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Understanding cosmic rays and searching for exotic sources with PAMELA

P. Picozza, R. Sparvoli, and the "PAMELA collaboration"

University of Rome Tor Vergata, Italy

Italian National Institute of Nuclear Physics, Italy

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Abstract. The instrument PAMELA, in orbit since 15 June 2006 on board of the Russian satellite Resurs DK1, is designed to study charged particles in the cosmic radiation, with a particular focus on antimatter and signals of dark matter annihilation. PAMELA is also looking for primordial antinuclei, measuring light nuclei energy spectra, studying the mechanisms of acceleration and propagation of the cosmic rays in the Galaxy, and monitoring the solar activity and the radiation belts.

A review of the main experimental results obtained by PAMELA is presented in this paper. The observed anomalous positron excess is discussed in terms of annihilation of dark matter particles as well as in terms of standard astrophysical sources. Moreover constraints on dark matter models from antiproton data are shown.

1 Introduction

The antimatter and dark matter are among the most controversial and fascinating problems that modern physics is facing to. In fact, the Universe we know is composed of matter; the few tracal.,es of anti-matter so far observed are consistent with a "secondary" production, caused by the collision of cosmic rays with the interstellar medium or the Earth's atmosphere. However, the most accredited theories of evolution of the Universe state that an equal amount of matter and antimatter have been generated just after the Big-Bang. Matter and antimatter would then be almost immediately annihilated each other. From this process it appears to have survived only the matter that forms the stars, planets and the world we know. The question, now unsolved, is how it was possible the complete disappearance of anti-matter and/or whether in some other portion of the Universe there is an abundance of anti-matter of primordial origin, to compensate what we observe locally.

Close to this question, in the last two decades another one appeared: today we know that the Universe consists only of 4% of the matter familiar to us, made of protons, neutrons and electrons (and of small amount of antimatter). It is estimated that 73% of what exists in the cosmos is made up of an invisible and homogenous substance called "dark energy". The last 23% would be made up of particles much different from ordinary matter, which do not aggregate in celestial bodies, which do not emit electromagnetic radiation and therefore not directly visible (dark matter). The presence of dark matter, inferred from gravitational effects it has on the motion of celestial bodies, has been highlighted since the 30's of last century, but only in recent decades various measures of astrophysical cosmological importance (abundance of light elements, cosmic radiation background, evolution of galactic structures) have clearly established its importance in the budget of energy that composes our universe. The fundamental question about what is the nature of the particles that make up the dark matter still remains.

From the cosmological point of view, the most promising candidate of dark matter is identified in a particle without electric charge or color, massive and weakly interacting (Weakly Interacting Massive Particle - WIMP). The absence of electrical charge prevents it from emitting electromagnetic radiation and justifies its darkness. The absence of color charge makes the WIMPs non interacting in the domain of strong interactions, keeping them away from forming anomalous nuclear states, absent in our universe. The weakness of the interaction limits the rate with which WIMPs can destroy themselves, thus ensuring its survival over billions of years of evolution of the universe. The presence of a mass of at least a few dozen $\mathrm{GeV\,c^{-2}}$ guarantees the non relativistic nature of these particles when they were decoupled from the thermal bath of the early universe, in agreement with the models

Correspondence to: P. Picozza
(piergiorgio.picozza@roma2.infn.it)

of “cold” dark matter required by the process of evolution of structures in our universe. In supersymmetric extensions of the Standard Model of elementary particles, there are several scenarios in which new particles can play the role of WIMP: determining the nature of dark matter would therefore not only solve a cosmological “puzzle” but open a new window in the panorama of fundamental physics. The most studied WIMP is the neutralino, a linear combination of the supersymmetric partners of the neutral gauge bosons of the standard model.

The search for these particles, fossils of the Big Bang and presumably inhabitants of dark halos of galaxies, stretches into two main directions: the direct search, conducted in underground laboratories aimed at revealing the interactions of WIMP particles with large mass detectors, and indirect search, carried out in space. The indirect searches are based on the principle that WIMP particles can annihilate each other and produce, through some primary annihilation channel, a number of standard elementary particles as final state. Other theoretical scenarios instead consider decaying WIMPs. Of particular interest, because of the low astrophysics background, are the possible signatures in gamma rays, neutrinos and cosmic antimatter fluxes, as positrons and antiprotons. In this way, a very strong connection between search for primordial antimatter and search for dark matter in space is created, both requiring experimental techniques based on magnetic spectrometers identifying the sign of the particle electrical charge.

