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Antiproton and Electron Measurements and Dark Matter Searches in Cosmic Rays

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1. Introduction

Particle Physics was born and developed for many years studying cosmic rays. Positrons, muons, pions and strange particles were discovered detecting directly cosmic rays or products of their interaction with matter targets. In the early 50's, with the advent of the accelerators, particle physicists joined the big ground laboratories while astrophysicists focused their studies on the mechanisms of production, acceleration and transport of cosmic rays. The return of particle physics in space occurred with the first historical discovery of antiprotons on the top of the atmosphere by the balloon-borne experiments that Robert Golden and Edward Bogomolov carried out in 1979 [1, 2]. They detected an amount of antiprotons much higher than expected from interactions of cosmic rays with the interstellar matter (fig.1). These data were interpreted in terms of primary antimatter coming from antimatter domains in a baryonic–symmetric Universe, of evaporation by Hawking effect of primordial mini black holes or of exotic particles annihilation. Furthermore, the positron/electron ratio measurements performed at that time gave the flux of positrons far exceeding expectations at energies higher than 5 GeV, explained with some exotic production.

However, the detectors used for the measurements were not sophisticated enough to assure a clear separation between antiparticles and standard particles. About ten years later novel techniques - developed for accelerator physics - became available for space research. Then, many other balloon-borne experiments followed these pioneer ones, mainly performed from the WiZard, BESS and HEAT collaborations, followed later on by the AMS-01 flight on board the Space Shuttle.

At the same time, while the negative results from the Gamma Ray Observatory (GRO), with the COMPTON and EGRET instruments, on the existence of antimatter large domains weakened the hypothesis of a baryonic symmetric Universe, another issue became more compelling, namely what kind of matter the Universe is made of. Actually, as WMAP data suggest, the energy budget of the Universe is believed to be shared among baryonic matter (4%), dark (unknown) matter (23%) and dark energy (73%). The more promising candidates for dark matter are the WIMPs, electrically-neutral weakly interacting massive particles with a mass in the range between 10's of GeV to TeV. The most studied is the lightest neutralino χ, a linear combination of the super-symmetric partners of the neutral gauge bosons of the Standard Model. Another possible WIMP candidate is the lightest Kaluza-Klein particle in the Universal Extra Dimension framework. WIMPs mutually annihilate and should produce high energy photons and matter and antimatter pairs, mixed with a huge background produced by interaction of cosmic rays with the ISM.

2. Antiparticle Balloon Experiments

The WiZard experiments MASS 89, MASS 91, TS93, CAPRICE94, CAPRICE98, on board of stratospheric balloons, were performed from a collaboration among USA, Italy, Germany and Sweden, and measured electrons, positrons and antiprotons in a energy interval up to about 50 GeV. The core of the instrument was a superconducting magnetic spectrometer for particle momentum and charge sign determination. The separation between the leptonic and hadronic components was assured by two detectors, an imaging calorimeter under the spectrometer and a Transition Radiation Detector or a Cherenkov on the top.

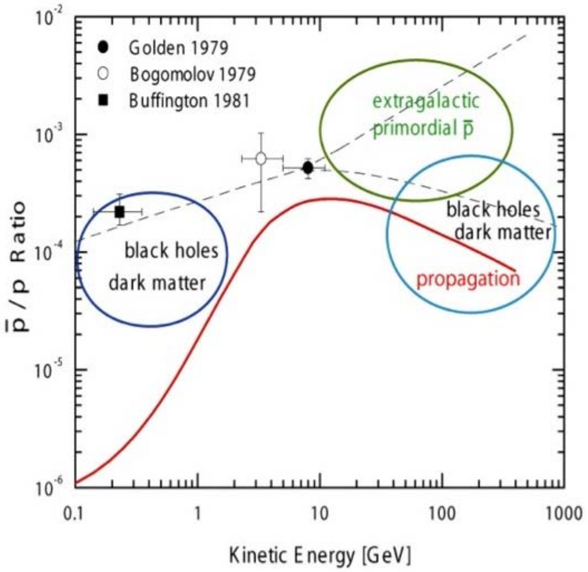

Figure 1: First pioneer measurements of the antiproton-to-proton ratio [1, 2].

