Brazilian Journal of Physics
ISSN: 0103-9733
luizno.bjp@gmail.com
Sociedade Brasileira de Física
Brasil

Braz J Phys (2014) 44:441–449
DOI 10.1007/s13538-014-0233-7

SOCIEDADE BRASILEIRA DE FÍSICA

Cosmic Ray Electrons and Protons, and Their Antiparticles

Mirko Boezio

Received: 28 April 2014 / Published online: 18 June 2014

Abstract Cosmic rays are a sample of solar, galactic, and extragalactic matter. Their origin, acceleration mechanisms, and subsequent propagation toward Earth have intrigued scientists since their discovery. These issues can be studied via analysis of the energy spectra and composition of cosmic rays. Protons are the most abundant component of the cosmic radiation, and many experiments have been dedicated to the accurate measurement of their spectra. Complementary information is provided by electrons, which comprise about 1 % of the cosmic radiation. Because of their low mass, electrons experience severe energy losses through synchrotron emission in the galactic magnetic field and inverse Compton scattering of radiation fields. Electrons therefore provide information on the local galactic environment that is not accessible from the study of the cosmic ray nuclei. Antiparticles, namely antiprotons and positrons, are produced in the interaction between cosmic ray nuclei and the interstellar matter. They are therefore intimately linked to the propagation mechanisms of the parent nuclei. Novel sources of primary cosmic ray antiparticles of either astrophysical (e.g., positrons from pulsars) or exotic origin (e.g., annihilation of dark matter particles) may exist. The nature of dark matter is one of the most prominent open questions in science today. An observation of positrons from pulsars would open a new observation window on these sources. Several experiments equipped with state-of-the art detector systems have recently presented results on the energy spectra of electrons, protons, and their antiparticles with a significant improvement in statistics and better control of systematics. The status of the field will be reviewed, with a focus on these recent scientific results.

Keywords ICRC2013 · Cosmic rays · Antiparticles

M. Boezio (✉)
INFN, Sezione di Trieste, 34149 Trieste, Italy
e-mail: mirko.boezio@ts.infn.it

1 Introduction

Cosmic rays are a sample of solar, galactic, and extragalactic matter that include all known nuclei and their isotopes, as well as electrons, positrons, and antiprotons. Their origin, acceleration mechanisms, and subsequent propagation toward Earth have intrigued scientists since their discovery. These issues can be studied through the analysis of the energy spectra and composition of the cosmic radiation.

The measured energy spectrum of all particle cosmic rays, shown in Fig. 1, covers roughly 32 orders of magnitude in flux and more than 15 in energy.

The cosmic ray particles, at least up to about 10^{15} eV, are considered to be of galactic origin, and diffusive shock acceleration at supernova remnants emerges as an ideal mechanism to supply their accelerations (see review talks [2, 3]). Once accelerated, particles undergo diffusive motion under the influence of the local magnetic field and remain confined within the Galaxy for about 10 million years (see, e.g., [2]). This random motion masks the direction of cosmic ray arrival, making the fluxes isotropic (although there are hints of anisotropy in the 10–100-TeV range [4–6]). During propagation, the particles undergo energy losses by ionization and hadronic interactions with the thermal nuclei of the interstellar medium.

Subsequently, the cosmic rays are affected by the solar wind when entering the heliosphere. Solar activity significantly affects the low-energy part of the gallactic cosmic

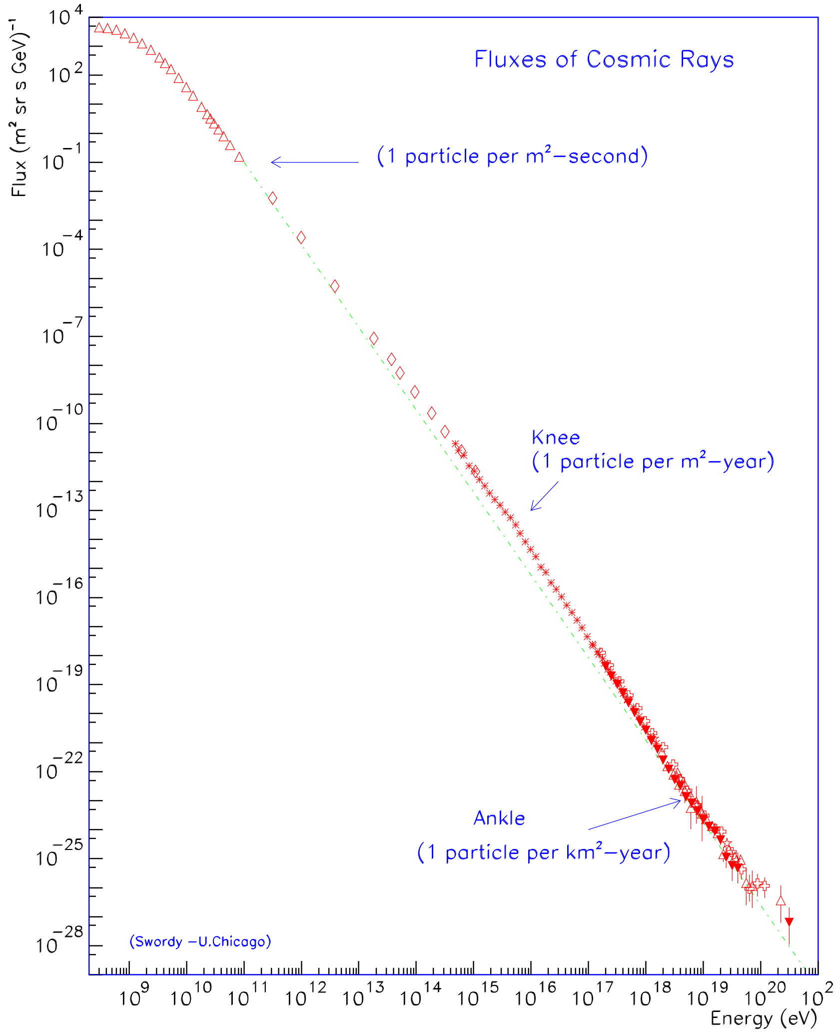

Fig. 1 All-particle cosmic ray energy spectrum. Figure from [1]

ray spectrum (below tens of GeV), which is suppressed and modulated by the solar magnetic cycle.

