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Cosmic Ray Study with the PAMELA Experiment

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Abstract. In six years of data collection years in space, the experiment PAMELA has discovered very interesting features in cosmic rays, namely in the fluxes of protons, helium, electrons, that might change our basic vision of the mechanisms of production, acceleration and propagation of cosmic rays in the Galaxy. In addition, PAMELA measurements of cosmic antiproton and positron fluxes are setting strong constraints to the nature of Dark Matter. The continuous particle detection is allowing a constant monitoring of the solar activity and detailed study of the solar modulation for a long period, giving important improvements to the comprehension of the heliosphere mechanisms. PAMELA is also measuring the radiation environment around the Earth, and has recently discovered an antiproton radiation belt.

1. Introduction

Cosmic rays and solar particles are the primary constituents of the radiation discovered by Victor Hess one hundred years ago. Twenty one orders of magnitude in energy have been up to now explored, with direct methods up to 10^{14} eV by balloon borne, satellite and space station experiments and with indirect methods at the highest energies by on ground large size instruments. In this spectrum there is the answer to many question related to the early Universe and its evolution in stars and galaxies. Where the particles are coming from? Are they galactic or also extragalactic? How and where they are getting accelerated? How do they propagate through the interstellar medium and what kind of interaction do they encounter? What role do they play in the energy budget of the interstellar medium? Do we find hints of the existing of exotic particles as relic from the early Universe, as antimatter and dark matter?

Cosmic rays are supposed to be of galactic origin at least up 10^{15} eV, accelerated by diffusive shock acceleration produced by Supernova shocks waves propagating in the interstellar medium. Direct measurements of their chemical composition and energy spectra are of particular interest for understanding the mechanisms of their production, acceleration and propagation in the Galaxy. An extensive work has been conducted in space and at the top of the atmosphere in the energy region between few GeV/n and hundreds TeV/n by the Proton satellite experiments, JACEE and RUNJOB on balloons, HEAO and SOKOL on board satellites and CRN on board the Space Shuttle. Recently ATIC, BESS, CREAM, TRACER, PPB-BETS have provided new data, as results of Long Duration Balloon flights in Antarctica. These experiments suffered of important limitations of statistical and systematic nature and were not able to clearly distinguish between different sources of cosmic rays and different possible acceleration mechanisms. The typical duration of a flight of stratospheric balloons of the oldest experiments, few tens of hours, put a serious limit to the statistic collected. Moreover, for these and for the new long duration balloon (tens of days) flight experiments, a subtraction of a large background of secondary particles produced in the residual air at the highest layers of the atmosphere is required, adding further uncertainties in the measurements.

Cosmic ray study has been also the origin of the Particle Physics and, for many years, of its development. Positrons, muons, pions and strange particles were discovered detecting directly cosmic rays or products of their interaction with matter targets. In the early 50s, with the advent of the particle accelerators, the cosmic ray scientific community divided in two groups; the particle physicists joined the accelerators, while the astrophysicists focused their efforts on the mechanisms of production, acceleration and transport of the cosmic rays. Later a major event happened with the first historical discovery of antiprotons on the top of the atmosphere by the balloon-borne experiments carried out by Robert Golden and Edward Bogomolov in 1979 [1, 2]. They measured an amount of antiprotons much higher than expected from interactions of cosmic rays with the interstellar matter. This measure could be considered the return to space of particle physics after more than twenty years. The prevalent theoretical interpretation was in terms of primary antimatter coming from antimatter domains in a baryon-antibaryon symmetric Universe. Detection in cosmic rays of a nucleus with $Z>2$ composed of antimatter would provide direct evidence of the existence of antistellar nucleosyntesis. Evaporation of primordial mini black holes for Hawking effect and exotic particles annihilation were also reported as possible explanations. In the same years the positron to electron ratio measurements were giving a too high flux of positrons at energies higher than 10 GeV, requiring some exotic productions. Many other experiments followed these pioneer ones, performed mainly by the WiZard, HEAT and BESS collaborations on board balloons and by AMS-01 on board the Shuttle; the first historical results were not confirmed.

However, while the problem of a possible matter-antimatter symmetry of the Universe was going to lose interest, because of the measurements of the Compton Gamma Ray Observatory that posed strictly limits to the existence of a notable amount of antimatter, at least at level of clusters of galaxies, another one appeared: today the Universe is believed to consist only of 4% of baryonic matter, while the 73% of what exists in the cosmos is made up of an invisible and homogenous substance called dark energy and the last 23% would be constitued of not directly visible particles much different from ordinary matter (dark matter). The presence of dark matter, inferred from the gravitational effects it has on the motion of celestial bodies, has been underlined since the 30s of last century, but only in recent decades various measures of astrophysical cosmological interest (abundance of light elements, cosmic radiation background, evolution of galactic structures) have clearly established its importance in the Universe energy budget. What is the nature of the particles that make up the dark matter? The most promising candidate is identified in a particle without electric charge or color, massive and weakly interacting (Weakly Interacting Massive Particle - WIMP). In supersymmetric extensions of the Standard Model of elementary particles the most studied WIMP is the neutralino, a linear combination of the supersymmetric partners of the neutral gauge bosons of the standard model. Other models consider as dark matter the lightest Kaluza Klein particle in a Universal Extra Dimension scenario. The property of the WIMP particles to annihilate each other and produce, through some primary annihilation channels, a number of ordinary elementary particles as final state is the reason of the search of dark matter signals in space. This contribution should appear as a distortion in the energy spectrum of the particle fluxes produced by standard interactions between cosmic rays and the interstellar matter. This spectrum, even known as astrophysics background, has thus to be accurately estimated. Of particular interest is a possible signature of dark matter in positrons and antiprotons, because of their low typical production.

