

## The PAMELA experiment and antimatter in the universe

M. Boezio · R. Carbone · O. Adriani · G. C. Barbarino · G. A. Bazilevskaya · R. Bellotti · E. A. Bogomolov · M. Bongi · V. Bonvicini · S. Bottai · A. Bruno · F. Cafagna · D. Campana · P. Carlson · M. Casolino · G. Castellini · C. De Donato · M. P. De Pascale · C. De Santis · N. De Simone · V. Di Felice · V. Formato · A. M. Galper · A. V. Karelin · S. V. Koldashov · S. Koldobskiy · Y. Krutkov · A. N. Kvashnin · A. Leonov · V. Malakhov · L. Marcelli · M. Martucci · A. G. Mayorov · W. Menn · M. Mergè · V. V. Mikhailov · E. Mocchiutti · A. Monaco · N. Mori · R. Munini · G. Osteria · F. Palma · P. Papini · M. Pearce · P. Picozza · C. Pizzolotto · M. Ricci · S. B. Ricciarini · R. Sarkar · V. Scotti · M. Simon · R. Sparvoli · P. Spillantini · Y. I. Stozhkov · A. Vacchi · E. Vannuccini · G. Vasilyev · S. A. Voronov · Y. T. Yurkin · G. Zampa · N. Zampa · V. G. Zverev

© Springer International Publishing Switzerland 2014

**Abstract** On the 15th of June 2006, the PAMELA satellite-borne experiment was launched from the Baikonur cosmodrome and it has been collecting data since July 2006. The primary scientific goal is the measurement of the antiproton and positron energy spectra. Antiparticles are a natural component of the cosmic radiation being produced in the interaction between cosmic rays and the interstellar matter. They have been shown to be extremely interesting for understanding the propagation mechanisms of cosmic rays. Furthermore, novel sources of primary cosmic-ray antiparticles of either astrophysical or exotic origin

---

Proceedings of the 11th International Conference on Low Energy Antiproton Physics (LEAP 2013) held in Uppsala, Sweden, 10-15 June, 2013

M. P. De Pascale is deceased.

C. Pizzolotto was Previously at INFN, Sezione di Trieste, 34149 Trieste, Italy

M. Boezio (✉) · R. Carbone · V. Bonvicini · V. Formato · E. Mocchiutti · R. Munini · R. Sarkar · A. Vacchi · G. Zampa · N. Zampa  
INFN Section of Trieste, Padriciano 99, 34149 Trieste, Italy  
e-mail: Mirko.Boezio@ts.infn.it

O. Adriani · M. Bongi · P. Spillantini  
Department of Physics, University of Florence 50019 Sesto Fiorentino, Florence, Italy

O. Adriani · M. Bongi · S. Bottai · N. Mori · P. Papini · S. B. Ricciarini · P. Spillantini · E. Vannuccini  
INFN, Sezione di Florence, 50019 Sesto Fiorentino, Florence, Italy

G. C. Barbarino · V. Scotti  
Department of Physics, University of Naples "Federico II", 80126 Naples, Italy

G. C. Barbarino · D. Campana · G. Osteria · V. Scotti  
INFN, Sezione di Naples, 80126 Naples, Italy

(e.g. annihilation of dark matter particles) can also be probed. In this paper we review the PAMELA antiparticle results and their significance for the field of astroparticle physics.

**Keywords** Antiparticles · Cosmic-ray · Space experiment

---

G. A. Bazilevskaya · A. N. Kvashnin · Y. I. Stozhkov  
Lebedev Physical Institute, 119991 Moscow, Russia

R. Bellotti  
Department of Physics, University of Bari, 70126 Bari, Italy

R. Bellotti · A. Bruno · F. Cafagna · A. Monaco  
INFN, Sezione di Bari, 70126 Bari, Italy

E. A. Bogomolov · Y. Krutkov · G. Vasilyev  
Ioffe Physical Technical Institute, 194021 St. Petersburg, Russia

P. Carlson · M. Pearce  
KTH, Department of Physics, and the Oskar Klein Centre for Cosmoparticle Physics, Albanova  
University Centre, 10691 Stockholm, Sweden

