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Recent results from on-orbit space experiments and future perspectives

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Summary. — Actual high-energy gamma-ray and cosmic-ray space experiments are providing an outstanding view of the high-energy universe with their great potential for discovery. Recent results from space are allowing significant steps forward in the understanding of cosmic-rays astrophysics. The main highlights of space experiments on-orbit and the perspectives expected in the future years are presented.

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1. – Introduction

The study of the high-energy sky has witnessed a dramatic revolution in the last years with the recent results from new space experiments, providing information about particle acceleration at high energy. Great improvements have been done in the study of cosmic rays concerning their origin, production and propagation. New highlights have been also pointed out in the understanding of the mechanism of particle acceleration in astrophysical objects like active galactic nuclei (AGN), pulsars and supernova remnants (SNR). Recent experiments are providing valuable data useful also to study the diffuse emission, resolve unidentified sources and probe the dark matter and the early universe.

There is a big Italian effort among the main high-energy and cosmic-ray space experiments and these proceedings will concentrate on recent results from PAMELA, AGILE and Fermi as well as on the last efforts before the launch of AMS. These few pages are giving an overview of the outstanding scientific results achieved in the last years.

2. – High-energy gamma-ray astrophysics

High-energy gamma-ray astrophysics studies the gamma-ray sky in the energy band from 10 MeV to more than 100 GeV, where the most energetic phenomena in the universe happen. After EGRET [1] on-board the Compton Gamma-Ray Observatory (CGRO) ended on June 2000, no space experiment had been able to look at the γ-ray sky above 100 MeV, until the AGILE and the Fermi satellites were launched in April 2007 and June 2008, respectively. In its nine-year lifetime, EGRET observed the entire γ-ray sky and detected 271 γ-ray sources as reported in the Third EGRET catalog [2]. Among these sources, 6 were pulsars, 90 were blazars and 170 were unidentified.

The new generation of high-energy space missions are addressing some of the fundamental issues that were left open or unresolved by EGRET. In order to allow a better and deeper understanding in the exploration of the γ-ray sky, identify the sources still not associated with known objects and perform population studies of sources such as pulsars, AGILE and Fermi have reached an unprecedented sensitivity, as they are based on advanced design and performance, larger field of view, more exposure and precise timing, as well as a higher angular resolution.

2˙1. *AGILE*. – AGILE, Astrorivelatore Gamma a Immagini Leggero, is an Italian Space Agency (ASI) mission launched on April 23, 2007 in a ~ 550 km equatorial orbit with low inclination angle, $\sim 2.5°$. It combines for the first time a gamma-ray imager —GRID, a pair conversion telescope sensitive in the 30 MeV–30 GeV energy band with a coded-mask hard-X-ray imager —SuperAGILE in the 18–60 keV band. Details on the detector and performance can be found in [3].

The very large field of view (2.5 sr) of the gamma-ray imager coupled with the hard X-ray monitoring capabilities, makes AGILE well suited to study galactic and extragalactic sources, as well as GRBs and other fast transients. AGILE reaches its optimal performance near 100 MeV with good imaging and sensitivity.

The first catalog reporting the high-confidence galactic and extra-galactic γ-ray sources detected by AGILE was based on the data collected during its first year in orbit from July 9, 2007 to June 30, 2008 [4], while a second catalog of AGILE gamma-ray sources is in preparation [5]. The extensive monitoring of Galactic microquasars is among the most important observations. A thorough study of the Cygnus region has been done, concentrating on Cygnus X-1 and Cygnus X-3. Gamma-ray emission from Cygnus X-3 was discovered by collecting a large number of observations from the Cygnus region [6]. Several prominent Cygnus X-3 gamma-ray flares were detected in a reproducible pattern, all preceding major radio-jet emissions. The results from observations in the Cygnus region have been also confirmed by Fermi [7].

