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Neutrino telescopes

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Summary. — In recent years the astro-particle community is involved in the realization of experimental apparatuses for the detection of high-energy neutrinos originated in cosmic sources or produced in the interaction of Cosmic Rays with the Cosmic Microwave Background. For neutrino energies in the TeV-PeV range, the optical Cherenkov technique is considered optimal. Water (or Ice)-Cherenkov technique is based on the detection of the charged leptons generated in the neutrino charged current weak interactions with the medium surrounding the detector. Those detectors measure the visible Cherenkov photons originated by charged particles propagating at velocities greater than the speed of light through a transparent medium and consist of array of photomultipliers. The charged-particle track can be reconstructed measuring the time of arrival of the Cherenkov photons on the photomultipliers. An overview of the current status of those experiments will be given.

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

1. – Neutrino astronomy

Almost everything we know about the Universe came from its observation by means of electromagnetic radiation. Using the photons as observation probe it has been possible to discover very energetic sources, however the photons are highly absorbed by matter and so their observation only allows to directly obtain information of the surface process at the source. Moreover energetic photons interact with the photon background (microwave, infrared and radio) and are attenuated during their travel from the source toward us. The main reaction that takes place is

$$\gamma + \gamma_{\mathrm{CMBR}} \rightarrow e^{+} + e^{+} \tag{1}$$

assuming a temperature of the cosmic microwave background (CMBR) equal to 2.73 K (mean energy $\approx 6.5 \times 10^{-4}$ eV) the cinematic threshold is equal to

$$E\gamma \approx 10^{4} m_e^2/14 \approx 2 \times 10^{14}\,\mathrm{eV}. \tag{2}$$

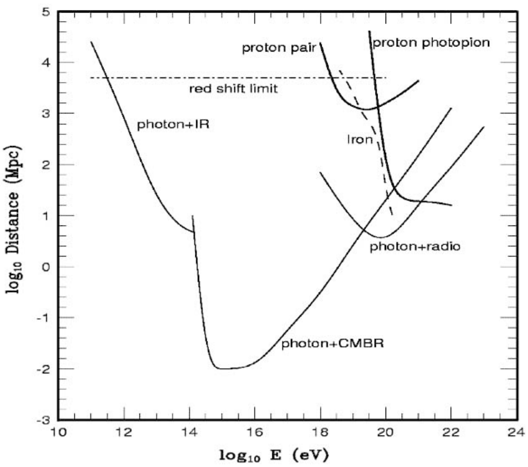

Fig. 1. – The attenuation length of p and γ with the photon background (IR, CMBR and radio) as a function of the incident particle.

This effect reduces the mean free path of a 10^{15} eV photon to about 10 kpc and make it impossible to study extragalactic sources using photons. Observation of the proton component of the cosmic rays can give information about the sources but, since they are charged, low energy protons are deflected by the magnetic galactic fields and loose the directional information that would allow us to point back to their source. High-energy protons are slightly deflected by magnetic fields and in principle could be good evidence for the high energy Universe. Unfortunately, as pointed out by Greisen-Zatsepin-Kuzmin [1, 2], the proton interactions with the CMBR will reduce the proton energy, for instance, by resonant pion production:

$$N + \gamma_{\mathrm{CMBR}} \rightarrow N + \pi. \tag{3}$$

The kinematic threshold for this reaction is about 5×10^{19} eV. This prevents the observation of protons with energy above 10^{20} eV coming from sources more distant than about 30 Mpc. In fig. 1 the attenuation length due to different interactions of protons and photons with the photon background is reported. In order to directly observe the inner physical mechanism of distant and energetic sources we need to use a neutral, stable and weakly interacting messenger: the neutrino. The interest in studying such high-energy sources arises from the fact that much of the classical astronomy is related to the study of the thermal radiation, emitted by stars or dust, while the non-thermal energy density in the Universe is roughly equal to the thermal one and is assumed to play a relevant role in its evolution. The presence of such non-thermal Universe is confirmed by the power law spectrum of the cosmic ray. The mechanism by which the cosmic rays are accelerated is still an open question. The supernova shock waves are generally assumed to be the place in which the cosmic rays are produced since the Fermi acceleration mechanism, that takes place in this case, can reproduce quite well their energy spectrum; however the experimental evidence is not complete. In fact few sources of high-energy gamma rays are not associated with supernova remnants and this seems to indicate that other mechanisms are present. It is widely accepted that this mechanism can accelerate particles up to 10^{15} eV may be 10^{17} eV, so the highest energy cosmic ray should be accelerated in a different way. All sources where protons are accelerated are sources of high energy neutrinos since the interaction of the accelerated particles with the photons, or matter near the source can produce charged pions that will decay into neutrinos, for instance by the following reaction:

$$p + \gamma \rightarrow n + \pi^{+} \rightarrow n + \mu^{+} + \nu_{\mu} \rightarrow n + e^{+} + \nu_{\mu} + \bar{\nu_{\mu}} + \nu_{e}. \tag{4}$$

