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Cosmic-ray observations of the heliosphere with the PAMELA experiment

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Abstract

The PAMELA experiment is a multi-purpose apparatus built around a permanent magnet spectrometer, with the main goal of studying in detail the antiparticle component of cosmic rays. The apparatus will be carried in space by means of a Russian satellite,

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due to launch in 2005, for a three year-long mission. The characteristics of the detectors composing the instrument, alongside the long lifetime of the mission and the orbital characteristics of the satellite, will allow to address several items of cosmic-ray physics. In this paper, we will focus on the solar and heliospheric observation capabilities of PAMELA.

Keywords: Cosmic rays; Satellite-borne experiment; Solar wind; Solar energetic particles; Jovian particles

1. Overview

The PAMELA experiment is a satellite-borne apparatus devoted to the study of cosmic rays, with an emphasis on its antiparticle component. The core of the instrument is a permanent magnet spectrometer (Adriani et al., 2003) equipped with a double-sided, microstrip silicon tracker. Under the spectrometer lies a sampling electromagnetic calorimeter (Boezio et al., 2002), composed of tungsten absorber plates and single-sided, macrostrip silicon detector planes. A Time-of-Flight (ToF) system, made of six layers of plastic scintillator strips arranged in three planes is employed for particle identification at low energies and albedo rejection (Barbarino et al., 2003). At the bottom of the instrument there is a neutron detector (Galper et al., 2001) made of ^{3}He counters enveloped in polyethylene moderator. Plastic scintillator counters are used for anticoincidence counting (Orsi et al., 2004); another scintillator between the calorimeter and the neutron detector is used to register the tails of particle showers. The instrument will be carried as a ''piggy-back'' on board of the Russian Resurs-DK1 satellite for Earth observation. The launch, by means of a Russian Soyuz rocket, is scheduled for the end 2005 from the cosmodrome of Baykonur. The satellite will fly on a quasi-polar (inclination 70.4°), elliptical (altitude 350–600 km) orbit with an expected mission length of 3 years. A more detailed description of the PAMELA instrument (Sparvoli et al., 2004), its acquisition (Casolino et al., 2004a) and on ground analysis procedures (Casolino et al., 2004b) can be found in these proceedings.

Taking advantage of the orbital characteristics of the satellite, its long observational lifetime, and the structure of the detector, the PAMELA mission will be able to address several items in cosmic-ray physics, mainly the study of its antiparticle component, with a statistic and over an energy range unreached by previous 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 addition, there is also the detailed study of the solar component of cosmic rays and other sources of particles within the heliosphere.

2. Solar energetic particles

The launch of PAMELA is expected at the end of 2005, about 5 years from the last maximum of solar activity (September 2000). The number of expected solar proton events in the three years of mission can be estimated from (Shea and Smart, 2001): since for protons the energy threshold to start a trigger in the PAMELA instrument is about 80 MeV, we expect about 10 significant solar events during the experiment's lifetime. The rate of background particles hitting the top trigger scintillator (S1) could be very high for intense solar events, hence a different trigger configuration has to be set in these cases. The usual trigger involves a coincidence of S1 with those located before (S2) and after (S3) the tracker. During solar particle events a devoted trigger mask (e.g. using only S2 and S3) can be programmed from ground.[3] The observation of solar energetic particle (SEP) events with a magnetic spectrometer will allow several aspects of solar and heliospheric cosmic-ray physics to be addressed for the first time.

2.1. Positron component

Positrons are produced mainly in the decay of π^+ coming from nuclear reactions occurring at the flare site. Up to now, they have only been measured indirectly by remote sensing of the gamma-ray annihilation line at 511 keV. Using the magnetic spectrometer of PAMELA, it will be possible to separately analyze the high energy tail of the electron and positron spectra at 1 Astronomical Unit (AU) obtaining information both on particle production and charge dependent propagation in the heliosphere.