It is worth to note the strong connection created between search in space for primordial antimatter and dark matter and very precise measurements of cosmic rays, both requiring long duration and atmospheric background free experiments, and instrumental techniques based on magnetic spectrometers identifying the sign of the particle electrical charge. New satellite experiments had been planned with the task to measure at the same time and by the same instrument not only antiprotons and positrons, but also experimental parameters included in the astrophysics background calculation.

In June 2006 the first of these experiments, PAMELA, was launched in orbit on board of the Russian Resurs DK1 satellite by a Soyuz-U rocket from the Bajkonur cosmodrome in Kazakhstan and placed in an elliptical orbit ranging between 350 and 610 km, with an inclination of 70 degrees. Since 2010 it is in a quasi-circular orbit at 600 km of altitude. In June 2008 Fermi gamma experiment on satellite and in May 2011 AMS-02 on board the International Space Station joined PAMELA in sky.

2. Pamela Instrument

PAMELA, a Payload for Matter-Antimatter Exploration and Light Nuclei Astrophysics, is an experiment conducted by an international collaboration constituted of several INFN Divisions and Italian Universities, three Russian institutions (MEPhI and FIAN Lebedev in Moscow and IOFFE in St. Petersburg), the University of Siegen in Germany and the Royal Technical Institute in Stockholm, Sweden. The mission is performed within the framework of the RIM (Russian Italian Missions) program, that took the heritage of the WiZard program. It has been mainly conceived for searching primordial antimatter, signals from dark matter annihilation and 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, by precise measurements of the absolute fluxes of primary and secondary light nuclei, the monitoring of the cosmic ray solar modulation and the detection of solar flares. Studies of the interaction of particles with the terrestrial magnetosphere complete the PAMELA research program.

The PAMELA apparatus, shown in fig. 1, is aimed to detect charged particles and antiparticles in a wide energy range. The core of the instrument is a magnetic spectrometer, made of a 0.43 T permanent magnet and a tracking system, that measures the rigidity (momentum divided by charge) of charged particles and the sign of their electric charge, through their deflection (defined as the inverse of rigidity) in the magnetic field. The magnet is composed of five modules, forming a tower 44.5 cm high, each comprising twelve magnetic blocks made of a NdFeB alloy. The blocks are configured to provide an almost uniform magnetic field direction inside a cavity that defines the geometrical factor of the PAMELA experiment to be 21.5 $\mathrm{cm}^2\mathrm{sr}$. The tracking system is made of six equidistant planes, each made of six 300 μm thick double-sided, microstrip silicon sensors, inserted inside the magnetic cavity, providing X-Y impact coordinates. The maximum detectable rigidity (MDR) of the spectrometer is 1.2 TV. A system of six layers of plastic scintillators, arranged in three double planes (S1, S2 and S3), provides a fast signal for triggering the data acquisition and for the measurement of the Time of Flight and the estimation of ionization energy loss (dE/dx) of traversing particles. It assures albedo particle rejection and charge particle absolute value determination. The separation between hadronic and electromagnetic components of cosmic rays is performed by an electromagnetic calorimeter and a neutron counter. The calorimeter is made of 44 single-sided silicon planes (each composed of nine 380 μm thick, 8 x 8 cm^2 wide, sensors) interleaved with 22 layers of tungsten absorber. The total depth of the calorimeter is 16.3 X_0 (0.6 nuclear interaction lengths). Its longitudinal and transverse segmentation, combined with the measurement of the particle energy loss in each silicon strip, allows an high identification for electromagnetic showers and a rejection power of interacting and non-interacting hadrons at the order of 10^5. The calorimeter provides also the measurement of the electron energy up to 300 GeV. A plastic scintillator, mounted beneath the calorimeter, increases the identication of high-energy electrons. It is followed by a neutron detection system made of 36 ^{3}He proportional counters, placed in two layers and surrounded by a polyethylene moderator enveloped in a thin cadmium cover. It complements the electron-proton discrimination capabilities of the instrument, by detecting the increased neutron production in the calorimeter associated with hadronic showers compared to electromagnetic ones. Furthermore, the calorimeter can also operate in self-trigger mode to perform, in combination with the neutron detector, an independent measurement of the lepton component up to 1 TV. Finally, an anticoindence system permits to reduce the background.

More details on the PAMELA instrument are reported in ref. [3]. The apparatus was inserted inside a pressurized container attached to the Russian Resurs DK1 Earth-observation satellite and it is daily delivering to Earth 16 Gigabytes of data that are analyzed by the collaboration for the different fields of research.

