IL NUOVO CIMENTO Vol. 36 C, N. 1 Gennaio-Febbraio 2013
DOI 10.1393/ncc/i2013-11416-7

Colloquia: IFAE 2012

Astroparticle physics review

A. Giuliani
CNRS/IN2P3, CSNSM - 91405 Orsay, France

ricevuto il 31 Agosto 2012

Summary. — This paper summarizes recent interesting achievements and future prospects in selected topics of astroparticle physics.

PACS `96.50.S-` – Cosmic rays.
PACS `95.85.Sz` – Gravitational radiation, magnetic fields, and other observations.
PACS `14.60.Pq` – Neutrinos mass and mixing.
PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).

1. – Introduction

Astroparticle physics [1] is a science which crosses the boundaries between astrophysics, particle physics and cosmology. It addresses fundamental questions like the physics of the Big Bang, the nature of dark matter and dark energy, the stability of protons, the properties of neutrinos and their role in cosmic evolution, the interior of the Sun or supernovae as seen with neutrinos, the origin of cosmic rays, the nature of the Universe at extreme energies and cosmic processes as seen with gravitational waves.

Experimentally, astroparticle physics has essentially an observational character: it deals with the detection and the study of messengers from the most violent phenomena occuring in the Universe, but also of very rare nuclear processes and interactions that can be revealed only in the cosmic silence of the underground laboratories. Sometimes, but less often, the phenomena to be detected are prepared on purpose, like in the case of neutrinos produced at reactors and accelerators.

Astroparticle physicists run their researches in the most disparate environments: from space to deep caverns, from high-altitude surface stations to uderwater and underice installations. Their detection technology arsenal is incredibly various: they employ all the traditional high-energy-physics techniques, often in extreme situations (like in spacecrafts or in the marine depths), but they rely also on non-standard ingenious methods, exploiting acoustic effects, tiny temperature increases of materials almost at the absolute zero, sophisticated interferometry, or fluorescence and radiowave emissions.

It is impossible to organically review and to provide an adequate bibliography over such a vast and rich landscape in just six pages. I have chosen therefore to make a topic selection, motivated either by recent important results, or by interesting future developments, or just by my personal taste and competence.

2. – The violent Universe

Violent phenomena in the Universe, which produce ultra-high-energy particles with mechanisms not fully understood, can be studied through the detection of messengers of different nature.

2·1. *Photons.* – High-energy gammas [2] remain the reference messengers, as privileged tracers of cosmic and astrophysics energetic processes. They in fact propagate in straight lines, while, compared to neutrinos, their interaction cross section is much higher so they are easier to detect. There are two main classes of detection methods.

1. Up to several tens/hundreds of GeV, detectors based on satellites are used, in order to avoid the effects of the atmosphere. The main scientific instrument presently providing data in this field is the Fermi Large-Area Telescope (LAT), an imaging high-energy gamma-ray telescope covering the energy range from about 20 MeV to more than 300 GeV [3]. It has observed and is still studying a large number of sources that include active galaxies, pulsars, compact binaries, globular clusters, supernova remnants, as well as the Sun, the Moon and the Earth. Together with the dedicated Gamma-ray Burst Monitor (GBM), it has uncovered surprising characteristics in the high-energy emission of gamma-ray bursts (GRBs) that have been used to set significant new limits on violations of Lorentz invariance. The Fermi LAT has also made important new measurements of the Galactic diffuse radiation and has made precise measurements of the spectrum of cosmic-ray electrons and positrons from 20 GeV to 1 TeV.

2. At higher energy, the photon flux becomes so low that large-area ground-based installations are mandatory. The detection is mediated by the air showers originating from gamma-ray interactions in the atmosphere. There are essentially two methods to study the showers: i) the particles reaching the ground are recorded either via the Cherenkov light they produce in water pools or via the ionization in tracking devices (Milagro, ARGO/YBJ and HAWC); ii) the Cherenkov light from air showers is recorded directly by means of large reflectors which focus the light onto cameras of hundreds to a few thousands of photomultipliers (in future possibly also solid-state detectors). From the shower image, the direction, energy and character of the primary particle (hadron *versus* gamma-ray) can be obtained (H.E.S.S., MAGIC and VERITAS). More than a hundred sources of gamma-rays at the 10^{11} to 10^{14} eV scale have been detected [4], many of them in the Galaxy and revealing a complex morphology. Most of the Galactic TeV sources correspond to objects like binary systems, pulsar wind nebulae and supernova remnants. Others are still entirely unknown at any other wavelength and emit most of their energy in the TeV range. Going outside the Galaxy, a large number of AGNs have been observed and their fast variability demonstrated. The future of the field is represented by the Cherenkov Telescope Array (CTA) [5], whose construction should start in 2015. Developed by an international consortium and run as an open observatory, it will be made available to astronomers on the same basis as optical or X-ray observing facilities. It will consist of two observatories in the two emispheres, allowing full

coverage of the sky. The energy bandwidth will be dramatically extended up to 100 TeV, with $\sim$ 1000 sources expected to be observed.