2.2. Proton component

PAMELA will be able to measure the spectrum of cosmic-ray protons from 80 MeV up to almost 1 TeV and therefore will be able to measure the solar component over a very wide energy range (where the upper limit will be limited by statistics). These measurements will be correlated with other instruments placed in different points of the Earth's magnetosphere to give information on the acceleration and propagation mechanisms of SEP events. Up to now there has been no direct measurement (Miroshnichenko, 2001) of the high energy (>1 GeV) proton component of SEPs. The importance of a direct

[3] This can occur using information coming from the satellite monitoring system (e.g. SOHO, ACE, GOES). In this way, observation and memory filling would therefore vary according to the event type (impulsive, gradual) and intensity.

measurement of this spectrum is related to the fact (Ryan, 2000) that there are many solar events where the energy of protons is above the highest ($\simeq$100 MeV) detectable energy range of current spacecrafts, but is below the detection threshold of ground Neutron Monitors (Bazilevskaya and Svirzhevskaya, 1998). However, over the PAMELA energy range, it will be possible to examine the turnover of the spectrum, where we find the limit of acceleration processes at the Sun. Our instrument has a maximum trigger rate of about 60 Hz and a geometrical factor of 20.5 cm^2 sr. This implies that we will be able to read all events with an integral flux (above 80 MeV) up to 4 particles/(cm^2 s sr). For such events, we expect about 2×10^6 particles/day (assuming a spectral index of $\gamma = 3$ we have 2×10^3 events/day above 1 GeV). Larger events will saturate the trigger, so in this case the number of protons will be reduced by dead time and mass memory limitations.

2.3. Nuclear component

Although not optimized for nuclear studies, the PAMELA detector can identify light nuclei up to Carbon and isotopes of hydrogen and helium. Thus we can investigate into the light nuclear component related to SEP events over a wide energy range. Applying the same estimates as above, we can expect $\simeq 10^4$ ^{4}He and $\simeq 10^2$ ^{3}He nuclei for gradual events, and more for impulsive ones. Such a high statistics will allow us to examine in detail the amount of the ^{3}He and deuterium (up to 3 GeV/c). These measurements will help us to better understand the selective acceleration processes in the higher energy impulsive (Reames, 1999) events.

2.4. Neutron component

Neutrons are produced in nuclear reactions at the flare site and can reach the Earth before decaying. Although there is no devoted trigger for neutrons in PAMELA, the background counting of the neutron detector will measure in great detail the temporal profile and distribution of solar neutrons. The background counting system keeps track of the number of neutrons which hit the neutron detector in the time elapsed since last trigger. The counter is reset each time it is read allowing for a precise measurement of background neutron conditions during the mission. On the occurrence of solar events, neutrons are expected to reach Earth before protons as they have no charge. They are not deflected by any magnetic field and will be directly recorded by PAMELA (if it is not in Earth's shadow).

2.5. Lowering of the geomagnetic cutoff

The high inclination of the orbit of the Resurs satellite will allow PAMELA to study (Ogliore et al., 2001; Leske et al., 2001) the variations of cosmic-ray geomagnetic cutoff due to the interaction of the SEP events with the geomagnetic field.

3. Jovian electrons

Since the discovery made by the Pioneer 10 satellite of Jovian electrons at about 1 AU from Jupiter (Simpson et al., 1974; Eraker, 1982), with an energy between 1 and 25 MeV, several interplanetary missions have measured this component of cosmic rays. Currently, we know that Jupiter is the strongest electron source at low energies (below 25 MeV) in the heliosphere within a radius of 11 AUs. Its spectrum has a power law with spectral index $\gamma = 1.65$, increasing above 25 MeV, where the galactic component becomes dominant. At 1 AU from the Sun the IMP-8 satellite could detect Jovian electrons in the range between 0.6 and 16 MeV and measure their modulation by the passage of Coronal Interaction Regions (CIR) with 27 days periodicity (Eraker, 1982; Chenette, 1980). There are also long-term modulation effects related to the Earth–Jupiter synodic year of 13 months duration. In fact, since Jovian electrons follow 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 the flux increases. On the other side, when the two planets lie on different spiral lines the electron flux decreases.

For PAMELA the minimum threshold energy for electron detection is 50 MeV. In this energy range, however, geomagnetic shielding will reduce the active observation time reducing total counts. Nevertheless, it will be possible to study for the first time the high energy Jovian electron component and test the hypothesis of reacceleration at the solar wind Termination Shock (TS). It is known that cosmic rays originating outside the heliosphere can be accelerated at the solar wind TS. 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. The position of the shock (still unknown and placed at about 80–100 AU) can affect the reaccelerated electron spectrum (Poitgieter and Ferreira, 2002). In Table 1 are shown the expected electron counts with PAMELA instrument (TS at 90 AU, Heliospheric boundary at 120 AU) using the spectrum calculated in (Poitgieter and Ferreira, 2002). The table shows the flux and the daily PAMELA counts (theoretical) outside the magnetosphere. In Table 2 are shown the total counts, expected from the galactic and Jovian component. In order to separate the two components, it will be necessary to gather statistics over a time of the order of one month (in the energy range 70–130 MeV at least 2 months will be needed). This time can vary according to the energy

