IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10471-y

Colloquia: IFAE 2009

Neutrino telescopes and high-energy astrophysics

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(ricevuto il 19 Settembre 2009; pubblicato online il 23 Novembre 2009)

Summary. — Neutrino astrophysics offers new perspectives on Universe investigation: high-energy neutrinos, produced by the most energetic phenomena in our Galaxy and in the Universe, carry complementary information with respect to photons. While the small interaction cross-section of neutrinos allows them to come from the core of astrophysical objects, it is also a drawback, as their detection requires a large target mass. This is why it is convenient to place neutrino telescopes in natural locations, like deep underwater or under-ice sites. In order to supply for such extremely hostile environmental conditions, new frontiers technologies are under development. We shortly discuss the motivations for HE neutrino astrophysics; a full and detailed version is reported in T. Chiarusi and M. Spurio, *High-Energy Astrophysics with Neutrino Telescopes*, arXiv:0906.2634 [astro.ph.HE].

PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS 95.85.Ry – Neutrino, muon, pion, and other elementary particles; cosmic rays.

The connection among primary cosmic rays, γ-rays and neutrino astronomy. The recent years have seen spectacular astrophysical discoveries using new experimental techniques or new photons wavelengths. High-energy (HE) neutrino astronomy is a young discipline derived from the fundamental necessity of extending conventional astronomy beyond the usual electro-magnetic messengers.

One of the main questions in astroparticle physics is the origin and nature of high-energy cosmic rays (CRs). While the energy spectrum of the cosmic rays can be measured up to very high energies, their origin remains unclear. There are many indications of the Galactic origin of the CR bulk (protons and other nuclei up to $\sim 10^{15}$–10^{16} eV). However, the highest energy CRs are probably originated by extragalactic sources, as indicated by recent measurements [1]. Assuming that, at acceleration sites, a fraction of the high-energy CRs interact with the ambient matter or photon fields, pions and hence γ-rays and neutrinos will be created.

Recent advances on ground-based γ-rays astronomy [2] have led to the discovery of more than 80 sources of TeV gamma-rays. Neutrino source candidates are in general also TeV γ-ray sources: neutrinos and HE photons are produced from CR interactions

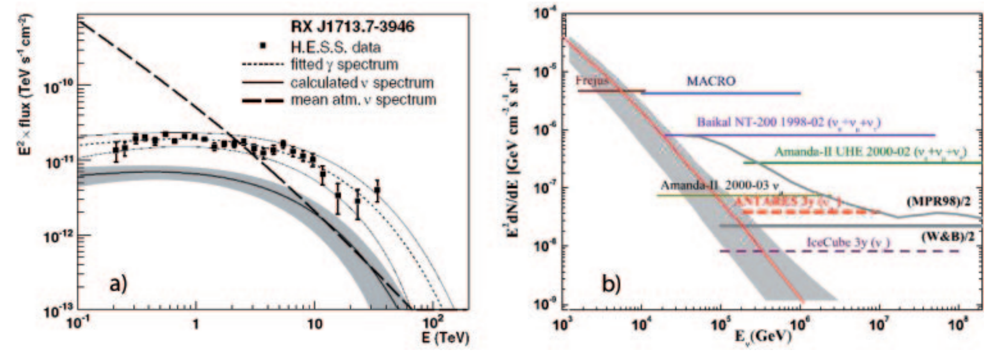

Fig. 1. – (a) Measured gamma-ray flux from the shell-type supernova RX J1713.7-3946 and estimated neutrino flux [3] with their error bands. (b) Sensitivities and upper limits for a E^{-2} diffuse HE neutrino flux. Experimental upper limits are indicated as solid lines, the ANTARES and IceCube 90% CL sensitivities with dashed lines. For reference, the W&B and MPR98 limits for transparent sources are also shown. Part of the MPR98 upper bound is already excluded by the AMANDA-II result.

