Recent PAMELA measurements of proton and helium nuclei and cosmic ray acceleration in the galaxy

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Abstract: PAMELA is a satellite borne experiment designed to study with great accuracy cosmic rays of galactic, solar, and trapped nature in a wide energy range (protons: 80 MeV-700 GeV, electrons 50 MeV-400 GeV). Main objective is the study of the antimatter component: antiprotons (80 MeV-190 GeV), positrons (50 MeV-270 GeV) and search for antinuclei with a precision of the order of 10^{-8}). The experiment, housed on board the Russian Resurs-DK1 satellite, was launched on June, 15^{th} 2006 in a 350×600 km orbit with an inclination of 70°. In this work we report on the recent results on proton and helium of galactic origin: data show several deviations from the pure power law spectrum. Furthermore the ratio proton/helium decreases with increasing rigidity,, hinting to different processes or sources undergone by the two species.

Keywords: cosmic rays, antimatter, dark matter

1 Introduction

The scientific program of the Wizard collaboration is devoted to the study of cosmic rays through balloon and satellite-borne devices. Aims of this research involve the precise determination of the antiproton [1] and positron [2] spectra, search of antimatter, measurement of low energy trapped and solar cosmic rays with the NINA-1 [3] and NINA-2 [4] satellite experiments. Other research on board Mir and International Space Station has involved the measurement of the radiation environment, the nuclear abundances and the investigation of the Light Flash [5] phenomenon with the Sileye experiments [6, 7]. PAMELA is the largest and most complex device built insofar by the collaboration, with the broadest scientific goals. In this work we describe the recent results on proton and helium of galactic origin.

2 PAMELA detector

PAMELA is constituted by a number of highly redundant detectors capable of measuring charge, rigidity and velocity of particles over a very wide energy range. The instrument is built around a permanent magnet with a silicon microstrip tracker and a scintillator system to provide trigger, charge and time of flight information. A silicon-tungsten calorimeter is used to perform hadron/lepton separation. A shower tail catcher and a neutron detector at the bottom of the apparatus are also employed to improve this separation. An anticounter system rejects off line spurious events produced in the side of the main body of the satellite. Around the detectors are housed the readout electronics, the interfaces with the CPU and all primary and secondary power supplies. All systems (power supply, readout boards etc.) are redundant with the exception of the CPU which is more tolerant to failures. The system is enclosed in a pressurized container located on one side of the Resurs-DK1 satellite. Total weight of PAMELA is 470 kg; power consumption is 355 W, geometrical factor is 21.6 cm^2 sr. A more detailed description of the device and the data handling can be found in [8, 9, 10]. The satellite was launched on June 15^{th} 2006 in a 70° inclination 350×600 km elliptical orbit around the Earth [11] and - at the time of writing - has been working for more than four years.

3 Galactic Cosmic rays

Since the discovery of cosmic rays, various mechanisms have been proposed to explain the acceleration of particles to relativistic energies and their subsequent propagation in the Galaxy. It was pointed out long ago (e.g. [12, 13]) that supernovae fulfill the power requirement to energize galactic cosmic rays. Subsequently, models were put forward to explain the acceleration of cosmic ray particles as diffusive shock acceleration (“first order Fermi mechanism”) produced by supernova (SN) shock waves propagating in the

