Study of Protons at solar minimum in space with Pamela detector.

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Abstract. **PAMELA** is a satellite borne experiment designed to study with great accuracy cosmic rays of galactic, solar, and trapped nature in a wide energy range (protons: 80 MeV-700 GeV, electrons 50 MeV-400 GeV). Main objective is the study of the antimatter component: antiprotons (80 MeV-190 GeV), positrons (50 MeV-270 GeV) and search for antinuclei with a precision of the order of 10^{-8}). The experiment, housed on board the Russian Resurs-DK1 satellite, was launched on June, 15th 2006 in a 350×600 km orbit with an inclination of 70 degrees. In this work we present the measurement of galactic and reentrant albedo proton spectra in the energy range between 100 MeV and 300 GeV. The galactic protons referto the period 2006-2008, showing evidence of Solar modulation effects even during the solar minimum.

Keywords: cosmic rays, antimatter, dark matter, solar particle events, trapped cosmic rays

I. INTRODUCTION

The scientific program of the Wizard collaboration is devoted to the study of cosmic rays through balloon and satellite-borne devices. Aims of this research involve the precise determination of the antiproton [1] and positron [2] spectrum, search of antimatter, measurement of low energy trapped and solar cosmic rays with the NINA-1 [3] and NINA-2 [4] satellite experiments. Other research on board Mir and International Space Station has involved the measurement of the radiation environment, the nuclear abundances and the investigation of the Light Flash [5] phenomenon with the Sileye experiments [6], [7]. PAMELA is an orbital instrument designed for the study of primary charged particles and antiparticles in the wide energy interval, from tens of MeV up to several hundred GeV. It was launched in an elliptical orbit at an altitude between 350 and 610 km and inclination of 70° in June 2006. In this work we report on the observations of quiet time protons in the energy Range 100 MeV - 100 GeV and the solar modulation of the flux at solar minimum.

II. MEASUREMENT OF COSMIC RAYS IN EARTH'S MAGNETOSPHERE

Earth's magnetic field can be used as a spectrometer to separate cosmic rays of various nature and origin. To separate the primary (galactic) component from the reentrant albedo (particles produced in interactions of

cosmic rays with the atmosphere below the cutoff and propagating along Earth's magnetic field line) component it is necessary to evaluate the local geomagnetic cutoff. This is estimated using the IGRF magnetic field model along the orbit; from this the McIlwain L shell is calculated[8]. In this work we have used the vertical Stormer (defined as $G = 14.9/L^2$) approximation[9] to separate between particles of different nature. Figure 1 shows the rigidity of particles as function of the evaluated cutoff G. The primary (galactic) component, with rigidities above the cutoff is clearly separated from the reentrant albedo (below cutoff) component, containing also trapped protons in the South Atlantic Anomaly (SAA).

Cuts in the energy loss (dE/dx) vs rigidity remove positrons, pions and $Z \geq 2$ as shown in Figure 2. Since energy loss of a charged particle follows Bethe Block formula, $dE/dx \propto Z^2/\beta^2$ (neglecting logarithmic terms), the measurement of the average energy released in the tracker planes for a given event at a given rigidity can be used to discriminate between different particles. The topmost band in the Figure is due to helium nuclei which have energy loss in the tracker $Z^2 = 4$ times the protons, identified in the cental band. Bottom left releases are due to positrons, relativistic also at low rigidities and the background of pion and secondary particles. The black line shows the energy dependent cuts used to select a proton sample. From the Figure it is also possible to identify at low rigidites the deuterium contribution, resulting in a band with higher energy releases due to the lower β for a given rigidity due to the double atomic number A of deuterium. In this analysis deuterium and protons have been considered together with the term proton implying $Z = 1$, $A = 1, 2, 3$.

III. Solar modulation of GCR

Launch of PAMELA occurred during the XXIII solar minimum. At solar minimum the magnetic field of Sun has an approximatively dipolar structure, currently with negative polarity (A<0, with magnetic field lines directed toward the sun in the northern emisphere). We are currently in an unusually long solar minimum with various predictions on the behavior of the intensity and peaking time of next maximum. In the 2006-2008 period PAMELA has been observing an increase of the flux of galactic cosmic rays at low energy (< 1 GeV) due to solar modulation caused by the decreasing solar activity. A long term measurement of the behaviour of the proton, electron and $Z \geq 2$ flux at 1 AU can provide information on propagation phenomena occurring in the heliosphere. The possibility to measure the antiparticle spectra will allow to study also charge dependent solar modulation effects.

