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Understanding cosmic rays and searching for dark matter with PAMELA

R. Sparvoli for the PAMELA Collaboration

INFN and Dipartimento di Fisica dell'Università di Roma "Tor Vergata" - I-00133 Rome, Italy

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Summary. — The instrument PAMELA, in orbit since June 15th, 2006 on board of the Russian satellite Resurs DK1, is delivering to ground 16 Gigabytes of data every day. The apparatus is designed to study charged particles in the cosmic radiation, with a particular focus on antimatter and signals of dark matter annihilation. A combination of a magnetic spectrometer and different detectors allows antiparticles to be reliably identified from a large background of other charged particles. After 4 years of operation in flight, PAMELA is now delivering coherent results about spectra and chemical composition of the charged cosmic radiation, allowing scenarios of production and propagation of cosmic rays to be fully established and understood.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `98.80.Cq` – Particle-theory and field-theory models of the early Universe (including cosmic pancakes, cosmic strings, chaotic phenomena, inflationary universe, etc.).
PACS `12.60.Jv` – Supersymmetric models.

1. – Introduction

One hundred years ago Victor Hess discovered cosmic rays and, from that moment, an impressive experimental study began. Cosmic rays are associated with the most impulsive events in the Universe, and the energies of the observed particles far exceed those reached by the most powerful accelerators at ground. Their chemical composition and energy spectrum give extensive information about their origin, acceleration and propagation mechanisms.

Twenty-one orders of magnitude in energy have been explored up to now, by direct methods—balloon-borne and satellite experiments—up to 10^{14} eV and by indirect methods—ground large-size apparata—at the highest energies. At medium energy the study is focused on the search of antimatter as a unique tool to investigate several physics and astrophysics phenomena. The search of antimatter is indeed strictly connected with the baryon-antibaryon asymmetry in the Universe, and the detection of antimatter of primary origin in cosmic rays would be a discovery of fundamental significance. Other possible contributions could come from evaporation of primordial mini black holes by the Hawking process or from exotic particles annihilation, this last having been a very hot physics topic for the last 10 years.

Several observations show that the Universe is prominently composed of dark matter and dark energy. Among the most plausible candidates for dark matter there are weakly interacting massive particles (WIMP), with the supersimmetric neutralino as a favourite candidate. The neutralino arises naturally in supersymmetric extensions of the standard model, and has the attractive feature of giving a relic density adequate to explain cosmological dark matter in a large region of the parameter space. Neutralinos are Majorana fermions and can annihilate in the halo, resulting in a symmetric production of particles and antiparticles, the latter providing an observable signature. Other models of WIMPs privilege lightest Kaluza-Klein particles in the Universal Extra Dimension scenario.

These ideas had a great improvement from the discovery of antiprotons on the top of the atmosphere made from Robert Golden [1] and Edward Bogomolov [2] in 1979 by balloon-borne experiments. They measured a rate of antiprotons much higher than expected from interactions of cosmic rays with the interstellar matter. Many other experiments followed these pioneer ones, performed mainly from the WiZard, HEAT and BESS Collaborations on board balloons, and from AMS-01 on board the Shuttle, using novel techniques developed for accelerator physics. Although the first historical results were not confirmed later, the way for a wide research for primary antimatter and dark matter signals in the cosmic rays was open.

However, possible contributions from dark matter annihilation or other exotic sources are mixed with a huge background produced in the interactions of cosmic rays with the ISM, so that they appear as a distortion of the antiproton and positron energy spectra. Then, a better knowledge of the standard mechanisms of production, acceleration and transport of cosmic rays is required.

New satellite experiments have been devised with the task to measure antiprotons and positrons, but also experimental parameters included in the background calculation. In June 2006 the first of these satellite, PAMELA, was launched in orbit by a Soyuz-U rocket from the Bajkonur cosmodrome in Kazakhstan. The PAMELA experiment is performed by an international collaboration composed by Italy, Russia, Germany and Sweden. Conceived mainly for searching primordial antimatter, signals from dark matter annihilation, exotic matter as strangelets, PAMELA achieves also other important tasks as the study of the mechanisms of acceleration and propagation of cosmic rays in the Galaxy, the cosmic ray solar modulation, the detection of solar flares. Studies of the interaction of particles with the terrestrial magnetosphere complete the PAMELA research program.

