Study of protons of solar origin in the events of 13 and 14 December 2006 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 ant mater 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 describe the scientific objectives and the measurements of the December 13th 2006 Solar Particle Event.

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

I. INTRODUCTION

We report the PAMELA measurements of the solar proton flux during the December 2006 solar particle events. Three events occurred between December 6th and 17th 2006 and were originated from active region NOAA 10930. Dec 6th event was originated in the East limb, resulting in a gradual proton event reaching Earth on Dec 7th and lasting until the events of Dec 13 and 14 [1]. On 13th December 2006, 02:38 UT an X3.4/4B solar flare occurred in active region NOAA 10930 (S06°W23°). The interaction between the fast rotating sunspot and the ephemeral regions triggers continual brightening and finally produces the major flare[2]. The intensity of the event is quite unusual for a solar minimum condition. Starting at 2:50 UT on the same day various neutron monitors, with cutoff rigidities below about 4.5 GV, recorded a Ground Level Enhancement (GLE70) with relative increases ranging from 20% up to more than 80% (Apaty, Oulu) [3], [4]. Apaty and Oulu also registered the peak of the event between 02:40 UT and 03:10 UT, while most of the neutron monitors had it between 03:10 UT and 03:40 UT. The spectrum and its dynamic was investigated at higher energies using ground measurements by neutron monitors at different cutoff rigidities [5] resulting in a spectral estimation assuming a power law in rigidity of γ ≃ 6. The onset time was later for the proton channels on-board of GOES-11 satellite: 03:00 UT for greater than 100 MeV protons and 03:10 for greater than
10 MeV protons [4]. PAMELA was in an high cutoff region at the flare occurrence and reached the South Polar region at about 03:10 UT. Muon monitors were also able to detect the GLE event and its spatial-angular anisotropy has been measured [6]. Differential proton spectra were directly measured by GOES, ACE, Stereo, SAMPEX at energies below 400 MeV.

The event produced also a full-halo Corona Mass Ejection (CME) with a projected speed in the sky of 1774 km/s [9]. The forward shock of the CME reached Earth at 14:38 UT on December 14, causing a Forbush decrease of galactic cosmic rays which lasted for several days. A second smaller event occurred in conjunction with a X1.5 flare from the same active region (NOAA 10930, S06°W 46°) on Dec 14, superimposing on the Forbush decrease. Galactic particle flux thus decreased in the energy range up to 3 GeV, whereas solar particles were accelerated up to 1 GeV for this event. The decrease was also observed by Wind, Stereo and Polar but not by the GOES satellites, with the exception of some variation in the 15-40 MeV channel of GOES-12 [10]. In case of PAMELA the relative decrease record by was up to more than 20%, extending above 5 GeV.

II. PAMELA OBSERVATIONS

In figure 1 is shown the differential energy spectrum measured with PAMELA in different periods of the event. It is possible to see that particles were accelerated up to 3-4 GeV.

The good energetic resolution and the statistic of the event allows for a detailed study of the temporal variations of the spectrum of this event in the energy range 100 MeV - 5 GeV, an interval usually not studied in observations of the spectrum of this event in the energy range up to 3-4 GeV.

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The rigidity spectrum at the beginning of the event (3:18 UT) is shown in the top panel of figure 1. With the passage of time the intensity of the spectrum increases (due to the increasing flux at low energy) with the lowering of $\alpha T$ implying a decrease of the acceleration phenomenon. It is interesting to note that the values obtained are compatible to what found for other events at lower energies in the energy range 10-100 MeV [11], sign that a similar description of the acceleration and propagation phenomena is valid at higher energies. Note however that at this stage we do not infer any conclusion on these processes from the spectral shape of fit performed.

Further studies will involve other particle species (He, $e^-$) and long term effects such as the Forbush decrease.

REFERENCES

Fig. 1: Proton differential energy spectra (flux vs kinetic energy) in different time intervals during the event of the 13th December 2006. The black line is the spectrum before the arrival of the charged particles with a small peak at low energy due to the presence of solar protons from previous events. It can be observed that the maximum flux of the high energy component of the solar protons arrives at the beginning of the event while only one hour later the maximum flux at low energy is detected. On the other hand, the flux at high energy decreases faster than at low energy. Only statistical errors are shown.

Fig. 2: Fit of the proton rigidity spectra at the beginning of the event. Different functions have been employed: from top to bottom at the high end of rigidity (red: Bessel K2 function; green: exponential in rigidity; blue: exponential in energy; black exponential in rigidity. Best fit function according to $\chi^2$ is the exponential in kinetic energy.)
Fig. 3: Top Panel: Fit of the rigidity proton spectra with Bessel K2 function as function of time (minutes from 2006-12-13-00:00 GMT). Top line: Absolute value. Bottom line: $\alpha T$. It is possible to see how particle flux increases and $\alpha T$ decreases with time. Bottom Panel: fit of the proton spectra with rigidity dependent power law as function of time ($\phi = AR^{-(\gamma + \delta(R-1))}$) (from top to bottom: $A$, $\gamma$, $\delta$). In this case particle flux decreases with time. The decrease of the rigidity dependent term $\delta$ implies a straightening of the spectrum.

Fig. 4: Proton differential energy spectra with galactic flux subtracted in different time intervals during the event of the 13th December 2006. The fluxes have been scaled in the plot. The fit with Bessel K2 function. Only statistical errors are shown.

Fig. 5: Particle flux vs time in selected energy bands with Pamela, Goes, and Neutron Monitor. Pamela data are two-minute averages and refer to relevant every polar passages. Black: 450MV; red: 700MV; green: 1GV; blue: 2GV; yellow: 3GV.