IL NUOVO CIMENTO Vol. 33 C, N. 6 Novembre-Dicembre 2010
DOI 10.1393/ncc/i2011-10746-8

Colloquia: IFAE 2010

Recent results and perspectives on cosmic-rays ground experiments

O. Pisanti(*)

Dipartimento di Scienze Fisiche, Università di Napoli "Federico II"
INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo
Via Cinthia, 80126 Napoli, Italy

(ricevuto l'8 Ottobre 2010; pubblicato online il 18 Gennaio 2011)

Summary. — I summarize in this paper the results and perspectives of representative ground experiments for the observation of very-high-energy cosmic rays.

PACS `95.55.Ka` – X- and γ-ray telescopes and instrumentation.
PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `95.85.Pw` – γ-ray.
PACS `95.85.Ry` – Neutrino, muon, pion, and other elementary particles; cosmic rays.

1. – Introduction

Although Cosmic Rays (CRs) were first discovered at the beginning of the 20th century, they are still today a subject of intense study since we miss a complete understanding of their origin, composition and acceleration mechanisms. Their energies extend from MeV values (with a flux of more than 1000 particles per second per square meter) to more than 10^{11} GeV (less than one particle per km^2 per century). In particular, unlike charged cosmic rays which are deflected by electromagnetic fields, photons and neutrinos travel almost unimpeded from their sources to the Earth; therefore, their observation is very promising for unveiling the details on production and acceleration mechanisms of CRs. In this paper, we will focus on Very High Energy (VHE) CRs in the energy range 100 GeV–100 EeV (1 EeV $= 10^{18}$ eV); in this energy region, due to the smallness of the flux, small detectors on balloons or in the outer space are not adequate, and the atmosphere is usually employed as a big calorimeter to detect primary particles through the secondaries (charged particles, fluorescence and Cherenkov light) that they produce hitting on air molecules. Since, on the one side, the dynamic energy range of a detector

(*) E-mail: `pisanti@na.infn.it`

is limited to 2–3 orders of magnitude, and we are still considering, on the other side, an energy range of more than 10 orders of magnitude, we can expect that different techniques are used at different energies; due to space limits, we will give details only on some representative experiment, both at low and high energy.

2. – Low-energy experiments

In the low-energy range ($E < 10^3$ TeV), two different type of detectors are used both in γ-ray astronomy and/or charged CRs detection: Imaging Atmospheric Cherenkov Telescopes (IACT) or Extensive Air Shower (EAS) arrays. Both of these techniques take advantage of the fact that, when a primary CR interacts with the atmosphere, it produces a shower of relativistic secondary particles which can be all collected or only sampled by an array of ground detectors in an EAS configuration: the shower relativistic particles emit also Cherenkov light, that can be focused by a mirror to a photomultiplier "camera" of a IACT detector.

In table 1 of ref. [1] a list of IACT experiments is given. An advantage of this approach over the satellite-based one is the collection area (typically $10^5\,\mathrm{m}^2$, increasing with energy), almost five orders of magnitude larger than in the case of space detectors. On the other side, IACT technique differs from the other ground-based approaches in the better angular resolution, typically $\sim 0.1^\circ$, which is the best of any astronomical technique above 0.1 MeV, and the lower energy threshold, $\sim$ 20–50 GeV, almost bridging the gap with space-borne γ experiments, which are limited to $E <$ few GeV. IACT instruments have also a superior instantaneous sensitivity, defined as the minimum flux (in % of that of the Crab Nebula) for which a source is detectable at a 5σ significance in 50 hours of observation. The advantages of stereoscopic measurements was firstly showed by the HEGRA Collaboration [2]: these allow a better reconstruction of direction and energy and the shower core location can be better established with improved resolution. A possible limit of IACT detectors is the restricted Field of View (FoV), $\sim$ 3–4°: a consequence of this is, for example, that in a Gamma Ray Burst (GRB) observation these detectors can only be operated in "follow-up" mode, requiring a time of the order of minutes for pointing the object (as an example, the MAGIC [3] telescopes have a slewing speed of $\sim 5^\circ\,\mathrm{s}^{-1}$, about 3 times faster than HESS's [4] ones). Moreover, a $\sim 10\%$ duty cycle is due to the need of astronomical darkness.