2. – The PAMELA instrument

An overview of the PAMELA apparatus is shown in fig. 1. The core of the instrument is a magnetic spectrometer, made of a permanent magnet and a silicon tracking system for a maximum detectable rigidity of 1 TV. A time-of-flight system consisting of three double layers of segmented plastic scintillator provides timing and $\mathrm{d}E/\mathrm{d}x$ measurements and defines the primary PAMELA trigger. The separation between hadronic and leptonic components is made by an imaging silicon-tungsten detector and a neutron counter. An imaging silicon calorimeter and a neutron detector assures a rejection of protons, compared to positrons, at the order of 10^5. The calorimeter permits also measurements of

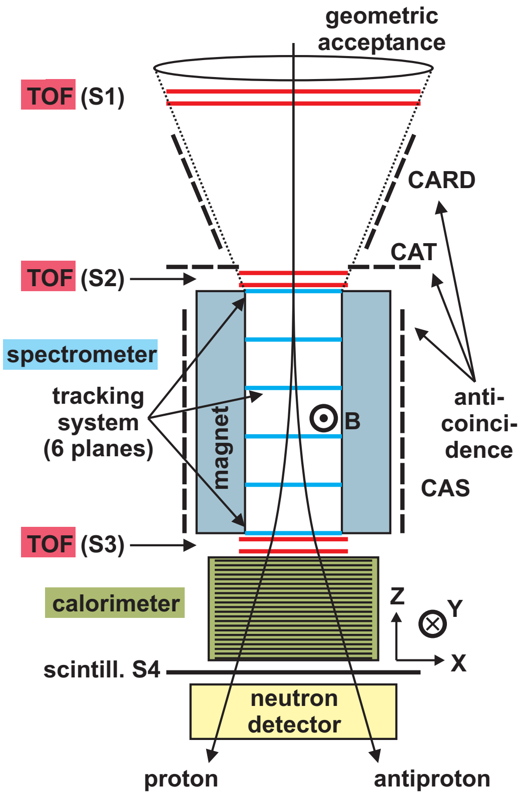

Fig. 1. – Schematic overview of the PAMELA apparatus.

the electron energy up to 300 GeV, with a resolution of few per cent. A thick scintillator placed between the calorimeter and the neutron counters and an anticoindence system complete the instrument. PAMELA can measure electrons, positrons, antiprotons, protons and light nuclei in an energy range from tens MeV up to hundreds GeV. More details can be found in [3].

PAMELA has been inserted in a pressurized vessel and installed on board of the Russian satellite DK-1 dedicated to Earth observation. It was launched on June 15th 2006 in an elliptical orbit, ranging between 350 and 610 km and with an inclination of 70 degrees. Since July 2006 PAMELA is daily delivering 16 Gigabytes of data to the Ground Segment in Moscow.

3. – Data analysis and results

The results presented here correspond to the data-set collected between July 2006 and December 2008. More than 10^9 triggers were accumulated during a total acquisition time of approximately 500 days.

3˙1. *Antimatter (antiprotons and positrons).* – Particle identification in PAMELA is based on the determination of the rigidity with the spectrometer and the properties of the energy deposit and interaction topology in the calorimeter. One source of background

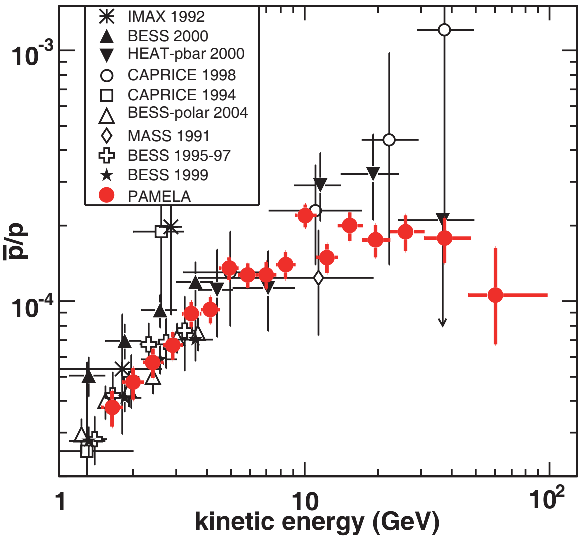

Fig. 2. – PAMELA antiproton-to-proton flux ratio compared with previous measurements [4].

in the antimatter samples comes from spillover (protons in the antiproton sample and electrons in the positron sample). This originates from incorrect determination of the charge sign due to the intrinsic deflection uncertainty in spectrometer measurements at the highest energies and to a possible multiple scattering of the particles in the tracking system. This limits the rigidity interval in which the measurements can be performed. Another source of background comes from the misidentification of like-charged particles (electrons in the antiproton sample and protons in the positron sample).

