Solar energetic particle events: trajectory analysis and flux reconstruction with PAMELA

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on behalf of the PAMELA collaboration
The PAMELA experiment

Main requirements → high-sensitivity particle identification and precise momentum measurement

Time-Of-Flight
- plastic scintillators + PMT
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Anticoincidence shield
- plastic scintillators + PMT

Electromagnetic calorimeter
- W/Si sampling (16.3 X₀, 0.6 λL)
- Discrimination e⁺ / p, anti-p / e⁻ (shower topology)
- Direct E measurement for e⁻

Bottom scintillator (+PMT)

Neutron detector
- ³He counters
- High-energy e/h discrimination

Spectrometer
- microstrip silicon tracking system + permanent magnet
- Magnetic rigidity: R=pc/Ze
- Charge sign
- Charge value from dE/dx
- Particle direction

Resurs DK-1 satellite:
- Semi-polar (70° inclination) and elliptical (350÷610 km altitude) orbit

Size: 130x70x70 cm³
GF: 21.5 cm² sr
Mass: 470 kg
Power Budget: 360W

see: M. Boezio’s Highlight Talk on 31 July
PAMELA SEP’s measurements

- Wide energy interval: ~80 MeV – several GeV
  - bridging the low energy data by other space-based instruments and the Ground Level Enhancement (GLE) data by the worldwide network of neutron monitors (NMs)

- Sensitive to particle composition
  - protons, He nuclei, ...

- Possibility to reconstruct the angular distribution
  - investigation of flux anisotropies

clearer and more complete view of SEP events!
In order to measure SEP angular distributions and investigate the degree of anisotropy, it is necessary to account for the effect of the geomagnetic field on particle propagation.

Typically (NMs) one is interested in particle arrival "asymptotic directions", i.e. the directions of approach before they enter the magnetosphere.

To determine asymptotic directions, particle trajectories are reconstructed in a model magnetosphere by means of numerical integration methods (Smart & Shea 2005).

The trajectory analysis also allows to evaluate geomagnetic cutoff rigidities and to separate protons of interplanetary (GCRs & SCRs) and atmospheric (trapped & albedo) origin.

[Shea & Smart, ERP No 524, AFCRL-TR-75-0381, 1975]
Trajectory analysis
Calculation outline

PAMELA data:
- spacecraft position & orientation
- particle rigidity and direction (provided by the tracking system)

IMF, SW and geomagnetic parameters:
- high-resolution (5-min) OMNIWeb data NASA/Goddard Space Flight Center

TRAJECTORY TRACING CODE

Runge-Kutta integration of motion equations
- Based on Smart & Shea (2000, 2005)

Realistic description of the geomagnetic field:
- internal sources: IGRF-11 model
- external sources: TS07D model

Interplanetary (SCR+GCR) particles
- Flux angular distributions

Geomagnetically trapped & albedo particles
- Discarded

trajectories escape the model magnetosphere

trajectories intersect the atmosphere (40km)

NB: the magnetospheric configuration is updated event by event, interpolating involved parameters
The Tsyganenko models are semi-empirical best-fit representations for the external magnetic field.

The TS07D model (Tsyganenko & Sitnov 2007):
- Dynamical, high-resolution description:
  - Large (~10^6 points) dataset based on recent (1995-2005) spacecraft measurements (Cluster, Polar, Geotail, IMP-8, GOES 8-12);
- Coverage: < 30-35 R_E;
- More flexible and strongly superior to all past empirical models in reconstructing distribution of storm-scale currents.

For more details: [http://geomag_field.jhuapl.edu/model/](http://geomag_field.jhuapl.edu/model/)
To improve the interpretation of results, the directions of approach and the entry points at the model magnetosphere boundaries can be visualized as a function of the particle rigidity and the spacecraft position.

Both Geographic (GEO) and Geocentric Solar Ecliptic (GSE) coordinates are used.
Trajectory analysis
Case study: the 2012 May 17 event (71° GLE)

Proton count distributions (0.39 ÷ 3.3 GV, first PAMELA polar pass)
Flux calculation

Isotropic distribution

- The factor of proportionality between flux intensities and counting rates, corrected by the detector efficiencies, is by definition the apparatus **gathering power** $\Gamma$ (cm$^2$sr).

- In the case of PAMELA, $\Gamma$ is rigidity dependent due to the spectrometer bending effect on particle trajectories.