The MDR (Maximum Detectable Rigidity) of the magnet spectrometer is $\sim 1 GTV$ (700 GV on average) allows to measure the spectrum of cosmic-ray protons from 80 MeV up to almost 1 TeV; in this work we present proton data up to 200 GeV. Proton fluxes have been obtained requiring a clean track hitting the scintillator and fitted in the tracker with energy loss compatible with protons (rejecting He nuclei and secondary pions produced in the satellite). Particles of galactic origin are selected requiring that the rigidity of the event R is above the local cutoff ($R > G * 1.3$) to avoid contamination of the secondary component. To evaluate absolute spectra it was necessary to take into account live time, geometrical factor and detector efficiencies, using Montecarlo simulations (Geant 3.21) to evaluate the efficiency of each cut at various energies for each detector configuration. A compared study of the temporal and energetic variations of the efficiencies with experimental data is currently in progress. The current approach with Montecarlo simulations has an associated systematic error estimated of the order of 10% not shown in figures and tables. In Figure 3 are shown the proton fluxes measured in various periods of the mission. The effect of decreasing solar activity on the increasing flux of cosmic rays is visible even at solar quiet period, in agreement with the increase of neutron monitor fluxes. From the flux $J(E, t)$ it is possible to evaluate the solar modulation parameter $\Phi(t)$. The heliosphere is thus approximated with a spherical structure[10], assuming that particles lose energy independently from the sign of the charge and incoming direction to enter the heliosphere according to the following:

$$J(E, t) = \frac{E^2 - E_0^2}{(E + |Z|e\Phi(t))^2 - E_0^2} J_{is}(E + |Z|e\Phi(t)) \tag{1}$$

More detailed models involve correlation of the particle flux and solar modulation with variation with time of tilt angle of the heliospheric current sheet. In this work we have assumed a dependence of the interstellar spectrum according to [11]:

$$J_{is} = A\beta_{is}^{0.7} R_{is}^{-\gamma} \tag{2}$$

With $\beta = v/c$ and v the speed of the particle. The value of γ is obtained from the fit at high energies (from 15-20 to 200 GeV), where solar modulation effects become negligible. For PAMELA we obtain $\gamma = 2.76 \pm 0.01$. The estimation of the value of A with a precision required to estimate Φ is more complex and can affect the determination of the absolute value of Φ. In table I are shown the values of $\Phi(t)$ obtained with different assumptions of the value A. All values used are compatible with the various fits and - even though differ by as little as 2.5% - produce different values of $\Phi(t)$. It should be noted, however, that the decrease of the modulation parameter from 2006 to 2008 $\Delta\Phi_{ij} = \Phi(t_i) - \Phi(t_j)$ depends less from the assumption of A and can be considered more reliable. The values of A are shown here only to show the effect on the absolute value of solar modulation and should not be used for the evaluation of the interstellar spectrum. A more detailed estimation of A, using the full dataset of PAMELA is currently in progress.
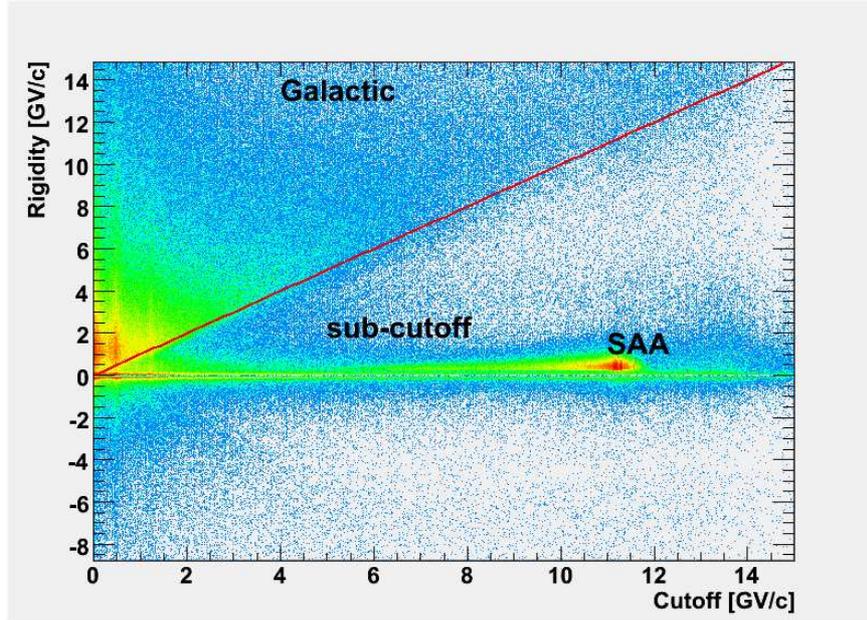
Fig. 1: Histogram of the rigidity R_{tr} measured in the tracker vs vertical Stormer Cutoff. Particles with positive charge (p, e^+) have $R_{tr} > 0$ and particles with negative charge have $R_{tr} < 0$. The effect of the geomagnetic field on galactic particles is clearly visible. Primary particles, of galactic or solar origin, have a rigidity above the local Stormer cutoff (see text) and are well separated from reentrant albedo events (below the cutoff) produced in the interaction of primaries with the Earth's atmosphere. It is also possible to see the spot of high fluence of low ($R < 2$ GV) protons trapped in the inner Van Allen belt, crossed by PAMELA in the South Atlantic Anomaly (SAA) region.