with the propagation medium through $p + \gamma \to \Delta^+ \to \pi^0 + p$ or $p + \gamma \to \Delta^+ \to \pi^+ + n$. Neutral mesons decay in photons: $\pi^0 \to \gamma\gamma$ while charged mesons decay in neutrinos:

$$
\begin{aligned}
&\pi^+ \to \nu_\mu + \mu^+ \\
&\qquad\qquad \hookrightarrow \mu^+ \to \overline{\nu_\mu} + \nu_e + e^+ \\
&\pi^- \to \overline{\nu_\mu} + \mu^- \\
&\qquad\qquad \hookrightarrow \mu^- \to \nu_\mu + \overline{\nu_e} + e^-
\end{aligned} \tag{1}
$$

This mechanism is denoted as the *astrophysical hadronic model*. In this framework and in the case of sources transparent to photons, the energy escaping from the source is distributed between CRs, γ-rays and neutrinos. The hadronic model predicts a strong relationship between the spectral index of the CR energy spectrum $E^{-\alpha_{\rm CR}}$, and that of γ-rays and neutrinos: $\alpha_{\rm CR} \sim \alpha_\nu \sim \alpha_\gamma$ [3]. The neutrino flux estimated from TeV γ-rays measurement for a specific source is shown in fig. 1a. To our present knowledge, a kilometer-scale detector is needed to detect neutrinos, with at least 5000 optical sensors.

Potential sources of HE neutrinos include both Galactic sources (supernova remnants, microquasars,..) and extragalactic sources (Active Galactic Nuclei (AGN), Gamma-Ray Bursters (GRBs)).

Galactic sources. Some galactic accelerators must exist to explain the presence of CRs with energies up to 10^{15} eV. Apart from details, it is expected that galactic sources are related to the final stage of the evolution of massive, bright and relatively short-lived stellar progenitors. Some of the most promising neutrino source candidates in our Galaxy are extremely interesting due to the recent results from TeV γ-ray telescopes. Detecting upgoing muons, a neutrino telescope in the Northern hemisphere is looking at the same Southern field-of-view as the HESS and CANGAROO Imaging Air Cherenkov telescopes, while the neutrino telescope in the South Pole looks for the Northern sky.

Extra-galactic sources. The prediction of HE neutrino sources of extra-galactic origin is a direct consequence of the Ultra HE CR observations. This connection between CRs, neutrinos and γ-rays was used to put upper bounds on the expected neutrino flux from extragalactic sources, since the neutrino energy generation rate will never exceed the generation rate of high-energy protons. As for the origin of UHE CRs, AGN and GRBs are the principal neutrino source candidates. Extra-galactic sources are very far and the possibility of a individual discovery also in a km^3 scale ν-telescope is expected only in particular theoretical models, or using the *source stacking* methods. This is a combined analysis for different classes of objects which enhance the neutrinos detection probability.

An alternative way to prove the existence of extragalactic neutrino sources is through the measurement of the *cumulative flux* in the whole sky. Since there is no directional information, the only way to detect this *diffuse flux of HE neutrinos* is looking for an excess of HE events in the energy spectrum over the background of the atmospheric neutrinos.

Theoretical models constrain the neutrino diffuse flux. These upper bounds are derived from the observation of the diffuse fluxes of γ-rays and UHE CRs. The Waxman-Bahcall (W&B) [4] upper bound predicts that the observable neutrino flux (within a factor of two) is limited by the CR observed at Earth and by the bolometric observed gamma-ray flux in the 1 MeV–100 GeV range. In [5] a new upper bound was derived considering two cases of sources *opaque* or *transparent* to neutrons. Other HE neutrinos are induced by the propagation of CR in the local Universe. Protons exceeding the threshold for pions production ($E_P \sim 5 \times 10^{19}$ eV), will lose most of their energy. The subsequent pions decay will produce a neutrino flux (called GZK or *cosmological* neutrinos) similar to the W&B bound above 5×10^{18} eV.

Figure 1b shows the upper limits on diffuse flux of cosmic neutrinos. The experimental upper limits are indicated as solid lines, the ANTARES and IceCube 90% CL sensitivities with dashed lines. The Frejus, MACRO, Amanda-II 2000-03 limits refers to muon neutrinos. The Baikal and Amanda-II UHE 2000-02 refers to neutrinos of all-flavors (see [6] for references). The red line (colour online) inside the shadowed band represents the Bartol atmospheric neutrino flux. The theoretical limits from [4] and [5] are also reported.

