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Direct detection of cosmic rays

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Abstract. Over the last three years, several satellite and balloon observatories have reported intriguing features in the cosmic-ray (CR) spectra. Experiments show an "anomalous" rise with energy of the CR positron fraction and some unexplained features in the electron+positron spectrum, motivating many interpretations in terms of dark matter or nearby sources scenarios. In addition, recent measurements of CR protons and nuclei revealed an unexpected spectral hardening in the spectra of CR species above a few hundred GeV per nucleon, and a harder spectrum of He compared to protons. These new features may offer a clue to the origin of the observed high-energy Galactic CR.
In the future, new results are expected from experiments currently taking data or in preparation. These experiments should be able to confirm and further investigate these observations.

1. Introduction

Cosmic Rays (CR) are high energy charged particles, originating from outer space, that travel at nearly the speed of light and hit the Earth from all directions. It is believed that most galactic CR gain their energy from supernova explosions and subsequent acceleration. CR include essentially all of the elements in the periodic table; about 89% of the nuclei are hydrogen (protons), 10% helium, and about 1% heavier elements. The latter (such as carbon, oxygen, magnesium, silicon, and iron) are present in about the same relative abundances as in the solar system, but there are important differences in elemental and isotopic composition interpreted as the effect of the interaction of CR during their propagation in the Galaxy. These abundances thus provide information on the origin and history of galactic CR. Electrons constitute much of the remaining 1% and "standard" positrons are supposed to be purely of secondary origin.

Given the size of the instruments, direct CR detection is possible up to energies of about 10^{14} eV. Due to the capabilities for the precise identification of CR particles, the physics achievable by direct observations is remarkable: the composition and fluxes of CR to put constraints on the production and propagation models, the search for nearby high-energy sources by the electron fluxes up to hundreds of GeV, the search for signatures of exotic matter (primordial black-holes, super-symmetric particles, Kaluza-Klein particles, ...) to solve the dark-matter puzzle and the study of primordial antimatter to understand the apparent matter-antimatter asymmetry.

Two types of observatory exist for the direct detection of CR: balloon-borne and space-borne detectors. Balloon experiments can be built in a relatively short time with a moderate budget. The flight can be repeated as long as the detector has been recovered in good con-

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dition. Thanks to the Long Duration Balloons (LDB) flight facility in Antarctica, missions can now last several weeks[1]. The residual atmosphere above the detector is affecting the fluxes and thus represents an important drawback for this type of experiments. Space-borne experiments are more expensive and risky but have a longer lifetime and fly above the atmosphere.

2. e^+/e^- Measurements

The Advanced Thin Ionization Calorimeter (ATIC) instrument contains a deep, fully active, bismuth germanate (BGO) calorimeter of 18 radiation lengths which gives an electron energy resolution of around 2%. Figure 1 presents the electron+positron differential energy spectrum measured by ATIC (Chang et al. 2008). These results show a large excess of electrons above 100 GeV followed by a steepening above 1000 GeV.

The High Energy Stereoscopic System (H.E.S.S.) is an imaging atmospheric Cherenkov telescope with a a very large collection area. In their results (see figure 2), they extend the measurement of the electron+positron spectrum beyond the range accessible to direct measurements. While the overall electron flux measured by H.E.S.S. is consistent with the ATIC data within statistical and systematic errors, the H.E.S.S. data exclude a pronounced peak in the electron spectrum. Data also show a substantial steepening in the energy spectrum above 600 GeV compared to lower energies.

The Fermi-LAT γ-ray observatory (Ackermann et al. 2010) confirmed the relatively flat electron spectrum at low energy, however, the excess of events reported by ATIC and PPB-BETS was not detected by Fermi-LAT (figure 3).

Launched in 2006, PAMELA is a satellite-based instrument dedicated to precision measurement of CR spectra. Its principal compo-

[1] The record-breaking balloon carried the Cosmic Ray Energetics And Mass (CREAM) experiment. It soared for nearly 42 days, making three orbits around the South Pole.