A guarantee source of high energy neutrino is the GZK effect reported in eq. (4). The existence of the GZK cut-off is based on solid theoretical predictions and nowadays is also experimentally evident in the Auger [3] and HIRES [4] data. As a consequence the interactions of the primary cosmic rays, during their propagation, will produce high energy neutrinos that will reach the Earth. The GZK neutrinos will retain the directional information that allows to point back to the source since the high energy protons, by which they are generated, are only weakly deflected by the galactic magnetic field.

2. – Cherenkov detectors

Water(or Ice)-Cherenkov technique is based on the detection of the charged leptons generated in the neutrino charged current weak interactions with the medium surrounding the detector. Those detectors measure the visible Cherenkov photons induced by charged particles propagating at velocities greater than the speed of light through a transparent medium and consist of array of photomultipliers. The charged particle track can be reconstructed measuring the time of arrival of the Cherenkov photons on the photomultipliers. Optical Cherenkov detectors look for upward-going charged leptons since the neutrinos are the only particles that can freely propagate through the Earth and interact with the medium producing upward-going particles. A major background for those kinds of detectors are the downward-going atmospheric muons. Water(or Ice)-Cherenkov detectors are usually deeply embedded in natural medium (water or ice) to reduce this muons background using the medium as natural shield. Those kinds of apparatuses, with a km^3 scale, can detect neutrinos in an energy interval that ranges from 100 GeV up to 10 PeV. The lower energy threshold is set by the photomultipliers spacing since the track length, in order to be reconstructed, must be long compared with the photomultipliers distance. The upper energy threshold is set by the effective volume of the detector. In the energy range in which those detectors work, the direction of the charged leptons, originated in the neutrino interactions, nearby coincides with the neutrino ones, allowing to reconstruct the neutrino direction. The angular resolution that can be achieved is a function of the hit time resolution, the scattering length and error in the photomultipliers positions. Water detector can reach angular resolution better than 0.5 degrees (for energy above 1 TeV) while, due to shorter scattering length of light in ice, the angular resolution for AMANDA/IceCube detector is worse and typically $\approx$ 1–2 degrees. The Cherenkov technique is well established and presently under use, but is unrealistic to built a detector bigger than few km^3 at a reasonable cost. There are several experiments currently taking data based on the Cherenkov detection technique. The Baikal [5] experiment, started in 1993 is located in the lake Baikal in Siberia and is the oldest. In 1998 it has been upgraded reaching 192 photomultipliers and an effective volume of about $10^{-4}\,\mathrm{km}^3$. The IceCube [6] detector, located in the South Pole, has been recently completed and is now taking data in its final configuration composed of about 5000 photomultipliers; it is the biggest neutrino telescope currently working. ANTARES [7] is an underwater detector composed of about 900 PMTs and is the biggest neutrino telescope operating in the

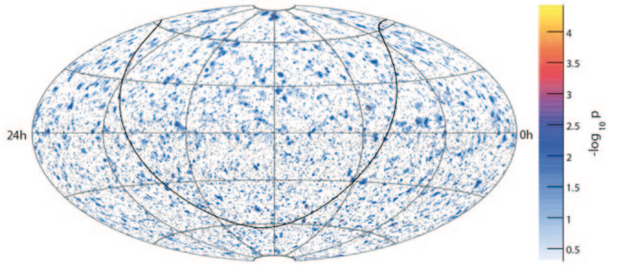

Fig. 2. – Icecube neutrino skymap [12] obtained with IC40 using 375.5 days exposure; the map contains 36900 events: 14121 upgoing and 22779 downgoing.

northern hemisphere. There is a European consortium called KM3NeT [8] planning to build a kilometer cubic scale detector in the northern hemisphere complementary to the IceCube detector. The consortium is formed around the institutes currently involved in the ANTARES [7], NESTOR [9] and NEMO [10] pilot projects. KM3NeT has recently released a technical design report [11] and is now working to prepare the production phase.