Hence, a precise measurement of the energy distribution of cosmic rays can be used to constrain models describing their origin and propagation in the Galaxy and in the heliosphere. Protons, the most abundant component of the cosmic radiation, are therefore perfectly suited for these studies, and over the years, many experiments have been dedicated to the accurate measurement of their energy spectrum.

2 Proton Measurements

Primary cosmic ray proton and helium nuclei spectra have been measured, over the years, both directly, with cosmic-radiation detectors on board satellites or high-altitude (≈40 km above sea level) balloons, and indirectly, with ground-based detectors sampling the shower produced by cosmic rays in the atmosphere.

Balloon- and space-borne experiments provide unambiguous detection of the proton component (more precisely, the hydrogen component, since separation between proton and deuterium has been achieved only up to ≈10 GeV/nucleon) sampling directly the primary cosmic radiation. Since protons are the most abundant cosmic ray species, the identification is relatively straightforward and performed with such charge detectors as scintillators. Precise measurement of the energies and absolute fluxes is challenging. Various techniques have been employed to measure the energy: magnet spectrometers (see, e.g., [13]) and RICH detectors [14] have been used for energies up to 1 TeV/n, while calorimetry measurements have covered higher energies (see, e.g., [7, 8]).

Figure 2 shows a compilation of direct proton flux measurements. Due to the steeply falling spectrum, data are

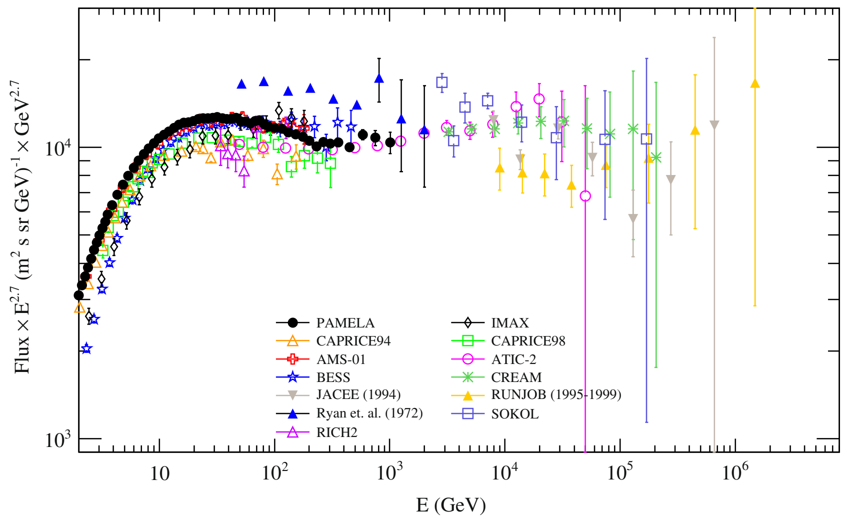

Fig. 2 Compilation of measurements of the proton (hydrogen) energy spectrum: Ryan et al. [8], SOKOL [9], RUNJOB [10], CREAM [11], ATIC-2 [12], CAPRICE98 [13], IMAX [15], RICH2 [16], JACEE [17] CAPRICE94 [18], BESS [19], AMS-01 [20], and PAMELA [21]

statistically limited to relatively low energies, usually well below the “knee” region (≈10^{15} eV). Ground-based detectors can extend measurements to higher energies, as the results from various ground arrays in Fig. 3 show. A few conclusions can be drawn from these data.

First, it should be noted that the fluxes in the figures are multiplied by $E^{2.7}$, where E is the energy in gigaelectronvolts. While depicting a clearer picture of the spectral shapes, this multiplication adds the absolute energy uncertainties to the flux uncertainties. The sharp deviation of the proton spectrum from a power-law behavior at low energies (<30 GeV) is due to solar modulation effects. The very large spread in the data at high energies is due to the uncertainties in the energy and particle identification associated with the measurements of atmospheric showers.

Also the direct measurements show differences well beyond the quoted statistical and systematic uncertainties. Given the relatively simple particle identification for these measurements, the likely sources of discrepancy are the efficiency and energy determinations. Selection efficiencies pose an experimental challenge, since they require very good knowledge of the detector performances during data collection. Efficiency uncertainties usually affect the absolute flux normalization and hence have less impact on the shape of the spectra. By contrast, precise energy measurements are essential. Various experiments employed different energy determination techniques, with different systematic uncertainties. Magnetic spectrometers measure the curvature of charged particles in a magnetic field, from which the rigidity and then the energy are derived. Very precise alignment of the tracking devices and mapping of the magnetic field are the key components of the rigidity/energy measurements. Calorimeters directly measure the particle energy, but weight considerations limit the depth of on-board calorimeters, hence allowing only partial containment of the particle energy. Calibration with test beams and extrapolation to the energy and flight conditions are the fundamental issues in such measurements.

