PROCEEDINGS OF SCIENCE

PAMELA measurements of solar energetic particle spectra

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The charged particle acceleration and transport during solar events have been widely studied in the past decades. The satellite-borne PAMELA experiment has been continuously collecting data since 2006. The apparatus is designed to study charged particles in the cosmic radiation. The combination of permanent magnet, silicon micro-strip spectrometer and silicon-tungsten imaging calorimeter, with the redundancy of instrumentation allows very precise studies on the physics of cosmic rays in a wide energy range and with high statistics. This makes PAMELA a well suited instrument for Solar Energetic Particles (SEP) observations. Not only it spans the energy range between the ground-based neutron monitor data and the observations of SEPs from space, but also PAMELA carries out the first direct measurements of SEP energy spectra, composition and angular distribution. PAMELA has observed many SEP events in solar cycle 24, offering unique opportunity to address several questions on high-energy SEP origin. A preliminary analysis on proton spectra during several events of the 24^{th} solar cycle is presented.

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1. Introduction

The PAMELA experiment, launched on the 15^{th} of June 2016, on-board the satellite Resurs-DK1 was designed to study the anti-matter and light-nuclei component of the galactic cosmic ray spectrum[2] [3], the study of the solar modulation and solar activity)[4][5]. The PAMELA spectrometer[1] allows to study primary charged cosmic ray's components in a wide energy range form tens of MeV to ~ 1.2 TeV and solar energetic particle (SEP) events down to ~ 400MeV for protons.
SEP events are usually accompanied by flares, coronal mass ejections (CMEs), γ/X ray bursts and broad radio emissions. The acceleration mechanisms involved are still mostly unknown and some of the favorite candidates are: stochastic acceleration, shock acceleration and acceleration by magnetic reconnection.
The energy spectra measured by PAMELA over 28 major solar events can shed light on the production, acceleration and propagation of these powerful particle events.
Moreover the PAMELA observational capability, over several orders of magnitude in energy, offers the possibility to bridge between space detection of SEPs by satellites like ACE, STEREO and GOES and ground based neutron and muon detectors.
This work is dedicated to give a brief description of the analysis performed on proton fluxes detected by PAMELA during several solar events between the 23^{rd} and 24^{th} solar cycles.

2. PAMELA detector

The particle identification in PAMELA is done matching data coming from 4 different detectors to select the components of the galactic cosmic rays. Details and technical specifications of the device and data handling can be found in [1] and [7].
The main task is the reconstruction of the track of the charged particles in the magnetic spectrometer[8] and the identification of the charge sign according to the bending of the track in the quasi-uniform magnetic field. The spectrometer consists of 5 layers of permanent magnet made of an high residual magnetic induction alloy (0.43 T) and 6 double sided silicon micro-strip detectors providing momentum, charge and it's sign data. A Time-Of-Flight (TOF) system built of 3 double layers, made of plastic scintillator bars, provides also trigger, charge and energy loss informations[6], is also used for the rejection of albedo particles which cross the detector from bottom to top. An anti-coincidence system (CARD, CAT and CAS) placed around the spectrometer allows to reject spurious events in the off-line analysis. Below the spectrometer a sampling-imaging electromagnetic calorimeter[9] made of 44 layers of silicon micro-strip detectors interleaved with 22 tungsten absorber layers for a total of 16.3 X_0(radiation length) and 0.6 λ_i(interaction length) to maximize the separation of leptons and hadrons. In the lower part of the apparatus a shower-tail catcher S4 and a neutron detector help to increase the lepton/hadron separation for events not fully contained in the calorimeter.