Detecting cosmic neutrinos. While the small interaction cross-section of neutrinos allows them to come from far away, it is also a drawback, as their detection requires a large target mass. The idea of a neutrino telescope based on the detection of the secondary particles produced in neutrino interactions was formulated in the 1960s by Markov [7]. He proposed *to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation*. The detection of cosmic neutrinos is mainly based on the detection of upward-going muons induced by charged-current interactions of ν_μ. These muons, at sufficiently high energies, retain information on the direction of the incident neutrinos and can traverse several kilometers of ice or water. Along their trajectory, the muons emit Cherenkov light. The direction of the muon can be determined from the measured arrival time of the Cherenkov light. This process is referred to as muon track reconstruction.

Experimental projects. The pioneering project for the construction of an underwater neutrino telescope was due to the DUMAND Collaboration, which attempted to deploy a detector off the coast of Hawaii in the 1980s. At that time technology was not advanced enough to overcome these challenges and the project was cancelled. In parallel, the BAIKAL Collaboration started to work in order to realize a workable detector system under the surface of the frozen Baikal lake.

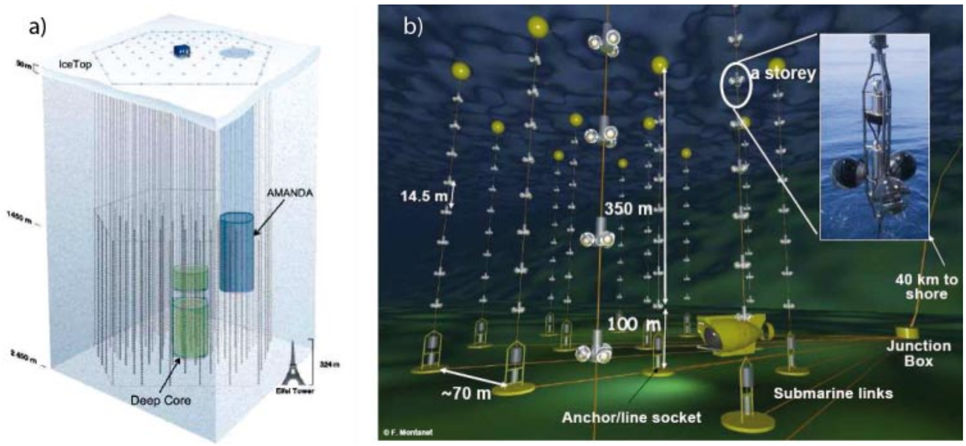

Fig. 2. – (a) The IceCube detector side view, with the AMANDA detector as a part in the right. Currently there are 59 buried InIce strings. The IceTop surface array and the DeepCore are also shown. (b) Schematic view of the ANTARES detector, completed in May 2008.

A major step towards the construction of a large under-ice neutrino detector was due to the AMANDA Collaboration. AMANDA deployed and operated the optical sensors under the ice surface of the Antarctic starting from 1993. After the completion of the detector in 2002, the construction of a much larger apparatus (IceCube, see fig. 2a) was started [8]. At present (June 2009) 59 of the 80 scheduled strings are already buried in the ice. Completion of this detector is expected around 2011.

In water, the pioneering DUMAND experience is being continued in the Mediterranean Sea by the ANTARES, NEMO and NESTOR Collaborations, which demonstrated the detection technique. In particular, the ANTARES [9] Collaboration has completed (May 2008) the construction of the largest neutrino telescope ($\sim 0.1\,\mathrm{km}^2$) in the Northern hemisphere, actually in data tacking. This project has lead to a common design study (KM3NeT) towards the construction of a European deep-sea research infrastructure, which will host a neutrino telescope with a volume of at least one km^3 at the bottom of the Mediterranean Sea.

HE neutrinos from astrophysical objects have not been observed so far; their flux can only be evaluated using models. The hunt for the first HE neutrino of cosmic origin has started.

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