2˙2. *Charged cosmic rays.* – The spectrum of the charged cosmic rays (mainly protons and other nuclei) extend by more than 30 orders of magnitude in flux and by 14 orders of magnitude in energy, up to above 10^{21} eV. Below about 10^{14} eV, the particles are all of galactic origins and are detected directly using satellites and balloons. This portion of the spectrum is being studied with unprecedented precision by the Alpha Magnetic Spectrometer, also designated AMS-02, a particle physics experiment module that is mounted on the International Space Station [6]. The AMS-02 physics program is important and rich, involving the indirect search for dark matter, the search for cosmic anti-nuclei, the precise measurement of spectrum and composition of cosmic rays up to 1 TeV, and the search for strange quark matter. In July 2012, AMS-02 had recorded over 18 billion cosmic ray events since its installation, much more than the total number of cosmic rays recorded in a full century of looking to date. Physics results will be released soon.

Above 10^{14}–10^{15} eV, where interesesting features of the energy spectrum appear (such as the so-called “knee” and “ankle”) , the extragalactic component becomes more and more important, especially at the highest energy [7, 8]. Here, the detection is indirect (once again exploiting air showers) and performed by ground-based installations. The present flagship experiment in the search for sources of ultra-high-energy cosmic rays is the Pierre Auger Observatory (in short Auger) in Argentina. This 3000 km^2 array of water tanks, flanked by 27 air-fluorescence telescopes, measures direction, energy, and profile of giant air showers. Present Auger results provide important information on key questions in the field. A transition from an isotropic to an anisotropic distribution of the arrival directions of ultra-high-energy cosmic rays is observed: above 55 EeV, a correlation of arrival directions is found with nearby concentrations of matter as traced by certain Active Galactic Nuclei (AGN). Such a correlation would be in agreement with theoretical expectations that only two classes of objects are able to accelerate particles up to 10^{20} eV or higher: the central black holes or emerging jets of AGNs, and GRBs. Understanding the primary composition above 10^{19} eV and the nature of the high-energy cut-off as well as identifying individual sources calls for significantly higher statistics. This is the primary motivation to build a much larger array than the present Auger. An alternative approach to reach the huge detection volumes necessary for cosmic ray studies at these colossal energies are space-based detectors which can record fluorescence light and reflected Cherenkov light from air showers (JEM-EUSO project).

2˙3. *High-energy astrophysical neutrinos.* – The physics case for neutrino astronomy is compelling: high-energy neutrinos can provide an uncontroversial proof that their astrophysical sources accelerate hadrons [9]. Moreover they can reach us from cosmic regions which are opaque to other types of radiation. However, no high-energy neutrino source of astrophysical origin was discovered so far.

The main actor in this field is currently the neutrino telescope IceCube [10], by far the world's largest neutrino detector, encompassing a cubic kilometer of ice in the Antarctica. This instrument has observed atmospheric neutrinos up to 400 TeV, and has provided flux limits for neutrinos from point sources, GRBs, and neutralino annihilation in the Sun, with implications for WIMP-proton cross sections. A shadowing effect from the Moon has been observed as well.

The future of high-energy neutrino astronomy is represented by KM3NeT [11], an underwater neutrino detector in the Mediterranean Sea, with a foreseen sensitivity 5 times larger with respect to IceCube and covering the Southern Emisphere. Based on a concept extensively tested in the running experiment ANTARES, KM3NeT is being pursued by a consortium formed by the three Mediterranean neutrino telescope projects (ANTARES, NEMO and NESTOR). It will increase the discovery potential for neutrino sources and will potentially allow for looking deeper into black hole environments and, at energies beyond 100 TeV, further out into the Universe than possible with gamma-rays. Together with gamma-ray and cosmic ray observations (and with IceCube), it could pave the way to real multi-messenger astronomy.

3. – Gravitational waves

The physics case motivating the detection and the study of gravitational waves is at least threefold: i) test of general relativity; ii) study of astrophysical sources exploiting unattenuated propagation; iii) more at long term, implications in cosmology and large-structure formation. No gravitational-wave signal has been detected so far.