3. Cosmic rays

The proton and helium energy spectra measured by PAMELA [4] in the range of energy between 1 GeV - 1 TeV and 1 GeV - 450 GeV, respectively, are shown in fig. 2. The results are consistent with those of other experiments, considering the statistical and systematic uncertainties. The different periods of solar activity in which data have been collected from the various experiments could explain the differences at energies lower than 30 GeV as due to different solar modulation effects. Instead, the spectral hardening of the two slopes, that appears at the highest energies explored by PAMELA, challenges the present paradigm of acceleration of cosmic rays by a single supernovae remnant (SNR). This sudden change is more evident at 230 - 240 GV in the data presentation in function of rigidity, as shown in fig. 3, and could be interpreted as an indication of different populations of cosmic ray sources, as novae stars and explosions in superbubbles [5].

Other important information can be deduced from the PAMELA data. For long time the possible uniqueness of the index spectrum for all nuclei, including protons and helium, has been a debated issue. It had been difficult to evidence subtle differences between the different spectra, because the spectral indices were determined by different measurements performed over a limited energy range or with low statistics and large background contamination. The precise

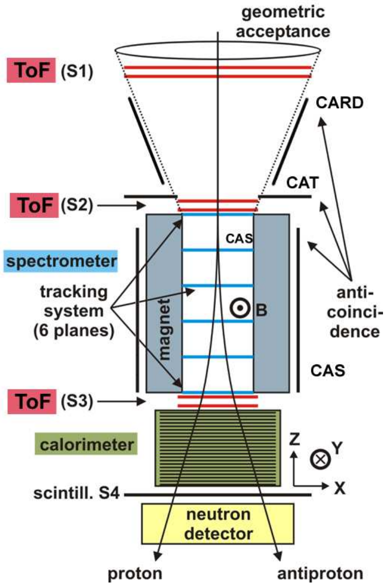

Figure 1. The PAMELA instrument.

PAMELA data, shown in fig. 4 as ratio of the proton to helium fluxes versus rigidity, in order to cancel systematic instrumental effects, clearly evidence a difference between the proton and helium slopes. The ratio shows a continuous and smooth decrease and it is well described by a power law down to 5 GV with a spectral index of 0.1.

PAMELA is also measuring the hydrogen and helium isotopes in cosmic rays. The combined effect of acceleration and propagation of cosmic rays in the Galaxy leads to a difference between the spectra at the source and those measured at Earth: secondary nuclei are produced by spallation in the interaction of primary nuclei with interstellar matter. Powerful tools to characterize the diffusion property of the interstellar matter and to test the propagation models are therefore the measurements of the abundances and energy spectra of secondary elements. The absolute fluxes of deuterium and ^{3}He measured by PAMELA in the energy range between 120 MeV - 550 MeV and 120 MeV - 800 MeV, respectively, are shown in the fig. 5 together with proton and ^{4}He ones, while the deuterium to proton and ^{3}He to ^{4}He ratios are reported in the fig. 6. Deuterium and ^{3}He are believed to be of secondary origin, resulting mainly from the nuclear interactions of primary cosmic ray ^{4}He with the interstellar medium. The interaction mean free path of ^{2}H and ^{3}He is considerably larger than the escape mean free path for cosmic rays from the Galaxy. For the heavier secondaries, the escape mean free path is of the same order or greater than their interaction length. As a consequence, light secondaries provide information concerning cosmic-ray interstellar propagation that is complementary to that obtained from the study of heavy secondaries, and their precise measurement could tell if the helium nuclei have the same propagation history as heavier nuclei.

4. Dark matter indirect search

PAMELA has been the first satellite experiment placed in space for searching signals of dark matter by detection of antiparticles coming from its annihilation or decay. The contemporary measurement of primary and secondary particles and nuclei in cosmic rays, crucial for the calculation of antiparticle astrophysics background, made PAMELA an experiment with unique features in this field, at least until the launch of AMS-02.

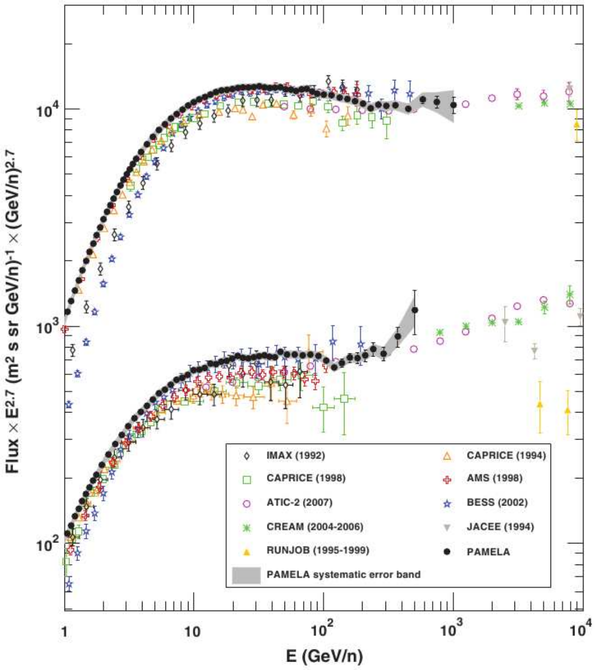

Figure 2. Proton and helium absolute fluxes measured by PAMELA above 1 GeV/n, compared with a few of the previous measurements. See ref. in [4].

