IL NUOVO CIMENTO Vol. 33 C, N. 6 Novembre-Dicembre 2010
DOI 10.1393/ncc/i2011-10762-8

Colloquia: IFAE 2010

High-energy neutrino telescopes

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(ricevuto l'8 Ottobre 2010; pubblicato online il 2 Febbraio 2011)

Summary. — Recent results from high-energy cosmic ray and gamma detectors indicate the occurrence of hadron acceleration in cosmic sources and possible production of very-high-energy gamma-rays and neutrinos through h-γ or h-h interactions. Underwater and under-ice neutrino telescopes are discovery apparatuses aiming at the detection of high-energy (> TeV) astrophysical neutrinos. The operation of the Baikal, AMANDA, ANTARES and NEMO demonstrators, validated the Čerenkov technique as preferred solution for the construction of larger HE neutrino telescopes: IceCube, operational at the South Pole, and KM3NeT, that will be built in the Mediterranean Sea. Several R&D activities are also conducted to develop complementary experimental techniques, based on the detection of coherent acoustic (tens of kHz) or e.m. (GHz) radiation, induced by ultra-high-energy neutrino interaction in deep sea or ice.

PACS 95.85.Ry – Neutrino, muon, pion, and other elementary particles; cosmic rays.
PACS 98.70.Sa – Cosmic rays (including sources, origin, acceleration, and interactions).
PACS 13.85.Tp – Cosmic-ray interactions.
PACS 29.40.Ka – Cherenkov detectors.

1. – Introduction

In the last years the AUGER [1] and HIRES [2] experiments have accurately measured the Cosmic Ray (CR) spectrum at energies above 10^{19} eV, confirming the detection of Ultra High Energy (UHE) protons and/or nuclei, with energies up to $\simeq 3 \cdot 10^{20}$ eV. The astrophysical sources proposed as acceleration sites for such particles are powerful extragalactic objects, such as Active Galactic Nuclei (AGNs) [3] and Gamma Ray Bursters (GRBs) [4], where charged particles could be accelerated statistically through the Fermi-Bell mechanism [5, 6]. However limited statistics of these experiments to date do not allow to confirm (or exclude) a definitive correlation between UHECR arrival direction and these sources [1]. A major limit is that the interaction length of UHE hadrons in the cosmic microwave background (CMB) is few tens Mpc, while powerful astrophysical sources are typically harboured at cosmological distances [7, 8]. On the other hand, gamma-rays with $E_\gamma > 100\,\text{TeV}$ are also absorbed in the cosmic MW and IR background ($L_{abs} \simeq 10\,\text{Mpc}$), limiting gamma astronomy in the study of very high-energy phenomena in these source. At lower energies (10^{14}–10^{17} eV) the observed CR flux is also explained in terms of particles (protons, mainly) accelerated via the Fermi-Bell mechanism in Galactic Supernova Remnants (SNRs). Also in this case a definitive correlation with the candidate sources is missing, due to deflection of charged CR in the Galactic magnetic field ($B_G \simeq \mu$G). An important piece of information was recently provided by Very High Energy (VHE) gamma telescopes that identified $> 10\,\text{TeV}$ gamma-ray fluxes in the direction of several Galactic SNRs: a typical example is SNR RXJ1713.7-3946 [9]. The gamma spectrum features and source morphology strongly suggest that Fermi-accelerated protons ($E_p > 10^{14}\,\text{eV}$) interact with a dense molecular cloud, close to the source. Neutral pions—produced in *pp* interactions—are responsible for the observed intense flux of TeV gamma-rays. The detection of TeV neutrinos—originated by charged-pions decay—in the direction of this class of sources will provide the ultimate proof for the occurrence of hadron acceleration in Galactic SNR. Similarly, the detection of $E >$ TeV neutrinos from AGNs and GRBs, will solve the puzzle of their role as sources of the observed UHECR [10].