In order to accurately measure antiprotons, the spillover was eliminated by imposing a set of strict selection criteria on the quality of the fitted tracks. Electrons in the antiproton sample have been rejected by applying conditions on the calorimeter shower topology. The measured antip/p ratio is shown in fig. 2 compared with recent results from other experiments (see [4] and references therein). The ratio increases smoothly from about 4×10^{-5} at a kinetic energy of 1 GeV and levels off at about 1×10^{-4} for energies above 10 GeV. The data do not present the features or structures expected from exotic sources, so they place strong limits to dark matter annihilation models. Moreover, they set tight constraints on parameters relevant for secondary production calculations, *e.g.*, the normalization and the index of the diffusion coefficient, the Alfven speed, and contribution of a hypothetical "fresh" local cosmic-ray component.

Positrons and electrons data need a very careful analysis, done using the most performing available instrumental and statistical tools, because of the possibility of misidentification of protons as positrons. In fact, the proton-to-positron ratio increases from about 10^3 at 1 GeV to approximately 10^4 at 100 GeV. Particle identification for PAMELA was based on the matching between the momentum measured by the tracker and the total energy measured in the calorimeter, the starting point, the lateral and longitudinal profiles of the reconstructed shower and the neutron detector response. This analysis technique has been tested at the proton and electron beams at CERN for different energies, by Monte Carlo simulations and by using flight data. Figure 3 reports the electron selection efficiency and the proton contamination of the analysis technique, measured on flight

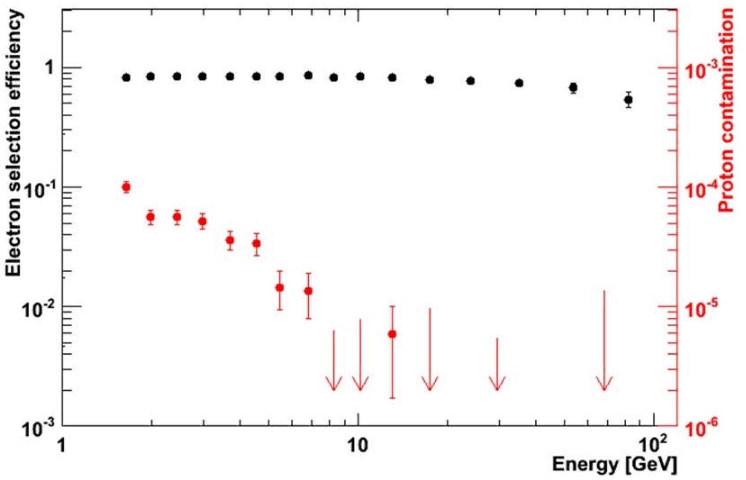

Fig. 3. – The electron selection efficiency and the proton contamination of the analysis technique, measured on flight data.

data; the proton contamination, measured at high energy ($> 10\,\text{GeV}$), was better than 10^{-5} on beam test data (upper limit due to statistics).

The positron-to-all-electron ratio measured by the PAMELA experiment is given in fig. 4, compared with other recent experimental results (see [5,6] and references therein). The calculation, shown in the same figure for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes, provides evidence that positron fraction is expected to fall as a smooth function of increasing energy if secondary production dominates. The data, covering the energy range 1.5–100 GeV, show two clear features. At low energies, below 5 GeV, the PAMELA

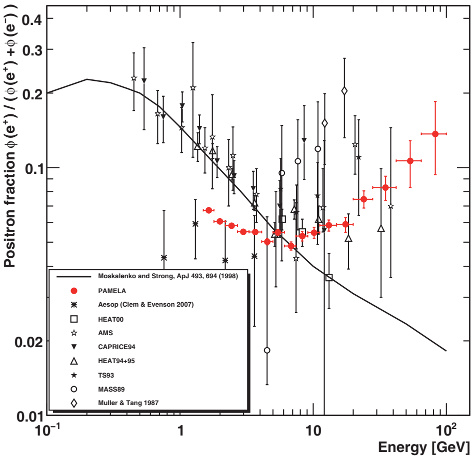

Fig. 4. – The positron fraction measured by the PAMELA experiment, compared with other recent experimental data [5].

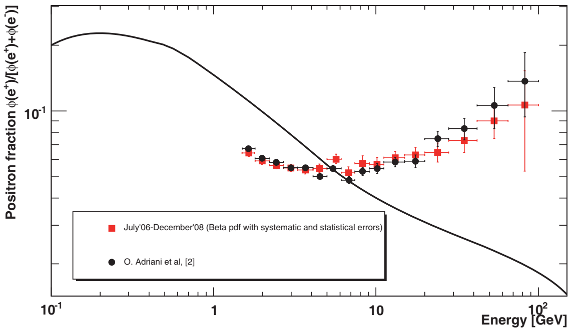

Fig. 5. – (Colour on-line) The positron fraction obtained using a beta-fit with statistical and systematic errors summed in quadrature (red) [7], compared with the positron fraction reported in fig. 4.

results are systematically lower than data collected during the 1990's; this can be convincingly explained by effects of charge-dependent solar modulation. At high energies, above 10 GeV, they show a positron fraction increasing significantly with energy.