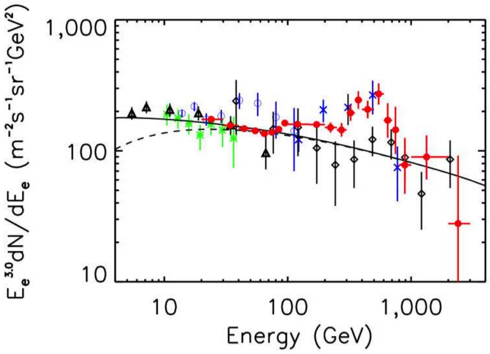

Fig. 1. The electron+positron differential energy spectrum measured by ATIC (scaled by E^3) at the top of the atmosphere (red filled circles) is compared with previous observations from the Alpha Magnetic Spectrometer AMS (green stars), HEAT (open black triangles), BETS (open blue circles), PPB-BETS (blue crosses) and emulsion chambers (black open diamonds) with uncertainties of one standard deviation. Solid line represents the general spectrum calculated with the GALPROP interstellar propagation code (Chang et al. 2008).

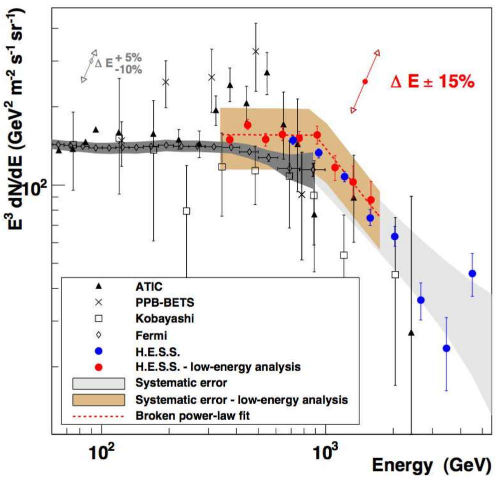

Fig. 2. The energy spectrum of CR electrons+positrons measured by H.E.S.S. and balloon experiments. The shaded bands indicate the approximate systematic error arising from uncertainties in the modeling of hadronic interactions and in the atmospheric model in the two analyses. The double arrow indicates the effect of an energy scale shift of 15%, the approximate systematic uncertainty on the H.E.S.S. energy scale (Aharonian et al. 2009).

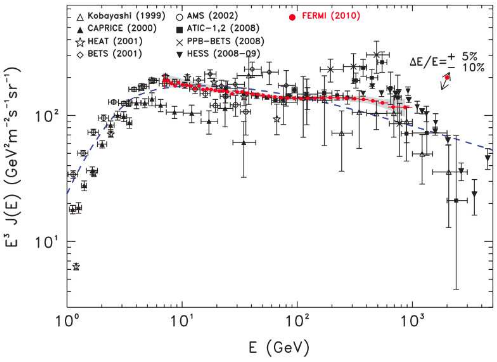

Fig. 3. Cosmic-ray electron spectrum as measured by Fermi-LAT for 1 year of observations shown by filled circles, along with other recent high-energy results (Ackermann et al. 2010).

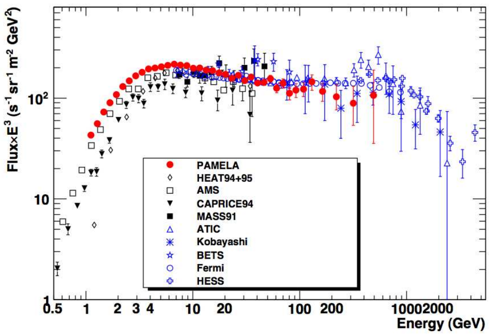

Fig. 4. The electron energy spectrum obtained by the PAMELA experiment (Adriani et al. 2011).

nent is a magnetic spectrometer with silicon-strip tracking which allows particle sign of charge identification, and therefore allows to separate electron and positron in the CR. They presented (Adriani et al. 2011) a precision measurement of the electron component in 2011 (see figure 4).