2. – High-energy neutrino detection

In order to identify astrophysical neutrino sources, the astro-particle physics community is constructing detectors capable to measure the cosmic-neutrinos arrival direction and energy. High-energy neutrinos are detected through deep-inelastic scattering of the ν with a target nucleon N. In the $\nu + N \rightarrow l + X$ interaction, the lepton l escapes while the hadronic debris X leads to a hadronic cascade. In weak charged-current (CC) interactions the outgoing lepton is charged and it preserves the neutrino flavour (e, μ or τ). In neutral-current (NC) interactions, the outgoing lepton is a neutrino, thus only the hadronic cascade is detectable. The detection of the ν interaction is, therefore, based on the observation of the outgoing charged lepton and/or of the hadronic cascade. Due to the low νN cross-section and to the faint expected astrophysical ν fluxes ($\propto E_\nu^{-2}$), the detectors must have a ν interaction target mass of several Gtons for $E_\nu \simeq 10^{12}$–10^{17} eV and much larger for higher energies. For this reason the use of natural media was suggested to detect cosmic neutrinos [11]. Depending on the candidate interaction target medium and on the energy range to explore, different experimental techniques were proposed: in the range $E_\nu \simeq 10^{11}\,\text{eV}$–$10^{17}\,\text{eV}$, the technique is based on the detection Čerenkov light originated by charged leptons outgoing a CC neutrino interaction in seawater or in the polar ice-cap [11]; at higher ν energies, the proposed experiments rely on: the detection of radio pulses produced by e.m. showers following a neutrino interaction in polar ice, salt domes or in the Moon Regolith [12,13]; the detection of acoustic waves produced by deposition of energy in the interaction of ν in seawater, polar ice-cap or salt domes [14]; the detection of air showers initiated by neutrinos interacting with rocks or deep Earth's atmosphere [15].

The underwater/ice Čerenkov technique is, at present, the most promising and advanced one. Underwater (ice) Čerenkov neutrino detectors are large arrays of optical sensors, typically photomultiplier tubes of about 10″ diameter, which permit charged leptons tracking, by timing the Čerenkov light wavefront radiated by these particle. The "golden channel" for astrophysical neutrino detection is the ν_μ CC interaction. The muon range in water is, at $E \simeq$ TeV, of the order of kilometres, therefore the ν_μ interaction can take place either within the detector or far outside it, providing a flux of high-energy muons, either contained or crossing the detector. The muon direction is recovered from the reconstruction of the Čerenkov wavefront, radiated along the muon track, within the detector instrumented volume. The detection of the neutrino-induced muon also allows "neutrino astronomy": the angle between the outgoing muon and the interacting neutrino decreases as a function of neutrino energy: at $E_\nu > \mathrm{TeV}$, the muon track is almost co-linear to the ν_μ one and permits pointing back to the ν cosmic source. These detectors are, in fact, also named as *Neutrino Telescopes*. For the muon neutrino detection, up-going or horizontal muon tracks are preferred. In fact, when an upward going muon is reconstructed, this is a unique signature of a neutrino event, being the up-going atmospheric muon background completely filtered out within few tens of km of water. The suppression of the intense down-going atmospheric muon flux is achieved installing the detector at large water(ice) depth: the muon stopping power of 3000 m of water is equivalent to the one of 1 km of rock. Neutrino telescopes are also expected to disentangle between neutrino flavours by reconstructing the Čerenkov wavefront shape of the event which depends on the different propagation of e, μ and τ in water (and ice).

Based on present astrophysical models and detailed Monte Carlo simulations, a rate of about 70 up-going events per year is expected in an underwater/ice detector of $1\,\mathrm{km}^3$ volume equipped with about 5000 optical sensors (for $E_\mu \simeq 1\,\mathrm{TeV}$ threshold). The expected angular resolution is of $\simeq 0.1°$ for $E_\mu > 10\,\mathrm{TeV}$ [16].

A number of demonstrator detectors have been built in the last decade to cope with major technological issues due to detector installation at high pressure, low temperature (polar ice), salinity (deep sea). To date, the most advanced HE neutrino detector is IceCube [17], born from the experience of the demonstrator AMANDA [18], and installed in the geographical South Pole. The detector will consist of 80 vertical strings (to date 73 strings are working), each equipped with 60 optical modules deployed between 1450 m and 2450 m depth below the surface, filling a volume of about $1\,\mathrm{km}^3$ of ice. An improvement of the telescope sensitivity in the low-energy range ($E_\mu \simeq 10\,\mathrm{GeV}$–$100\,\mathrm{GeV}$) has been recently achieved thanks to the DeepCore detector [19] formed by six densely instrumented strings, deployed in the bottom center of the telescope. In the IC40 configuration (40 strings, 365 days lifetime from 2008 to 2009) IceCube has set an upper limit to diffuse neutrino flux, for a $E_{\nu_\mu}^{-2}$ spectrum, of $1.7 \cdot 10^{-8}\,\mathrm{GeV}$, that does not show any excess with respect to the expected atmospheric neutrino flux, within systematics errors [17]. The good detector angular resolution (about 1 degree) allowed also a detailed study of the neutrino event direction. The ν sky map seen by IceCube is reported in fig. 1. No significant excess from any sky direction has been observed up to now [20].