Recent experiments have produced energy spectra in relatively good mutual agreement. The measurements by two balloon-borne experiments particularly have been significant: Advanced Thin Ionization Calorimeter (ATIC)-2 [12] and Cosmic Ray Energetics and Mass (CREAM) [11] and the space-borne magnetic spectrometer Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) [21]. At energies below 100 GeV, the PAMELA data are in good agreement with older magnetic spectrometer measurements (Alpha Magnetic Spectrometer (AMS)-01 [20], Cosmic Antiparticle Ring Imaging Cherenkov Experiment (CAPRICE)98 [13], and Balloon-borne Experiment with Superconducting Spectrometer (BESS) [19]). At higher energies, they are consistent with the calorimeter-based measurements by ATIC-2 and, when PAMELA fluxes are extrapolated to energies above 1 TeV, with the calorimeter-based measurements by CREAM. This agreement is quite interesting because the two types of experiments involve systematically different energy determination uncertainties.

The fluxes shows two interesting features:

- The proton and the helium spectra have different spectral shapes.
- The proton spectrum exhibits spectral hardening above 200 GeV.

These features may be due to injection and interstellar propagation effects. Their discussion is beyond the scope of this work; more details can be found in the review talk by Blasi [2].

During the conference, new results on the proton spectrum have been presented. The balloon-borne magnetic

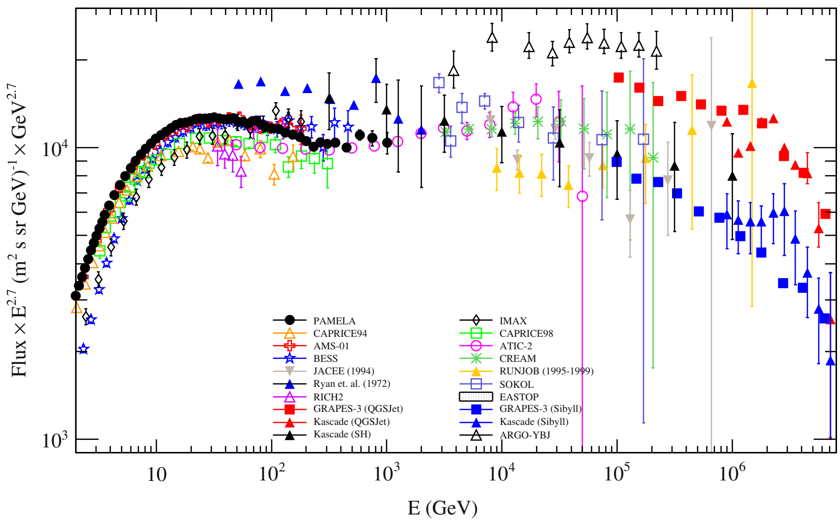

Fig. 3 Compilation of measurements of the proton (hydrogen) energy spectrum. Data from ground-based detectors: ARGO-YBJ [22], Kascade [23, 24], GRAPES-3 [25], and EASTOP [26] are shown along with the direct measurements from Fig. 2

spectrometer BESS-II, which flew over Antarctica in the winter of 2007, presented a preliminary high-statistics proton spectrum up to 120 GeV (and helium spectrum up to 60 GeV/n) [27], in excellent agreement with contemporary measurements by PAMELA. The magnetic spectrometer AMS-02 on board the International Space Station presented preliminary results on the proton and helium spectra with very high statistics up to $\simeq$1.8 TeV/n. The AMS data confirm the different spectral shapes between proton and helium, yielding a proton to helium flux ratio in good agreement with PAMELA result. However, the AMS proton spectrum, while in relatively good agreement with PAMELA data, shows no spectral hardening; instead, it is consistent with a single power law above $\sim$50 GeV. AMS is delivering and is expected to continue producing high-statistics data for the next decade, at least. In the next years, new spaceborne experiments designed to extend the direct detection of cosmic ray protons using calorimeters (e.g., ISS-CREAM [29], Calorimetric Electron Telescope (CALET) [30]) up to 10^{15}–10^{16} eV will start to take data.

Resolving the discrepancy between AMS and the previous results will significantly improve our understanding of the systematics in these measurements and hence provide a wealth of very precise data to test the cosmic ray paradigm.

3 Electron Measurements

Electrons are the most abundant negatively charged component of cosmic rays but constitute only about 1 % of the total cosmic ray flux. They provide important information regarding the origin and propagation of cosmic rays in the Galaxy that is not accessible from the study of the cosmic ray nuclear components due to their differing energy-loss processes. In fact, high-energy electrons are mostly of local origin due to the severe energy losses they suffer through synchrotron radiation in the galactic magnetic field and inverse Compton scattering with the ambient photons.

There are two possible origins of high-energy electrons in the cosmic radiation: primary electrons accelerated at sources such as supernova remnants (SNR) and secondary electrons produced by processes such as nuclear interactions of cosmic rays with the interstellar matter. SNRs are acceleration sites of cosmic ray electrons as shown by X-ray and teraelectronvolt gamma-ray measurements (e.g., see [31–33]).

As with protons, over the years, electrons have been detected by calorimeters, transition radiation detectors, magnetic spectrometers, and atmospheric-shower samplings. A calorimetric approach (either placed on a satellite or on a balloon or using the atmosphere as a calorimeter) provides sufficient energy resolution and acceptance to extend the measurement of the electron spectrum beyond 1 TeV. However, negative particles cannot be straightforwardly[1] separated from positive ones; hence, the energy spectrum refers to the sum of electrons and positrons. Magnetic spectrometers provide a clear sign of charge separation; however, their relatively small acceptance usually limits the identification of this rare cosmic ray component to a few hundred gigaelectronvolts. Figure 4 shows the e^- energy spectrum measured by recent cosmic ray experiments [41–45] (the highest data point from High-Energy Antimatter Telescope (HEAT) [42] refers to the sum of electrons and positrons) along with measurements of the all-electron spectrum [34, 36, 38, 39]. Like the proton spectrum, at low energies (<30 GeV), the electron spectrum is significantly affected by solar modulation.