Considering statistical and systematic uncertainties, no significant disagreements are found between PAMELA, ATIC and Fermi data, even considering an additional positron component in these measurements of order a few percent. However, the PAMELA electron spectrum appears softer than the (electron+positron) spectra presented by ATIC and Fermi. This difference is within the systematic uncertainties but it also could be explained by

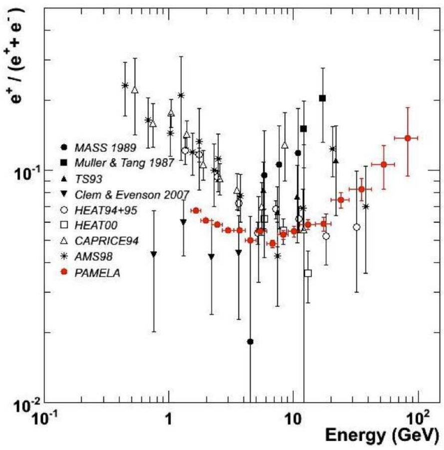

Fig. 5. Positron fraction measured by the PAMELA experiment (Adriani et al. 2009).

a positron component growing with energy. At higher energy, PAMELA data are compatible with previous measurement but their precision is limited by the statistics.

The PAMELA satellite experiment had also presented the measurement of the positron fraction (Adriani et al. 2009). Their results (figure 5) show an increase of the positron fraction above 10 GeV instead of the decrease expected at higher energy. The low positron to electron ratio below 10 GeV is due to the new solar magnetic field polarity after the year 2001.

The increase in the positron fraction was confirmed by the results recently presented by the Fermi-LAT collaboration. Fermi, unlike PAMELA, does not have a magnet to discriminate positively charged particles from negatively charged ones but they used the geomagnetic field and the earth shadow to select positrons and electrons and to derive the positron fraction (Fermi 2011). These results (see figure 6), still affected by large statistical errors bars, are consistent with the results obtained by the PAMELA experiment.

To summarize, there is still some disagreement between ATIC and Fermi measurements but the high statistic measurement from Fermi seems to rule out the possibility to have a large

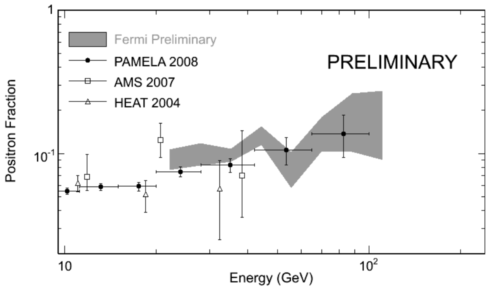

Fig. 6. Positron fraction measured by the Fermi experiment by using the geomagnetic field to identify electron and positron (Fermi 2011).

excess in the range 300-800 GeV as the one reported by the ATIC experiment. However, the positron fraction is in excess compared to steady-state background calculation, and the features seen in the electron+positron spectra indicate that there is a need for positron (or positron and electron) additional sources. Two scenarios are considered in the literature:

- Dark Matter annihilation: however, simplest dark matter scenarios are strained:
  - A strong boost factor is needed (typically 2-3 orders of magnitude).
  - Leptophilic annihilation channels are required to not overproduce antiproton.
  - TeV and higher mass are favored.
- Nearby pulsars are natural sources of e^-/e^+: several studies (Hooper et al. 2009; Yuksel et al. 2009; Profumo 2008) have shown that this type of source readily reproduce the data.

3. Cosmic-ray nuclei measurements

There are several new measurements of the CR nucleus fluxes in the recent years. The balloon-borne experiment Cosmic Ray Energetics And Mass (CREAM) achieves long exposures by flying repeatedly on long-duration high-altitude balloon flights in Antarctica. The experiment measured the energy spectra of the major species from proton to iron in the energy range from tens of GeV/nucleon to tens of TeV/nucleon (Ahn et al. 2009, 2010). Results (see figures 7 and 8) indicate a hardening of the spectra at 200 GeV/nucleon for all species.

