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Heliospheric cosmic ray observations with Pamela experiment

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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, 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.

1. Introduction

The PAMELA experiment[2] 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 equipped with a double-sided, microstrip silicon tracker. Under the spectrometer lies a sampling electromagnetic calorimeter, 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. At the bottom of the instrument there is a neutron detector made of ^{3}He counters enveloped in polyethylene moderator. Plastic scintillator counters are used for anticoincidence counting; 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.

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. Additional objectives are the studies of Solar Particle Events, trapped and secondary particles in Earth's magnetosphere and particles of Jovian origin[3]

2. Jovian electrons

Since the discovery made by the Pioneer 10 satellite of Jovian electrons at about 1 AU from Jupiter [13, 5], 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 γ = 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 [5, 4]. 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

Table 1. Top: Expected Jovian electron counts with the PAMELA detector in different energy ranges. 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 [9]. Using the power law γ (third column), estimated from [9] 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.

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

Table 2. Expected Total (Galactic and Jovian) electron counts with the PAMELA detector in different energy ranges (see caption of previous table).

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

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 [9]. 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 [9]. 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 range and the efficiency of the detector. In these work we have have taken into account the vertical geomagnetic cutoff (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 [6], 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.

3. 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 [12]: 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 observation of solar energetic particle (SEP) events with a magnetic spectrometer will allow to study in detail the:
1. *Positron component*, 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. Proton and Nuclear 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). Up to now there has been no direct measurement [8] of the high energy (>1 GeV) proton component of SEPs. The importance of a direct measurement of this spectrum is related to the fact [11] that there are many solar events where the energy of protons is above the highest (≃100 MeV) detectable energy range of current spacecrafts, but is below the detection threshold of ground Neutron Monitors [1]. 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[1].

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 [10] events.

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.

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[1] 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 γ = 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