its unique observational capabilities include the possibility of measuring the flux angular distribution and thus investigating possible anisotropies associated to SEP events. The analysis is supported by an accurate back-tracing simulation based on a realistic description of the Earth's magnetosphere, which is exploited to estimate the SEP energy spectra as a function of the asymptotic direction of arrival with respect to the Interplanetary Magnetic Field (IMF). In this work we report the results for the May 17, 2012 event.

1. Introduction
The PAMELA satellite experiment, operating since 2006 June, is providing precise and detailed observations of the cosmic-ray radiation environment in low Earth orbit [1]. In particular, the instrument offers the rare opportunity to directly measure the SEP energy spectra and angular distribution from 80 MeV to several GeV during solar cycles 23 and 24. Recently, PAMELA reported its measurement of the May 17, 2012 event, associated to the first GLE of the new solar cycle [2]. This paper presents the results of the SEP analysis with the emphasis on the methods developed to estimate the fluxes as a function of the asymptotic arrival direction.

2. The PAMELA Experiment
PAMELA (a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a space-borne experiment designed for a precise measurement of the charged cosmic radiation in the kinetic energy range from some tens of MeV up to several hundreds of GeV [3]. The Resurs-DK1 satellite, which hosts the apparatus, was launched into a semi-polar (70 deg inclination) and elliptical (350÷610 km altitude) orbit on June 15, 2006; in 2010 it was changed to an approximately circular orbit at an altitude of about 580 km. The spacecraft is 3-axis stabilized; its orientation is calculated by an onboard processor with an accuracy better than 1 deg. Particle directions are measured with a high angular resolution (< 2 deg). Details about apparatus performance, proton selection, detector efficiencies and measurement uncertainties can be found elsewhere (e.g. [6]).

3. Geomagnetic Field Models
The analysis of SEP events reported in this work is based on the IGRF-11 [7] and the TS07D [8, 9] models for the description of the internal and external geomagnetic field sources, respectively. The TS07D is a high resolution dynamical model of the storm-time geomagnetic field in the inner magnetosphere, based on recent satellite measurements. Consistent with the data-set coverage, the model is valid up to about 30 Earth’s radii (Re). Solar wind and IMF parameters are obtained from the high resolution (5-min) Omniweb database [10].

4. Trajectory Analysis
Using spacecraft ephemeris data (position, orientation, time), and the particle rigidity ($R = \text{momentum/charge}$) and direction provided by the PAMELA tracking system, trajectories of
all detected protons were reconstructed in the Earth’s magnetosphere by means of an accurate tracing program [4] based on the aforementioned geomagnetic models. The asymptotic arrival directions were evaluated with respect to the IMF direction, with polar angles $\alpha$ and $\beta$ denoting the pitch-angle and the gyro-phase angle, respectively.

5. Flux Evaluation
Fluxes were obtained by averaging data over single polar passes. In order to account for possible anisotropies, SEP intensities were evaluated as a function of particle rigidity $R$ and asymptotic pitch-angle $\alpha$:

$$
\Phi(R, \alpha) = \frac{N(R, \alpha)}{2\pi \int_{\Delta R} dR \int_{\Delta \alpha} d\alpha \int_{T} dt H(R, \alpha, t)},
$$

where $N$ is the number of proton counts corrected by selection efficiencies, $T$ is the livetime and $H$ is the apparatus effective area ($cm^2$):

$$
H(R, \alpha) = \frac{\sin \alpha}{2\pi} \int_{0}^{2\pi} d\beta [A(R, \theta, \phi) \cdot \cos \theta],
$$

where $A$ is the apparatus response function, and $\theta$ and $\phi$ are the polar angles denoting the particle direction in the PAMELA frame [5]. The used approach is analogous to the one developed for the measurement of geomagnetically trapped protons [11], but in this case the transformation between local ($\theta, \phi$) and magnetic ($\alpha, \beta$) angles cannot be obtained by simple trigonometric operations since it depends on particle propagation in the geomagnetic field; thus, back-tracing methods were exploited. To assure a high resolution, $\sim$2800 trajectories (uniformly distributed inside PAMELA field of view - FoV) were reconstructed in the magnetosphere for 1-sec time steps along the satellite orbit and 22 rigidity values between 0.39÷4.09 GV. At a later stage, results were extended over the full FoV through a bilinear interpolation. Since the PAMELA semi-aperture is $\sim$20 deg, the observable pitch-angle range is relatively small (a few deg) except in regions close to the geomagnetic cutoff, where trajectories become chaotic and corresponding asymptotic directions rapidly change with particle rigidity and looking direction; this ends up increasing measurement uncertainties. Consequently, these zones were excluded from the analysis.

6. Results
Figure 1 reports PAMELA’s vertical asymptotic directions of view during the first polar pass that registered the event (01:58 – 2:20 UT), for different values of particle rigidity (color code). Left panels show the reconstructed directions in terms of GEO (top) and GSE (bottom) coordinates, for different rigidity range (color code). The spacecraft position is indicated by the grey curve. The contour curves represent values of constant pitch angle with respect to the IMF direction, denoted with crosses. It can be noted that IMF direction is almost perpendicular to the sunward direction. As PAMELA is moving (eastward) and changing its orientation along the orbit, observed asymptotic directions rapidly vary performing a (clockwise) loop over the region above Brazil. Right panels in the same figure display the distributions of asymptotic directions as a function of UT, and particle rigidity (top) and pitch-angle (bottom); the color codes refer to the corresponding pitch-angle and rigidity values, respectively. Solid curves in the top-right panel denote the estimated Störmer vertical cutoff for the PAMELA epoch ($\sim 14.3/L^2$ GV).

Preliminary results of PAMELA’s differential proton fluxes averaged over the first polar pass are shown in figure 2. The top panel reports the rigidity spectra for different pitch-angle bins (color code); for comparison, the dashed line in the top panel represents the galactic proton background (included in the results) measured by PAMELA during two days prior to the
Figure 1. PAMELA’s vertical asymptotic directions of view during the first polar pass that registered the event. See the text for details.

Figure 2. Top: proton rigidity spectra measured by PAMELA during the first polar pass, for different pitch-angle bins (color code). Bottom: corresponding pitch-angle profiles, for different rigidity bins (color code). SEP arrival, which was estimated to be isotropic. The bottom panel displays corresponding pitch-angle profiles, for different rigidity bins (color code). The vertical error bars include only statistical uncertainties.

Two populations with very different pitch angle distributions can be noted: a low-energy
component (< 1 GV) confined to pitch angles < 90 deg and exhibiting significant scattering or redistribution; and a high-energy component (1÷2 GV) that is beamed with pitch angles < 30 deg and relatively unaffected by dispersive transport effects, consistent with neutron monitor observations. The presence of these simultaneous populations can be explained by postulating a local scattering/redistribution in the Earth’s magnetosheath, as discussed in [2].

7. Conclusions
The PAMELA space experiment is providing detailed measurements of the SEP fluxes with energies from about 80 MeV to several GeV in near-Earth orbit, bridging the low energy data by other spacecrafts and the GLE data by the worldwide network of neutron monitors. Its unique observational capabilities include the possibility of measuring the SEP angular distribution. The analysis is supported by an accurate back-tracing simulation based on a realistic modeling of the Earth’s magnetosphere. The results of the calculation for the May 17, 2012 event are discussed in this paper. The trajectory analysis enables the investigation of flux anisotropies, providing fundamental information for the characterization of SEPs. It will prove to be a vital ingredient for the interpretation of the solar events observed by PAMELA during solar cycles 23 and 24.

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