A p/(cm^2 s sr GeV^{-1} GV$^{-2.76}$)	2.0	1.95	1.91
	$\Phi\,(MV)$		
July 2006	635 ± 3	627 ± 2	621 ± 3
August 2007	565 ± 2	558 ± 3	552 ± 3
February 2008	561 ± 3	553 ± 2	546 ± 2

TABLE I: Solar modulation parameter obtained with the fit of the proton spectrum in different periods. Note the dependence of Φ from the assumed value of the absolute spectrum A. The variations of Φ are however more independent from A.

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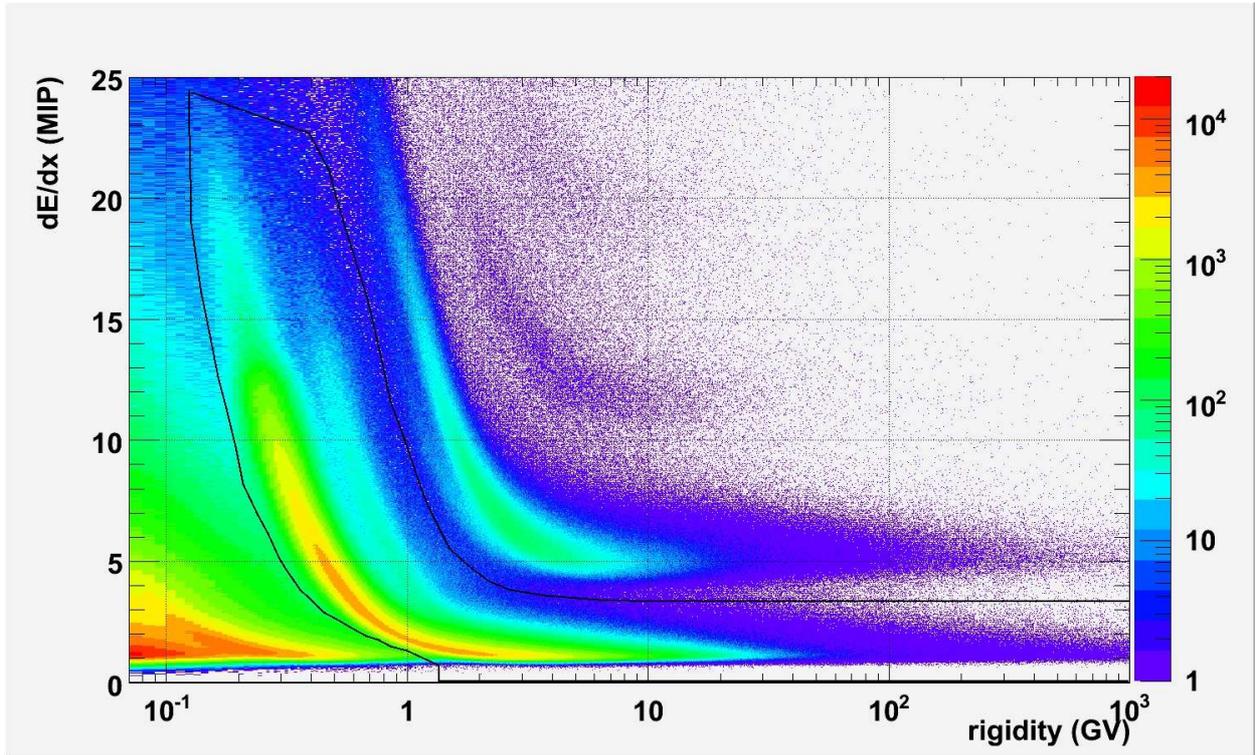