Particular attention has been also devoted to the observations of pulsars and to the study of Pulsar Wind Nebulae (PWNe) as well as to the investigations of SNRs. Thanks to the capability of simultaneously monitoring a large fraction of the sky (2.5 sr) AGILE has been able to recognize many gamma-ray blazars. One of the most interesting observations is that of the Flat Spectrum Radio Quasar (FSRQ) 3C454.3, dubbed as the "Crazy Diamond". This FSRQ has turned out to be one of the most prolific blazars in the gamma-ray energy range during the last 2–3 years, showing multiple flare activity and a variety of very interesting spectral and intensity behaviors. In early December 2009, 3C454.3 became the brightest gamma-ray source in the sky, surpassing in intensity the Vela pulsar [8, 9]. The breakthroughs and most important results on the study of galactic and extra-galactic sources are referred to in [10].

Starting in early November 2009, AGILE changed its scientific operation mode. The non-operatibility of the satellite reaction wheel led to a new configuration for scientific observations in "spinning mode". AGILE is now spinning around its solar panel axis with an angular speed of about 1 degree/s and is collecting data over a large fraction of the sky and is expected to produce a wealth of data in this new configuration.

2˙2. *Fermi*. – The Fermi satellite was launched on June 11, 2008 from Cape Canaveral Air Force Station, Florida, into a circular orbit at 565 km altitude and 25.6° inclination. It hosts two instruments: the Large Area Telescope (LAT), a pair conversion gamma-ray telescope covering the energy range from 20 MeV to more than 300 GeV [11], and the Gamma-ray Burst Monitor (GBM) that covers the lower-energy range from 8 keV to 40 MeV [12].

Fermi is providing the scientific community with a huge amount of valuable data shedding new light on a wide range of astrophysical phenomena. During the first year of scientific operations, it mapped the extreme sky with unprecedented resolution and sensitivity. Fermi has been performing a survey of the high-energy astrophysical phenomena, including pulsars, black holes, active galactic nuclei and gamma-ray bursts, trying to understand the nature of unidentified sources, the mechanisms of particle acceleration in celestial sources, the origin of cosmic rays and supernova remnants and to search for new phenomena such as super-symmetric dark-matter annihilation, etc.

The first Fermi-LAT catalog [13] reports the high-energy gamma-ray sources detected by the Large Area Telescope during the first 11 months of the science phase of the mission. It contains 1451 sources detected and characterized in the 100 MeV to 100 GeV energy range, with a significance higher than 4σ.

Among the main highlights, the Fermi-LAT is providing a major increase in the known gamma-ray pulsar population, with 46 high-confidence pulsars detected in the first 6 months of data collection [14]. Sixteen previously unknown pulsars have been discovered in blind search using only γ-ray data, by looking for pulsed signals in the positions of bright gamma-ray sources seen with the LAT, or in the positions of objects suspected to be neutron stars based on observations at other wavelenghts [15]. Pulsed gamma-ray emission was discovered from twenty-four known pulsars by using radio ephemerides. The LAT discovered also a new population of eight gamma-ray pulsars with millisecond periods, known from radio observations as the second life of normal pulsars in binary systems and never observed before at high energies. Eight of these new gamma-ray pulsars are millisecond pulsars [16].

Other outstanding results have been obtained for extra-galactic observations. A summary is reported in the first Fermi-LAT AGN catalog that includes 671 gamma-ray sources located at high Galactic latitudes ($|b| > 10°$) detected with a test statistic (TS) greater than 25 and associated statistically with AGN. Some LAT sources are associated with multiple AGN, and consequently, the catalog includes 709 AGN, comprising 300 BL Lacertae objects (BL Lacs), 296 flat-spectrum radio quasars (FSRQs), 41 AGN of other types, and 72 AGN of unknown type [17]. For the main published results refer to [18].