The most faithful astrophysics messengers, which can give us information over the primordial Universe, are the cosmic rays (CR). The CR are constituted for the most part of protons and helium nuclei (99%) but also of heavier nuclei, electrons, positrons, antiprotons and tracks of even more rare components. The study of this radiation, from the pioneering experiments of the Nobel Prize Victor Hess at the beginning of the last century, has been accelerating in the ’80s and ’90s thanks to a massive campaign of experiments mounted on balloons or on small satellites.The measurement campaigns undertaken in the 80’s have completed the transition from the early observation of cosmic radiation as a laboratory for production and direct detection of new particles (as was the discovery of the positron) to the study of the properties and the role that cosmic rays have in the physics of the cosmos.

To date, however, the measurements of cosmic-ray performed by instruments carried on stratospheric balloons (we remember MASS, TS93, Caprice, IMAX, BESS, ATIC, TRACER, CREAM, ..) or in space (NINA, NINA-2, AMS-01, ..) suffered of important limitations of statistical and systematic nature. The search for rare signals requires long periods of observation and an environment where the “local” production in a standard way of the sought signal is low. The typical duration of a flight of the 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, secondary particle production in the residual air at the highest layers of the atmosphere requires a subtraction of a large background - with the associated uncertainties - in the measurements.

Then, new satellite experiments have been devised with the task to measure antiprotons and positrons, but also experimental parameters included in the astrophysics background. In June 2006 the first of these satellites, 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 formed 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 and 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.

2 The PAMELA instrument

The central part of the PAMELA apparatus is a magnetic spectrometer, consisting of a 0.43 T permanent magnet and a tracking system to measure the sign and the rigidity (momentum over charge) of charged particles through their deflection in the magnetic field.

A Time–of–Flight system, composed of a set of three double-layer planes of segmented scintillators, arranged two above and one under the magnetic spectrometer, provides a fast signal for triggering the data acquisition and for measuring the time-of-flight and ionization energy losses (dE/dx) of traversing particles. The separation between the leptonic and hadronic components is mainly carried out by an imaging silicon-tungsten calorimeter, 16 radiation length deep with a rejection power of 10^5 for protons versus positrons, placed under the spectrometer. A neutron detector on the bottom of the instrument improves the rejection power, by counting the neutrons produced in the shower initiated in the calorimeter by the incident particles and more abundant for hadrons than for leptons. A large scintillator under the calorimeter and an anticoincidence system complete the PAMELA instrument. The experimental capabilities of PAMELA in cosmic ray measurements are reported in Table 1.

More technical details can be found in (Picozza et al., 2007). 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 15 June 2006 in an elliptical orbit, ranging between 350 and 610 km, with an inclination of 70 degrees. Since July 2006 PAMELA is daily delivering about 16 Gigabytes of data to the Ground Segment in Moscow.

Table 1. Design goals for PAMELA performance.

Cosmic-ray particle	Energy range
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV - 270 GeV
Electrons	50 MeV - 600 GeV
Protons	80 MeV - 1200 GeV
Electrons+positrons	up to 2 TeV
Light nuclei (up to Z=6)	100 MeV/n - 200 GeV/n

3 PAMELA results

3.1 Data analysis

Particle identification in PAMELA is based on the determination of the rigidity measured by the spectrometer and the properties of the energy deposit and interaction topology in the calorimeter. One source of background in the antimatter samples comes from the "spillover" (protons in the antiproton sample and electrons in the positron sample) that can be eliminated by imposing a set of strict selection criteria on the quality of the fitted tracks. The spillover limits the rigidity interval in which the measurements can be performed. Another important source of background comes from the misidentification of like-charged particles (electrons in the antiproton sample and protons in the positron sample). While the electron to antiproton ratio is of the order of 10^2, the proton to positron ratio increases from about 10^3 at 1 GeV to approximately 10^4 at 100 GeV. Then, positron data need a very careful analysis, to be done using the most performing available instrumental and statistical tools, because of the possibility of misidentification of protons as positrons. Electron and positron 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 and the lateral and longitudinal profiles of the reconstructed shower and the neutron detector response. This analysis technique has been tested by the proton and electron beams at CERN for different energies, by Monte Carlo simulations and by using flight data. An extensive discussion of the different methods used to assure and cross check a correct separation between the different components can be found in Adriani et al. (2009a) and Adriani et al. (2010a).