The HEAT experiments, performed from an American collaboration, measured, in two different flights, positrons and electrons and antiprotons, respectively. The common parts of the instruments were a superconducting magnetic spectrometer and a Time-of-Flight system. For electron measurements, a TRD and an electromagnetic calorimeter, placed respectively above and under the spectrometer, were installed. Instead, for antiprotons the apparatus included two sets of Multiple Ionization (dE/dx) detectors, placed respectively above and under the magnetic spectrometer.

Many balloon-borne experiments have been conducted from the American and Japanese collaboration BESS, with the scientific objectives to search for antiparticles and antimatter in the low energy region. The instrument was basically composed of a superconducting solenoid magnet with internal JET and drift chambers, and a Time-of-Flight hodoscope with three sets of scintillators placed, respectively, one on the top and two on the bottom of the solenoid vessel. An aerogel Cherenkov counter was used for e/p rejection.

In 1998, in a week technological flight on board the Space Shuttle, the AMS-01 collaboration performed the first antimatter experiment outside the atmosphere using a very large magnetic spectrometer.

The results of all these missions are presented in fig.2, for the antiproton-to-proton ratio (left panel) and for the positron-to-all-electron ratio (right panel), together with different calculations accounting for a pure secondary component. Loofing at the left image, itr is visible that the antiprotons excess found in the early experiments has not been confirmed and the data seem to agree with a standard antiproton production. Moreover, the charge dependence of solar modulation at low energy in the data collected by the BESS flights, in different solar phases, is clearly evident. The increase of the solar activity strongly suppresses the low energy primary protons, while the secondary antiprotons are less affected because of their steeply decreasing spectrum in the low energy region. A very rapid increase of the ratio was seen by BESS-2000, resulting from the large suppression of the proton flux at solar maximum after the phase transition to the negative solar

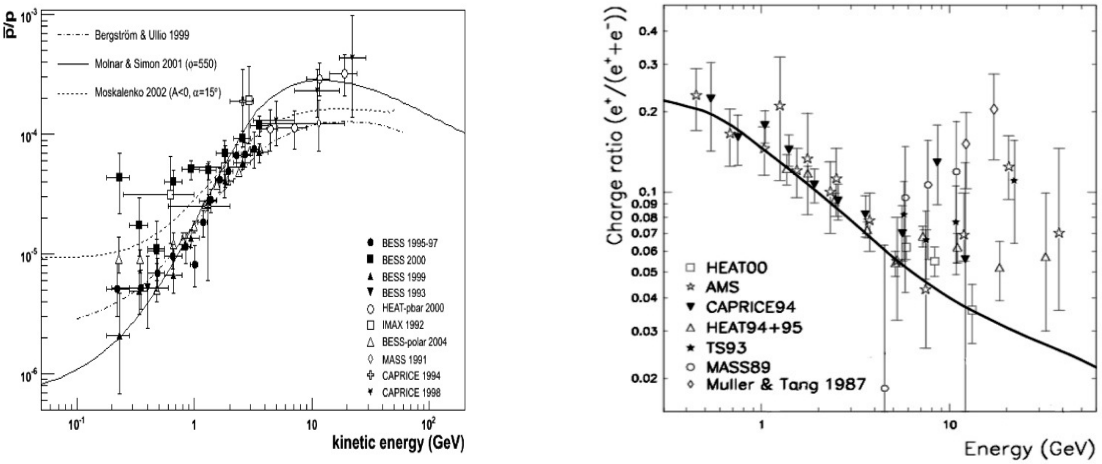

Figure 2: Measurements of the antiproton-to-proton ratio and of the positron-to-all-electron ratio before PAMELA.

polarity.

