Detection of the high energy component of Jovian electrons in Low Earth Orbit with the PAMELA experiment.

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Abstract

The PAMELA experiment is devoted to the study of cosmic rays in Low Earth Orbit with an apparatus optimized to perform a precise determination of the galactic antimatter component of c.r. It is constituted by a number of detectors built around a permanent magnet spectrometer. PAMELA was launched in space on June 15\textsuperscript{th} 2006 on board the Russian Resurs-DK1 satellite for a mission duration of three years. The characteristics of the detectors, the long lifetime and the orbit of the satellite, will allow to address several aspects of cosmic-ray physics. In this work we discuss the observational capabilities of PAMELA to detect the electron component above 50 MeV. The magnetic spectrometer allows a detailed measurement of the energy spectrum of electrons of galactic and Jovian origin. Long term measurements and correlations with Earth-Jupiter 13 months synodic period will allow to separate these two contributions and to measure the primary electron Jovian component, dominant in the 50-70 MeV energy range. With this technique it will also be possible to study the contribution to the electron spectrum of Jovian $e^{-}$ reaccelerated up to 2 GeV at the Solar Wind Termination Shock.

Key words: Cosmic rays, Satellite-borne experiment, Solar wind, Jovian electrons

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1 Introduction

PAMELA is a satellite-borne apparatus devoted to the study of cosmic rays, with an emphasis on its antiparticle component. The satellite was launched on June the 15th 2006 from the cosmodrome of Baikonur with a Soyuz rocket. The Resurs-DK1 satellite housing PAMELA on one side flies on a quasi-polar (inclination 70°), elliptical (altitude 350–600 km) orbit with an expected mission duration of 3 years (Casolino and Picozza 2007). Taking advantage of the orbital characteristics of the satellite, its long observational lifetime, and the structure of the detector, the mission will be able to address several aspects of cosmic-ray physics over an energy range not previously reached by balloon-borne experiments. The results will increase our knowledge of cosmic ray origin and propagation, as well as shed some light on some cosmological questions. In the field of heliospheric physics it will be possible to study solar modulation and solar particle events over an energy range and with a precision insofar not measured in orbit (Casolino and Picozza 2007b). In this work we evaluate the observational capabilities of PAMELA in respect to electrons of Jovian origin. PAMELA is sensitive to jovian electrons in the energy range 50-70 MeV, where they are dominant over the galactic component. At higher energies it should be possible to identify the component reaccelerated at the Solar Wind Termination Shock, up to ≃ 2 GeV by extracting the component modulated over the Earth-Jupiter synodic year of 13 months.

1.1 The PAMELA instrument

PAMELA is constituted by a number of highly redundant detectors capable of identifying particles providing charge, mass, rigidity and velocity information over a very wide energy range. The instrument (see Figure 1) is built around a permanent magnet with a silicon microstrip tracker. A scintillator system provides trigger, charge and time of flight information; a silicon-tungsten calorimeter is used to perform hadron/lepton separation. A shower tail catcher and a neutron detector at the bottom of the apparatus increase the particle identification capability. An anticounter system is used to reject spurious events in the off-line phase. Around the detectors are housed the readout electronics, the interfaces with the CPU and all primary and secondary power supplies. All systems (power supply, readout boards etc.) are redundant with the exception of the CPU (Casolino et al. 2006) which is more tolerant to failures. The system is enclosed in a pressurized container located on one side of the Resurs-DK1 satellite. In a twin pressurized container is housed the Arina experiment, devoted to the study of the low energy trapped electron and proton component. Total weight of PAMELA is 470 kg; power consumption is 355 W, geometrical factor is 21.5 cm$^2$sr. The satellite flies on a quasi-polar
(inclination $70^\circ$), elliptical (altitude 350–600 km) orbit with an expected mission length of 3 years. Here we briefly describe the main characteristics of PAMELA subdetectors; a more detailed description of the device can be found in (Picozza et al. 2007; Casolino et al. 2007).