M. Casolino · C. De Donato · M. P. De Pascale · C. De Santis · N. De Simone · V. Di Felice ·  
M. Mergè · F. Palma · P. Picozza · R. Sparvoli  
INFN, Sezione di Rome “Tor Vergata”, 00133 Rome, Italy

M. Casolino  
RIKEN, Advanced Science Institute, Wako-shi, Saitama, Japan

G. Castellini · S. B. Ricciarini  
IFAC, 50019 Sesto Fiorentino, Florence, Italy

M. P. De Pascale · C. De Santis · L. Marcelli · M. Martucci · M. Mergè · F. Palma · P. Picozza ·  
R. Sparvoli  
Department of Physics, University of Rome “Tor Vergata”, 00133 Rome, Italy

V. Formato · R. Munini  
Department of Physics, University of Trieste, 34147 Trieste, Italy

A. M. Galper · A. V. Karelin · S. V. Koldashov · S. Koldobskiy · A. Leonov · V. Malakhov ·  
A. G. Mayorov · V. V. Mikhailov · A. Voronov · Y. T. Yurkin · V. G. Zverev  
NRNU MEPhI, 115409 Moscow, Russia

M. Martucci · M. Ricci  
INFN, Laboratori Nazionali di Frascati, Via Enrico Fermi 40, 00044 Frascati, Italy

W. Menn · M. Simon  
Department of Physics, Universitat Siegen, 57068 Siegen, Germany

C. Pizzolotto  
INFN, Sezione di Perugia, 06123 Perugia, Italy

C. Pizzolotto  
Agenzia Spaziale Italiana (ASI) Science Data Center, 00044 Frascati, Italy

## 1 Introduction

After one century of experimental study, since Victor Hess' discovery in 1912, cosmic rays observations still play a preminent role in reconstructing the puzzle about the origin and evolution of the Universe. By means of balloon, satellite-borne and ground large size experiments, it has been possible to explore energy spectra and chemical composition of the cosmic radiation over an extremely wide energy range, spanning 21 orders of magnitude. As a consequence, the experimental results obtained in this field were and are able to shed light on several aspects of cosmology and astrophysics, from the low energy effects of Solar phenomena to the extremely energetic physics of the GZK region.

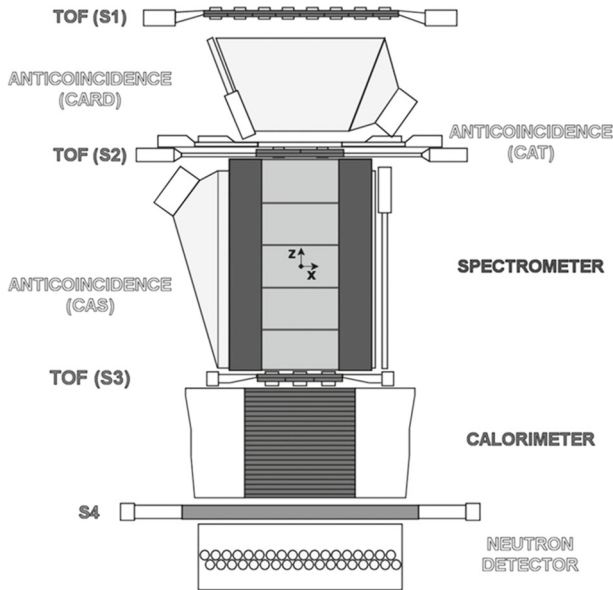
In the intermediate energy region before the so called "knee" an important topic is the evaluation of the antiparticle content. Antiprotons and positrons are a natural component of the cosmic radiation, being produced in the interaction between cosmic rays and the interstellar matter. The detection of antimatter of primary origin in the radiation would be a fundamental discovery because of the strict connection with the baryon-antibaryon asymmetry in the Universe. Moreover, an excess of antiparticles in our Galaxy could be a signature of dark matter annihilations.