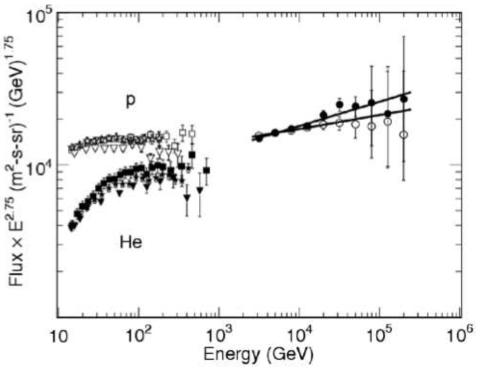

Fig. 7. Measured energy spectra of CR protons and helium nuclei. The CREAM-I spectra are compared with selected previous measurements using open symbols for protons and filled symbols for helium: CREAM (circles), AMS (stars), BESS (squares), CAPRICE (inverted triangles). The lines represent power-law fits to the CREAM data (Ahn et al. 2010).

Recently the satellite experiment PAMELA reported the precise measurement about the proton and Helium spectra with rigidity from GV to 1.2 TV (Adriani et al. 2011b). PAMELA data show that the proton and Helium spectra deviate from the single power-law function above 30 GV with a hardening at rigidity 200 GV, which is basically consistent with the results of CREAM.

The hardening of the CR spectra challenges the traditional CR acceleration and propagation paradigm. Models which can explain such a spectral hardening include the multi-component sources (V. I. Zatsepin and N. V. Sokolskaya 2006) or the nonlinear particle acceleration scenarios with feedback of CRs on the shock (Ptuskin et al. 2010).

4. Future experiments

The second and final version of the Alpha Magnetic Spectrometer experiment (AMS-02) is a large acceptance CR detector which was placed on-board the International Space Station, ISS on May 2011. Over its mission duration, it will measure with unprecedented statistics and precision the spectrum of CR over an energy range of approximately 100

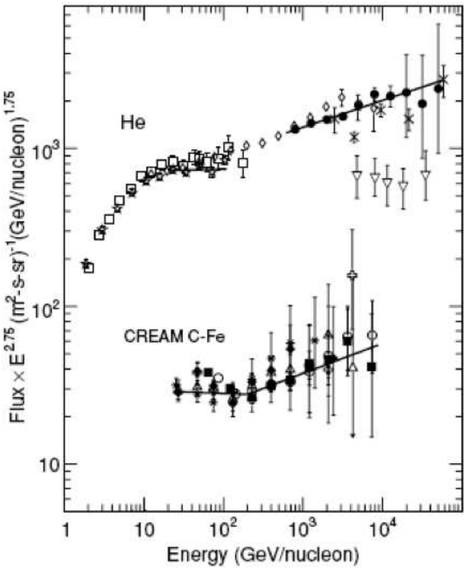

Fig. 8. Broken power-law fit to helium and heavier nuclei data. The lines for helium represent a power-law fit to AMS (open stars) and CREAM (filled circles) data, respectively. Also shown are helium data from other experiments: BESS (open squares), ATIC-2 (open diamonds), JACEE (X), and RUNJOB (open inverted triangles). The lines for C-Fe data represent a broken power-law fit to the CREAM heavy nuclei data: carbon (open circles), oxygen (filled squares), neon (open crosses), magnesium (open triangles), silicon (filled diamonds), and iron (asterisks) (Ahn et al. 2010).