Another km^3-scale neutrino telescope is planned to be built in the Northern Hemisphere, namely in the Mediterranean Sea. The Mediterranean km^3 neutrino telescope will provide important complementary information with respect to the results expected by IceCube. Since the two detectors are located in opposite Hemispheres, they can observe different sky regions, being the Mediterranean km^3 more sensitive to the Galactic Centre Region, where several VHE gamma ray sources are harboured. Moreover, deep sea water presents better optical characteristics than ice, allowing the construction of a less dense and larger detector.

Since the '90s three collaborations aimed at the construction of a km^3 neutrino telescope in the Mediterranean Sea: ANTARES [21], NEMO [22] NESTOR [23]. ANTARES is presently the largest neutrino telescope operating in the Northern Hemisphere. The detector, deployed at a depth of about 2400 m, offshore Toulon (France) is made of 12 strings, hosting 75 optical modules each. The present detector size is about $0.035\,\mathrm{km}^3$. The detector has well measured the atmospheric muon flux as a function of slant water

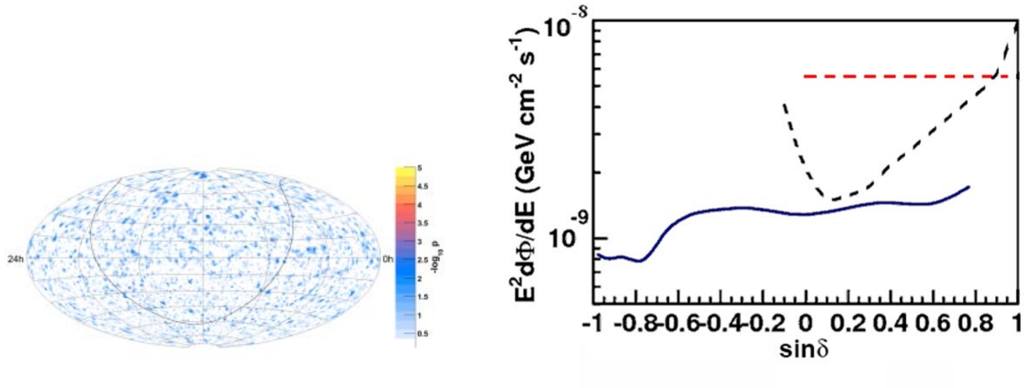

Fig. 1. – (Colour on-line) Left: the neutrino sky map seen by IceCube. Right: expected sensitivity to E^{-2} neutrino-point sources as a function of source declination for IceCube (red line: standard analysis [20]; black line: improved analysis [20]) and KM3NeT (blue line from [26]).

depth indicating good agreement between ANTARES data, other measurements and expectations. The search for cosmic neutrino point-like sources is on-going. Although no significant excess is found (at present), the actual detector sensitivity represents the best existing limits for point-like neutrino sources in the Southern Sky, even if compared to the multi-year experiment SuperKamiokande [24]. The NEMO (NEutrino Mediterranean Observatory) Collaboration has conducted an intense R&D programme aimed at developing and validating key technologies for a cubic-kilometre scale underwater neutrino telescope. Moreover, after more than 30 sea campaigns an optimal deep-sea site for the installation of the km^3-scale detectors was found in the Mediterranean Sea offshore the village of Capo Passero (Sicily). The site located at a depth of 3500 m and 90 km offshore the Southern Sicily coast, shows optimal features to host the km^3 detector: low optical background (30 kHz on 10$''$ PMTs at 0.5 s.p.e. threshold), blue light absorption length of 70 m (close to optically pure water), low currents (3 cm/s in average) and low sedimentation rate. The site is located on a wide abyssal plateau, showing very stable environmental conditions and a flat seabed morphology, allowing for possible extension of the telescope. NEMO has also successfully proven a new mechanical structure, a semirigid tower, that can be a favourable solution for deep-sea detectors, compared to the string. In this structure several optical modules are displaced in a 3D geometry increasing the muon track reconstruction capabilities of a single structure compared to 1D line structures. A small-size tower prototype was tested offshore Catania (Sicily) in 2006, demonstrating excellent capabilities in measuring the atmospheric muon flux [25]. The efforts of ANTARES, NEMO and NESTOR are now converging in the KM3NeT Consortium, funded by the EU and now coordinated by the INFN, aims at the construction of the Mediterranean km^3 neutrino telescope. The goal of the project is to achieve a sensitivity for point-like sources of $E_\nu^2 \Phi_\nu \simeq 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ in 1 year [16]. This result is expected to be reached thanks to larger detector size compared to IceCube and thanks to better angular resolution of deep seawater detectors (see fig. 1) [26].