Looking at the positron fraction, there is a good agreement between data and a standard background calculation at low energy, while a hint of an increase or a flatness in the positron-to-all-electron ratio above 5 GeV is still present, in agreement with the early measurements. This change in the spectral index has been tentatively explained by introducing new sources of positrons, as pulsars or dark matter.

No clear assumption can be obtained from this large amount of data; indeed additional measurements at higher energies, a better knowledge of the astrophysics background, an higher statistics and a continuous monitoring of solar modulation are compulsory to extract possible exotic components from the standard production.

An important improvement in the antimatter and dark matter searches by balloon-borne experiments with magnetic spectrometer was made with the BESS Long Duration Flights. On December 2004, BESS Polar I made its first successful polar flight in Antarctica, 8.5 days long, detecting 1520 antiprotons in the energy range 0.1-4.2 GeV. The results for the $\overline{p}/p$ ratio are shown in fig.2. On 23rd of December 2008 BESS Polar II flew also in Antarctica. The floating time was of 29.5 days with 24.5 days of data taking. Promising results on $\overline{p}/p$ ratio and on the $\overline{D}$ and $\overline{He}$ search are expected from the analysis of the collected data.

3. Antiparticle Satellite Experiments

A great progress in antiparticle detection in space has been made with the PAMELA satellite experiment [3] and a further improvement is expected with AMS-02 [4] that will be installed in February 2011 outside the International Space Station. Primary scientific objectives of PAMELA (fig.3) and AMS-02 (fig.4) are precise measurements of the antiparticle energy spectra, in order to disentangle possible contributions from exotic sources. They search also for heavy antimatter, in particular anti-helium (primordial antimatter) and heavy anti-nuclei (anti-stars), for new matter in the Universe (strangelets?) and perform accurate studies of nuclei and their isotopes to test cosmic-

Figure 3: A photograph of the PAMELA telescope.

ray propagation models. Concomitant goals include the study of solar physics, solar modulation and radiation belts.

The PAMELA experiment is carried out by an international collaboration including several Italian Universities and INFN divisions, the Russian Institutes MEPhI and FIAN Lebedev in Moscow and Joffe in S. Petersburg, the University of Siegen in Germany and the Royal Technical Institute of Stockholm, Sweden. The core of the instrument is a magnetic spectrometer for particle momentum and charge sign determination. A Time-of-Flight system provides timing, dE/dx measurements and the primary PAMELA trigger. The separation between hadronic and leptonic components is made by an imaging silicon-tungsten calorimeter, 16 radiation lengths deep, that allows rejection of protons versus positrons at the order of 10^5. A neutron counter placed at the bottom of the instrument gives a further improvement to the rejection power by detecting the neutrons produced in the showers that incident particles create in the calorimeter - more numerous in the hadronic showers compared with the electromagnetic ones. A thick scintillator under the calorimeter and an anticoincidence system complete the apparatus. More technical details can be found in [3]. 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 June 15, 2006, in an elliptical orbit, ranging between 350 and 610 Km and with an inclination of 70 degrees. Since July 2006 PAMELA is daily delivering 16 Gigabytes of data to a Ground Segment in Moscow.

Particle identification in PAMELA is based on the combination of the data obtained by the different detectors. One source of background in the antimatter samples comes from the ”spillover”