- **Scintillator / Time of Flight** The scintillator system (Osteria et al. 2004) provides trigger for the particles and time of flight information for incoming particles. There are three scintillators layers, each composed by two orthogonal planes divided in various bars (8 for S11, 6 for S12, 2 for S21 and S22 and 3 for S31 and S32) for a total of 6 planes and 48 phototubes (each bar is read by two phototubes). S1 and S3 bars are 7 mm thick and S2 bars are 5 mm. Interplanar distance between S1-S3 of 77.3 cm allows for a TOF determination of 250 ps precision for protons and 70 ps for C nuclei (determined with beam tests in GSI), allowing separation of electrons from antiprotons up to $\approx 1$ GeV and albedo rejection. The scintillator system is also capable of providing charge information up to $Z = 8$.

- **Magnetic Spectrometer** The permanent magnet is composed of 5 blocks, each divided in 12 segments of Nd-Fe-B alloy with a residual magnetization of 1.3 T arranged to provide an almost uniform magnetic field along the $y$ direction. The size of the cavity is $13.1 \times 16.1 \times 44.5 \, cm^3$, with a mean magnetic field of 0.43 T. Six layers of 300 $\mu m$ thick double-sided microstrip silicon detectors (Bonechi et al. 2007) are used to measure particle deflection with $3.0 \pm 0.1 \, \mu m$ and $11.5 \pm 0.6 \, \mu m$ precision in the bending and non-bending views. Each layer is made by three ladders, each composed by two $5.33 \times 7.00 \, cm^2$ sensors coupled to a VA1 front-end hybrid circuit. Maximum Detectable Rigidity (MDR) has been measured on CERN proton beam and found $\approx 1$ TV.

- **Silicon Tungsten Calorimeter** Lepton/Hadron discrimination is performed by the Silicon Tungsten sampling calorimeter (Boezio et al. 2002) located on the bottom of PAMELA. It is composed of 44 silicon layers interleaved by 22 0.26 cm thick tungsten plates. Each silicon layer is composed arranging $3 \times 3$ wafers, each of $80 \times 80 \times 0.380 \, mm^3$ and segmented in 32 strips, for a total of 96 strips / plane. 22 planes are used for the X view and 22 for the Y view in order to provide topological and energetic information of the shower development in the calorimeter. Tungsten was chosen in order to maximize electromagnetic radiation lengths ($16.3 \, X_o$) minimizing hadronic interaction length ($0.6 \, \lambda$). The CR1.4P ASIC chip is used for front end electronics, providing a dynamic range of 1400 mips (minimum ionizing particles) and allowing nuclear identification up to Iron.

- **Shower tail scintillator** This 1 cm thick scintillator ($48 \times 48 \, cm^2$ wide) is located below the calorimeter and is used to improve hadron/lepton discrimination by measuring the energy not contained in the shower of the calorimeter. It can also function as a standalone trigger for the neutron detector.
• **Neutron Detector** The \(60 \times 55 \times 15\, \text{cm}^3\) neutron detector (Galper et al. 2001) is composed by 36 \(^3\text{He}\) tubes arranged in two layers and surrounded by polyethylene shielding and a 'U' shaped cadmium layer to remove thermal neutrons not coming from the calorimeter. It is used to improve hadron/lepton identification by detecting the number of neutrons produced in the hadronic and electromagnetic cascades. Since the former have a much higher neutron cross section than the latter, where neutron production comes essentially through a nuclear giant resonance, it is estimated that PAMELA overall identification capability is improved by a factor 10. As already mentioned, the neutron detector is used to measure neutron field in Low Earth Orbit (LEO) and in case of solar particle events, as well as in the high energy lepton measurement.

• **Anticoincidence System** To reject spurious triggers due to interaction with the main body of the satellite, PAMELA is shielded by a number of scintillators used with anticoincidence functions (Orsi et al. 2006). CARD anticoincidence system is composed of four 8 mm thick scintillators located in the area between S1 and S2. The Top Anticounter (CAT) is a scintillator placed on top of the magnet: it is composed by a single piece with a central hole where the magnet cavity is located and read out by 8 phototubes. Four scintillators, arranged on the sides of the magnet, make the side (CAS) lateral anticoincidence system.