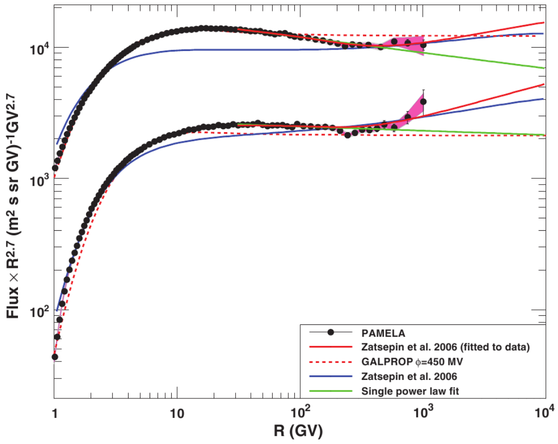

Figure 3. Proton (top points) and helium (bottom points) PAMELA data versus rigidity. The lines represent the fit with a single power law and the Galprop and Zatsepin [5] models.

Antiparticle identification in PAMELA is mainly based on the determination of their electrical charge and rigidity measured by the spectrometer and the energy deposit and interaction topology in the calorimeter. Due to the very large amount of cosmic ray protons compared to antiprotons, precise information from the spectrometer are crucial for selecting antiprotons. Infact, the finite spectrometer resolution may assign the wrong sign of curvature to high rigidity (low deflection) protons. An additional background comes from protons that scatter in the material of the tracking system and mimic the trajectory of negatively-charged particles. These spillovers, eliminated by imposing a set of strict selection criteria on the quality of the fitted

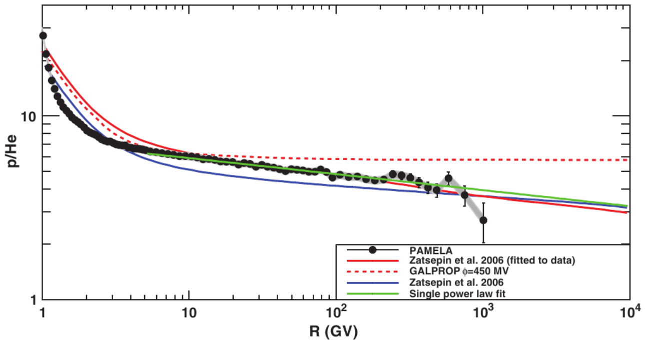

Figure 4. Ratio of the proton to helium of PAMELA data versus rigidity. See ref. in [4].

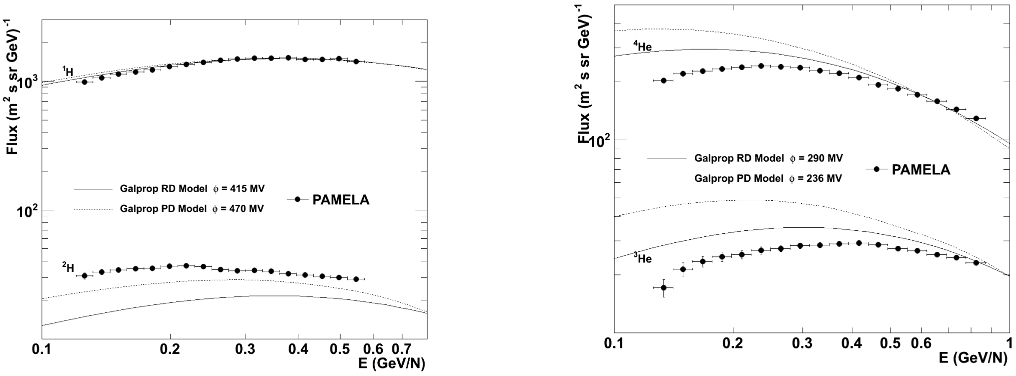

Figure 5. Absolute fluxes of H and ^{2}H (left panel) and of ^{4}He and ^{3}He (right panel).

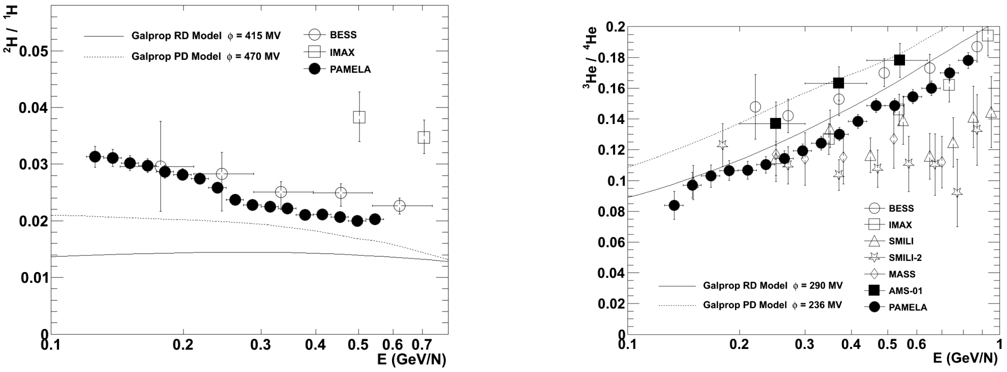

Figure 6. Ratio ^{2}H/H (left panel) and ^{3}He/^{4}He (right panel), together with data from other experiments.