With a large FoV ($\sim 2\,\mathrm{sr}$) and a duty cycle of almost 100%, EAS arrays are a complementary technique to IACT's for the detection of CRs. Unlike the experiments of the first generation (CIGNUS [5], CASA [6]), where the instrumented area was $\sim 1\%$ of the total one, implying high-energy thresholds, the new generation of experiments (see table 1 of ref. [7] for a list of them) used two different approaches to lower the energy threshold: to instrument a larger fraction of the total area, in such a way to raise the number of particles arriving to the Earth which are detected, and/or locate the detectors at a higher altitude, where it is possible to detect the shower maxima of low-energy showers.

The observations coming from IACT and EAS experiments allow us to shed light on phenomena taking place in several galactic and extragalactic sources of CR: pulsars, binary systems, supernovae remnants, Active Galactic Nuclei (AGN), GRB. In the following, we will report some example for the two experiments MAGIC [3] and ARGO-YBJ [8].

The two MAGIC IACTs, spaced a distance of 85 m apart, are among the biggest instruments of this kind in operation and are located in La Palma (Canary Islands). The MAGIC threshold for γ-rays is 50 GeV (but it goes down to 25 GeV when the so-called SUM trigger system is employed) and the energy resolution is $\sim 25\%$ above 200 GeV. In recent years MAGIC gave several contributions to galactic and extragalactic astrophysics. One example is the observation of the emission of the SuperNova Remnant IC-443, at a distance of 1.5 Kpc (see fig. 1 of ref. [9]): it appears not coincident with the center of the SNR shell, but is correlated with a maser emission. A possible source of this VHE radiation is the π^0 decay coming from CR accelerated in the dense molecular cloud. The second example (see fig. 2 of ref. [9]) is the measure of the γ-ray flux of the X-ray binary system LSI +61 303, which clearly shows the periodic nature of the emission. Very interesting is the regular monitoring campaign of the giant elliptical radio-galaxy M87, made together with HESS [4] and VERITAS [10]. On February 1, 2008, MAGIC detected a flare which reached a maximum of 15% of the Crab Nebula flux (see fig. 5 of ref. [9]).

ARGO-YBJ [8] is a collaboration between Italy and China located in Tibet. The detector consists of modules of 12 RPCs, to form an inner area of $5600\,\mathrm{m}^2$, surrounded by 23 additional clusters ("guard ring"). The array works in two independent data acquisition modes: "scaler" and "shower" mode. In scaler mode, each module counts the rates of events with a total number of hits ≥ 1, ≥ 2, ≥ 3, ≥ 4 every 0.5 s, without any direction information (GRB searches). In shower mode, a valid event requires at least 20 particles registered within 420 ns, with an angular resolution of $0.2°$ for a primary above 10 TeV and $2.5°$ at ~ 100 GeV. Figure 1 of ref. [11] shows the sky map for events with $N_{PAD} \geq 40$, corresponding to 424 days of data taking, after correcting for excesses in CR flux from the galactic anticentre. The Crab Nebula and Mrk 421 are detected with statistical significance 7.0 and 8.0, respectively. In fig. 5 (left) of ref. [12] it is reported the distribution of statistical significance of 26 GRB detected by satellites in the period July 2006–July 2007 and November 2007–January 2009, showing no excess either as prompt or prior/delayed emission. An important contribution of this experiment was also the measure of the production cross-section of protons and air nuclei [13], which follows from the angular distribution of showers.

3. – High-energy experiments

Gamma-ray astronomy at high energies has to face the problem of the photon pair production over the infrared and microwave backgrounds, which restricts the distances over which gamma-rays can travel without attenuation. Neutrinos would be the best messenger particles, if not for their very small cross-section with matter, which is an obstacle for their efficient detection. High-energy experiments usually rely on charged CR detection. The biggest challenge of CR observations at high energy lies in the fact that the flux of particles is very small, implying the need of enormous exposures. Two detector techniques are used in this range of energy: surface detector arrays on the ground (as Haverah Park or AGASA [14]), or air fluorescence detectors (as HiRes [15]), which collect the fluorescence light emitted by nitrogen molecules hit by the secondary particles of an atmospheric shower. While in the first case the experiment samples only the lateral distribution of particles at a given atmospheric depth, relying on simulations for the determination of mass and energy of the primary particle, in the second case one can infer the longitudinal evolution of the shower in atmosphere, using the known proportionality between air fluorescence and charged-particle energy loss. In particular, stereo configurations of fluorescence telescopes can be used, allowing an angular resolution of less than $1°$ [15]. However, while a surface array operates continuously, a drawback of the fluorescence technique is the low duty cycle of $\sim 10\%$, due to the fact that one needs dark, moonless nights with good atmospheric conditions. The two types of detection techniques are complementary and the new generation of experiments (Pierre Auger Observatory [16], TA&Tale [17]) uses both of them to check systematic errors.