[1]The Fermi Collaboration was able to separate electrons from positrons using the curvature of cosmic rays in the magnetic field of the Earth, derived from the arrival direction of the particle into the apparatus, a map of the Earth magnetic field, and the location of the satellite [46].

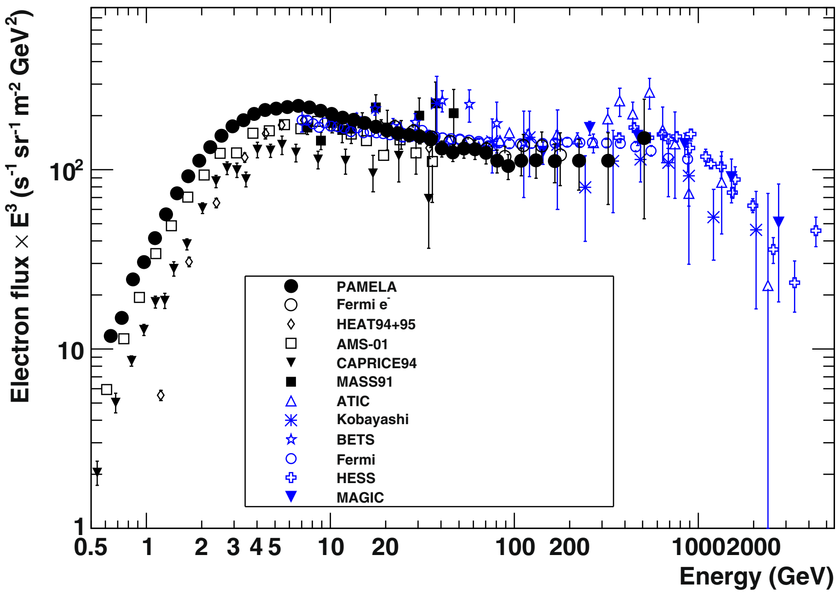

Fig. 4 Recent measurements of the cosmic ray e⁻ energy spectrum: CAPRICE94 [41], HEAT [42], AMS [43], MASS91 [44], PAMELA [45] and Fermi [46]; and the all-electron energy spectrum, indicated by the *blue symbols*, measured by Kobayashi[34], PPB-BETS [35], ATIC [36], H.E.S.S. [37, 38], Fermi [39], and MAGIC [47]. The fluxes are multiplied by E^3, where E is the energy in gigaelectronvolts

Figure 5 shows the high-energy part of the electron spectrum measured by various experiments along with a theoretical calculation based on the popular GALPROP code [90] assuming a diffusive reacceleration propagation (with propagation parameters from [79]) of primary electrons accelerated at SNR and secondary ones produced by cosmic rays interacting with the interstellar medium. At high energies, the electron spectrum is harder than expected from propagation models. The spectral flattening can be reproduced by standard cosmic ray models by adjusting the injection spectrum at source; however, these models cannot explain the positron fraction data (see next section). The hardening has been interpreted as a contribution from new sources ranging from astrophysical objects such as pulsars (e.g., [48]) or more exotic ones such as dark matter particles (e.g., [49]). Also, the excess at energies between 300 and 800 GeV reported by the ATIC Collaboration [36] (see Fig. 4) has been interpreted in terms of a dark matter signal or a contribution of a nearby pulsar. The same energy region was originally probed by the balloon-borne experiment by Kobayashi et al. [34] and later on by the balloon-borne experiment Polar Patrol Balloon-borne Electron Telescope with Scintillating fibers (PPB-BETS) [35], by the satellite-borne experiment Fermi [39, 40], and by the atmospheric Cherenkov experiments High-Energy Stereoscopic System (HESS) [37, 38] and Major Atmospheric Gamma Imaging

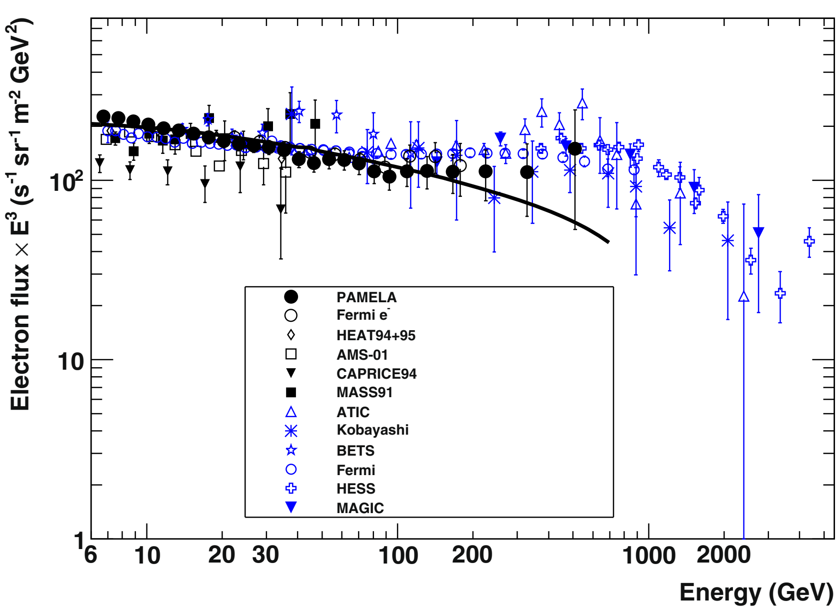

Fig. 5 Data as in Fig. 4 (*black symbols*, e⁻ spectrum; *blue symbols*, all-electron energy spectrum) compared to a theoretical calculation based on the GALPROP code [90]

Cherenkov (MAGIC) [47]. Figure 4 shows that the recent measurements by Fermi, HESS and MAGIC are consistent with the ATIC results within statistical and systematic uncertainties, but they do not confirm this structure in the spectrum.