tracks, limit at 180 GeV the antiproton energy spectrum. This spectrum and the antiproton-to-proton flux ratio measured by PAMELA in the energy interval between 60 MeV and 180 GeV are shown in fig. 7, and compared with recent experimental data and theoretical calculations in which pure secondary production of antiprotons during the propagation of cosmic rays in the Galaxy was assumed. The PAMELA results are in agreement with the previous measurements and in overall agreement with a secondary production without any particular feature to relate to possible exotic contributions. The experimental uncertainties are smaller than the spread in the different theoretical curves and, therefore, the data provide important constraints on signals from exotic sources, e.g. dark matter particle annihilation, and 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 still more accurate analysis, by using the most performing available instrumental and statistical tools. Because the proton to positron ratio increases from about 10^3 at 1 GeV to approximately 10^4 at 100 GeV, there is a large possibility of misidentification of protons as positrons. Particle identification was based on the matching between the momentum obtained by the tracker and the total energy measured in the calorimeter, the starting point and 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.

The positron to all electron ratio measured by the PAMELA experiment in the energy range 1.5 - 100 GeV is given in figure 8, along with other recent experimental results [7]. The calculation, shown in the same figure, performed for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes, suggests that positron fraction is expected to fall as a smooth function of increasing energy if secondary production dominates. Two features are clearly visible in the PAMELA data. At low energies, below 5 GeV, they are systematically lower than data collected during the 1990's, while at high energies, above 10 GeV, they show a positron fraction increasing significantly with the energy. Between 5 GeV and 10 GeV, the PAMELA data are compatible with other measurements. This interesting excess of positrons in the range 10-100 GeV has led to many speculations about its origin, as annihilation of dark matter, decaying dark matter, cosmic strings, young pulsars, a few nearby SNR. In a supersymmetric scenario, the PAMELA results set an intriguing theoretical challenge because 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. A suitable explanation requires a very high mass ($M \cong 10$ TeV) neutralino, which is unlikely in the context of allowed energy supersymmetry breaking models. Better explanations are obtained in terms of direct leptonic annihilation, e^+, e^-, μ^+, μ^-, channels for a wide range of the WIMP mass. Furthermore, explanations in term of dark matter annihilation request a boost factor for the annihilation standard rate ranging between 10^2 to 10^4, to be explained by high density dark matter clumps or modifications in the annihilation mechanisms.

Another interpretation considers 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. These gammas, in presence of the pulsar huge magnetic field, can evolve in positrons and electrons pairs that, after a permanence of about one-hundred thousand years in the nebula surrounding the pulsar, escapes into the interstellar medium, giving a further contribution to the electron and positron components. Some other theoretical works explain this positron excess in terms of few nearby SNR or of secondary positron production taking place in the same region where cosmic rays are being accelerated. ar modulation effects. The energy spectra of cosmic rays are modified by the solar wind within the solar system, mainly at energy lower than 10 GeV. These effects depend on the cosmic ray sign of charge and on the positive and negative phase of the Sun and it is due to gradient, curvature and drift effects. These mostly affect low mass particles as positrons and electrons and are more important in the phase of low solar activity. The older results were mainly obtained during the previous positive polarity of the solar cycle, when the mechanical rotation axis of the Sun and the Sun

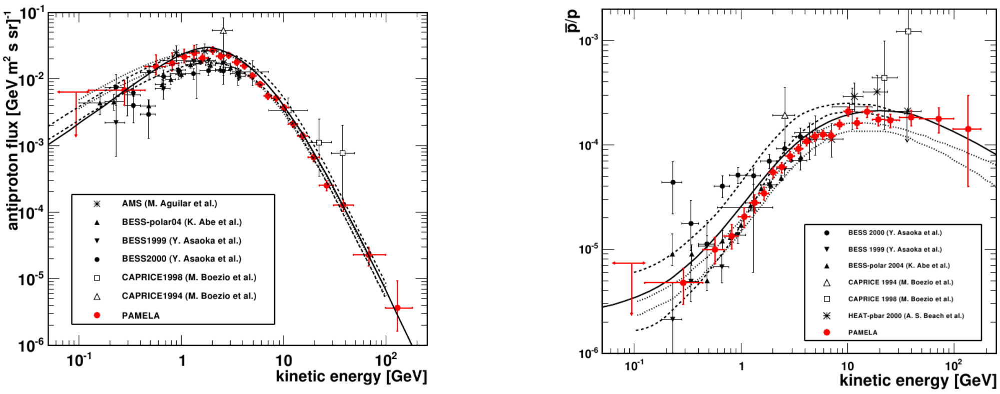

Figure 7. Left panel: The antiproton energy spectrum together with contemporary measurements and theoretical calculations for a secondary production by Donato et al. (dotted and dashed lines) and Ptuskin et al. (solid line). See ref. in [6]. Right panel: The antiproton-to-proton flux measured by PAMELA, compared with contemporary measurements and theoretical calculations for a secondary production of antiproton by Simon et al. (dashed lines), Donato et al. (dotted lines), Ptuskin et al. (solid line). See ref. in [6].