This excess of positrons in the range 10–100 GeV has led to many theoretical models explaining its origin as due to annihilation or decaying of dark matter. The most problematic challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton-proton ratio), difficult to explain in the framework in which the neutralino is the dominant dark matter component. The best explanations are obtained in terms of a direct leptonic annihilation channel for a wide range of the WIMP mass. Another explanation relates to a contribution from nearby and young pulsars, objects well known as particle accelerators. Primary electrons are accelerated in the magnetosphere of pulsars in the polar cup and in the outer gap along the magnetic field lines emitting gamma-rays by synchrotron radiation, gammas that in the presence of pulsar gigantic magnetic field can evolve in positrons and electrons pairs. These, escaping into the interstellar medium, give a further contribution to the electron and positron components.

Results published in [5] refer to data collected by PAMELA between July 2006 and February 2008. We analyzed a larger data set, collected between July 2006 and December 2008, and we applied a different statistical methodology [7]. Figure 5 shows the positron fraction obtained through a beta-fit with statistical and systematic errors summed in quadrature, compared with the PAMELA positron fraction of fig. 4. Compared to what is reported in [5]: a) new experimental data, b) the application of three novel background models and c) an estimate of the systematic uncertainties have been used. The new experimental results are in agreement with what reported in [5] and confirm both solar modulation effects on cosmic rays with low rigidities and an anomalous positron abundance above 10 GeV.

3˙2. *Cosmic rays*. – Reliable calculations of the secondary production contribution in the antiproton and positrons energy spectra are of paramount importance to clearly disentangle a possible signal from not standard sources, but they are affected by uncertainties on the nuclear composition and energy spectra of the cosmic rays. For example, ratios between "secondary" and "primary" nuclei, where the primaries are produced by stellar nucleosynthesis while the secondaries are produced by fragmentation of pri-

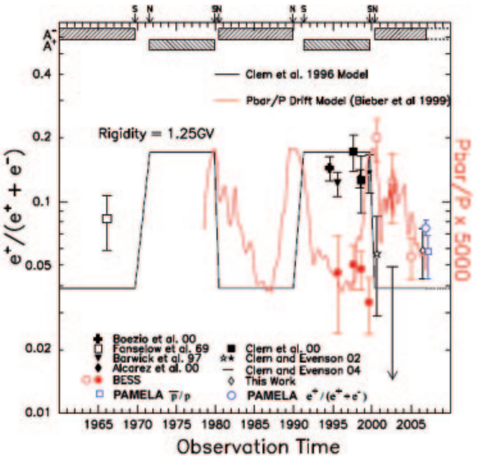

Fig. 6. – Phenomenological calculations for the positron-electron and antiproton-proton ratios along with the PAMELA and other experimental results.

maries interacting with the matter of the interstellar medium, are directly related to the encountered amount of matter and to the nuclei lifetime before escaping from the galaxy. PAMELA is measuring with good precision and high-statistics protons, ^{4}He, carbon and oxigen (primaries) together to ^{3}He, Li, Be, B (secondaries). These data constrain existing production and propagation models, providing detailed information on the galactic structure and the various mechanisms involved. Moreover, protons and alphas give the major contribute to the atmospheric neutrino production, therefore an accurate measurement of these components reduces the uncertainties on the expected flux on ground and on the estimation of hadronic cross sections (protons and alphas on O or N) at high energies, not otherwise determinable on ground. Proton and helium fluxes measured by PAMELA will be published very soon, together with the B/C ratio.

3˙3. *Solar physics.* – Continuous monitoring of the solar activity and the detection of solar energetic particle events are other important issues addressed by PAMELA. It is well known that the low energy part of the cosmic ray energy spectra up to about 5–10 GeV is affected by solar modulation in a way depending on the particle electric charge sign. Moreover, this effect is different if the magnetic dipole projection on the solar rotational axis and the same axis is parallel (phase A^+) or anti-parallel (pase A^-). This is due to a systematic deviation from the reflection symmetry of the interplanetary magnetic field. The Parker field has opposite magnetic polarity above and below the equator, but the spiral field lines themselves are mirror images of each other. This anti-symmetry produces drift velocity fields that for positive particles converge on the heliospheric equator in the A^+ state or diverge from it in A^- state. PAMELA positron/electron data have been collected during a A^- phase when the positrons are modulated more than electrons, and this explains the difference at low energy with the results obtained by previous experiments that were performed in A^+ phase. In fig. 6 phenomenological calculations for the positron/electron and antiproton/proton ratios for several solar phases A^+ and A^- and compared with data at 1.25 GV momentum of different experiments are shown [8]. PAMELA data are very important also considering the long duration of its permanence