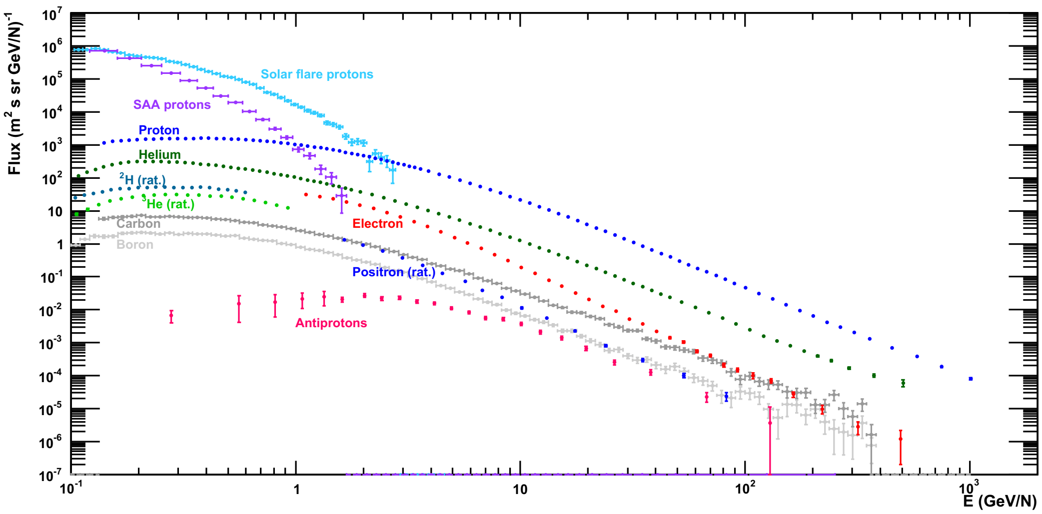

Figure 1: Differential spectrum of particles measured with PAMELA. The most abundant component is due to protons of galactic origin, with solar particles increasing by several orders of magnitude for a short time. Trapped particles in the inner Van Allen belt dominate in some regions of Low Earth Orbit. The antiparticle component of antiprotons and positrons is the least abundant one. Deuterium, He^3 and e^+ fluxes have been calculated from the ratios.

interstellar medium (see [14, 15] for a review). This simple SN-only paradigm has been challenged several times in the past with authors introducing several different sources or acceleration models to describe data in the 1 - 10^7 GeV range [16, 17].

Evidence for SN shock acceleration of cosmic rays to a maximum energy of $\simeq 3 \times 10^{15}$ eV comes from a number of observations. For example, TeV emission from the young supernova remnant (SNR) RX J1713.7-3946, detected by the H.E.S.S. collaboration [18], has been interpreted as originating from hadronic interactions of cosmic rays with energies above 10^{14} eV in the shell of the SNR (even though leptonic processes cannot be ruled out [19]). X-ray measurements of the same SNR provide evidence that protons and nuclei can be accelerated to energies $\geq 10^{15}$ eV [20]. Recent AGILE observations of diffuse gamma ray emission in the 100 MeV - 1 GeV range from the outer shock region of SNR IC 443 have been explained in terms of hadronic acceleration [21]. Likewise, Fermi observations of the shell of SNR W44 have been attributed to the decay of π^0s produced during interactions of accelerated hadrons with the interstellar medium [22].

The hypothesis that cosmic rays are accelerated in supernova explosions is further corroborated by observations of other galaxies. In starburst galaxies (SG), the SN rate at the galactic center is much higher than in the Milky Way and the density of cosmic rays deduced from observations of TeV gamma rays is much higher. This has been confirmed by H.E.S.S. which measures gamma rays with energies ≥ 220 GeV. At the end of the acceleration phase, particles are injected into the interstellar medium where they propagate, diffusing in the turbulent galactic magnetic fields. Nowadays, this propagation is well described by solving numerically (e.g. the GALPROP simulation code [23]) or analytically (e.g. [24]) the transport equations for the particle diffusion in the Galaxy. One of the most striking features of cosmic ray spectra measured prior to PAMELA observations is that they are apparently featureless. Up to now, the spectra have been described by a single power law for each species, with similar spectral indices ($\gamma \simeq -2.7$) for protons and heavier nuclei, up to energies of $\approx 10^{15}$ eV (the so called 'knee' region) as predicted by the shock diffusion acceleration model and diffusive propagation in the Galaxy. Recent PAMELA measurements of the antiparticle component of the cosmic radiation [2, 25, 26] have prompted a re-evaluation of possible contributions from additional galactic sources, either of astrophysical (such as pulsars [27]) or exotic (dark matter [28]) origin. A precise determination of the proton and helium fluxes, the most abundant components in cosmic rays, is of crucial importance for the understanding of astrophysical phenomena taking place in the Galaxy, in the galactic neighborhood of the Sun (1-2 kpc radius) and within the solar system. With a detailed knowledge of cosmic ray spectra it will be possible to: a) identify sources and acceleration/propagation mechanisms of cosmic rays; b) estimate the production of secondary particles, such as positrons and antiprotons, in order to disentangle the secondary particle component from possible exotic sources; c) estimate the particle flux in the geomagnetic field and in Earth's atmosphere for in-orbit dose estimations and to derive the atmospheric muon and neutrino flux. In Figure 2 are shown the proton and helium fluxes measured with PAMELA as function of the kinetic energy. It is possible to see the good agreement with previous measurements below 100 GeV. Below about 30 GeV, the differences are due to different solar modulation conditions between the various measurements. At $\simeq$ 200 GV both spectra show an increase of the flux, hinting probably to an additional source which is injecting particles above this energy.