2 **Jovian electrons**

Since the discovery of Jovian electrons of \(1.75\, \text{MeV} \leq E \leq 25\, \text{MeV}\) at about 1 AU from Jupiter by Pioneer 10 (Simpson et al. 1974; Eraker 1982), several interplanetary missions have measured this component of cosmic rays in different points of the heliosphere. At 1 AU from the Sun the IMP-8 satellite could detect Jovian electrons in the range between 0.8 and 16 MeV and measure their 27 days modulation by the passage of Coronal Interaction Regions (CIR) (Eraker 1982; Chenette 1980). Measurements performed with the electron spectrometer on board ISEE spacecraft in the energy range 5-30 MeV over 6 synodic periods during solar maximum (Moses 1987) and obtaining a power law index \(\simeq 1.5\) up to 10 MeV and steepening to \(\leq 6\) above. Most prominent feature of the Jovian flux is the long term modulation of 13 months related to the Earth-Jupiter synodic year. Since Jovian electrons propagate along the interplanetary magnetic field lines, when the two planets are on the same solar wind spiral line, the electron transit from Jupiter to the Earth is eased and flux increases. When the two planets lie on different spiral lines the electron flux decreases. Currently we know that Jupiter is the strongest electron source at low energies (below 25 MeV) in the heliosphere within a radius of 11 AU from the Sun. Measurement of the power law spectrum
up to \( \approx 10\ MeV \) with EPHIN instrument on board SOHO spacecraft confirmed a power law spectrum with spectral index \( \gamma = 1.65 \) in maximum jovian flux days and \( \gamma = 1.51 \) in minimum jovian flux (del Peral et al. 2002; del Peral et al. 2003; Gomez-Herrero et al. 2001). Ulysses has performed detailed measurements in a wide range of heliographic latitudes and at various distances from Jupiter studying the geographical and temporal variability of the diffusion coefficients (Heber et al. 2002; Heber et al. 2007) and the high energy (up to 9 GeV) galactic electron component (Ferrando 1997). Assuming those spectral indexes (Potgieter and Ferreira 2002) estimated the galactic component to become dominant above the primary Jovian component above \( \approx 70\ MeV \).

Many models attempt to describe the complex processes of Jovian and galactic electron diffusion in the solar wind. For instance, in (Chenette 1980) a convection diffusion model is used applying the results to IMP8 and Pioneer 10 and 11 data. More recently, (Ferreira et al. 2001) and (Ferreira 2005) developed a three dimensional model with convection, gradient and curvature drift and current sheet effects. Measurements in the energy range 50-130 MeV at Earth will contribute to test the validity of these models at high energies and in the recovery period from solar minimum. It is known that cosmic rays originating outside the heliosphere can be accelerated at the solar wind termination shock (Jokipii and Kota 1991; Moraal et al. 1999; Potgieter and Ferreira 2002). This applies also to Jovian electrons, which are transported outward by the solar wind, reach the TS and undergo shock acceleration thus increasing their energy. Some of these electrons are scattered back in the heliosphere and reach Earth. Reacceleration intensity and spectral feature depends upon shock position (Potgieter and Ferreira 2002; Fichtner et al. 2001): a precise measure of the high energy component and its modulation with synodic year could also contribute to determine the overall characteristics of the shock.

3 PAMELA observational capabilities

Electrons can be detected by PAMELA in the energy range between 50 MeV and 400 GeV measuring their energy with the magnetic spectrometer. The spectrometer allows also separation and identification of the positron component in the 50 MeV - 290 GeV range. The electron spectrum has been measured at Earth by several space-borne (e.g. OGO-V (L’Heureux and Meyer 1976) \( \sim 10 - 200\ MeV \)) and balloon-borne experiments (e.g. (Evenson et al. 1983; Boezio et al. 2000), \( \gtrsim 30\ GeV \)). A precise determination of the electron and positron spectra and the temporal variation during recovery from the solar minimum will allow to gather information on solar modulation, also in respect to charge dependent (Jokipii and Thomas 1981; Asaoka 2002) effects,
reducing the systematics constraining propagation models in the galaxy and in the solar system. To determine the observational capabilities of PAMELA in the range 50 MeV to 2 GeV we have divided the particle spectra in different ranges according to the spectral shape of galactic and Jovian electrons:

- **50–70 MeV:** *non-reaccelerated component of Galactic and Jovian e−*. The electrons in this range, at the lower limit of PAMELA detection capabilities, represent the primary non-reaccelerated component. These electrons are mostly of Jovian origin and do not undergo acceleration at the TS. Their long and short term modulation would give information on high energy acceleration phenomena in the Jovian magnetosphere and on propagation effects in the inner heliosphere.