3.2 Antiprotons

The antiproton energy spectrum and the antiproton-to-proton flux ratio measured by PAMELA (Adriani et al., 2010b) in the energy interval between 60 MeV and 180 GeV are shown respectively in Figs. 1 and 2, along with other recent experimental data and theoretical calculations done assuming pure

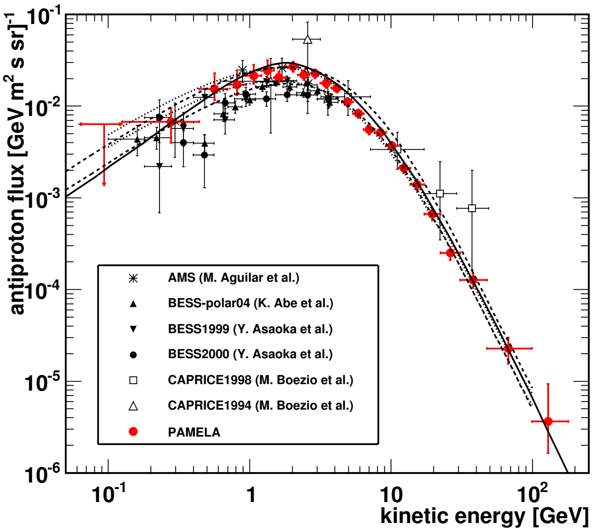

Fig. 1. The antiproton energy spectrum at the top of the payload compared with contemporary measurements (Boezio et al., 1997, 2001; Asaoka et al., 2002; Abe et al., 2008; Aguilar et al., 2002) and theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dotted and dashed lines indicate the upper and lower limits calculated by Donato et al. (2001) for different diffusion models, including uncertainties on propagation parameters and antiproton production cross-sections, respectively. The solid line shows the calculation by Ptuskin et al. (2006) for the case of a Plain Diffusion model.

secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The curves were calculated for solar minimum, which is appropriate for the PAMELA data taking period, using the force field approximation (Gleeson and Axford, 1968).

The PAMELA results are in agreement with the previous measurements. They reproduce the expected peak around 2 GeV in the antiproton flux (due to the kinematic constraints on the antiproton production) and are in overall agreement with a pure secondary production. The experimental uncertainties are smaller than the spread in the different theoretical curves and, therefore, the data provide important constraints on parameters relevant for secondary production calculations. However, a possible contribution from non thermally produced dark matter annihilation is suggested by some authors (Kane et al., 2009).

3.3 Positrons

The positron to all electron (i.e. electron + positron) ratio measured by the PAMELA experiment is given in Fig. 3, compared with other recent experimental results. 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 the positron fraction is expected to fall as a smooth

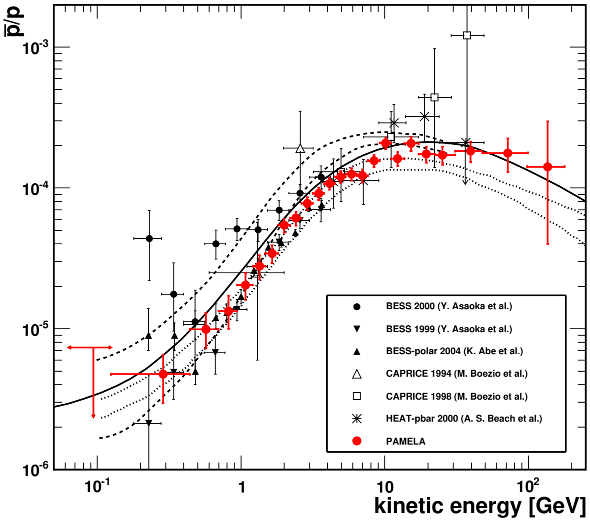

Fig. 2. The antiproton-to-proton flux ratio at the top of the atmosphere compared with contemporary measurements (Boezio et al., 1997, 2001; Asaoka et al., 2002; Abe et al., 2008; Beach et al., 2001) and theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dashed lines show the upper and lower limits calculated by Simon et al. (1998) for the Leaky Box Model, while the dotted lines show the limits from Donato et al. (2009) for a Diffusion Reacceleration with Convection model. The solid line shows the calculation by Ptuskin et al. (2006) for the case of a Plain Diffusion model.