At the conference, new results on the all-electron and on the e^- spectra from ≈1 GeV to more than 500 GeV were presented by the AMS Collaboration . The results significantly improve the existing e^- statistics and are in good agreement with the previous measurements by PAMELA showing a slightly softer spectrum than those measured by Fermi. Also, the Cosmic Ray Electron Synchrotron Telescope (CREST) Collaboration presented their maiden balloon flight that took place in Antarctica in winter 2011 [28]. Using the novel technique of detecting synchrotron radiation of primary electrons as they pass through the Earth's magnetic field, CREST samples the very high-energy part of the cosmic ray electron spectrum from a few teraelectronvolts up to tens of teraelectronvolts.

The near future is very promising for electron measurements. Along with the extended measurements by AMS and CREST, new space-borne experiments such as CALET [30], DAMPE [51] and GAMMA-400 [50] have been designed to study the all-electron cosmic ray spectra and will be placed in orbit in the next years.

4 Antiparticles

Cosmic ray positrons and antiprotons were first observed during pioneering experiments in the 1960s [52] and late 1970s [53, 54], respectively, using balloon-borne magnetic spectrometers. While not the only way for detecting antiparticles, magnetic spectrometers provide a robust, simple separation between particles and their antipartners.

Measurements of cosmic ray antiparticles (antiprotons and positrons) address a number of questions in contemporary astrophysics, such as the nature and distribution of particle sources in our Galaxy, and the subsequent propagation of cosmic rays through the Galaxy and the solar magnetosphere. Antiparticles are a natural component of the cosmic radiation being produced in the interaction between cosmic rays and the interstellar matter. The first measurements of the antiproton-to-proton flux ratio and of the positron fraction at high energy pointed toward an excess of antiparticles relative to the expectations [55, 56]. Particularly significant was the first measurement of low-energy antiproton by Buffington et al. [57], obtained using a calorimetric approach, that reported a large, 2 orders of magnitude higher than expected antiproton signal at energies of a few hundred megaelectronvolt. Such results prompted the study of novel sources of primary cosmic ray antiparticles of either astrophysical or exotic origin. For example, primary antiprotons can be produced by the annihilation of dark matter particles [58, 59] and by the evaporation of primordial black holes [60, 61]. Positrons can be produced through pair production processes in the magnetosphere of pulsars (for example, see [62]) from which they can escape into the interstellar medium contributing to the cosmic ray positron (and electron) components. Furthermore, positrons can be a product of dark matter annihilation [63–69].

Recently, a series of cosmic ray experiments, equipped with state-of-the art detectors, have provided a wealth of new data significantly improving the existing statistics and energy range. Figures 6 and 7 show the antiproton-to-proton flux ratio and the antiproton energy spectrum measured by recent cosmic ray experiments [70–75, 77].

These new experimental data reproduce the falloff below around 2 GeV, characteristic of a secondary spectrum, in the antiproton flux and are in overall agreement with pure secondary calculations (e.g., [79]). The good agreement between the experimental data and the calculations of secondary-produced antiprotons can be used to significantly constrain models of galactic dark matter such as those predicting heavy weakly interacting massive particle (WIMP) candidates (e.g., [78]). As stated in [80], these recent results and the expected data from AMS-02 allow to probe large regions of the parameter space for annihilation and decay of dark matter particles on par with gamma rays.

Figures 8 and 9 show the positron fraction, ratio of positron and all-electron fluxes, and the positron energy spectrum measured by recent cosmic ray space- [43, 81–83] and balloon-borne [41, 42, 84–87, 89] experiments.

Two features are clearly visible in the data. At low energies (below 5 GeV), PAMELA [81], Aesop [89], and AMS-02 [83] results are systematically lower than other data, while at high energies (above 10 GeV), they show that the e^+ spectrum is harder than the e^- one opposite to the expectation for secondary production (e.g., see [90]). The low-energy discrepancy with data collected during the 1990s, i.e., from the previous solar cycle that favored positively-charged particles, are interpreted as a consequence of solar modulation effects.

In order to explain the positron excess, many explanations invoking more-or-less exotic sources have been proposed (e.g., see [91]. Also, a few ideas concerning subtleties of cosmic ray propagation have been put forward. For more details on these explanations, see [92].

As for the case of the flattening of the electron spectrum, astrophysical sources such as pulsars have been considered. Primary electrons are accelerated in the magnetosphere of pulsars resulting in the emission of synchrotron gamma rays. In the presence of the pulsar magnetic field, these gamma rays can produce positron and electron pairs. These can escape into the interstellar medium after $\sim 10^4$–10^5 years when the pulsar leaves the nebula, thus

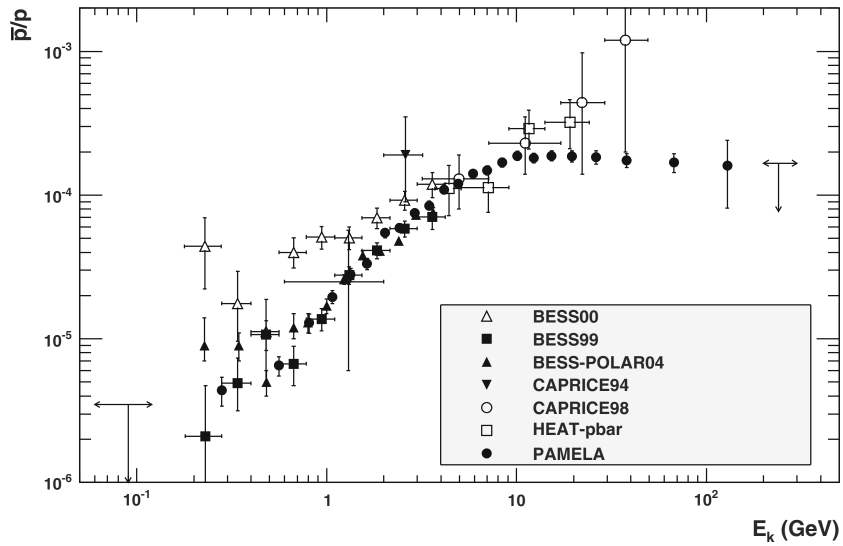

Fig. 6 Recent measurements of the antiproton-to-proton flux ratio: HEAT-pbar [73], CAPRICE94 [71], CAPRICE98 [72], BESS99-00 [74], BESS-POLAR04 [75], and PAMELA [70]. The PAMELA and AMS-01 results are from space-borne experiments