- **70–130 MeV:** *accelerated component of Galactic e−, primary Jovian e−*. This is the highest energy electrons are believed to be accelerated by Jupiter. In this range Jovian flux is less abundant than Galactic one, but it will be possible to extract this signal thanks to its synodic modulation.

- **130–600 MeV:** *accelerated component of Galactic and Jovian e− toward the maximum*. In this energy range Jovian electrons are reaccelerated at the TS.

- **600 MeV–2 GeV:** *accelerated component of Galactic and Jovian e− from the maximum*. These allows to gather a large number of events of the high energy component of electrons of Jovian origin. 2 GeV has been taken as the maximum detectable energy for accelerated electrons according to (Potgieter and Ferreira 2002). In this and the former case it will be possible to extract the signal assuming the presence of synodic year modulation at these energies.

Given a differential electron flux $\phi(E)$ in an energy range $[E_1, E_2]$ with an instrument with geometrical factor $G(E)$ and live time $T(E)$ due to energy dependent cutoff, the expected number of electrons $N$ is given by:

$$N = \int_{E_1}^{E_2} \phi(E) G(E) T(E) \, dE \quad (1)$$

assuming an efficiency 1 of the detector. PAMELA minimum threshold energy for electron detection is 50 MeV. Below this energy particles are completely deflected by the magnetic field of the permanent magnet and do not reach the bottom scintillator (S3). At this threshold energy the geometrical factor of PAMELA is equal to $G_0 = 1.4 \, cm^2 sr$ due to the fact that only a small percentage of particles can reach S3 to give a valid trigger for the apparatus. The energy dependent geometrical factor has been approximated with the
following formula (Ricciarini 2005):

\[
G(E) = \begin{cases} 
\alpha E + G_0 & E < 130 \text{ MeV} \\
\alpha E^b & 130 < E < 600 \text{ MeV} \\
21.5 \text{ cm}^2 \text{ sr } E > 600 \text{ MeV}
\end{cases}
\] (2)

Also geomagnetic shielding reduces total counts, allowing low energy particles to be acquired only in high latitude regions where cutoff is lower. The amount of time \(T(E)\) that PAMELA spends in locations accessible to electrons of energy \(E\) or higher has been evaluated with the Stormer cutoff approximation and linearly approximated in the energy range of interest:

\[
T(E) = \beta E + T_0 
\] (3)

The galactic and Jovian fluxes can be approximated by power law spectra of the form:

\[
\phi(E) = N_1 \left( \frac{E}{E_1} \right)^\gamma
\] (4)

in Table 2 are shown the flux and spectral indexes evaluated from (Potgieter and Ferreira 2002) assuming a TS at 90 AU, and Heliospheric boundary at 120 AU. The integral 1 can be calculated analytically, resulting in:

\[
N = -N_1 E_1 \left\{ \frac{\alpha \beta}{\gamma + 3} \left[ 1 - \left( \frac{E_2}{E_1} \right)^{\gamma + 3} \right] E_1^2 + \frac{(\alpha T_0 + \beta G_0)}{\gamma + 2} \left[ 1 - \left( \frac{E_2}{E_1} \right)^{\gamma + 2} \right] E_1 + \frac{G_0 T_0}{\gamma + 1} \left[ 1 - \left( \frac{E_2}{E_1} \right)^{\gamma + 1} \right] \right\}
\] (5)

for \(E < 130\) MeV and \(E > 600\) MeV and

\[
N = \frac{N_1 \alpha \beta}{E_1^2 (\gamma + b + 2)} \left[ E_2^{\gamma + b + 2} - E_1^{\gamma + b + 2} \right] + \frac{N_1 \alpha T_0}{E_1^2 (\gamma + b + 1)} \left[ E_2^{\gamma + b + 1} - E_1^{\gamma + b + 1} \right]
\] (7)

for \(130 < E < 600\) MeV.