Particular attention has been focused on the measurement of the high-energy cosmic-ray electron spectrum with the Fermi-LAT [19]. Even though it was designed to be a high sensitivity gamma-ray telescope, the Fermi-LAT has proved to be an excellent e^+/e^- detector. A dedicated analysis has been developed to reconstruct the primary cosmic-ray e^+/e^- combined spectrum. The result in fig. 1 shows that in the energy range from 20 GeV up to 1 TeV the spectrum follows a simple power law with spectral index close to 3.0 and does not exhibit prominent spectral features. Possible interpretations can be found in a harder electron spectrum at the source or in the presence of a local source of high-energy electrons and positrons, a nearby pulsar or dark-matter annihilation. This interpretation allows also to explain the increase in the positron to all electron ratio observed by PAMELA above 10 GeV as mentioned in the following section.

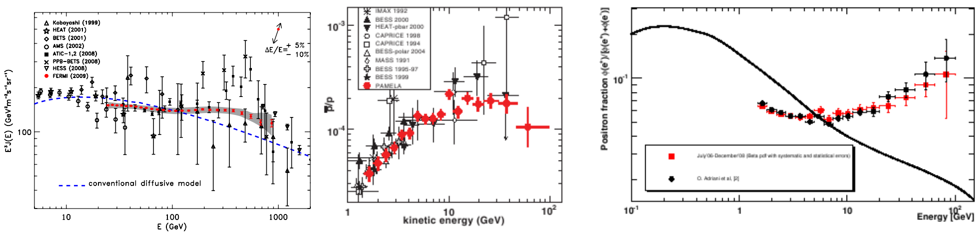

Fig. 1. – (Colour on-line) Left: the Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of $+5\% - 10\%$ of the absolute energy, corresponding to the present estimate of the uncertainty of the LAT energy scale. Other high-energy measurements and a conventional diffusive model [20] are shown. Center: the PAMELA antiproton-to-proton flux ratio. Right: PAMELA positron fraction results.

3. – PAMELA

The PAMELA experiment (a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a satellite-borne apparatus designed to study charged particles in the cosmic radiation with a particular emphasis on antiparticles. The statistics, particularly at high energies, is significantly increased compared to the total data sets provided by all previous experiments. The PAMELA apparatus is inserted inside a pressurized container (2 mm aluminum window) attached to the Russian Resurs-DK1 satellite and comprises the following subdetectors: a time-of-flight system (ToF); a magnetic spectrometer; an anticoincidence system (AC); an electromagnetic imaging calorimeter; a shower tail catcher scintillator and a neutron detector. Technical details about the entire PAMELA instrument can be found in [21]. PAMELA has been acquiring data since July 11, 2006.

Figure 1 center reports the antiproton-to-proton flux ratio measured by PAMELA in the 1 to 100 GeV energy range, showing that PAMELA data are in excellent agreement with recent results from other experiments. Details are reported in [22]. On the right of fig. 1 is the positron fraction with statistical and systematic errors summed in quadrature, compared with the PAMELA positron fraction reported in [23]. The solid line shows a calculation by Moskalenko and Strong [24] for pure secondary production of positrons during the propagation of cosmic rays in the galaxy. The new experimental results are in agreement with what reported in [23] and confirm both solar modulation effects on cosmic rays with low rigidities and an anomalous positron abundance above 10 GeV. Antiproton results do not show any clear deviation from a secondary production. Positrons instead clearly show an excess at high energy; this can be due to dark-matter particle annihilation halo or to nearby sources such as pulsar. Actually, the positron data presented here are insufficient to distinguish between astrophysical primary sources and dark-matter annihilation, but the experiment is continuously taking data and the increased statistics will allow the measurement of the positron fraction to be extended up to an energy of about 300 GeV. The combination of these efforts together with results coming from Fermi, will help in discriminating between various dark-matter and pulsar models.