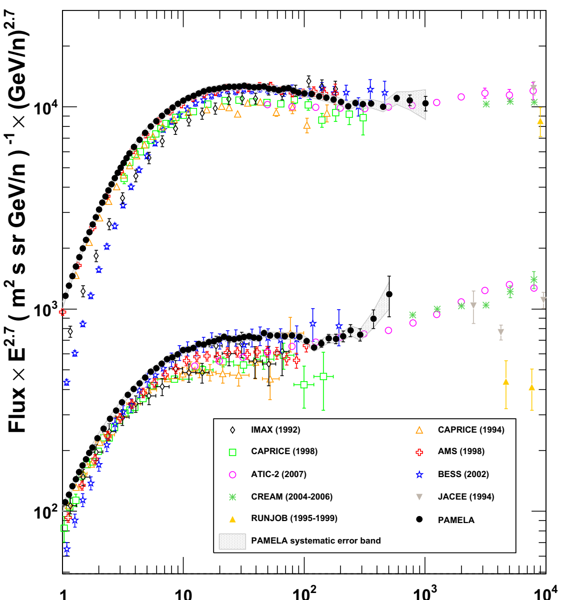

Figure 2: Proton and helium absolute fluxes measured by PAMELA above 1 GeV/n, compared with some previous measurements [29, 30, 31, 32, 33, 34, 35, 36]. Error bars are statistical, the shaded area represents the estimated systematic uncertainty. From the plots it is possible to see the different spectral indexes for the two species and a change in the spectral slopes above $\simeq$ 200 GeV/n.

References

[1] O. Adriani, *et al.*, *Physical Review Letters* **102**, 051101 (2009).

[2] O. Adriani, *et al.*, *Nature* **458**, 607 (2009).

[3] V. Bidoli, *et al.*, *ApJS* **132**, 365 (2001).

[4] V. Bidoli, *et al.*, *Journal of Geophysical Research (Space Physics)* **108**, 1211 (2003).

[5] M. Casolino, *et al.*, *Nature* **422**, 680 (2003).

[6] V. Bidoli, *et al.*, *Journal of Physics G Nuclear Physics* **27**, 2051 (2001).

[7] M. Casolino, *et al.*, *Advances in Space Research* **37**, 1691 (2006).

[8] P. Picozza, *et al.*, *Astroparticle Physics* **27**, 296 (2007).

[9] M. Casolino, *et al.*, *Advances in Space Research* **37**, 1857 (2006).

[10] M. Casolino, *et al.*, *Advances in Space Research* **37**, 1884 (2006).

[11] M. Casolino, The Pamela collaboration, *ArXiv e-prints* (2009).

[12] P. O. Lagage, C. J. Cesarsky, *Astron. Astrophys.* **118**, 223 (1983).

[13] V. L. Ginzburg, S. I. Syrovatskii, *The Origin of Cosmic Rays* (1964).

[14] A. R. Bell, *Monthly Notices of the Royal Astronomical Society* **182**, 147 (1978).