contributing to the high-energy electron and positron cosmic ray components (e.g., [95]). Several calculations (e.g., [93, 94]) have been undertaken taking into account this contribution, and they have shown that the positron component can be explained by a few prominent astrophysical sources.

Positrons can also be produced at SNR if secondary production takes place also in the same region where cosmic rays are being accelerated. In this case, an increase in the positron fraction, as well as in other secondary components (e.g., antiprotons), at high energy can be explained [96–98].

Like antiprotons, positrons can result from the annihilation of dark matter particles. While intriguing, such an explanation is challenged by the asymmetry between the leptonic (positrons) and hadronic (antiprotons) PAMELA data. Such an asymmetry is difficult to explain in a framework where the neutralino is the dominant dark matter component. In this case, a suitable explanation requires a very high-mass neutralino; another possibility is a direct leptonic annihilation channel over a wide range of the WIMP mass (e.g., [49]).

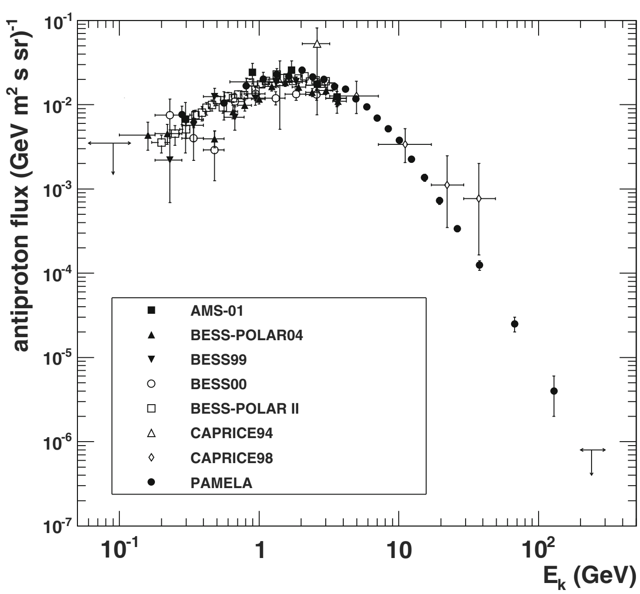

Fig. 7 Recent measurements of the antiproton energy spectrum: CAPRICE94 [71], CAPRICE98 [72], BESS99-00 [74], BESS-POLAR04 [75], BESS-POLAR II [76], AMS-01 [77], and PAMELA [70]. The PAMELA and AMS-01 results are from space-borne experiments

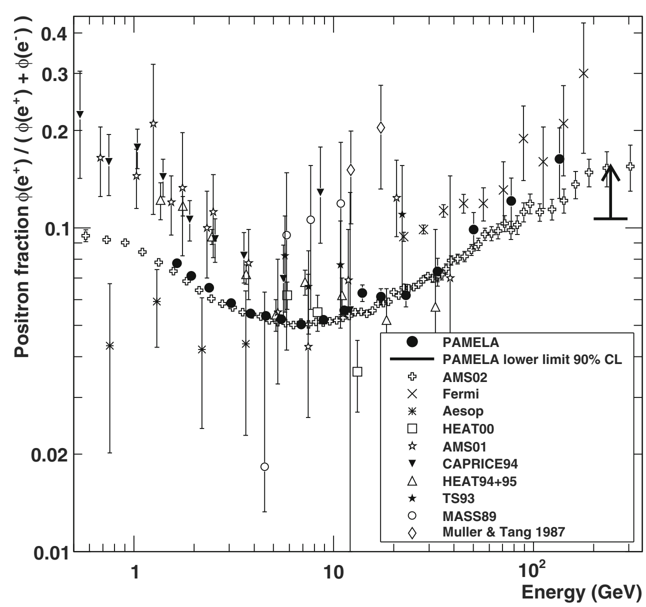

Fig. 8 Recent measurements of the positron fraction (*left*): Müller & Tang [84], MASS89 [85], TS93 [86], HEAT94+95 [87], CAPRICE94 [41], AMS-01 [43, 82], Aesop [89], Fermi [46], and PAMELA [81], and AMS-02 [83]. The PAMELA, Fermi, AMS-01, and AMS-02 results are from space-borne experiments. The PAMELA lower limit is at the 90 % confidence level

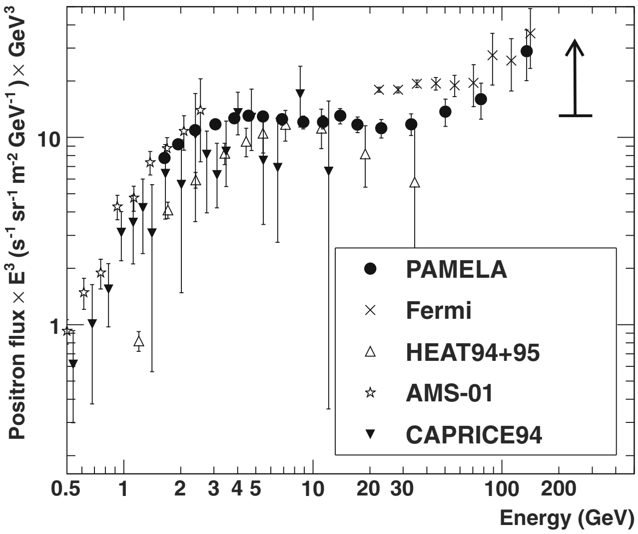

Fig. 9 Recent measurements of the positron energy spectrum (*right*): CAPRICE94 [41], HEAT94+95 [42], AMS-01 [43], Fermi [46], and PAMELA [81]. The PAMELA, Fermi, and AMS-01 results are from space-borne experiments. The PAMELA lower limit is 90 % confidence level