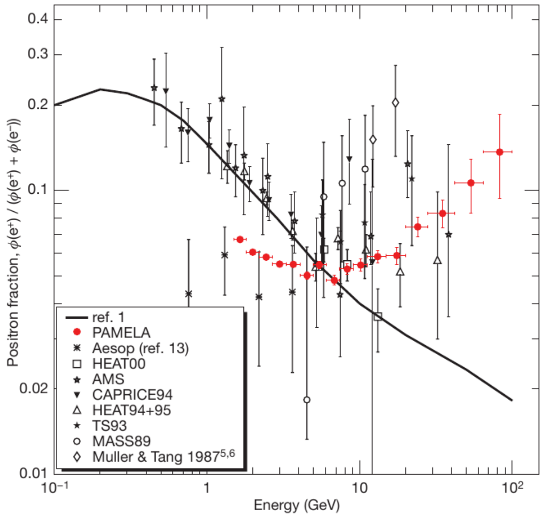

Figure 8. Positron fraction measured by PAMELA compared with data from other experiments and a calculation of Moskalenko and Strong for pure secondary production of positrons. See ref. in [7].

magnetic dipole had the same versus and positive charges underwent a lower solar modulation. The ASEOP balloon borne experiment which flew in June 2006 has also observed a suppressed positron fraction at low energies [8].

5. Electrons

Main uncertainties in the calculations of the astrophysics background and, subsequently, in disentangling possible contributions from annihilation of dark matter in cosmic ray spectra, are due to an incomplete knowledge of the primary cosmic ray nuclei and electron fluxes.

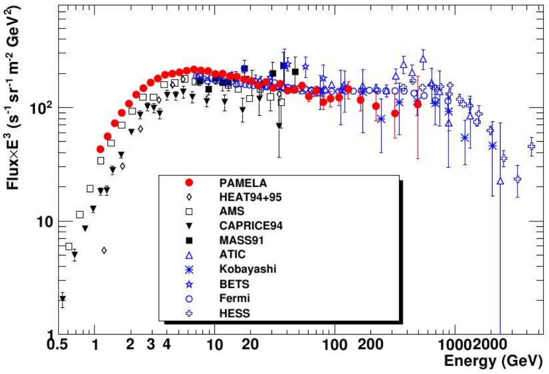

Figure 9. The electron energy spectrum obtained by PAMELA compared with modern measurements. See ref. in [9].

PAMELA performed accurate measurements of the absolute fluxes of electrons and positrons, in addiction to proton and helium ones. The electron energy spectrum between 1 GeV and 625 GeV is shown in fig. 9, along with other recent experimental data. It is described by a single power law energy dependence, with spectral index -3.18 ± 0.05 above the energy region influenced by the solar wind ($>$ 30 GeV). No significant spectral features are observed, although the data are also consistent with models including new cosmic ray sources that could explain the rise in the positron fraction. No significant disagreements are found between PAMELA and the recent ATIC and Fermi data, if statistical and systematics uncertainty are considered. The differences with previous magnetic spectrometer measurements are larger and probably due to uncertainties in the energy and efficiencies determination of the various experiments. Below 10 GeV, discrepancies can be partially explained by the different effects of solar modulation for the various data taking periods. The results on the positron energy spectrum will be released in the next future.

6. Solar physics

The long time in orbit of the PAMELA mission has allowed a continuous monitoring of the solar activity and the resulting modulation of the galactic cosmic rays, including the charge sign dependent effect of the modulation, and the detection of several Solar Energetic Particle (SEP) events.

Solar modulation, that has an 11 year cycle varying from a period of maximum activity to a minimum, produces a significant effect mostl

Concerning the lower energy part of the spectrum, a disagreement between our data and the previous measurements is interpreted as a consequence of time and charge dependent soly on cosmic ray with rigidities less than about 10 GV. At each maximum the polarity of the solar magnetic field reverses. PAMELA has been operating in these years during the very long 23^{rd} solar minimum when the magnetic field of the Sun had an approximately dipolar structure and the effects of the drift were more relevant, and in phase A^-, when the magnetic dipole projection on the solar rotational axis and the rotational axis itself are anti-parallel (in phase A^+ are parallel). The low energy galactic fluxes of protons, helium, electrons and positrons, measured in the period between 2006, launch date of PAMELA, and 2009, when the solar activity reached its minimum, are shown in fig. 10. The increasing of the fluxes with the decreasing of the solar activity is clearly visible, in agreement with the enhancement of the counting rate measured by the on-ground neutron monitors.