Considering the wave frequency, two different classes of instruments [12] are required for detection in the ranges below and above $\sim 1\,\text{Hz}$, corresponding, respectively, to supermassive sources (of the order of 10^4–10^6 solar masses) and to neutron stars or black holes up to 10^3 solar masses. In the higher frequency range, with sensitivities peaking at 100–1000 Hz, the close future will be dominated by the interferometric projects advanced VIRGO and LIGO, which will increase the present sensitivity by a factor 10, and correspondingly by a factor 1000 the number of observables source. Some tens of neutron star binaries per year should be detectable, and the first scientific data are expected in 2016.

At the end of this decade and in the next one, new ambitious projects should i) cover the low-frequency region (with the spaceborne LISA mission) and ii) further extend the sensitivity in the high-frequency region (with the underground interferometer Einstein Telescope).

4. – Basic properties of neutrinos

Neutrinos are peculiar particles: much lighter than the other fermions, they are characterized by an inter-generation mixing much more important than the corresponding phenomenon in the quark sector. Since they can be produced as coherent superpositions of mass eigenstates by weak interactions, flavour oscillations take place and are observable, providing a wealth of information about masses and mixing. Being electrically neutral, unlike the other fermions they could coincide with their antiparticles (Majorana neutrinos) and constitute therefore a new form of matter. In addition, they can mix with non-interacting fermions, giving rise to sterile states.

4˙1. *Status of neutrino oscillations.* – Very recently, the study of neutrino oscillations at reactors with the experiments Daya-Bay [13] and RENO [14] – confirming previous hints from T2K – has allowed to set the missing element in the neutrino mixing parameters, *i.e.* the value of θ_{13} (with $\sin^2(2\theta_{13})$ of the order of 0.1), by far the smallest of the three angles parametrizing the mixing matrix. This relatively high value allows to plan carefully future long-baseline oscillations experiments capable to study CP violation in the lepton sector and the neutrino mass hierarchy. These projects (LAGUNA-LBNO in Europe and LBNE in the US) allow also to study the baryon number conservation with unprecedented sensitivity and to perform low-energy neutrino astronomy.

Anomalies in several low-energy neutrino experiments suggest a possible departure from a 3-flavour scenario, with an additional mass splitting in the eV range and at least one sterile state [15]. It does not look easy to reconciliate these tiny effects in a coherent scheme, therefore a rich experimental program is going on in order to investigate them deeply (NESSiE, Nucifer, STEREO, SCRAAM, DANSS, Ce-LAND and others).

4˙2. *Status of neutrinoless double-beta decay.* – Double-beta decay (DBD) is a very rare, second-order weak nuclear transition which is possible for a few tens of even-even nuclides [16]. Its observation in the neutrinoless version would imply first of all lepton number non-conservation, which, in a beyond-standard-model perspective, is as important as baryon number non-conservation. Simultaneously, the Majorana nature of neutrino would be ascertained. In the case of neutrinoless DBD driven by the exchange of a virtual light neutrino, one would have additional informations on the neutrino mass scale and possible on the mass hierarchy.

The richness and the importance of the physics reach of DBD study explains why many projects worldwide are in preparation or already taking data. After the conclusion of the now historical Cuoricino and NEMO3 experiments, which set limits of the order of 0.5 eV on the neutrino mass scale, similar to the value claimed to be observed by a part of the Heidelberg-Moscow (HM) collaboration, now three new experiments have started the data taking: EXO-200 [17], KamLAND-Zen [18] and GERDA-1. CUORE will take data in 2014, and its first tower CUORE-0 is ready for a physics run. New data are starting to come, and some tension begins to appear with the HM claim. When the present experimental phase will be completed (about 5 years from now), the degenerate region of the neutrino mass pattern will have been fully explored. Several advanced technologies (such as that using scintillating bolometers) seem to be able to go further and to deeply explore the inverted hierarchy region.

5. – Dark matter

While there is a compelling evidence of the gravitational effects due to dark matter (DM) in the Universe, there is no indication at all of the type of particle (if this is the case!) which consitutes it [19]. There are complementary actions aiming at identifying such a particle: i) its direct production and discovery at LHC; ii) the detection of traces of its annihilation in the cosmic rays (the so-called "indirect searches"); iii) last but not least, the detection of its interactions with terrestrial underground detectors (the so-called "direct searches"). Motivated candidates are axions (non-thermal relics with mass in the μeV-meV range) and WIMPs (especially in the form of Lightest Supersymmetric Particles — neutralinos — with masses at the Fermi scale), but there is a plethora of other models, partially covered by WIMP searches but including also cases of non-detectable particles.