Another antiparticle, the antideuteron, has the potential to clarify this issue. Antideuterons have not yet been observed in the cosmic radiation but a secondary component; likewise, antiprotons and positrons are expected. The detection of antideuterons is a challenging measurement because of the extremely low secondary flux, about 4 orders of magnitude smaller than the antiproton flux. However, the rewards of the detection can be very high since a possible primary component due to dark matter annihilation, if it exists, is expected to be about a factor 10 larger than the secondary flux in the few hundred megaelectron-volts/nucleon range [99]. This measurement requires very large acceptance/exposure time and extremely high identification power. Two experiments, one of which is already taking data, might yield results in the near future: AMS-02 and GAPS [100].

5 Conclusions

Cosmic ray physics is a fascinating field, fertile and rich with scientific potentials. Several important experiments are measuring, or are going to measure the cosmic ray energy spectra, their composition and their antimatter component with unprecedented precision. Important results have already been published, and more is to come.

Acknowledgments We would like to thank P. Blasi, D. Caprioli, and P. Serpico for helpful discussions on the experimental data and their relevance, and V. Formato and E. Mocchiutti for helping in the production of several figures. This work was supported in part by the National Science Foundation under Grant No. PHYS-1066293, by the Simons Foundation and the hospitality of the Aspen Center for Physics.

References

1. J. Cronin, T.K. Gaisser, S.P. Swordy, Sci. Amer. **276**, 44 (1997)
2. P. Blasi, *Recent results in cosmic ray physics and their interpretation*, this volume (2014)
3. A.R. Bell, *Particle acceleration by shocks in supernova remnants*, this volume (2014)
4. M. Amenomori, et al., Sci. **314**, 439 (2006)
5. A.A. Abdo, et al., Astrophys. J. **698**, 2121 (2009)
6. R. Abbasi, et al., Astrophys. J. **718**, L194 (2009)
7. V.V. Akimov, et al., *Proceedings of 11th International Cosmic Ray Conference*, vol. 29, p. 517 (1970)
8. M.J. Ryan, J.F. Ormes, V.K. Balasubrahmanyan, Phys. Rev. Lett. **28**, 985 (1972)
9. I.P. Ivanenko, et al., *Proceedings of 23rd International Cosmic Ray Conference*, vol. 2, p. 17 (1993)
10. M. Hareyama, et al., J. Phys. Conf. Ser. **31**, 159 (2006)
11. H.S. Ahn, et al., Astrophys. J. Lett. **714**, L89 (2010)
12. J.P. Wefel, et al., *Proceedings of 30th International Cosmic Ray Conference* vol. 2, p. 31 (2008)
13. M. Boezio, et al., Astropart. Phys. **19**, 583 (2003)
14. J. Buckley, et al., Astrophys. J. **429**, 736 (1994)
15. W. Menn, et al., Astrophys. J. **533**, 281 (2000)
16. E. Diehl, et al., Astropart. Phys. **18**, 487 (2003)
17. K. Asakimori, et al. Astrophys. J. **502**, 278 (1998)
18. M. Boezio, et al., Astrophys. J. **518**, 457 (1999)
19. S. Haino, et al., Phys. Lett. B. **594**, 35 (2004)
20. J. Alcaraz, et al., Phys. Lett. B. **490**, 27 (2000)
21. O. Adriani, et al., Science. **332**, 69 (2011)
22. S.M. Mari, et al., *Proceedings of 32nd International Cosmic Ray Conference* (2011)
23. T. Antoni, et al., Astrophys. J. **612**, 914 (2004)
24. T. Antoni, et al., Astropart. Phys. **24**, 1 (2005)
25. Y. Hayashi, et al., *Proceedings 29th International Cosmic Ray Conference*, vol. 10, p. 243 (2005)
26. M. Aglietta, et al., Astropart. Phys. **19**, 329 (2003)
27. K. Sakai, *Proceedings of 33rd International Cosmic Ray Conference* (2013)
28. S. Coutu, *Proceedings of 33rd International Cosmic Ray Conference* (2013)
29. W.V. Jones, *Proceedings of 33rd International cosmic Ray Conference*, this volume (2013)
30. P.S. Marrocchesi, Nucl. Instrum. and Meth. A. **692**, 240 (2012)
31. G.E. Allen, et al., Astrophys. J. Lett. **487**, L97 (1997)
32. F. Aharonian, et al., Nat. **432**, 675 (2004)
33. A.A. Abdo, et al., Astrophys. J. **734**, 28 (2011)
34. T. Kobayashi, et al., *Proceedings of 26th International Cosmic Ray Conference*, vol. 3, p. 61 (1999)
35. S. Torii, et al., (2008). arXiv:0809.0760
36. J. Chang, et al., Nat. **456**, 362 (2008)
37. F. Aharonian, et al., Phys. Rev. Lett. **101**, 261104 (2008)
38. F. Aharonian, et al., Astron. Astrophys. **508**, 561 (2009)
39. M. Ackermann, et al., Phys. Rev. D. **82**, 092004 (2010)
40. A.A. Abdo, et al., Phys. Rev. lett. **102**, 181101 (2009)
41. M. Boezio, et al., Astrophys. J. **532**, 653 (2000)
42. M.A. DuVernois, et al., Astrophys. J. **559**, 296 (2001)
43. J. Alcaraz, et al., Phys. Lett. B. **484**, 10 (2000)
44. C. Grimani, et al., Astron. Astrophys. **392**, 287 (2002)
45. O. Adriani, et al., Phys. Rev. Lett. **106**, 201101 (2011)
46. M. Ackermann, et al., Phys. Rev. Lett. **108**, 011103 (2012)