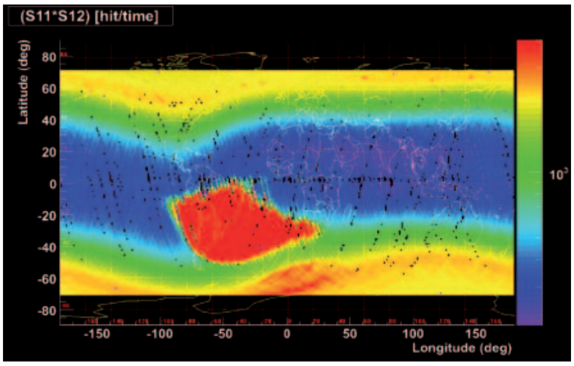

Fig. 7. – A 3-dimensional (latitude, longitude, altitude) mapping of the Van Allen Belts between 350 and 610 km.

in orbit in the recovery phase going towards solar maximum at cycle 24. It is interesting to stress that without a complete modeling of the solar modulation it becomes almost impossible to disentangle exotic signals at low energy.

PAMELA also detected the solar impulsive event of December 13th 2006. The observation of solar energetic particles (SEP) events with a magnetic spectrometer allows for several aspects of solar and heliospheric cosmic ray physics to be addressed for the first time.

3˙4. *Radiation environment.* – One of the first measurements performed by PAMELA was a detailed 3-dimensional (latitude, longitude, altitude) mapping of the Van Allen Belts between 350 and 610 km, showing spectral and latitude electron radiation belt and the proton belt in the South Atlantic Anomaly (fig. 7).

In fig. 8 the particle flux measured in different cutoff regions is shown. It is possible to see the primary (galactic—above cutoff) and the secondary (reentrant albedo—below cutoff) components. At the poles, where field lines are open and cutoff is below the minimum detection threshold of PAMELA, the secondary component is not present. Moving toward lower latitude regions the cutoff increases and it is possible to see the two components, with the position of the gap increasing with the increase of the cutoff.

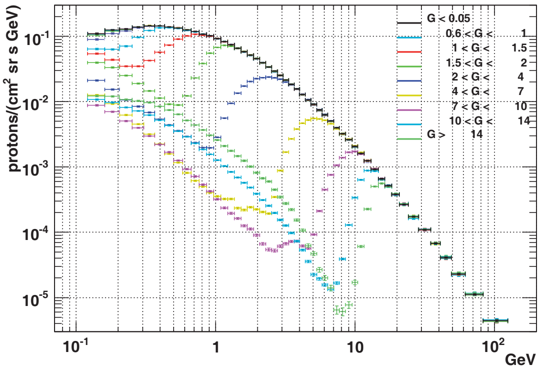

Fig. 8. – PAMELA proton flux in different cutoff regions.

4. – Conclusion

PAMELA is a general-purpose charged particle detector system exploring the antiparticle components of the cosmic radiation over a wide energy range. It has been in orbit since June 2006 and it is daily transmitting to ground 16 GB of data.

The main results obtained by PAMELA in 2009 concern the antiproton-to-proton and the positron-to-electron ratios. In 2010 the PAMELA Collaboration will release results on the energy spectra of charged cosmic particles (protons, alphas, light nuclei, antimatter), allowing scenarios of production and propagation of cosmic rays to be fully established and understood.

REFERENCES

[1] Golden R. *et al.*, *Phys. Rev. Lett.*, **43** (1979) 1196.
[2] Bogomolov E. *et al.*, *Proc. 16th ICRC*, **1** (1979) 330.
[3] Picozza P. *et al.*, *Astropart. Phys.*, **27** (2007) 296.
[4] Adriani O. *et al.*, *Phys. Rev. Lett.*, **102** (2009) 051101.
[5] Adriani O. *et al.*, *Nature*, **458** (2009) 607.
[6] Boezio M. *et al.*, *New J. Phys.*, **11** (2009) 105023.
[7] Adriani O. *et al.*, *Astropart. Phys.*, **34** (2010) 1.
[8] Clem J. and Evenson P., *Proc. 30th ICRC, Merida*, **1** (2007) 477.