At $6 \cdot 10^{19}$ eV pion photoproduction of protons over the microwave background radiation gives a suppression of the CR flux (nuclei photodisintegration and gamma-ray pair production are the corresponding processes for the other CR components): this is the so-called Greisen-Zatsepin-Kuz'min (GZK) effect [18]. Other physics highlights for UHE CRs are: their mass composition, the identification of their sources, the presence of photons or neutrinos together with charged CRs. Recent observations coming from new experiments allowed us to shed light on these topics. In the following, for the sake of brevity, we will only report some results of the Pierre Auger Observatory (PAO) experiment.

Eighteen countries cooperate in the PAO experiment [16] for building two CR observatories, one in the Southern hemisphere, at Malargüe in Argentina, completed in June 2008, and one in the Northern hemisphere, in Colorado, under development. Auger South consists of a Surface Detector (SD) array of 1600 water Cherenkov, covering an area of about $3000\,\mathrm{km}^2$ on a triangular grid with 1.5 km spacing, and a Fluorescence Detector (FD) made by 24 optical telescopes in 4 buildings at four peripheral sites.

Figure 5 of ref. [19] shows the energy spectrum of UHE CRs derived from the combination, with a maximum-likelihood method, of two kinds of data: hybrid data, that is events detected with both the FD and the SD, which have a more accurate reconstructed energy (data were collected between November 2005 and May 2008) and SD data (until December 2008). While the two sets have the same systematic uncertainty in the energy, the normalization uncertainties are additional constraints in the combination. The comparison with HiRes data shows some discrepancies, which can be partly reconciled by an energy shift of the energy scale of the two experiments. Results single out the break in the power law of the CR spectrum called "ankle" at $\log_{10}(E/\mathrm{eV}) = 18.61 \pm 0.01$ and give indication of the GZK suppression at $\log_{10}(E/\mathrm{eV}) = 19.61 \pm 0.03$ with more than 20σ statistical significance. The mass composition of CR at different energies can be inferred by the so-called "elongation rate", that is the change of the average depth of the shower maximum, $\langle X_{max} \rangle$, as a function of the energy. This is shown in fig. 3 of ref. [20] (left plot), together with its shower-to-shower fluctuation, $\mathrm{rms}(X_{max})$ (right plot), a measure which is possible only thanks to the excellent resolution of FD ($\sim 20\,\mathrm{g/cm}^2$). The behaviors of $\langle X_{max} \rangle(E)$ and $\mathrm{rms}(X_{max})$ give indication of an increasing average mass of the primary particles with energy, somehow in contradiction with corresponding data from HiRes [21]. Some explanation was proposed for solving the puzzle, for example the unexpected changes of the depth of first interaction due to a rapid increase of cross-section and/or increase of inelasticity above $2 \cdot 10^{18}$ eV, which enhance the role of biases due to small statistics [22]. Finally, we briefly mention the PAO results on the arrival directions of CRs, referring for details the interested reader to the published papers [23,24]. Table I of ref. [24] summarizes the results of the scan on the high-energy events ($E > 55\,\mathrm{EeV}$) detected by the Auger experiment in the period 1 January, 2004 through 26 May, 2006 (exploratory period or Period I) and 27 May, 2006 through 31 March, 2009 (Periods II and III). A correlation over angular scales of less than 6° with directions towards nearby AGNs, listed in the Véron-Cetty and Véron catalog, is established, even if its degree seems to be weaker than suggested by earliest data (Period II). While a clear interpretation of this signal has to wait for more data, remarkable features are that the values of the parameters that characterize the correlation are stable with time and, in particular, the threshold energy which maximizes it coincides with the GZK suppression one.