The pioneering experiments of Golden [1] and Bogomolov [2], resulting in historical measurements of an antiproton excess, paved the way for several successors, either on balloons, performed mainly by the WIZARD, BESS and HEAT collaborations, and on-board the Space Shuttle, by the AMS-01 collaboration. Although the excess was not confirmed, the search for antimatter resulted in a better understanding of the background, mainly due to the estimation of secondary positrons and electrons. Nonetheless, all these experiments suffered of important limitations of statistical and systematic nature, depending on the short duration of flights and large background signals from Cosmic-Ray interactions with the residual atmosphere.

New satellite long-duration experiments have been devised with the aim of measuring antiprotons and positrons at unprecedented precision level. PAMELA [3] is the first of this new class of apparatus.

## 2 The PAMELA mission

The core of PAMELA apparatus is a magnetic spectrometer [4], consisting of a permanent magnet and a six-planes silicon tracking system, to measure the sign and the rigidity (momentum over charge) of charged particles through their deflection in the uniform 0.43 T magnetic field. A Time-of-Flight system [5], 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 [6], 16 radiation length deep with a rejection power of  $10^5$  for protons versus positrons, placed under the spectrometer. A neutron detector, at 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 [7]. A large scintillator under the calorimeter, acting as a shower tail catcher, and an anticoincidence system, useful to reject false trigger and multiparticle events produced by secondary particles generated inside the apparatus, complete the PAMELA instrument. A schematic drawing of the PAMELA detector is shown in Fig. 1.



**Fig. 1** Schematic drawing of the PAMELA detector

PAMELA has been inserted in a pressurized vessel and installed on board of the Russian satellite Resurs-DK1 dedicated to Earth observation. It was launched on 15th June 2006 in an elliptical orbit, ranging between 350 and 610 km, with an inclination of  $70^\circ$ ; since September 2010 the orbit has been changed to be circular, placing the satellite at a fixed altitude of 570 km.

Since July 2006 PAMELA is daily delivering about 16 Gigabytes of data to the Ground Segment in Moscow, for a total of  $\sim 5 \times 10^9$  recorded triggers.

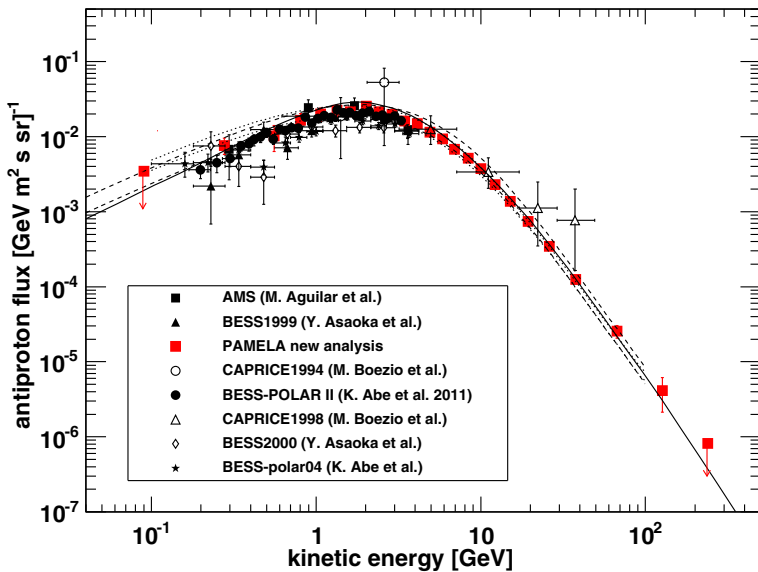
### 3 PAMELA results on antimatter

Starting from 2008 the PAMELA collaboration published data concerning many fields of charged cosmic ray physics. Studies of antimatter have been considered particularly interesting and received most attention of the scientific community.