3. – Selected experimental results

I will report the latest results of the IceCube experiment concerning the search for neutrino point sources where the detector was operated with a 40-string configuration. Neutrino telescopes normally use the Earth as a shield for upgoing atmospheric muon tracks, the IceCube Collaboration extended the point source analysis to directions above the horizon by applying cuts in the energy estimator; since only the highest energy events pass the selection, sensitivity in this part of the sky is restricted to neutrino sources at PeV energies and above. The hottest spot in the resulting skymap (reported in fig. 2) has a p-value of 5.6×10^{-6} ($\approx 4.5\sigma$ for this specific analysis) about 18% of the random generated skys have at least one point with an equal or higher significance thus it is well compatible with a background fluctuation.

The atmospheric muons are an important, even if reducible, background; due to the huge amount of downgoing atmospheric muons reaching the detector, even a small fraction of misreconstructed events can contaminate the upgoing sample. However this

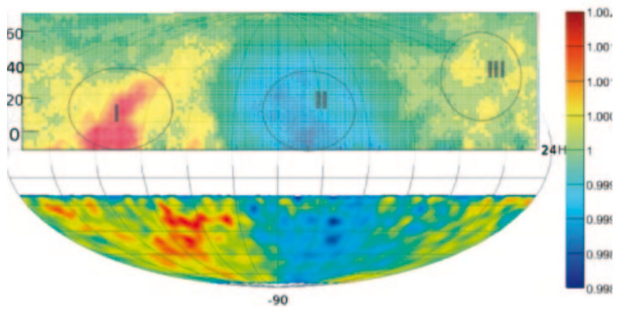

Fig. 3. – Comparison between the CR anisotropy measured by IceCube [13] and Tibet [14] Collaborations.

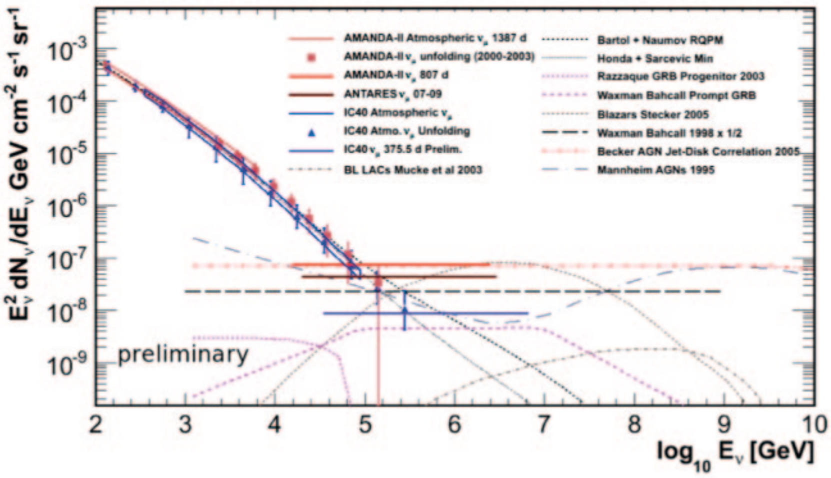

Fig. 4. – Sensitivity of different detectors compared with theoretical models.

huge amount of data can be fruitful used to study the anisotropy of the cosmic ray as reported in fig. 3. The data set used consists of 4.3×10^9 events with a median angular resolution (angle between the reconstructed muon and the primary particle) of 3 degrees and a median energy per CR particle of 14 TeV (according to simulations). The resulting map shows a good agreement with similar results from Tibet Collaboration and is a good example of how a neutrino telescope can be used to perform cosmic ray physics.

4. – Conclusions

Few neutrino telescopes have been built and are operating all over the world: the first cubic kilometer detector has been completed by the IceCube Collaboration and is successfully taking data in Antarctica; the KM3NeT consortium is planning to build an even bigger underwater detector is the Mediterranean sea in the next years. Although there is still no evidence of astrophysical neutrinos we are close to reach the expected neutrino diffuse fluxes (fig. 4). Moreover many sources, discovered using gamma-ray telescopes (*i.e.* SNR RXJ1713.7-3946), could be explained as sources of hadronic acceleration and thus possible neutrino sources. In my opinion the multi-messanger approach is the proper way to investigate many of the open astrophysical questions and neutrino telescopes play a key role in this.

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