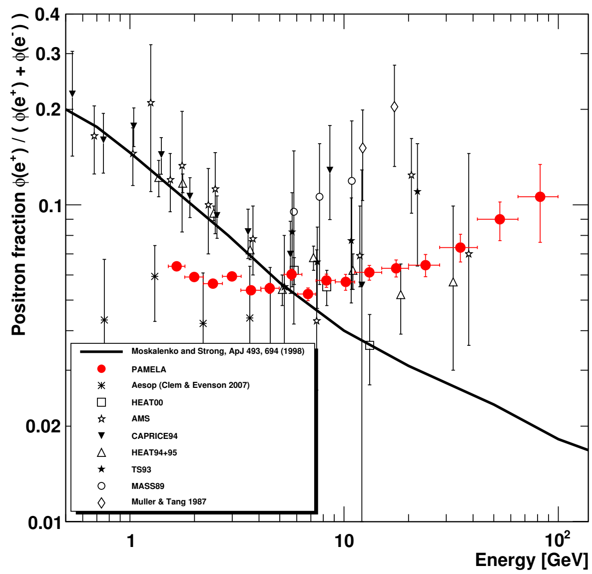

Fig. 3. The positron fraction measured by the PAMELA experiment (data from Adriani et al., 2010a), compared with other recent experimental data (Clem and Evenson, 2007; Beatty et al., 2004; Gast et al., 2006; Boezio et al., 2000; Barwick et al., 1997; Golden et al., 1996, 1994; Müller and Tang, 1987), and a theoretical calculation (Moskalenko and Strong, 1968).

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

The background propagation model considered in Fig. 3 is clearly not able to fully account for the experimental data. In particular the rising at E>10 GeV seems a very difficult feature to be reproduced by a pure secondary component without using an unrealistic soft electron spectrum (Delahaye et al., 2009), suggesting the existence of other primary sources (Serpico, 2009).

It is worth to note that a physical process creating a positron from a zero charge system also implies the creation of a corresponding electron. Therefore an exotic source of positrons in our Galaxy is presumably also a source of electrons. In order to explain the positron excess, many explanations about its origin in terms of more or less exotic sources have been proposed, ranging from purely astrophysical one, like pulsars or few nearby Supernova remnants (SNR), to the more speculative ones, as annihilation of dark matter, decaying of lightest superparticle dark matter, even cosmic strings. All theories predict a spectral index change around an energy of few GeV, with respect to the secondary propagation models, needed to explain the excess.

The explanations in terms of annihilating dark matter or decaying particles is extremely suggestive, since the PAMELA data would constitute in this case a clear evidence of the existence of dark matter. A rise in the positron fraction at high energy has been postulated for the annihilation of dark matter particles in the galactic halo since the HEAT data publication (Baltz and Edsjö, 1999; Baltz et al., 2002). The most problematic theoretical challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton-proton ratio) data, 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>10 TeV) neutralino (Cirelli et al., 2009), which is unlikely in the context of allowable energy supersymmetry breaking models. Better descriptions are obtained in terms of leptonic annihilation channels for a wide range of the WIMP masses (Cirelli et al., 2009). Furthermore, all explanations in terms of dark matter annihilation require a boost factor for the annihilation standard rate ranging between 10^2 to 10^3.

Among the models proposed to explain the PAMELA data, it is worth to cite also the Kaluza-Klein (KK) dark matter (Hooper and Zurek, 2009), in the Universal Extra Dimension framework.

Besides particle physics interpretations, a variety of astrophysical models have been put forward to explain the positron excess. One plausible 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 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.

Finally, it has also been suggested that the PAMELA positron data can be explained without invoking a primary component. This is possible if secondary production takes place in the same region where cosmic rays are being accelerated (Blasi, 2009; Fujita et al., 2009). An increase in the antiproton (Blasi and Serpico, 2009) and secondary nuclei abundances (Mertsch and Sarkar, 2009) are also predicted in this model.