The comparison between the antiproton-to-proton flux ratio (published in the 1-100 GeV energy range [8] and then upgraded in the wider range 60 MeV - 180 GeV [9]) and the positron fraction (published in the 1.5 - 100 GeV energy range [10, 11]) generated many interpretations and a lively discussion.

The positron fraction measured by PAMELA is significantly above the background expected from a standard production of positrons and electrons during propagation of cosmic ray protons and nuclei in the Galaxy [12]. Conversely, in the  $\bar{p}/p$  energy spectrum no excess is found with respect to the predicted background. A proper interpretation of those results requires a careful estimation of the expected antiparticle secondary production, in order to disentangle possible contributions from exotic sources of antiprotons and positrons.

The excess in the positron fraction reported by the PAMELA collaboration has been interpreted in many works as due to annihilation or decay of dark matter in the Galaxy



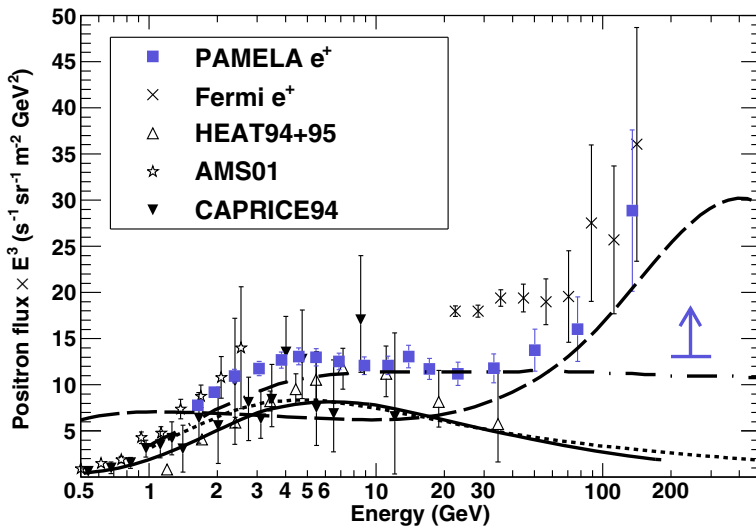
**Fig. 2** New PAMELA results on the antiproton energy spectrum from 60 MeV to 350 GeV, along with other recent measurements of the antiproton energy spectrum: CAPRICE94 [19], CAPRICE98 [20], BESS99-00 [21], BESS-POLAR04 [22], BESS-POLAR II [23], AMS-01 [24]. The *dotted lines* show the upper and lower limits calculated for a pure secondary production of antiprotons during the propagation of cosmic rays in the Galaxy for a Diffusion Reacceleration with Convection model [25]. The *solid line* shows a calculation [26] for the case of a Plain Diffusion model

(e.g. [13]). Alternatively, it has been ascribed to direct production of positrons by nearby pulsars (e.g. [14]), or due to pion production during stochastic acceleration of hadronic cosmic rays in nearby sources (e.g. [15]).

The PAMELA collaboration has published also the antiproton energy spectrum in the energy interval between 60 MeV and 180 GeV [9]. In this case PAMELA results are in agreement with the previous measurements, reproducing the expected peak around 2 GeV (due to the kinematic constraints on the antiproton production), and are in overall agreement with a pure secondary production. Nevertheless, 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 and set new stringent limits to dark matter annihilation and decay [16, 17].

Recently, PAMELA data acquired until January 2010 were reanalysed using a calorimeter-based antiproton selection analysis using multivariate algorithms [18]. Furthermore, the requirements on the tracking information were relaxed to extend the energy range up to  $\sim 400$  GeV. This resulted in an increased antiproton selection efficiency over the entire energy range, providing a  $\sim 40\%$  increase in the statistics of antiprotons. The resulting antiproton energy spectrum between 60 MeV and 350 GeV is shown in Fig. 2.