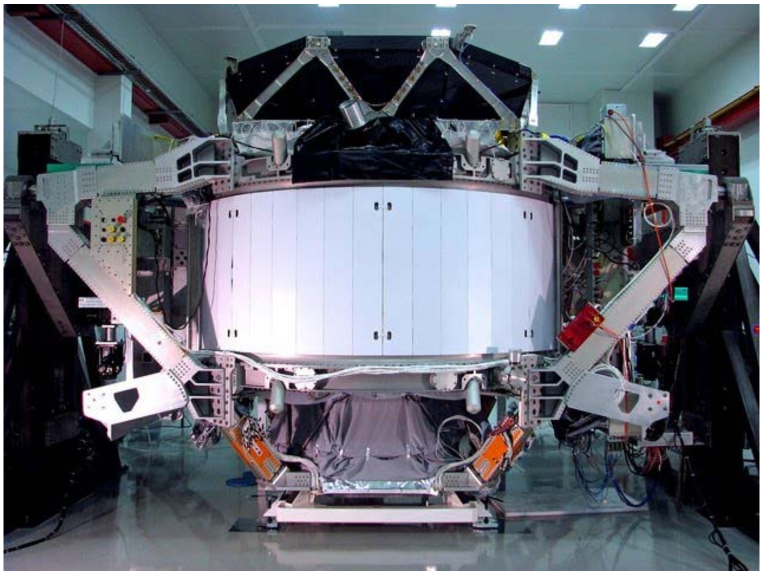

Figure 4: A photograph of the AMS-2 experiment.

protons in the antiproton sample and electrons in the positron sample. The spillover is eliminated by imposing a set of strict selection criteria on the quality of the fitted tracks, that however limits the rigidity interval where the measurements can be performed. Another important source of background comes from a possible misidentification of electrons in the antiproton sample and protons in the positron sample. Electrons and positrons are recognized by matching the momentum measured by the magnetic spectrometer with the total energy obtained in the calorimeter, by asking a specific starting point of the shower in the calorimeter and by carefully studying the lateral and longitudinal profiles of the shower. The neutron detector response is taken into account as well.

In fig.5 and fig.6 the antiproton absolute flux and the antiproton-to-proton ratio measured by PAMELA [5, 6] are shown for the kinetic energy range between 60 MeV and 180 GeV, along with other recent experimental data [7, 8, 9, 10, 11, 12] and theoretical calculations; they assume a pure secondary production of antiprotons during the propagation of cosmic rays in the Galaxy [13, 14, 15, 16]. No particular feature appears to suggest a strong contribution from exotic sources. However, the experimental uncertainties of the PAMELA data are smaller than the spread in the different theoretical curves and, therefore, provide important constrains on parameters relevant for secondary production.

The positron-to-all-electron ratio measured by the PAMELA experiment is given in fig.7 compared with other recent experimental results [17, 18] and a GALPROP based calculation [31]. The data, covering the energy range between 1.5 to 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, but they are in agreement with data obtained from the balloon ASEOP experiment that flew from Scandinavian to Canada in June 2006. At high energies, above 10 GeV, the positron ratio increases significantly with energy. This behavior cannot be explained by standard calculations of positron secondary production, which predict a continuous decrease of the positron fraction. For this reason, the observed excess of positrons in the range 10-100 GeV has led to many theoretical

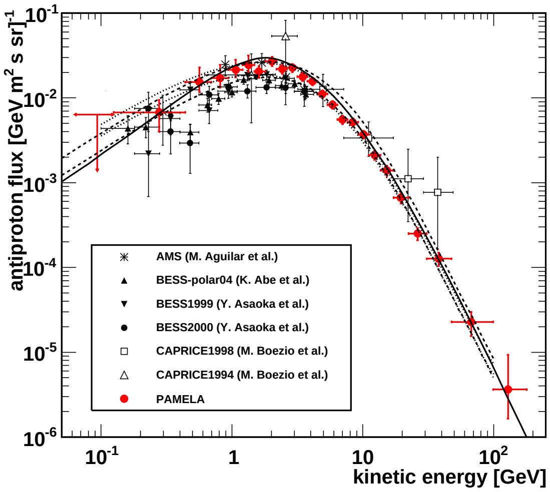

Figure 5: The antiproton energy spectrum measured by PAMELA [6] compared with contemporary measurements [7, 8, 9, 10, 11] and theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dotted and dashed lines indicate the upper and lower limits calculated by Donato et al. [13] 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. [14] for the case of a Plain Diffusion model.