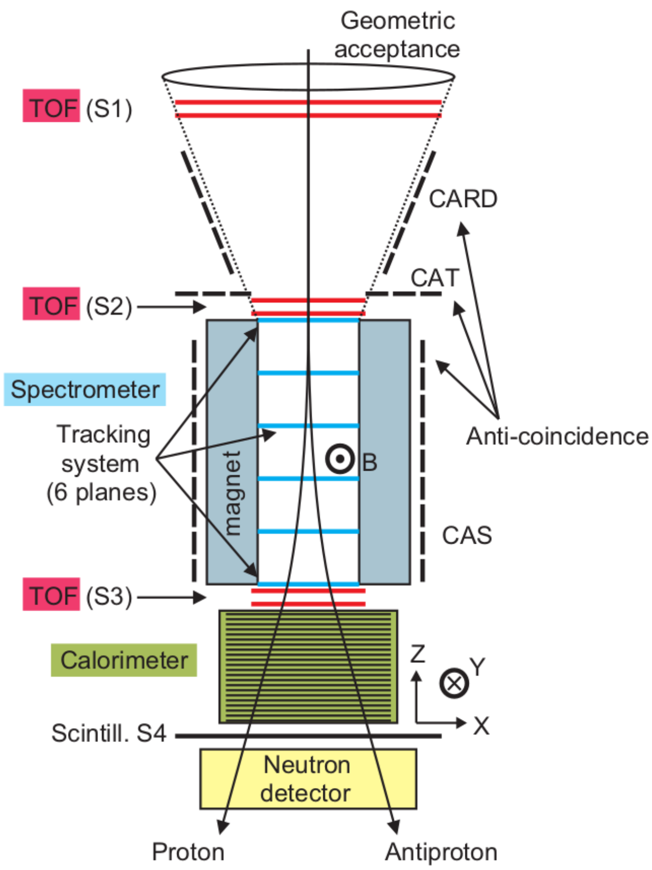

Figure 1: Scheme of the PAMELA apparatus and main sub-systems.

3. Particle selection and flux estimation

After quality and consistency checks the event selection is performed requiring a single track fully contained in the tracking system. To obtain a clean proton event sample the main charge selection comes from the average energy release in the tracker planes. A selection band in the energy release vs rigidity plane identifies the hydrogen and deuterium events as shown in figure 2. Events interacting within the apparatus are rejected using the anti-coincidence sub-system. Moreover a correction for energy loss is applied to the low energy events that lose energy in the dome of the pressurization vessel in which the detector is housed. In order to separate the primary component form reentrant albedo and geomagnetically trapped particles an estimate of the local geomagnetic vertical cutoff is evaluated accorging to the International Geomagnetic Reference Field (IGRF) [17], requiring the particle to have a rigidity $R > 1.3 \times cutoff$ this with the velocity information coming from the ToF sub-system ensure the selection of down-ward going particles of solar and galactic origin.

The flux computation is obtained dividing the measured energy spectrum for the acquisition time, the geometrical acceptance and the selection efficiencies. The live-time is estimated with the on-

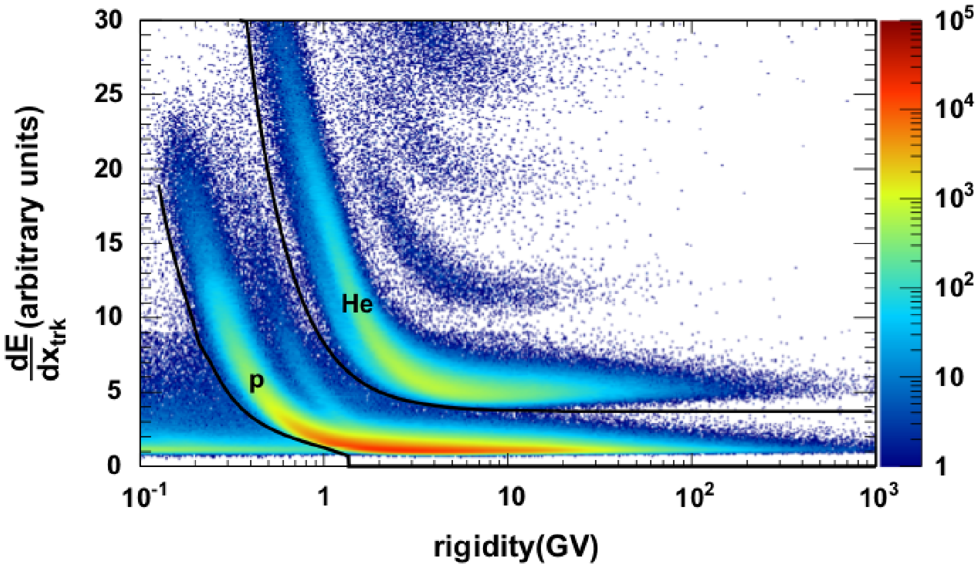

Figure 2: Energy loss (dE/dx) as function of the measured rigidity in PAMELA with no selection applied to the sample. The proton component is clearly separated from the helium by the selection band in solid black line.