In Table 3 are shown the expected counts for the all particle flux and the Jovian component. Aside from the 50-70 MeV range, where Jovian component is dominant, to separate the two components at higher energies it will be necessary to gather statistics over a time of the order of some months assuming
Table 1
Fitting parameters for geometrical factor $G(E)$ ($\alpha$, $G_0$, a, b), and live time $T(E)$ ($\beta$, $T_0$) for the different energy ranges considered (see text).

| $\mathcal{E}_{1,2}$ (GeV) | $\alpha$ ($m^2 \text{sr GeV}^{-1}$) | $G_0$ ($m^2 \text{sr}$) | $\beta$ ($s/GeV$) | $T_0$ ($s$) | a ($\text{cm}^2 \text{sr}$) | b (MeV) |
|--------------------------|-------------------------------|-------------------|-----------------|--------------|-----------------|--------|
| 0.05 - 0.07              | $3.4 \cdot 10^{-2}$           | $1.4 \cdot 10^{-4}$ | $2.5 \cdot 10^4$ | $3.4 \cdot 10^3$ |                 |        |
| 0.07 - 0.13              | $1.5 \cdot 10^{-2}$           | $-3.5 \cdot 10^{-4}$ | $2.5 \cdot 10^4$ | $3.4 \cdot 10^3$ |                 |        |
| 0.13 - 0.60              | $2.1 \cdot 10^{-3}$           | $2.1 \cdot 10^4$   | $4.1 \cdot 10^3$ | $23$         | $76$            |        |
| 0.60 - 2.0               |                               |                   |                 |              |                 |        |

that this signal will be modulated by Earth-Jupiter relative position. It is possible to see how, with PAMELA, it will be possible to study for the first time the high energy Jovian electron component and measure the intensity of reacceleration at the solar wind termination shock and how this component is affected by the Earth-Jupiter synodic year.

4 Conclusions

In this work we have described the possibilities of PAMELA to observe electrons of Jovian origin. This will be the first time a magnetic spectrometer telescope in low Earth orbit will be operational for long duration observation. Thus, it will be possible to perform direct measurements of both the primary and reaccelerated electron component extracting the reaccelerated Jovian component from the galactic flux and studying the effect of modulation due to synodic year. In addition to these phenomena, charge dependent modulation effects will be studied by comparing the temporal dependence of electron and positron spectra.

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\[1\] The two signals can also be separated using the maximum likelihood method assuming a sinusoidal signal with 13 months periodicity.
Table 2
Particle flux and spectral indexes assumed to estimate galactic and Jovian fluxes in the different energy ranges.

| $[E_1, E_2]$ (GeV) | $N_{gal}$ ($m^2 s sr GeV^{-1}$) | $\gamma_{gal}$ | $N_{jov}$ ($m^2 s sr GeV^{-1}$) | $\gamma_{jov}$ |
|---------------------|-------------------------------|----------------|-------------------------------|----------------|
| 0.05 - 0.07         | 10                            | -2.5           | 10                            | -3.42          |
| 0.07 - 0.13         | 4                             | 1.38           | 3.3                            | -3.42          |
| 0.13 - 0.60         | 12.5                          | 1.38           | 0.143                          | 0.98           |
| 0.60 - 2.0          | 60.5                          | -2.18          | 0.6                            | -2.8           |

Table 3
Expected counts for all particle and Jovian flux according to equation 5. The sampling time shows the minimum time required to get a signal at a 2$\sigma$ level above galactic background, assuming statistical errors.

| $[E_1, E_2]$ (GeV) | $N_{tot}$ ($\text{month}^{-1}$) | $N_J$ ($\text{month}^{-1}$) | Min. Sampl. time (months) | Percent. signal |
|---------------------|---------------------------------|-----------------------------|---------------------------|-----------------|
| 0.05 - 0.07         | 10 ± 3                          | 9 ± 3                       | 1                         | 90%             |
| 0.07 - 0.13         | 86 ± 9                          | 12 ± 3                      | 5                         | 14%             |
| 0.13 - 0.60         | (220 ± 2) · 10$^2$              | (150 ± 12)                  | 5                         | 0.7%            |
| 0.60 - 2.0          | (339 ± 2) · 10$^2$              | (250 ± 16)                  | 4                         | 0.7%            |

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Fig. 1. Left: Photo of the PAMELA detector during the final integration phase in Tor Vergata clean room facilities, Rome. It is possible to discern, from top to bottom, the topmost scintillator system, S1, the electronic crates around the magnet spectrometer, the baseplate (to which PAMELA is suspended by chains), the black structure housing the Si-W calorimeter, S4 tail scintillator and the neutron detector. Right: scheme - approximately to scale with the picture - of the detectors composing PAMELA.