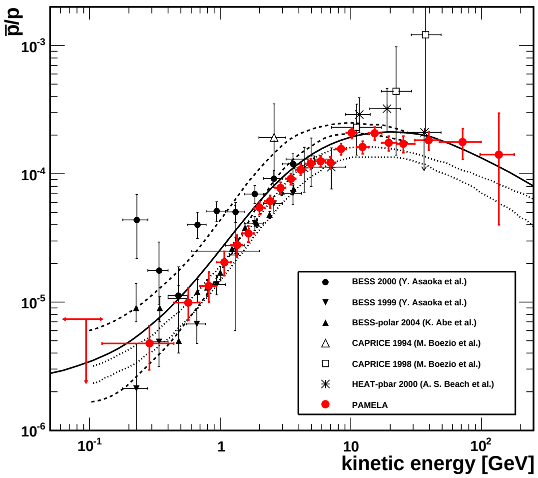

Figure 6: The antiproton-to-proton flux ratio measured by PAMELA [5, 6] compared with contemporary measurements [7, 8, 9, 10, 12] and theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dashed lines show the upper and lower limits calculated by Simon et al. [15] for the Leaky Box Model, while the dotted lines show the limits from Donato et al. [16] for a Diffusion Reacceleration with Convection model. The solid line shows the calculation by [14] for the case of a Plain Diffusion model.

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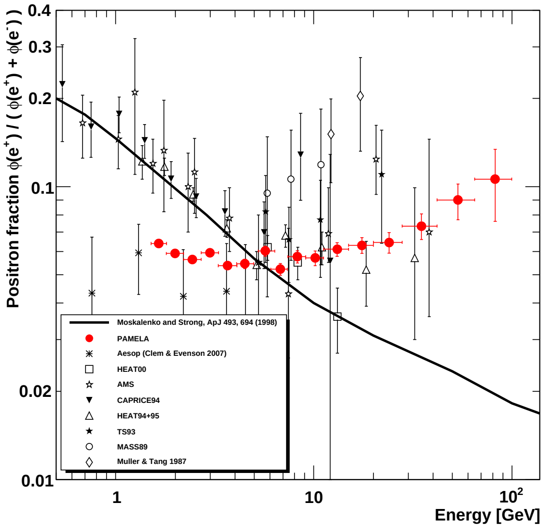

Figure 7: The positron fraction measured by the PAMELA experiment [17, 18], compared with other recent experimental data [23, 24, 25, 26, 27, 28, 29, 30], and a theoretical calculation [31].

models explaining its origin as due to annihilation or decaying of dark matter (see references in [19]). The most problematic challenge posed by the PAMELA results is the asymmetry between the leptonic (positron fraction) and the hadronic (antiproton-to-proton ratio) component, difficult to explain in the framework in which the neutralino is the dominant dark matter component. The best explanation is obtained considering a direct leptonic annihilation channel for a wide range of the WIMP mass, although in this case a large boost factor is required. Other explanations claim for a contribution of electron and positron pair from nearby and young pulsars, objects well known as particle accelerators, or from annihilation of high energy photons with background photons, i.e., photon-photon with pair production. Other models connect this excess to some inhomogeneity in the SNR density in our Galaxy [20] or to a production and acceleration of secondary positrons in the same site where protons are accelerated [21, 22].

In the next future the AMS-02 instrument [4], realized by a worldwide collaboration, will substitute PAMELA in the antimatter search. The detector is composed of a magnetic spectrometer, a Time-of-Flight system, a Ring Imaging Cherenkov and an electromagnetic calorimeter. The very large acceptance and the combination of all these detectors will allow high precision and high statistics in the search for light and heavy antimatter in space, and in the measurement of cosmic rays spectra and chemical composition up to 1 TeV. In particular AMS-02 will improve the PAMELA positron and electron data, extending the explored energy interval up to 800 GeV. The instrument is also a performant gamma detector. A unique feature of AMS-02 is the combined search for dark matter in different channels - antiprotons, positrons, antideuterons, gammas - that will considerably increase the sensitivity to SUSY DM signals detection.