4. – Future perspectives: the Alpha Magnetic Spectrometer AMS-02

AMS-02 is a space-borne magnetic spectrometer designed to measure with accuracies up to one part in 10^9 the composition of cosmic rays near the Earth. With a large acceptance ($5000\,\text{cm}^2\,\text{sr}$), an intense magnetic field and an accurate particle identification, AMS-02 will provide the highest accuracy in cosmic rays measurements up to the TeV region. During a three years long mission on the ISS, AMS-02 will achieve a sensitivity of one part in a billion to the existence of anti-He in the cosmic ray as well as important information on the origin of dark matter.

AMS purpose is to perform accurate, high-statistics, long-duration measurements of the spectra of energetic (up to multi-TeV) primary cosmic rays in space. It will search for antinuclei of primordial origin into the cosmic-ray flux: the detector design allows to reject almost all the background to an anti-He nucleus signal. The nowadays most interesting goal of AMS-02 is the search for signatures of dark-matter annihilations by the study of the rare cosmic-rays components, as antiprotons and positrons, and of the gamma-ray flux.

AMS-02 will have a unique opportunity of measuring at the same time the spectra of electron, positrons, antiprotons, protons, photons and also antideuteron. The availability of new and accurate measurements is looked forward. The combination of the efforts of all these experiments will help in discriminating between various dark-matter and pulsar models put forward to explain the recent results about the lepton fluxes from the PAMELA and Fermi experiments.

REFERENCES

[1] Thompson, D. J. *et al.*, *Astrophys. J. Suppl. Ser.*, **86** (1993) 629.
[2] Hartman R. C. *et al.*, *Astrophys. J. Suppl. Ser.*, **123** (1999) 79.
[3] Tavani M. *et al.*, *Astron. Astrophys.*, **502** (2009) 3.
[4] Pittori C. *et al.*, *Astron. Astrophys.*, **506** (2009) 1563.
[5] Feroci M. *et al.*, to be published in *Astron. Astrophys.*
[6] Tavani M. *et al.*, *Nature*, **462** (2009) 620; doi:10.1038/nature08578 (arXiv:0910.5344).
[7] Abdo A. A. *et al.*, *Science*, doi:10.1126/science.1182174 (2009).
[8] Pacciani L. *et al.*, to be published in *Astron. Astrophys. Lett.*, arXiv:1005.3263.
[9] Striani E. *et al.*, to be published in *Astrophys. J.*, arXiv:1005.4891.
[10] `http://people.roma2.infn.it/~agile/AGILE_pub.html`.
[11] Atwood W. B. *et al.*, *Astrophys. J.*, **697** (2009) 1071.
[12] Meegan C. *et al.*, to be published in *Astrophys. J.*
[13] Abdo A. A. *et al.*, *Astrophys. J. Suppl. Ser.*, **188** (2010) 405, doi:10.1088/0067-0049/188/2/405.
[14] Abdo A. A. *et al.*, *Astrophys. J. Suppl. Ser.*, **187** (2010) 460, doi:10.1088/0067-0049/187/2/460.
[15] Abdo A. A. *et al.*, *Science*, **325** (2009) 840.
[16] Abdo A. A. *et al.*, *Science*, **325** (2009) 848.
[17] Abdo A. A. *et al.*, *Astrophys. J.*, **715** (2010) 429, doi:10.1088/0004-637X/715/1/429.
[18] `https://www-glast.stanford.edu/cgi-bin/pubpub`.
[19] Abdo A. A. *et al.*, *Phys. Rev. Lett.*, **102** (2009) 181101, doi:10.1103/PhysRevLett.102.181101.
[20] Strong A. W., Moskalenko I. V. and Reimer O., *Astrophys. J.*, **613** (2004) 962.
[21] Picozza P. *et al.*, *Astropart. Phys.*, **27** (2007) 296.
[22] Adriani O. *et al.*, *Phys. Rev. Lett.*, **102** (2009) 051101.
[23] Adriani O. *et al.*, *Nature*, **458** (2009) 697.
[24] Moskalenko I. V. and Strong A. W., *Astrophys. J.*, **493** (1998) 694.