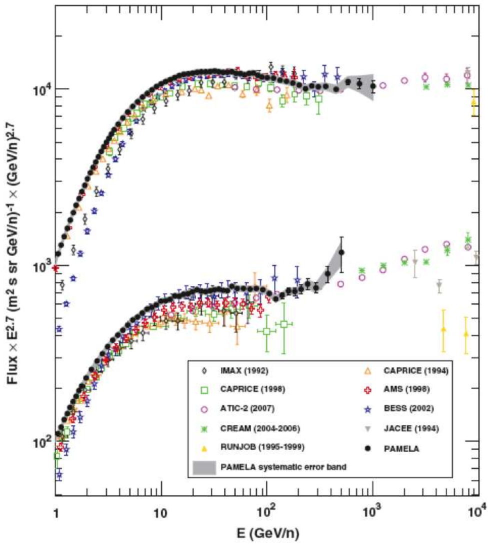

Fig. 9. Proton and helium absolute fluxes measured by PAMELA above 1 GeV/n, compared with a few of the previous measurements. Error bars are statistical, the shaded area represents the estimated systematic uncertainty (Adriani et al. 2011b).

MeV to 1 TeV. The AMS detector uses a large permanent magnet to produce a strong, uniform magnetic field (0.14 Tesla) over a large volume of 1m^3. The magnetic field is used to bend the path of charged cosmic particles as they pass through five different types of detectors. The Transition Radiation Detector (TRD) measures particles passing at speeds nearly that of the speed of light. The Time of Flight (TOF) measures the charge and velocity of passing particles. The Silicon Tracker measures the coordinates of charged particles in the magnetic field. The Ring Image Cerenkov Counter (RICH) measures both the velocity and charge of the particles and the Electromagnetic Calorimeter (ECAL) measures the energy and coordinates of electrons, positrons and gamma rays. The AMS-02 instrument will be able to detect and identify nuclei as heavy as iron ($Z < 26$) with rigidity up to a few TV. High precision measurements of the ratios B/C and sub- Fe/Fe up to energies of 1 TeV/n are anticipated. These data will improve our understanding of the interstellar propagation and of the mechanisms at the origins of CR. For instance, it should provide very precise measurements allowing to investigate and study the hardening of the CR nuclei spectra. In addition, AMS will provide very precise electron flux and positron fraction up to several hundreds of GeV with a simultaneous measurement of antideuton and antiproton components. These data will put stronger constrains on the models that produce additional source of positron and electron.

Calorimetric Electron Telescope (CALET) is being developed to be on board the Japanese Experiment Module Exposed Facility, JEM/EF, of the International Space Station. Major goals of the mission are to search for nearby CR sources and dark matter by carrying out a precise measurement of the electrons in the range 1 GeV - 20 TeV and the gamma-rays in the range 20 MeV - few TeV. CALET will also measure the protons and the nuclei up to 1000 TeV as well. The main detector is composed of Imaging Calorimeter, IMC, Total Absorption Calorimeter, TASC, Silicon Array, SIA, and Anti-Coincidence Detector, ACD, to detect various kinds of particles in very wide energy range. Concerning balloon experiments, the development of Ultra-Long Duration Balloon (ULDB) is in progress by NASA. The ULDB is made of advanced materials and uses a new pumpkin-shaped balloon designed to achieve flights of up to 100 days. The ULDB is completely sealed and pressurized in order to maintain constant altitude night and day. A successful test flight of 54 days as been performed during the 2008/2009 campaign in Antarctica.

5. Conclusion

Several CR experiments have presented new results during the last years. The ATIC experiment has presented an electron/positron flux with a spectrum enhancement in the 300-800 GeV range but this results has not been confirmed by the Fermi-LAT collaboration. A rise with energy of the positron fraction has been presented by the PAMELA collaboration and this has been recently confirmed by Fermi. In the forthcoming years, new experiments like AMS should be able to further investigate these excess with higher statistics on an extended energy range.

Concerning the CR nuclei, recent data indicate an hardening of the spectra at high energy, which challenges the traditional CR acceleration and propagation paradigm. New results from forthcoming experiments in the next coming years should provide very precise measurements to investigate and study these features.

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