The Sun has long been known to be also a source of energetic particles. To fully explore the

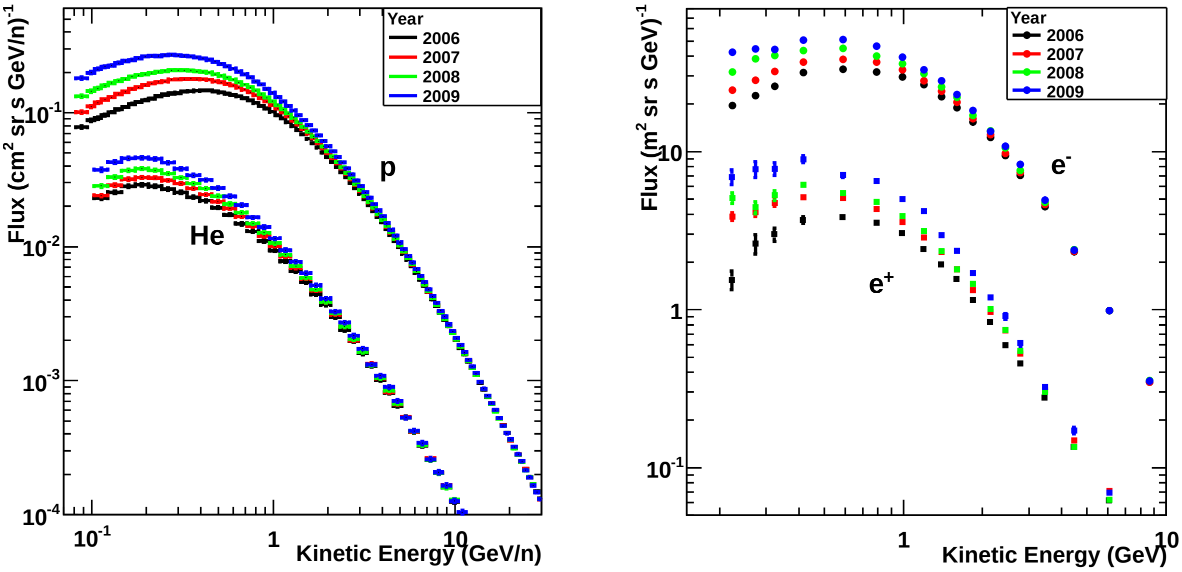

Figure 10. Low energy proton and helium fluxes (left panel) and electron and positron fluxes (right panel) measured by PAMELA for different temporal intervals during the phase of decreasing activity of the Sun (2006-2010).

nature and capacity of solar particle acceleration processes, extremes in energy and flux of the produced particles must be studied. PAMELA, in six years of operation has already recorded many solar energetic events associated with occurrences at the Sun. Particularly interesting have been the events of December 13, 2006, and March 7, 2012, shown in fig. 11 for proton flux in the energy range from ∼80 MeV/n up to few GeV/n [10]. During the first hours of the event, solar energetic particles had a quite exponential form, a demonstration of a rather significant temporal evolution.

7. Radiation environment

PAMELA is studying the radiation environment along the orbit with a good accuracy. Due to the precession of the satellite elliptical orbit, in its six years of operation PAMELA performed a detailed 3-dimensional (latitude, longitude, altitude) mapping of the Van Allen Belts between 350 and 610 km, showing spectral and geometrical features. In fig. 12 a map of the measured radiation environment is shown. The high latitude electron radiation belt and the proton belt in the South Atlantic Anomaly (SAA) are clearly visible. The particle flux measured at different cut-off regions (expressed in GV/c) is shown in fig. 13. A very interesting result obtained by PAMELA in the radiation environment study has been the discovery of an antiproton radiation belt around the Earth. The trapped antiproton energy spectrum measured by PAMELA [11] in the SAA region for a kinetic energy range between 60 MeV and 750 MeV is shown in fig. 14, together with a measurement of the atmospheric sub-cutoff antiproton spectrum and galactic antiproton spectra. The magnetospheric antiproton flux in the SAA exceeds the cosmic ray antiproton flux by three orders of magnitude at the present solar minimum, and exceeds the subcutoff antiproton flux outside radiation belts by four orders of magnitude, constituting the most abundant source of antiprotons near the Earth.