board clock while the apparatus is waiting for a trigger and the energy dependence comes from the orbital position with respect to the accessible energies according to the cutoff maps. The geometrical acceptance is obtained requiring a fiducial frame of 0.15 cm form the first layer of the tracker on the entrance of the magnetic cavity. The selection efficiencies are estimated, for each sub-system involved in the flux sample definition, both on flight data and simulated data with a good agreement between the two. For this analysis the fluxes where evaluated with 48-min time resolution, half orbit, in this time the low rigidities (energies) are accessible due to geomagnetic shielding, only in the polar regions, where the cutoff is lower than the detection threshold of the apparatus.
To obtain a clean solar particle sample the GCR flux, evaluated according to a force-field approach [12] as:

$$F_{gcr}(E) = F_{LIS}(E+\phi) \times \left[\frac{E \times (E+2m_p)}{(E+\phi) \times (E+\phi+2m_p)} \right], \tag{3.1}$$

and extrapolated at low energies, is subtracted by the flux. This becomes rather crucial when the solar events are associated with a forbush decrease and the nominal GCR background becomes suppressed by the shielding effect of a CME.

4. Observed events

Table 1 reports the list of the 28 major SEP events observed by PAMELA between 2006 July and 2014 September. For each event, the class/location information about the source flare are displayed, along with the related CME speed and width. All events were associated with X- and M-class flares except for the 2013 September 30 (C-class), and with full halo CMEs except for the 2011 September 06, the 2012 July 08 and the 2013 October 28 events (partial halo CMEs).

SEP Event		Flare		CME	
#	Date	Class	Location	Speed	Width
1	2006 Dec 13	X3.4	S06W23	1774	H
2	2006 Dec 14	X1.5	S06W46	1042	H
3	2011 Mar 21	N.A.	>W90	1341	H
4	2011 Jun 07	M2.5	S21W54	1255	H
5	2011 Sep 06	M5.3	N.A.	N.A.	N.A.
6	2011 Sep 07	X2.1	N.A.	N.A.	N.A.
7	2011 Nov 04	N.A.	N.A.	N.A.	N.A.
8	2012 Jan 23	M8.7	N28W21	2175	H
9	2012 Jan 27	X1.7	N27W71	2508	H
10	2012 Mar 07	X5.4	N17E27	2684	H
11	2012 Mar 13	M7.9	N17W66	1884	H
12	2012 May 17	M5.1	N11W76	1582	H
13	2012 Jul 06	X1.1	S13W59	1828	H
14	2012 Jul 08	M6.9	S17W74	1497	157
15	2012 Jul 12	X1.4	N.A.	N.A.	N.A.
16	2012 Jul 19	M7.7	S13W88	1631	H
17	2012 Jul 23	N.A.	>W90	2003	H
18	2013 Apr 11	M6.5	N09E12	861	H
19	2013 May 22	M5.0	N13W75	1466	H
20	2013 Sep 30	C1.3	N17W29	1179	H
21	2013 Oct 28	M5.1	N.A.	N.A.	N.A.
22	2013 Nov 02	N.A.	N.A.	N.A.	N.A.
23	2014 Jan 06	N.A.	>W90	1402	H
24	2014 Jan 07	X1.2	S15W11	1830	H
25	2014 Feb 25	X4.9	S12E82	2145	H
26	2014 Apr 18	M7.3	S20W34	1203	H
27	2014 Sep 01	N.A.	>W90	N.A.	N.A.
28	2014 Sep 10	X1.6	N14E02	1267	H

Table 1: List of the major SEP events observed by PAMELA between 2006 July and 2014 September. For each event, the class/location information about the source flare are displayed, along with the related CME speed (km/s) and width (deg, or "H" in case of full halo CMEs). Flare/CME data are from https://cdaw.gsfc.nasa.gov/CME_list/sepe/.