As for the indirect searches [20], excess of electrons and positrons in the cosmic rays, possibly related to DM particle annihilation, was detected by PAMELA, Fermi LAT and other observatories. The wisest conclusion, waiting for the expected wealth of data from AMS-02 and for the space antideuteron spectrum measured by GAPS, is that this excess is due to a source of astrophysical nature. No hints of DM is coming from photons and neutrinos in cosmic rays so far.

In the direct searches, the healthy competition between hybrid bolometer-based and double-phase noble gas detectors (especially Xenon TPCs) has lead to significant progress recently. The XENON-100 experiment has set a limit of $\sim 2 \times 10^{-45}\,\text{cm}^2$ (for 55 GeV WIMP mass) on the WIMP-nucleus cross section in the spin independent case [21].

The planned extension to 1 ton should improve this result by two orders of magnitudes, allowing to test most of the relevant neutralino parameter space. Future developments of the bolometric experiments (EURECA and GEODM projects) should achieve comparable sensitivities, with different target and experimental approach. Hints for signals at low WIMP masses ($< 10\,\mathrm{GeV}$) [19], such as the DAMA modulation signal and the CoGeNT and CRESST results, need further clarification.

The lack of a fast observation of SUSY at LHC has not weakened the motivations for direct and indirect searches for dark-matter particles. The exclusion of most of the parameter space for CMSSM, a minimal option to extend the standard model, has made less constrained extensions (like pMSSM) more popular. While LHC results and indirect/direct searches compete in the spin dependent case, in the spin independent case the coherent effect in the WIMP-nucleus interaction makes direct searches by far more sensitive at the moment.

6. – Conclusions

Astroparticle physics is a vibrant discipline, which encompasses a large variety of interconnected phsyics problems and experimental technologies. Many fundamental topics have progressed to levels of sensitivity which promise a high discovery potential in the next few years. Longer-term projects (on a five-ten year time scale) are under definition: they deal with still unresolved crucial physics issues and each of them represents a formidable, fascinating challenge.

REFERENCES

[1] For an overview on astroparticle physics, see the updated ASPERA roadmap: `http://www.aspera-eu.org/images/stories/roadmap/SAC-Roadmap-Nov-1-2011-final.pdf`.
[2] Lorenz E. and Wagner R., *Eur. Phys. J. H*, **37** (2012) 459.
[3] Michelson P. F., Atwood W. B. and Steven Ritz, *Rept. Prog. Phys.*, **73** (2012) 074901.
[4] For a catalog of the TeV astronomical sources, see: `http://tevcat.uchicago.edu/`.
[5] The CTA Consortium, e-print arXiv:1008.3703v2 [astro-ph.IM], 2010.
[6] Bertucci B., *PoS*, **EPS-HEP2011** (2011) 067.
[7] Letessier-Selvon A. and Stanev T., *Rev. Mod. Phys.*, **83** (2011) 907.
[8] Kotera K. and Olinto A. V., *Annu. Rev. Astron. Astrophys.*, **49** (2011) 119.
[9] Waxman E., e-print arXiv:1101.1155v1 [astro-ph.HE], 2011.
[10] Halzen F. and Klein S. R., *Rev. Sci. Instrum.*, **81** (2010) 081101.
[11] The KM3NeT Collaboration, *Technical Design Report for a Deep-Sea Research Infrastructure in the Mediterranean Sea Incorporating a Very Large Volume Neutrino Telescope*, `http://www.km3net.org/TDR/TDRKM3NeT.pdf`.
[12] Pitkin M., Reid S., Rowan S. and Hough J., e-print arXiv:1102.3355v2 [astro-ph.IM], 2011.
[13] An F. P. *et al.*, *Phys. Rev. Lett.*, **108** (2012) 171803.
[14] Soo-Bong Kim *et al.*, *Phys. Rev. Lett.*, **108** (2012) 191802.
[15] Abazajian K. N. *et al.*, e-print arXiv:1204.5379v1 [hep-ph], 2012.
[16] Gómez-Cadenas J. J. *et al.*, *Riv. Nuovo Cimento*, **35**, N. 2 (2012) 29.
[17] Auger M. *et al.*, e-print arXiv:1205.5608v2 [hep-ex], 2012.
[18] Gando A. *et al.*, e-print arXiv:1201.4664v2 [hep-ex], 2012.
[19] Peter A. H. G., e-print arXiv:1201.3942v1 [astro-ph.CO], 2012.
[20] Morselli A., *J. Phys. Conf. Ser.*, **337** (2012) 012072.
[21] Aprile E. *et al.*, e-print arXiv:1207.5988v1 [astro-ph.CO], 2012.