- In terms of the zenith $\vartheta$ and the azimuth $\varphi$ angles describing particle direction in the PAMELA frame:

$$\Gamma(R) = \int_0^1 d\cos \vartheta \int_0^{2\pi} d\varphi [A(R, \vartheta, \varphi) F(R, \vartheta, \varphi) \cos \vartheta]$$

where $F(R, \vartheta, \varphi)$ is the flux angular distribution ($F=0÷1$), $A(R, \vartheta, \varphi)$ is the apparatus response function in units of area and the $\cos \vartheta$ factor accounts for the trajectory inclination.

- For **isotropic fluxes** $\Gamma$ does not depend on looking direction (i.e. $F = 1$), and it is usually called the **geometrical factor** $G_F$.

Using Monte Carlo methods (Sullivan 1971):

$$G_F(R) = G_{\text{gen}} \cdot \frac{n_{\text{sel}}(R)}{n_{\text{tot}}(R)}$$

where $n_{\text{tot}}$ and $n_{\text{sel}}$ are the number of generated and selected trajectories, and $G_{\text{gen}}$ is the gathering power of the generation surface.
In presence of an anisotropic flux distribution the gathering power depends on the direction of the observation as well, and $F \neq \text{const.}$

SCR fluxes can be conveniently expressed in terms of asymptotic polar angles $\alpha$ (pitch-angle) and $\beta$ (gyro-phase angle) with respect to the IMF direction:

$$ \Gamma(R) = \int_0^\pi d\alpha \sin \alpha \int_0^{2\pi} d\beta [A(R, \vartheta, \varphi)F(R, \alpha, \beta)\cos \vartheta] $$

with $\vartheta = \vartheta(R, \alpha, \beta)$ and $\varphi = \varphi(R, \alpha, \beta)$. The flux angular distribution $F(R, \alpha, \beta)$ is unknown a priori.

For simplicity, we assume that SCR fluxes depend only on particle rigidity $R$ and pitch-angle $\alpha$, estimating the corresponding apparatus “effective area” (cm$^2$) as:

$$ H(R, \alpha) = \frac{\sin \alpha}{2\pi} \int_0^{2\pi} d\beta [A(R, \vartheta, \varphi)\cos \vartheta] $$

by averaging over the $\beta$ angle.

$H(R, \alpha)$ is obtained by assuming an isotropic flux distribution within each asymptotic pitch-angle bin $\alpha \pm \Delta\alpha/2$:

$$ 2\pi \cdot H(R, \alpha) \cdot \Delta\alpha = G_{\text{gen}} \cdot \frac{n_{\text{sel}}(R, \alpha)}{n_{\text{tot}}(R, \alpha)} = G_{\text{gen}} \cdot \frac{\sum n_{\text{sel}}(R, \vartheta, \varphi)_{\vartheta, \varphi \to \alpha}}{\sum n_{\text{tot}}(R, \vartheta, \varphi)_{\vartheta, \varphi \to \alpha}} $$
Flux calculation
Anisotropic distribution

PAMELA effective area:

\[ H(R, \alpha) = \frac{\sin \alpha}{2\pi} \int_0^{2\pi} d\beta [A(R, \vartheta, \varphi) \cos \vartheta] \]

- The method is similar to the one developed for the estimate of geomagnetically
  trapped fluxes as a function of pitch-angle with respect to the local geomagnetic field
  
  - see: A. Bruno, Geomagnetically trapped and albedo protons,
    session: Poster 1 CR, CR-EX, 214, on 30 July 2015

- but in the present case the considered pitch-angle is the asymptotic one
  
  - not evaluable with simple trigonometric operations
  
  - the relationship between local and asymptotic angles depends on particle propagation in the magnetosphere
  
  - trajectory analysis is required

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SEPs: trajectory analysis and flux reconstruction with PAMELA
Flux calculation
Effective area calculation

To convert local into asymptotic directions, a large number of trajectories (uniformly distributed inside PAMELA field of view) has to be reconstructed in the magnetosphere, for each rigidity value and each orbital position.

To assure a high resolution, the calculation is performed for time steps with a 1-sec width, by back-tracing about 2800 trajectories, for 22 rigidity bins (0.39 \( \div \) 4.09 GV)

- more than \( 8 \times 10^7 \) trajectories for each polar pass (~23 min)!

At a later stage, results are extended over the full field of view of PAMELA through bilinear interpolation.

Top: distribution of reconstructed directions (red points) inside the PAMELA field of view.