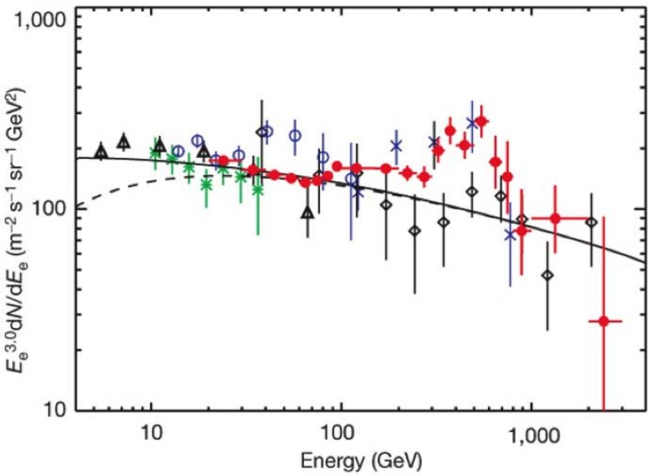

Figure 8: The electron differential energy spectrum measured by ATIC (scaled by E $^{+3}$) at the top of the atmosphere (red filled circles) is compared with previous observations by AMS (green stars), HEAT (open black triangles), BETS (open blue circles), PPB-BETS (blue crosses) and emulsion chambers (black open diamonds), with uncertainties of one standard deviation (references in [32]). The GALPROP code calculates a power-law spectral index of -3.2 in the low-energy region (solid curve). The dashed curve is the solar modulated electron spectrum.

4. All Electrons Measurements

Few months before the publication of PAMELA positron data, the ATIC collaboration [32] reported an excess in the galactic ”all-electrons” (sum of electrons plus positrons) energy spectrum at energies of 500-800 GeV, observed also from PPB-Bets, although with larger uncertainty (see fig.8). ATIC is a balloon borne experiment that performed three flights from a launch base in Antartica. The instrument comprised a fully active bismuth germanate calorimeter, a carbon target with embedded scintillator hodoscopes, and a silicon matrix that was used as a main charge detector. ATIC data have been interpreted by the same theoretical models of the PAMELA positron results. The most interesting feature of these data, if read as WIMP annihilation, is their capability to fix the mass of the WIMP, both in case of annihilation or decay.

The ATIC bump has not been confirmed by the Fermi experiment [33]. Fermi is conducted from a large international collaboration; it is mainly dedicated to high energy gamma ray measurements but is able to detect and recognize all-electrons between few GeV to 1 TeV as well. Fermi is composed of 16 identical towers, each constituted of a silicon-tungsten gamma converter and tracker, and a CsI (Tl) calorimeter. The very large acceptance allows very precise all electrons measurements. The energy spectrum, shown in fig.9, falls 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, combined with the cutoff in the energy spectrum at 1 TeV measured from HESS telescope, suggests the presence of one or more local sources of high energy CR electrons, as shown in fig.9, but also dark matter scenarios cannot be excluded.

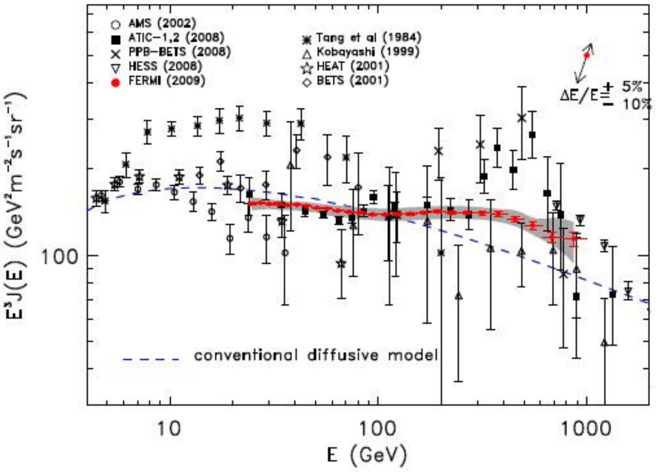

Figure 9: The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. Other high energy measurements and a conventional diffusive model are shown (references in [33]) .