Only a few months before the publication of PAMELA positron data, the ATIC collaboration reported an excess in the galactic all electron (sum of electrons plus positrons) energy spectrum at energies of $\sim 500-800$ GeV (Chang et al., 2008), which led to the speculation over the existence of a nearby source of energetic electrons, either of astrophysical or exotic nature. As an example, assuming an annihilation signature of Kaluza-Klein dark matter, the authors managed to reproduce the experimental data with a Kaluza-Klein mass of 620 GeV and a boost factor of ~ 200.

Later in 2009 the Fermi collaboration released results about the all electron spectrum up to 1 TeV (Abdo et al., 2009). Fermi high precision data show that this spectrum falls with energy as $E^{-3.0}$ - harder than the conventional diffusive model - but does not exhibit the same prominent spectral features of ATIC. The significant flattening of the Fermi data may suggest the presence of one or more local sources of high energy CR electrons, but also dark matter scenarios cannot be excluded.

Many different articles appeared, which took into account in the same theoretical frame the data from PAMELA, ATIC and Fermi.

3.4 Astrophysics background

A theoretical modeling of the fluxes of secondary species, as antiprotons and positrons, produced by interaction of cosmic rays nuclei with the interstellar medium, is the starting point to highlight the presence of components produced by exotic sources such as dark matter. The detection of primary cosmic rays - charged and neutral - and secondaries species allowed to propose models of the galaxy and its key processes of CR production, acceleration, diffusion, interaction, and loss of energy. The relative abundances observed in cosmic rays for different nuclear species (sensitive to the processes of fragmentation) or radioactive isotopes (sensitive to the time of propagation from the sources) have been used - in conjunction with observational data on the properties of the galaxy - to construct models able to predict the flux and the energy spectra of the components of anti-matter and "ordinary" gamma rays. It is also crucial for other fields of investigations in astroparticle physics, as atmospheric neutrino studies.

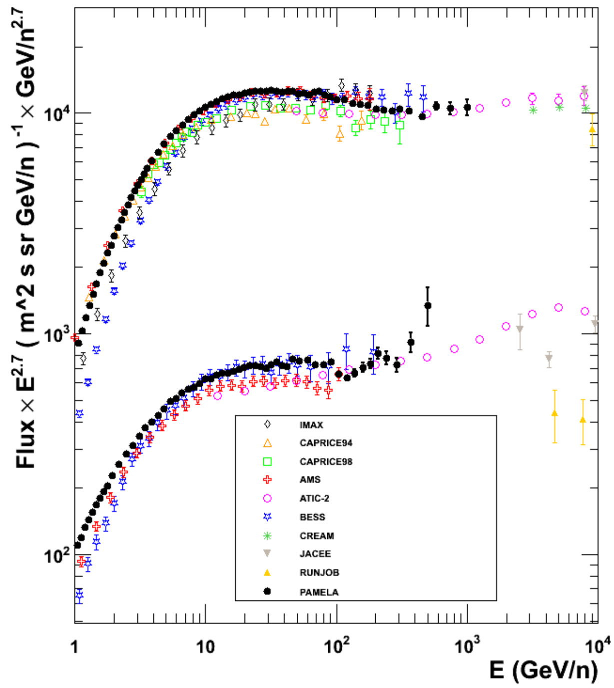

Fig. 4. Proton and helium absolute fluxes measured by PAMELA above 1GeV/n, compared with some previous measurements. Error bars are statistical.

PAMELA is measuring with good precision and high statistics protons, ^{4}He, carbon and oxygen (primaries) together to ^{3}He, Li, Be, B (secondaries). Preliminary data from PAMELA (Fig. 4) suggest a hardening in p and He spectra and a different index between the two spectra. If these measurements reflect intrinsic features in the interstellar fluxes, appreciable modifications are expected in the sub-TeV range for the secondary yields, such as antiprotons and diffuse gamma–rays (Donato and Serpico, 2011).