[15] M. A. Malkov, L. O'C Drury, *Reports on Progress in Physics* **64**, 429 (2001).

[16] A. R. Bell, S. G. Lucek, *Monthly Notices of the Royal Astronomical Society* **283**, 1083 (1996).

[17] V. I. Zatsepin, N. V. Sokolskaya, *Astron. Astrophys.* **458**, 1 (2006).

[18] F. Aharonian, *et al.*, *Astron. Astrophys.* **464**, 235 (2007).

[19] D. C. Ellison, D. J. Patnaude, P. Slane, J. Raymond, *Astrophysical Journal* **712**, 287 (2010).

[20] Y. Uchiyama, F. A. Aharonian, T. Tanaka, T. Takahashi, Y. Maeda, *Nature* **449**, 576 (2007).

[21] M. Tavani, *et al.*, *ApJL* **710**, L151 (2010).

[22] A. A. Abdo, *et al.*, *Science* **327**, 1103 (2010).

[23] A. W. Strong, I. V. Moskalenko, *Astrophysical Journal* **509**, 212 (1998).

[24] F. Donato, *et al.*, *Astrophysical Journal* **563**, 172 (2001).

[25] O. Adriani, *et al.*, *Physical Review Letters* **102**, 051101 (2009).

[26] O. Adriani, *et al.*, *Phys. Rev. Lett.* **105**, 121101 (2010).

[27] C. Grimani, *Classical and Quantum Gravity* **26**, 235009 (2009).

[28] G. Kane, R. Lu, S. Watson, *Physics Letters B* **681**, 151 (2009).

[29] W. Menn, M. Hof, O. Reimer, M. Simon, *et al.*, *Astrophysical Journal* **533**, 281 (2000).

[30] M. Boezio, P. Carlson, T. Francke, N. Weber, *et al.*, *Astrophysical Journal* **518**, 457 (1999).

[31] M. Boezio, V. Bonvicini, P. Schiavon, A. Vacchi, *et al.*, *Astroparticle Physics* **19**, 583 (2003).

[32] J. Alcaraz, B. Alpat, G. Ambrosi, H. Anderhub, *et al.*, *Physics Letters B* **490**, 27 (2000).

[33] J. P. Wefel, J. J. H. Adams, H. S. Ahn, et al., *International Cosmic Ray Conference* (2008), vol. 2 of *International Cosmic Ray Conference*, pp. 31–34.

[34] T. Sanuki, H. Matsumoto, M. Nozaki, K. Abe, *et al.*, *Advances in Space Research* **27**, 761 (2001).

[35] H. S. Ahn, *et al.*, *ApJL* **714**, L89 (2010).

[36] S. Haino, *et al.*, *Physics Letters B* **594**, 35 (2004).

[37] J. Z. Wang, E. S. Seo, *et al.*, *Astrophysical Journal* **564**, 244 (2002).

[38] G. A. de Nolfo, *et al.*, *Acceleration and Transport of Energetic Particles Observed in the Heliosphere*, R. A. Mewaldt, J. R. Jokipii, M. A. Lee, E. Möbius, & T. H. Zurbuchen , ed. (2000), vol. 528 of *American Institute of Physics Conference Series*, pp. 425–428.

[39] O. Reimer, *et al.*, *Astrophysical Journal* **496**, 490 (1998).

[40] W. R. Webber, R. L. Golden, S. J. Stochaj, J. F. Ormes, R. E. Strittmatter, *Astrophysical Journal* **380**, 230 (1991).

[41] J. J. Beatty, *et al.*, *Astrophysical Journal* **413**, 268

(1993).
[42] A. W. Strong, *et al.*, *ArXiv e-prints* (2009).
[43] L. J. Gleeson, W. I. Axford, *Astrophysical Journal* **154**, 1011 (1968).
[44] A. E. Vladimirov, *et al.*, *1008.3642* (2010).
[45] F. James, M. Roos, *Computer Physics Communications* **10**, 343 (1975).