The most recent PAMELA result regards the precision measurement of the cosmic rays positron flux (reported in Fig. 3, together with other previous measurements) and fraction [27], the latter extending previously published measurements up to 300 GeV in kinetic energy. Such results, still showing a significant increase in the positron component at high energy, cannot be easily reconciled with purely secondary production and confirm the

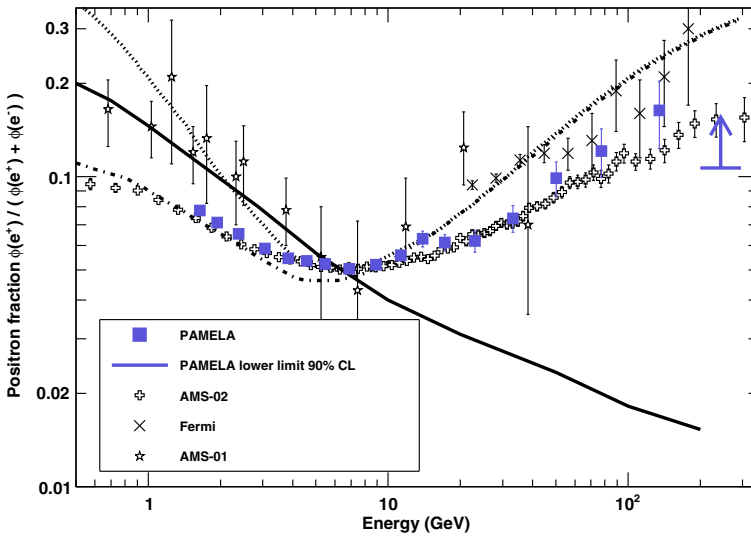


**Fig. 3** PAMELA data, from [27], superimposed to other recent measurements of the positron energy spectrum: CAPRICE94 [28], HEAT94+95 [29], AMS-01 [30], Fermi [31]. Notice that PAMELA, Fermi and AMS-01 results are from space-borne experiments. The PAMELA lower limit is that for a 90 % confidence level. PAMELA data points include both statistical and systematic errors. The *solid line* is the original GALPROP calculation [12] for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy. The *dotted and dash-dotted lines* show a recent calculation [32] for secondary and secondary plus primary (from astrophysical sources) positrons, respectively. The *dashed line* shows a calculation [33] for secondary plus primary positrons from dark matter annihilation

necessity of accounting for additional sources of either astrophysical or exotic origin, as it is noticeable comparing measurements to a few theoretical calculations, as in Figs. 3 and 4.

Innovative and useful information is also coming, and is currently a main topic for ongoing PAMELA data analysis, from the low energy part of the energy spectra and ratios, which is the region below  $\sim 10$  GeV where solar modulation dominates, for both leptons and hadrons (e.g. [36, 37]). As an example, new models of the solar modulation accounting for the polarity reversal of the magnetic field of the Sun have been developed [35] to explain the trend of PAMELA positron fraction below 10 GeV, measured during a  $A^-$  period, and the discrepancy with the measurement by AMS-01 [30], performed in a  $A^+$  period (theoretical curves calculated for both cases are reported in Fig. 4).

Another interesting result concerning antimatter in space was obtained by PAMELA: the first detection of antiprotons trapped in the Earth's magnetosphere [38]. The existence of a significant flux of antiprotons produced in nuclear interactions of energetic cosmic rays with the terrestrial atmosphere and accumulate in the geomagnetic field, predicted by several theoretical works, has been confirmed by the measurement of the trapped antiproton energy spectrum in the South Atlantic Anomaly (SAA) region, for the kinetic energy range 60-750 MeV, and of the atmospheric sub-cutoff antiproton spectrum outside the radiation belts. PAMELA results show that the magnetospheric antiproton flux in the SAA exceeds the cosmic ray antiproton flux by three orders of magnitude at the just passed solar minimum, and exceeds the sub-cutoff antiproton flux outside radiation belts by four orders of magnitude, constituting the most abundant source of antiprotons near the Earth.