5. Conclusions

Search for dark matter in space is continuously improving by new detectors derived from particle physics at accelerators and by satellite and ISS experiments, along with very long-duration balloon flights. Interesting results have been obtained from PAMELA, ATIC and Fermi measurements. The antiproton data of PAMELA do not present particular features requiring a strong contribution from some exotic source. Instead, the excess in the positron to all electron fraction detected from PAMELA and the all electron fluxes measured from ATIC and Fermi, although not in complete agreement with each other, suggest the existence of some supplementary sources of positrons and electrons, in addition to the standard particle production in the interaction of cosmic rays with the interstellar matter. Pulsars seem to be the most plausible candidate, but a large possibility is still left for contributions from dark matter annihilation.

References

[1] Golden R. et al., Phys. Rev. Letter 43, 1196 (1979).

[2] Bogomolov E. et al., Proc. 16th ICRC 1, 330 (1979).

[3] Picozza P. et al., Astropart. Phys. 27, 296 (2007).

[4] Beischer B. et al., New Journal of Physics 11, 105021 (2009).

[5] Adriani O. et al., Phys. Rev. Lett. 102 , 051101 (2009).

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

[7] Boezio M. et al., Astrophys. J. 487, 415 (1997).

[8] Boezio M. et al., Astrophys. J. 561, 787 (2001).

[9] Asaoka Y. et al., Phys. Rev. Lett. 88, 051101 (2002).

[10] Abe K. et al., Phys. Lett. B 670, 103 (2008).

[11] Aguilar M. et al, Phys. Rep. 366, 331 (2002).

[12] Beach A. S. et al., Phys. Rev. Lett. 87, 271101 (2001).

[13] Donato F. et al., Astrophys. J. 563, 172 (2001).

[14] Ptuskin V. S. et al., Astrophys. J. 642, 902 (2006).

[15] Simon M., Molnar A. and Roesler S., Astrophys. Journal 499, 250 (1998).

[16] Donato F. et al., Phys. Rev. Lett. 102, 071301 (2009).

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

[18] Adriani O. et al., Astropart. Phys. 34, 1 (2010).

[19] Fan Y., Zhang B. and Chang J., arXiv:1008.4646 (2010).

[20] Shaviv N. J., Nakar E. and Piran T., arXiv:0902.0376 (2009).

[21] Blasi P. , Phys. Rev. Lett. 103, 051104 (2009).

[22] Fujita Y., Phys. Rev. D 80, 063003 (2009).

[23] Clem J. and Evenson P., Proc. 30th Int. Conf. on Cosmic Rays (Merida), 2007.

[24] Beatty J. J. et al., Phys. Rev. Lett. 93, 241102 (2004).

[25] Gast H., Olzem J. and Schael S., Proc. XLIst Rencontres de Moriond, vol 421 (2006).

[26] Boezio M. et al., Astrophys. J. 532, 653 (2000).

[27] Barwick S. W. et al., Astrophys. J. 482, L191 (1997).

[28] Golden R. L. et al., Astrophys. J. 457, L103 (1996).

[29] Golden R. L. et al., Astrophys. J. 436, 769 (1994).

[30] Müller D. and Tang K. K., Astrophys. J. 312, 183 (1987).

[31] Moskalenko I. V. and Strong A. W. , Astrophys. J. 493, 694 (1998).

[32] Chang J. et al. Nature 456, 362 (2008).

[33] Abdo, A. A. et al., Phys. Rev. Lett. 102, 181101 (2009).