5. Data Analysis

An integration of the 48-min fluxes is made to obtain the SEP fluence:

$$\Phi_{sep}(E) = \int_T F_{sep}(E)dt \simeq \sum_{i=1}^{n} [F_{sep,i}(E) \times \Delta t_i] = \frac{T}{n} \times \sum_{i=1}^{n} F_{sep,i}(E), \tag{5.1}$$

where n is the number of time bins (Δt_i=T/n=48 min). The integration interval (fixed for all energies) is computed by identifying the event start/stop bins in the temporal profiles, comparing the event duration with other space and ground based observations.
As pointed out in the previous sections, the PAMELA duty cycle for low energies depends on the orbital position. For orbits far from the polar regions a correction is applied using EPEAD data, interpolating its intensity with the calibrated median with PAMELA data, more details are available in [18].
The resulting event-integrated fluences are fitted using the Ellison-Ramaty (E-R) function [16]:

$$\Phi_{sep}(E) = A \times (E/E_s)^{-\gamma} \times e^{-E/E_0}, \tag{5.2}$$

where A is the normalization, γ is the spectral index and E_0 the roll-over energy; the scaling energy E_s is fixed to the PAMELA energy threshold (80 MeV). This lead to a power-law governed by efficiency of the shock acceleration, driven by the shock parameters, the Mach number and compression ratio, while the roll-over energy reflects the available acceleration time and particle losses in the acceleration region.

6. Conclusions

We report the analysis performed on 28 major solar events observed from 2006 to 2014 by PAMELA detector, 2 GLE and several sub-GLEs. Figure 3 displays the event-integrated fluences (color code) above 80 MeV, as a function of the source flare heliographic locations (see Table 1). Only front-side events with available flare information are reported.
PAMELA gives the unprecedented possibility to measure SEP events spectra, fluences, angular distributions and composition in a wide energy range, thus providing significant constraints on current SEP models. Data were compared with main flare/CME parameters, investigating possible correlations, including their dependency on energy.

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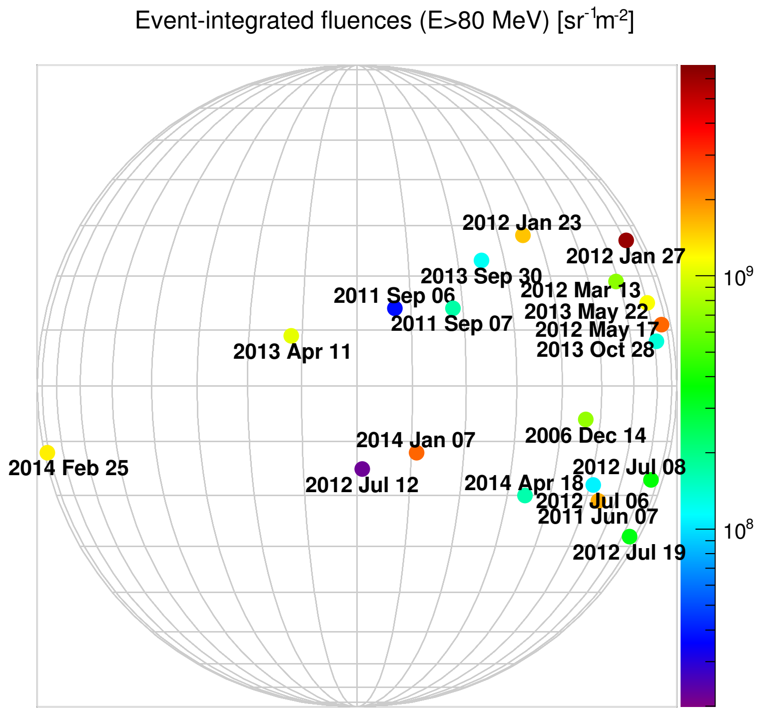

Figure 3: Event-integrated fluences (>80 MeV, color codes) as a function of source flare heliographic locations. Only events with available flare information are reported.

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