Fig. 2: Energy loss in tracker (mean in all planes hit) vs tracker rigidity for positively charged particles. The Proton and Helium bands are clearly visible. The black lines represent cuts used to select protons.
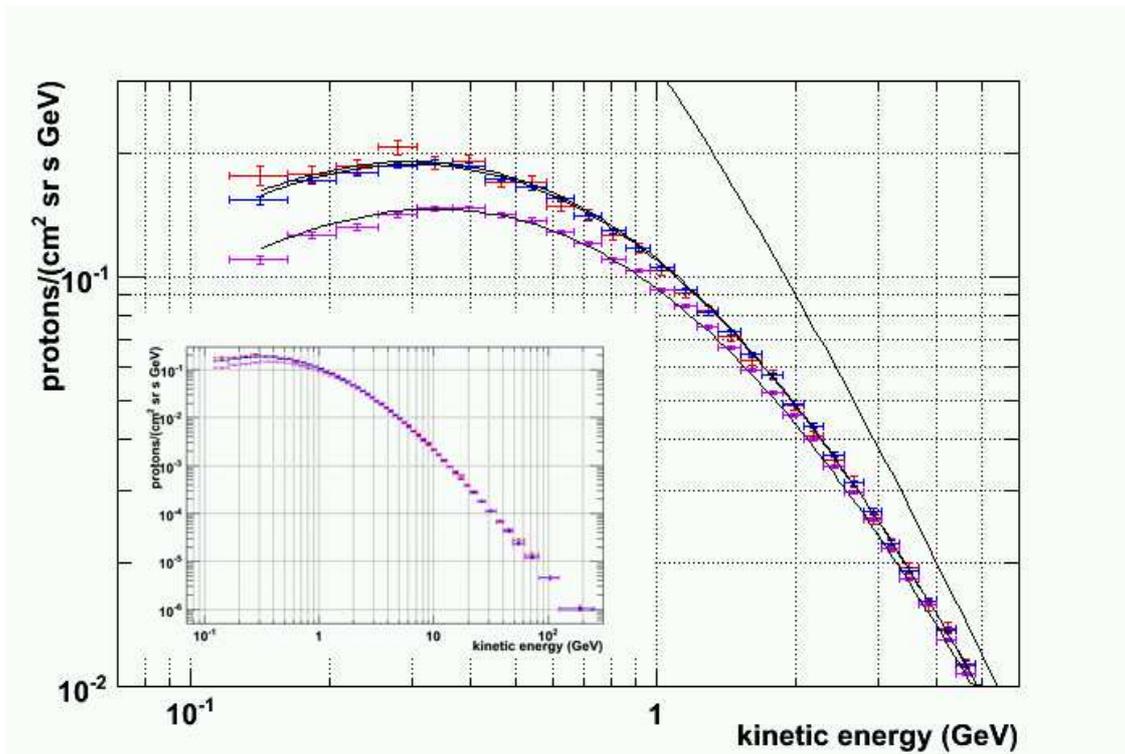

Fig. 3: Differential spectrum of protons measured in July 2006 (purple - bottom), August 2007 (black - central), February 2008 (red - top curve). Below 1 GeV it is possible to see the effect of solar modulation on the flux variation. The straight black line represent the assumed interstellar spectrum. Only statistical errors are shown.