**Fig. 4** Most recent PAMELA measurement of the positron fraction [27] and other results from space-borne experiments AMS-01 [30], Fermi [31] and AMS-02 [34]. Such new results are in agreement to those previously published by the collaboration [10, 11], extending the energy range to 300 GeV. The PAMELA lower limit is that for a 90 % confidence level. *Solid line* is GALPROP calculation [12] for a pure secondary production of positrons. The observed increase in the fraction above 10 GeV, incompatible with a pure secondary component of positrons originating in the propagation of cosmic rays, has been confirmed by Fermi and AMS-02. Fermi results are higher than PAMELA and AMS-02 data, which might indicate a residual proton contamination in the positron sample, but shows the same increasing trend as the energy increases. The discrepancy of both PAMELA and AMS-02 measurements with those from AMS-01, below 10 GeV, is instead well explained by the switch in the polarity of the solar magnetic field: dotted and dash-dotted curves are in fact recent calculations [35] that account for polarity + (well matching AMS-01 data) and - (at which PAMELA and AMS-02 measurements were performed)

#### 4 Conclusions

PAMELA has measured the cosmic-ray antiparticle energy spectra over some of the most extended energy range ever achieved with no atmospheric overburden. The positron data show interesting features: an increase in the abundance over the secondary expectation above 10 GeV and a time dependence at lower energies which is different from that observed for the electron flux. Two different scenarios have been proposed as an explanation of the positron excess: one involving standard astrophysics, e.g. nearby young pulsar or non-standard processes in the secondary production of positrons, and the other involving more exotic explanations, like dark matter annihilations. The antiproton spectrum is in agreement with standard secondary production models. This result places strong constraints on dark matter models since they usually do not predict an asymmetry between leptonic and hadronic production.

#### References

1. Golden, R.L., et al.: Evidence for the existence of cosmic ray anti-protons. *Phys. Rev. Lett.*, 43 (1979)
2. Bogomolov, E.A., et al.: A stratospheric magnetic spectrometer investigation of the singly charged component spectra and composition of the primary and secondary cosmic radiation. *Proc. 16th Int. Conf. on Cosmic Rays* 1, 330 (1979)