Middle: calculated pitch-angle coverage (color code, deg).

Bottom: the apparatus effective area as function of pitch-angle. Results correspond to 0.39 GV protons, for a sample orbital position (May 17, 2012, 02:07 UT).
Flux calculation
Effective area calculation

peaks: vertical asymptotic directions

PAMELA effective area for 22 rigidity values (color code), at sample orbital position
Flux calculation
Effective area calculation

PAMELA’s vertical asymptotic viewing directions, $0.39 \div 10$ GV

May 17, 2012, 01:51:28 - 02:19:55 UT

First PAMELA polar pass (01:57-02:20 UT) during the May 17, 2012 SEP event
Flux calculation
Effective area calculation

Asymptotic cones of acceptance evaluated for the first PAMELA polar pass (01:57÷02:20 UT) during the May 17, 2012 SEP event. Results for sample rigidity values are shown as a function of GEO (top panel) and GSE (middle panel) coordinates;

The pitch-angle coverage as a function of the orbital position is displayed in the bottom panel.

During the satellite polar pass the asymptotic cones move in a clockwise direction and a large pitch-angle interval is covered, (0÷145 deg).

In particular, PAMELA is looking at the IMF direction between 02:14 and 02:18 UT, depending on the proton rigidity.
Since the PAMELA semi-aperture is \( \sim 20 \) deg, the observable pitch-angle range at each orbital position is relatively small (a few deg), except in regions close to the geomagnetic cutoff (the so-called “penumbra”)

- where trajectories become chaotic and corresponding asymptotic directions rapidly change with particle rigidity and looking direction.
- Large uncertainties on the direction measurement.

These zones are excluded from the analysis.
Solar fluxes are obtained by subtracting the GCR contribution from the total measured flux.

The GCR component is evaluated by measuring proton fluxes during two days prior to the SEP arrival (May 15 and 16).

We found that the GCR flux is isotropic with respect to the IMF direction.

Consequently, the same flux is subtracted for all pitch-angle bins.
**Final results**

Rigidity spectra and pitch-angle profiles

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**Total (GCR+SCR) proton rigidity spectra**
(for different pitch-angle bins)

**SCR proton rigidity spectra**
(for different pitch-angle bins)

**SCR pitch-angle profiles**
(for different rigidity bins)

Adriani et al., *PAMELA’s measurements of magnetospheric effects on high-energy solar particles*, ApJ 801 L3, 2015.

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Fluxes are averaged over the polar pass. Lines are to guide the eye.

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see: M. Martucci’s talk, Parallel CR15 Direct/Aniso, 4 Aug
Final results
Time-profiles (2-min intervals)

Adriani et al., PAMELA's measurements of magnetospheric effects on high-energy solar particles, ApJ 801 L3, 2015.

NB: at each time bin, the flux is averaged over the corresponding pitch-angle range:

\[
\Phi(R) = \frac{\int_{\alpha_{\text{min}}}^{\alpha_{\text{max}}} \Phi(R, \alpha) \sin \alpha \, d\alpha}{\int_{\alpha_{\text{min}}}^{\alpha_{\text{max}}} \sin \alpha \, d\alpha}
\]
The trajectory analysis can be applied to the worldwide network of NMNs and to geostationary spacecrafts (e.g. the GOES series):
- to model the SEP directional distribution in combination with PAMELA measurements (determination of the anisotropy axis)

PAMELA can also investigate the impact of large SEP events (CMEs) on the Earth’s magnetosphere:
- see: A. Bruno, Geomagnetic cutoff variations during SEP events, session: Poster 1 CR, CR-EX, 213, 30 July 2015
Conclusions

The PAMELA satellite-experiment is providing accurate SEP measurements in a wide energy range (≥80 MeV).

- Its unique observational capabilities include the possibility of measuring the flux angular distribution and thus investigating possible SEP anisotropies.

- The developed analysis methods, based on trajectory tracing techniques with a realistic description of the Earth’s magnetosphere, allow SEP fluxes to be reconstructed as a function of particle rigidity and asymptotic pitch-angle with respect to the IMF direction.

- The trajectory analysis will prove to be a vital ingredient for the interpretation of solar events observed by PAMELA during solar cycles 23 and 24.

- PAMELA data can be combined with data from NM s and other space-based detectors, in order to model the directional distribution of solar events, estimating the omnidirectional density and weighted anisotropy.

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