A large experimental effort is also addressed to the detection of cosmic neutrinos with $E > 10^{18}$ eV, that are produced in the interaction of UHECR with the CMB ($p\gamma \to \Delta^+ \to N\pi$) or by annihilation of exotic $M > 10^{20}$ eV dark-matter particles [8, 7].

Recent results from the balloon-based ANITA radio-Čerenkov detector already allowed to exclude the neutrino production models from super-heavy DM [27]. These results are pushing towards the construction of a large GHz radio-Čerenkov detector to complement IceCube in South Pole ice. In deep seawater, where radio-waves propagate for short distances, the detection of kHz acoustic waves produced by neutrino-originated UHE showers, seem to be a viable solution. An intense R&D activity was carried out in recent years by several groups aiming at complementing the KM3NeT telescope with acoustic sensors for further studies on acoustic neutrino detection [28].

3. – Conclusions

High-energy neutrino telescopes are expected to prove the occurrence of hadronic processes in astrophysical sources and, eventually, identify the sources of Cosmic Rays. The experimental activity has undergone a strong acceleration during the last decade: on the one hand, IceCube will soon reach the sensitivity requested to detect the first astrophysical neutrino sources (based on present limits). On the other hand, after many years of prototyping and validation of deep-sea technologies, the KM3NeT Consortium is ready for the start-up of the construction phase of the km^3-scale underwater neutrino telescope in the Mediterranean Sea. Moreover, after the results of several pioneering experiments, the construction of very large arrays based on radio-Čerenkov and acoustic-detection techniques, could be affordable in the future years.

REFERENCES

[1] The Pierre Auger Observatory Collaboration, *Science*, **318** (2007) 938.
[2] Abbasi R. *et al.*, *Astropart. Phys.*, **32** (2009) 53.
[3] Biermann P. and Strittmatter P. A., *Astrophys. J.*, **322** (1997) 643.
[4] Waxmann E. and Bahcall J., *Phys. Rev. Lett.*, **78** (1997) 2292.
[5] Fermi E., *Phys. Rev.*, **75** (1949) 1169.
[6] Bell A. R., *Mont. Not. R. Astron. Soc.*, **182** (1978) 147.
[7] Greisen K. *et al.*, *Phys. Rev. Lett.*, **16** (1966) 748.
[8] Zatsepin G. T. and Kuzmin V. A., *JETP Lett.*, **4** (1966) 78.
[9] Aharonian F. *et al.*, *Nature*, **432** (2004) 75.
[10] Sapienza P. and Riccobene G., *Riv. Nuovo Cimento*, **32** (2009) 591.
[11] Markov M. A. and Zheleznykh I. M., *Nucl. Phys.*, **27** (1961) 385.
[12] Askaryan G. A., *JETP*, **14** (1962) 441.
[13] Askaryan G. A., *JETP*, **21** (1965) 658.
[14] Askaryan G. A. *et al.*, *Nucl. Instrum. Methods*, **164** (1979) 267.
[15] Fargion D. *et al.*, *Astrophys. J.*, **613** (2004) 1285.
[16] Bagley P. *et al.*, *KM3NeT C.D.R.*, (2008) http://www.km3net.org/CDR/CDR-KM3NeT.pdf.
[17] DeYoung T. for the IceCube Collaboration, *Mod. Phys. Lett. A*, **24** (2009) 1543.
[18] Andres E. *et al.*, *Astropart. Phys.*, **13** (2000) 1.
[19] Wiebusch C. for the IceCube Collaboration, *Proceedings of the 31st ICRC, Lodz, Poland* (2009).
[20] Abbasi R. for the IceCube Collaboration, *Astrophys. J. Lett.*, **701** (2009) L47.
[21] Circella M. for the ANTARES Collaboration, *Nucl. Instrum. Methods A*, **602** (2009) 2.
[22] Migneco E. *et al.*, *Nucl. Instrum. Methods A*, **588** (2008) 111.
[23] Rapidis P. for the NESTOR Collaboration, *Nucl. Instrum. Methods A*, **602** (2009) 54.

[24] Abe K. *et al.*, *Astrophys. J.*, **652** (2006) 198.
[25] Aiello S. *et al.*, *Astropart. Phys.*, **33** (2010) 263.
[26] the KM3NeT Consortium, *KM3NeT T.D.R.* (2010) in preparation.
[27] Gorham P. W. *et al.*, *Phys. Rev. Lett.*, **103** (2009) 051103.
[28] Riccobene G., *J. Phys. Conf. Ser.*, **136** (2008) 022053.