Table 1
Expected Jovian electron counts with the PAMELA detector in different energy ranges

E_0 (MeV)	Jovian electrons				
	$N(E_0)$ (particles/(cm^2 s sr MeV))	γ	ϕ (particles/(cm^2 s sr))	$N_{\text{out.mag.}}$ (e$^-$/day)	N_{cutoff} (e$^-$/month)
50–70	1×10^{-2}	−3.42	0.115	20 ± 5	36 ± 6
70–130	3.16×10^{-3}	−3.42	0.04533	8 ± 3	21 ± 5
130–600	1.4×10^{-4}	0.98	0.1807	32 ± 6	199 ± 14
600–2000	6.0×10^{-4}	−2.8	0.1771	31 ± 6	353 ± 20

The first energy range is the primary component, dominated by electrons coming directly from Jupiter, while the other three correspond to the reaccelerated components. Second column is the flux shown in Poitgieter and Ferreira (2002). Using the power law γ (third column), estimated from Poitgieter and Ferreira (2002) we evaluate the flux (fourth column). This results in a theoretical daily count at 1 AU from the Sun of PAMELA shown in column five. The rightmost column represents PAMELA expected counts in a month (Geometrical Factor $G = 20.5$ cm^2 sr) taking into account the vertical geomagnetic cutoff using Stormer approximation.

Table 2
Expected total (Galactic and Jovian) electron counts with the PAMELA detector in different energy ranges (see caption of Table 1)

E_0 (MeV)	Total (Galactic and Jovian electrons)				
	$N(E_0)$ (particles/(cm^2 s sr MeV))	γ	ϕ (particles/(cm^2 s sr))	$N_{\text{out.mag.}}$ (e$^-$/day)	N_{cutoff} (e$^-$/month)
50–70	1×10^{-2}	−2.5	0.132	23 ± 5	41 ± 6
70–130	4×10^{-3}	1.38	0.396	70 ± 8	183 ± 14
130–600	9.4×10^{-3}	1.38	3.968	700 ± 25	4380 ± 70
600–2000	6.0×10^{-2}	−2.18	23.14	4100 ± 60	46200 ± 210

range and the efficiency of the detector. In these work, we have taken into account the vertical geomagnetic cut-off (using Stormer's approximation) along the orbit of the Resurs and assumed an efficiency of 1 of the PAMELA detectors. The expected counts are shown in the last column of the two tables. Electrons can be grouped in the following energy ranges:

- 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 propagation phenomena in the inner heliosphere. If we assume a modulation of a factor 2 due to CIR modulation effects (Fichtner et al., 2001), we would need at least a 10 day binning to observe this effect at a 1 sigma level. Short-term modulation might thus not be observable due to statistics, although 13 month synodic modulation and solar modulation effects would be clearly visible.
- 70–130 MeV: *accelerated component of Galactic e$^-$, non-reaccelerated of Jovian e$^-$*. In this energy range, Galactic electrons are more abundant than the Jovian ones. Only long-term modulation effects would thus be visible by gathering statistics on a bi-monthly basis.
- 70–600 MeV: *accelerated component of Galactic and Jovian e$^-$ toward the maximum.* In this energy range, the main reaccelerated component will be clearly observable allowing to separate the two components.
- above 600 MeV: *accelerated component of Galactic and Jovian e$^-$ from the maximum.* Also in this energy range the two components will be identifiable on a bi-monthly basis. The large energy range allows to gather a large number of events of electrons of Jovian origin in an energy range where they have never been observed.

Overall, Jovian electrons amount to about 1% of the total galactic flux. This component can however be extracted from the galactic background with observation periods of the order of two months (with the notable exception of the 50–70 MeV where it is dominant). In addition, it is possible that the reacceleration of electrons at the solar wind TS is modulated by the solar cycle. With three years of observations toward the solar minimum it will be possible to detect also this effect. In addition to these phenomena, charge dependent modulation effects will be studied by comparing the temporal dependence of electron and positron spectra.

4. Conclusions

In this work, we have briefly described some of the observational possibilities of PAMELA in relation to solar and heliospheric physics. This will be the first time a magnetic spectrometer telescope in low Earth orbit will be operational for long duration observation. It will thus be possible to perform direct measurements in an energy range and with a precision up to now never reached for direct observations.

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