47. D. Borla Tridon, et al., *Proceedings of 32nd International Cosmic Ray Conference*, vol. 6, p. 47 (2011)
48. D. Malyshev, I. Cholis, J. Gelfand, Phys. Rev. D. **80**, 063005 (2009)
49. M. Cirelli, et al., Nucl. Phys. B. **813**, 1 (2008)
50. A. Galper, et al. Astrophys. Space Sci. Trans. **7**, 75 (2011)
51. P. Wang, et al., arXiv:1309.7638 (2013)
52. J.A. De Shong, R.H. Hildebrand, P. Meyer, Phys. Rev. Lett. **12**, 3 (1964)
53. R.L. Golden, et al., Phys. Rev. lett. **43**, 1196 (1979)
54. E.A. Bogomolov, et al., *Proceedings of 16th International Cosmic Ray Conference*, vol. 1, p. 330 (1979)
55. T.K. Gaisser, E.H. Levy, Phys. Rev. D. **10**, 1731 (1974)
56. R.J. Protheroe, Astrophys. J. **254**, 391 (1982)
57. A. Buffington, et al., Astrophys. J. **248**, 1179 (1981)
58. G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. **267**, 195 (1996)
59. L. Bergstro¨m, Rep. Prog. Phys. **63**, 793 (2000)
60. S. Hawking, Nat. **248**, 30 (1974)
61. P. Kiraly, et al., Nature. **293**, 120 (1981)
62. A.M. Atoyan, F.A. Aharonian, H.J. Volk, Phys. Rev. D. **52**, 3265 (1995)
63. A.J. Tylka, Phys. Rev. lett. **63**, 840 (1989)
64. M.S. Turner, F. Wilczek, Phys. Rev. D. **42**, 1001 (1990)
65. M. Kaminkowski, M.S. Turner, Phys. Rev. D. **43**, 1774 (1990)
66. G.L. Kane, L.L. Wang, J.D. Wells, Phys. Rev. D. **65**, 057701 (2002)
67. E.A. Baltz, et al., Phys. Rev. D. **65**, 063511 (2002)
68. E.A. Baltz, L. Bergström, Phys. Rev. D. **67**, 043516 (2003)
69. G. Bertone, D. Hooper, J. Silk, Phys. Rept. **405**, 279 (2005)
70. O. Adriani, et al. Phys. Rev. Lett. **105**, 121101 (2010)
71. M. Boezio, et al., Astrophys. J. **487**, 415 (1997)
72. M. Boezio, et al., Astrophys. J. **561**, 787 (2001)
73. A.S. Beach, et al., Phys. Rev. Lett. **87**, 271101 (2001)
74. Y. Asaoka, et al., Phys. Rev. Lett. **88**, 051101 (2002)
75. K. Abe, et al., Phys. Lett. B. **670**, 103 (2008)
76. K. Abe, et al., Phys. Rev. Lett. **108**, 051102 (2012)
77. M. Aguilar, et al., Phys. Rep. **366**, 331 (2002)
78. F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, Phys. Rev. Lett. **102**, 071301 (2009)
79. V.S. Ptuskin, et al., Astrophys. J. **642**, 902 (2006)
80. M. Cirelli, G. Giesen, JCAP. **1304**, 015 (2013)
81. O. Adriani, et al., Phys. Rev. Lett. **111**, 081102 (2013)
82. M. Aguilar, et al., Phys. Lett. B. **670**, 103 (2008)
83. M. Aguilar, et al., Phys. Rev. Lett. **110**, 141102 (2013)
84. D. Müller, K. K. Tang, Astrophys. J. **312**, 183 (1987)
85. R.L. Golden, et al., Astrophys. J. **436**, 769 (1996)
86. R.L. Golden, et al., Astrophys. J. **457**, L103 (1996)
87. S.W. Barwick, et al., Astrophys. J. **482**, L191 (1997)
88. J.J. Beatty, et al., Phys. Rev. Lett. **93**, 241102 (2004)
89. J. Clem, P. Evenson, *Proceedings of 30th International Cosmic Ray Conference (Pune)* (2007)
90. A.W. Strong, I.V. Moskalenko, Astrophys. J. **493**, 694 (1998)
91. M. Boezio, et al., New J. Phys. **11**, 105023 (2009)
92. M. Israel, *Proceedings of 33rd International cosmic Ray Conference*, this volume (2013)
93. T. Delahaye, J. Lavalle, R. Lineros, F. Donato, N. Fornengo, Astron. Astrophys. **524**, A51 (2010)
94. D. Gaggero, et al., Phys. Rev. lett. **111**, 021102 (2013)
95. P. Blasi, E. Amato. arXiv:1007.4745 (2010)
96. P. Blasi, Phys. Rev. Lett. **103**, 051104 (2009)
97. Y. Fujita, K. Kohri, R. Yamazaki, K. Ioka, Phys. Rev. D. **80**, 063003 (2009)
98. M. Ahlers, P. Mertsch, S. Sarkar, Phys. Rev. D. **80**, 123017 (2009)
99. F. Donato, N. Fornengo, P. Salati, Phys. Rev. D. **62**, 043003 (2000)
100. C.J. Hailey, et al., Adv. Space Res. **51**, 290 (2013)