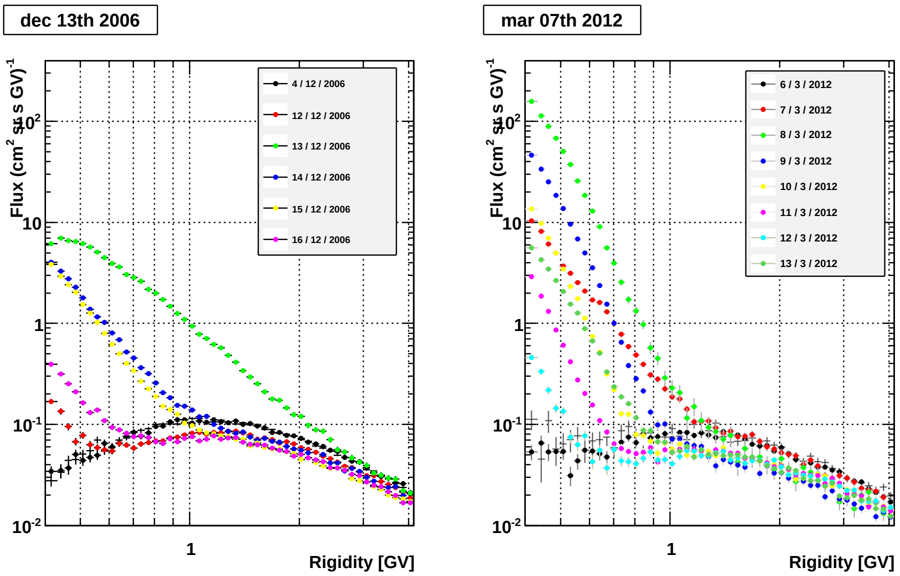

Figure 11. Proton spectrum as measured by PAMELA for the SEP event of December 13, 2006 (left panel) and SEP event of March 7, 2012 (right panel).

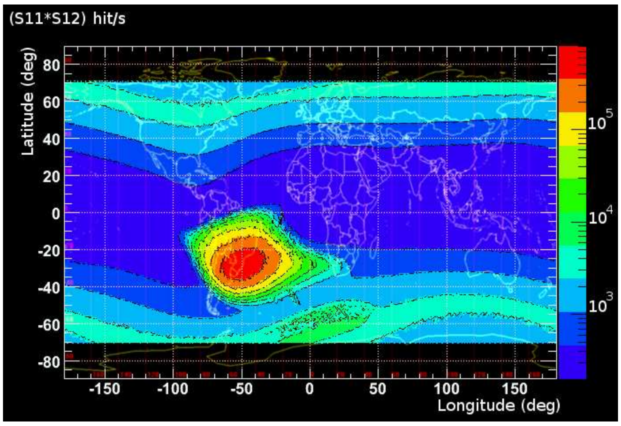

Figure 12. A 3-dimensional (latitude, longitude, altitude) mapping of the Van Allen Belts between 350 and 610 km obtained by PAMELA.

8. Conclusions

PAMELA, in orbit since June 2006, has collected a huge amount of data on different fields of Astrophysics and Particle Physics. Much debated in many papers has been the increase of the positron fraction above 10 GeV, compared as expected from the standard secondary production. This excess has been interpreted introducing exotic sources, like dark matter annihilations in direct leptonic channels, although particular attention has been brought even on standard astrophysics processes, as nearby young pulsars or nearby SNR contributions and non-standard processes in the secondary production of positrons. Also the energy spectra of proton and helium measured by PAMELA present features questioning the current models on production, acceleration and propagation of cosmic rays in the Galaxy. Data on the solar activity and solar modulation of galactic cosmic rays and the discovery of an antiproton radiation belt are other important results achieved from the PAMELA mission.

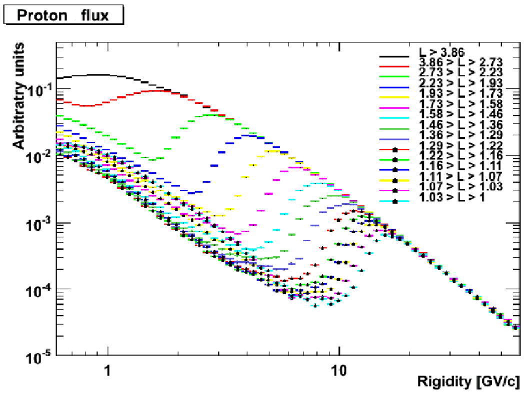

Figure 13. Proton flux measured by PAMELA in different cutoff regions.

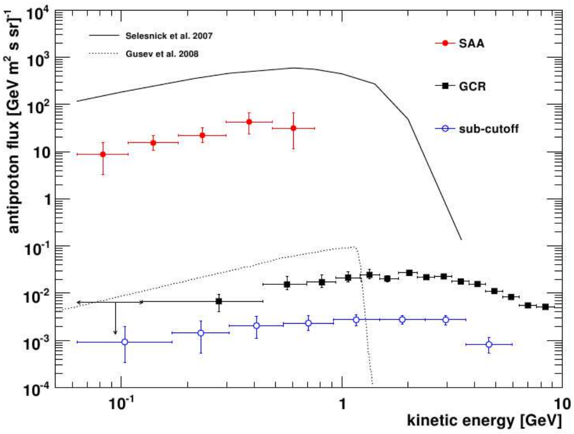

Figure 14. The geomagnetically trapped antiproton spectrum measured by PAMELA in the SAA region (red full circles). Trapped antiproton predictions by Selesnick et al. for the PAMELA satellite orbit (solid line), and by Gusev et al. at L = 1.2 (dotted line). The mean atmospheric undercutoff antiproton spectrum outside SAA region (blue open circles) and the galactic cosmic ray antiproton spectrum (black squares) measured by PAMELA are also shown for comparison. See ref. in [11].

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