3. Picozza, P., et al: PAMELA: A payload for antimatter-matter exploration and light-nuclei astrophysics. *Astropart. Phys.* **27**, 296 (2007)
4. Adriani, O., et al: The magnetic spectrometer of the PAMELA satellite experiment. *Nucl. Instr. and Meth. A* **72**(2003), 511
5. Osteria, G., et al: *Nucl. Instr. and Meth. A* **152**, 535 (2004)
6. Boezio, M., et al: A high granularity imaging calorimeter for cosmic-ray physics. *Nucl. Instr. and Meth. A* **407**(2002), 487
7. Stozhkov, Y.I., et al: About separation of hadron and electromagnetic cascades in the pameLA calorimeter. *Int. J. Mod. Phys. A* **20**, 6745 (2005)
8. Adriani, O., et al: A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation. *Phys. Rev. Lett.* **102**, 051101 (2009)
9. Adriani, O., et al: PAMELA results on the cosmic-ray antiproton flux. *Phys. Rev. Lett.* **105**, 121101 (2010)
10. Adriani, O., et al: Observation of an anomalous positron abundance in the cosmic radiation. *Nature* **458**, 607 (2009)
11. Adriani, O., et al: A statistical procedure for the identification of positrons in the PAMELA experiment. *Astropart. Phys.* **34**, 1 (2010)
12. Moskalenko, I.V., Strong, A.W.: Production and propagation of cosmic - ray positrons and electrons. *Astrophys. J.* **493**, 694 (1998)
13. Bergstrom, L., et al.: New positron spectral features from supersymmetric dark matter - a way to explain the PAMELA data? *Phys. Rev. D* **78**, 103520 (2008)
14. Hooper, D., et al.: Pulsars as the sources of high energy cosmic ray positrons. *JCAP* **0901**, 025 (2009)
15. Blasi, P.: The origin of the positron excess in cosmic rays. *Phys. Rev. Lett.* **103**, 0151104 (2009)
16. Cirelli, M., Giesen, G.: Antiprotons from Dark Matter: current constraints and future sensitivities. *JCAP* **1304**, 015 (2013)
17. Cerdeno, G., et al.: Cosmic-ray antiproton constraints on light singlino-like dark matter candidates. *Nucl.Phys. B* **854**, 738 (2012)
18. Krzanowski, W.J.: *Principles of Multivariate Analysis: A Users Perspective*. Oxford University Press, New York (1988)
19. Boezio, M., et al: The Cosmic ray anti-proton flux between 0.62 GeV and 3.19 GeV measured near solar minimum activity. *Astrophys. J.* **487**, 415 (1997)
20. Boezio, M., et al.: The Cosmic ray anti-proton flux between 3 GeV and 49 GeV. *Astrophys J.* **561**, 787 (2001)
21. Asaoka, Y., et al.: Measurements of cosmic ray low-energy anti-proton and proton spectra in a transient period of the solar field reversal. *Phys. Rev. Lett.* **88**, 051101 (2002)
22. Abe, K., et al.: Measurement of cosmic-ray low-energy antiproton spectrum with the first BESS-Polar Antarctic flight. *Phys. Lett. B* **670**, 103 (2008)
23. Abe, K., et al.: Measurement of the cosmic-ray antiproton spectrum at solar minimum with a long-duration balloon flight over Antarctica (2011). arXiv:1107.6000
24. Aguilar, M., et al.: The alpha magnetic spectrometer (AMS) on the international space station. I: results from the test flight on the space shuttle. *Phys. Rept.* **366**, 331 (2002)
25. Donato, F., et al.: Constraints on WIMP dark matter from the high energy PAMELA pbar/p data. *Phys. Rev. Lett.* **102**, 071301 (2009)
26. Ptuskin, V.S., et al.: Dissipation of magnetohydrodynamic waves on energetic particles: impact on interstellar turbulence and cosmic ray transport. *Astrophys. J.* **642**, 902 (2006)
27. Adriani, O., et al.: Cosmic-ray positron energy spectrum measured by PAMELA. *Phys. Rev. Lett.* **111**, 081102 (2013)
28. Boezio, M., et al: The cosmic-ray electron and positron spectra measured at 1 AU during solar minimum activity. *Astrophys. J.* **532**, 653 (2000)
29. Du Vernois, M.A., et al.: Cosmic ray electrons and positrons from 1-GeV to 100-GeV: measurements with HEAT and their interpretation. *Astrophys. J.* **559**, 296 (2001)
30. Alcaraz, J., et al.: Leptons in near earth orbit. *Phys. Lett. B* **484**, 10 (2000)
31. Ackermann, M., et al.: Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope. *Phys. Rev. Lett.* **108**, 011103 (2012)
32. Delahaye, T., et al: Galactic electrons and positrons at the Earth: new estimate of the primary and secondary fluxes. *Astron. Astrophys. A* **51**, 524 (2010)
33. Finkbeiner, D.P., et al: Consistent scenarios for cosmic-ray excesses from sommerfeld-enhanced dark matter annihilation. *JCAP* **1105**, 002 (2011)
34. Aguilar, M., et al: First result from the alpha magnetic spectrometer on the international space station: precision measurement of the positron fraction in primary cosmic rays of 0.5350 GeV. *Phys. Rev. Lett.* **110**, 141102 (2013)



35. Maccione, L.: Low energy cosmic ray positron fraction explained by charge-sign dependent solar modulation. *Phys.Rev.Lett.* **1108**, 081101 (2013)
36. Adriani, O., et al.: Time dependence of the proton flux measured by PAMELA during the July 2006 - December 2009 solar minimum. *Astrophys. J.* **765**, 91 (2013)
37. Potgieter, M., et al.: Modulation of galactic protons in the heliosphere during the unusual solar minimum of 2006 to 2009 (2013). arXiv:[1302.1284](https://arxiv.org/abs/1302.1284) [astro-ph.SR]
38. Adriani, O., et al.: The discovery of geomagnetically trapped cosmic ray antiprotons. *Astrophys. J. Lett* **L29**, 737 (2011)