4. – Future prospects

IACT technique is very promising for future experiments, since it has the potential for large improvements, like the increase of flux sensitivity, at the level of $\sim 10^{-3}$ the Crab Nebula flux, by increasing the collection area from $0.1\,\mathrm{km}^2$ to $\geq 1\,\mathrm{km}^2$ with the concept of large arrays of IACTs. This enhancement, together with its good angular resolution, will allow joint studies with satellite experiments, like Fermi-LAT [25], which will help, for example, in breaking the degeneracy of leptonic and hadronic emission models. However, γ-ray astronomy requires also new advanced EAS array experiments, like HAWC [26], since these can view continuously a large region of the sky.

At higher energies, some enhancements are proposed for existing experiments, like areas of denser detector arrays, called "infill", for surface detectors, or extra fluorescence telescopes for enlarging the Field of View of fluorescence detectors, both at the aim of going to lower energies, or/and the use of radio-detection technique. These will be very helpful in answering some of the unknown questions about CRs. In fact, we can be confident in some physical results indicated by experiments, like the existence of the GZK suppression at energies $> 6 \cdot 10^{19}\,\mathrm{eV}$ and the correlation between event directions and the supergalactic plane. However, several questions remain still uncertain, like the mass composition at high energy or the identity of objects with which CR events correlate, which we trust will be addressed by the near future UHE cosmic-ray experiments.

REFERENCES

[1] Hinton J., *New J. Phys.*, **11** (2009) 055005.
[2] Daum A. *et al.*, *Astropart. Phys.*, **8** (1997) 1.
[3] Cortina J., *Astrophys. Space Sci.*, **297** (2005) 245.
[4] Hinton J. A., *New Astron. Rev.*, **48** (2004) 331.
[5] Alexandreas D. E., *Nucl. Instrum. Methods A*, **311** (1992) 350.
[6] Borione A. *et al.*, *Nucl. Instrum. Methods A*, **346** (1994) 329.
[7] Sinnis G., *New J. Phys.*, **11** (2009) 055007.
[8] D'Ettorre-Piazzoli B., in *Proceedings of the International Workshop on Neutrino Telescopes, Venice, 1992*, edited by Baldo Ceolin M., p. 349.
[9] Majumdar P., *Nuc. Phys. B (Proc. Suppl.)*, **196** (2009) 221.
[10] Holder J., *Astropart. Phys.*, **25** (2006) 391.
[11] Di Girolamo T., *J. Phys. Conf. Ser.*, **203** (2010) 012119.
[12] Aielli G. *et al.*, *Astropart. Phys.*, **32** (2009) 47.
[13] Aielli G. *et al.*, *Phys. Rev. D*, **80** (2009) 092004.
[14] Edge D. M., Evans A. C. and Garmston H. J., *J. Phys. A*, **6** (1973) 1612; Chiba N. *et al.*, *Nucl. Instrum. Methods A*, **311** (1992) 338.
[15] Abu-Zayyad T. *et al.*, *Astrophys. J.*, **557** (2001) 686.
[16] Auger Collaboration, *The Pierre Auger project design report*, FERMILAB-PUB-96-024 preprint.
[17] Takeda M. *et al.*, *Mod. Phys. Lett. A*, **23** (2008) 1301.
[18] Greisen K., *Phys. Rev. Lett.*, **16** (1966) 748; Zatsepin G. T. and Kuzmin V. A., *JETP Lett.*, **4** (1966) 78.
[19] Abraham J. *et al.*, *Phys. Lett. B*, **685** (2010) 239.
[20] Abraham J. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 091101.
[21] Abbasi R. U. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 161101.
[22] Wilk G. and Włodarczyk Z., arXiv:1006.1781 preprint (2010).
[23] Abraham J. *et al.*, *Astropart. Phys.*, **29** (2008) 188; **30** (2008) 45 (Erratum); Roulet E. (for the Auger Collaboration), *Nucl. Phys. Proc. Suppl.*, **190** (2009) 169.

[24] Hague J. D. (for the Auger Collaboration), *Proc. 31st ICRC, Lodz* (2009), ID # 0143.
[25] Abdo A. A. *et al.*, *Astrophys. J. Suppl.*, **183** (2009) 46.
[26] Gonzales M. M. (for the HAWC Collaboration), *Proc. 30th ICRC, Merida*, **3** (2007) 1563