4 Solar modulation of GCR

The solar modulation has a significant effect mostly on CR with rigidities less than about 10 GV. This modulation has an 11 year cycle varying from a period of maximum activity and maximum effect on CR to a minimum. At each maximum the polarity of the solar magnetic field reverses. PAMELA launch occurred during the XXIII solar minimum, when the magnetic field of the Sun has an approximatively dipolar structure and the effect of the drift are more relevant,

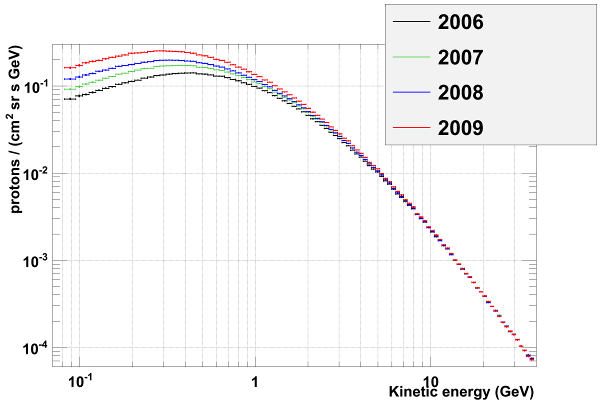

Fig. 5. Proton absolute flux in 2006, 2007, 2008 and 2009. The effect of solar modulation is clearly visible.

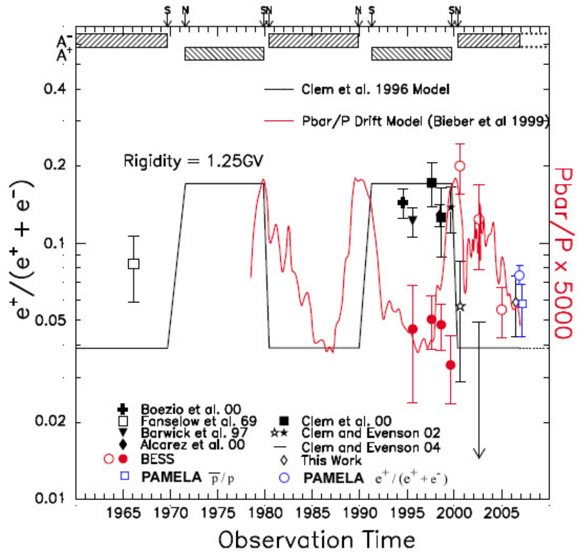

Fig. 6. Phenomenological calculations for the positron-electron and antiproton-proton ratios along with the PAMELA and other experimental results.

and in phase A^-, where the magnetic dipole projection on the solar rotational axis and the rotational axis itself are anti–parallel (in phase A^+ are parallel). The galactic proton fluxes measured in various periods of the mission during the years 2006 - 2009 are shown in Fig. 5. The increasing of the flux of the cosmic rays with the decreasing of the solar activity is clearly visible, in agreement with the enhancement of the counting rate of the on-ground neutron monitors. Finally, as anticipated in Sect. 3.3, the lower energy part of the positron ratio spectrum (Fig. 3) shows an evident disagreement between PAMELA data and almost all previous measurements. This is justified by the fact that the charge sign–dependent effect of the solar modulation is different between the positive and negative phases, due to a systematic deviation from reflection symmetry of the interplanetary magnetic field (Clem and Evenson, 2007). 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 antisymmetry produces drift velocity fields that for positive particles converge on the heliospheric equator in the A^+ state or diverge from it in A^- state. Negatively charged particles behave in the opposite manner and the drift patterns interchange when the solar polarity is inverted. In Fig. 6, phenomenological calculations (Clem et al., 1996; Bieber et al., 1999) for the positron-electron and antiproton-proton ratios are shown for several solar phases and compared with data at 1.25 GV momentum for different experiments, including PAMELA. The positrons are modulated more than electrons in the A^- phase and less in A^+ phase.

5 Conclusions

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

The main results obtained by PAMELA in 2009 concern the antiproton–to–proton and the positron–to–electron ratios. Above 10 GeV, an increase in the positron–to–electron ratio appears, compared as expected from the standard secondary production. Two different scenarios have been proposed as an explanation of the positron excess: one involving standard astrophysics, either nearby young pulsars or nearby SNR or non-standard processes in the secondary production of positrons, and the other involving more exotic explanations, like DM annihilations. The antiproton–to–proton flux ratio appears in agreement with the standard secondary production models, though the statistical precision of the measurements overcomes the current knowledge on the parameters of CR production and propagation. This result puts strong constraints on DM models since they usually do not predict a large asymmetry between leptonic and hadronic production.

The energy spectra of charged cosmic particles (positrons, electrons, protons, alphas, light nuclei and isotopes) will be soon released by the PAMELA collaboration, allowing scenarios of production and propagation of cosmic rays to be better established and understood. This is the starting point to highlight the presence of components produced by exotic sources such as dark matter.

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