Search for cosmic neutrinos with ANTARES

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Summary

During these four years of research as a Ph.D. student, I have tried several times to explain to my family and friends what I was doing. I am not sure I succeeded since many times I was not able to finish the conversation. Though I have to admit, the look on their face when I introduced "mysterious" topics such as cosmic rays acceleration and the ANTARES detection principle was pretty funny. This summary is probably my last attempt to explain them what I did in The Netherlands in the last four years, so I hope that a more expert reader will not be disappointed if I will first start with a general introduction to astronomy and cosmic rays. After this, I will focus on ANTARES and start to explain how it is possible to detect this elusive particle, called neutrino, with a big detector at the bottom of the sea. Finally, the third and last part of this summary will describe the results obtained.

1. Multimessenger astronomy

Almost a thousand years ago, in 1054 A.D., Chinese, Japanese and Arab astronomers observed the presence of a new "guest" star in the constellation Taurus. At the time, astronomers used the term "guest" to identify bright celestial objects which temporarily appear in the sky where no star had previously been observed. Although it was clear that this guest star was somehow different from what we now called comets, they could not know what they were observing: a supernova explosion.

When a massive star burns up all of its hydrogen fuel, it begins a gravitational collapse. The equilibrium is broken, the radiation pressure from the nuclear reactions can no longer sustain the gravitational pressure due to the star's own mass. Due to the collapse, the density and the temperature of the star increase reaching the critical values which start the process of helium burning. This restores the equilibrium. After the helium is also exhausted, the collapse continues until the fusion of heavier elements of the iron group starts. This mechanism, which strongly depends on the initial mass of the star, continues until the fusion reactions stop and the star collapses under its own gravitational pressure. This implosion may give rise to ejection of stellar matter into the interstellar space and the release of an enormous amount of energy. The material is ejected at a velocity up to 30.000 km/s and a shock wave is created by the interaction of the material with the interstellar medium. This shock wave sweeps up the surrounding shell of gas and dust, creating what is now called a remnant. A neutron star, or a black hole if the star was very massive, is now formed.

This is what happened to the "guest" star observed in 1054 A.D.. We now refer to this supernova remnant as the Crab Nebula which is shown in Figure 1. The Crab Nebula is located at a distance of approximately 2 kpc from the Earth, which means that the light emitted by this object travels for 6523 years before reaching our planet.

In the last 50 years, the Crab Nebula has become one of the most studied object of our Galaxy mainly due to its brightness and historical importance. These observations were made at different wavelengths: from the radio to the visible band, and from x-ray to the gamma-ray band.

What is more important for the work presented in this thesis is that the Crab Nebula and other Galactic supernovae are responsible for the acceleration of cosmic rays. Beside supernovae other objects are considered possible candidate sources like the Galactic plerions and microquasars or the extra-Galactic gamma-ray bursts and active galactic nuclei.

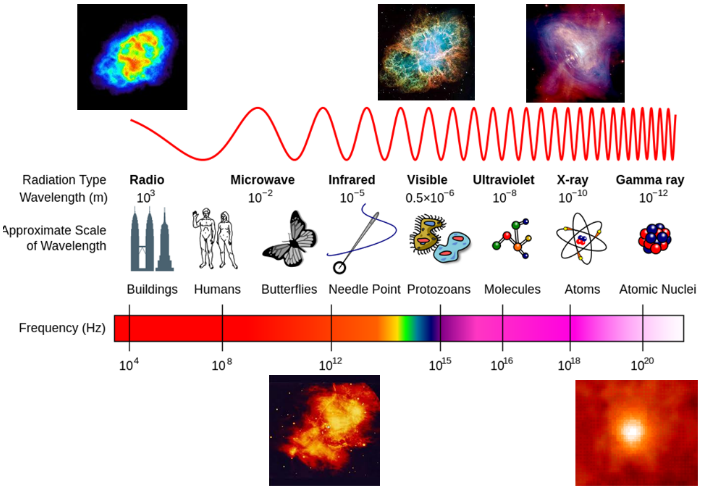

Figure 1.: A schematic representation of the electromagnetic spectrum with pictures of the Crab Nebula observed at different wavelengths.

Cosmic rays

Cosmic rays are energetic particles which continuously hit and penetrate the Earth's atmosphere. They were discovered at the beginning of the 20th century by Victor Hess who carried three electrometers to an altitude of 5.3 km using balloons with the purpose to investigate the ionisation of the atmosphere (see Figure 2). To his surprise, he observed that the ionisation rate at the highest altitudes was larger than at the ground. The only possible explanation was that the radiation comes from above, with extra-terrestrial origin.

One century after their discovery, there are still many open questions about cosmic rays. Are supernovae the sources responsible for the acceleration of cosmic rays? How does this acceleration work exactly? What are the "knee" and the "ankle" of the energy spectrum? One way to answer these question is to search for and detect astrophysical neutrinos. This is the subject of this thesis.

Figure 2.: Victor Hess ready to measure the ionisation of the atmosphere with his balloon. Picture taken from [175].

Neutrino production

Neutrinos are neutral particles which interact only via the weak force. Their existence was first proposed in 1930 by Wolfgang Pauli to explain the conservation of energy and angular momentum in beta decay. Very famous is the comment said by Pauli about it: "I have done a terrible thing, I have postulated a particle that cannot be detected" [176]. Fortunately (for this thesis), this statement was proven wrong 25 years later when Reines and Cowan detected antineutrinos created in a nuclear reactor by beta decay.

The reader would probably ask at this point: "What is the relation between cosmic rays and neutrinos?". The answer of this question is the key to understand my work. Neutrinos and cosmic rays share the same origin, i.e., they are created by the same sources. The production of high-energy neutrinos is due to the interaction of accelerated cosmic rays, mostly nucleons, with dense matter or photons field near the cosmic-ray source. The nucleon-photon interactions are for example:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p,$$
$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n.$$

$$n + \gamma \rightarrow \Delta^0 \rightarrow \pi^0 + n,$$
$$n + \gamma \rightarrow \Delta^0 \rightarrow \pi^- + n.$$

The main channels for nucleon-nucleon processes are:

$$\begin{aligned} p + p &\rightarrow p + p + \pi^0, \\ &\rightarrow p + n + \pi^+. \end{aligned}$$

$$\begin{aligned} p + n &\rightarrow p + n + \pi^0, \\ &\rightarrow p + p + \pi^-. \end{aligned}$$

All these reactions produce so-called pions, the lightest mesons. Pions are unstable particles, therefore they decay. Charged pions decay into muons, a lepton similar to the electron but more massive, producing a muon neutrino. The decay of the muons into electrons generates another muon neutrino, and an additional electron neutrino. Neutral pions decay into two gamma-ray photons:

$$\begin{aligned}
&\pi^0 \rightarrow \gamma + \gamma \\
&\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\
&\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu .
\end{aligned}$$

Beside neutral pion decay, there are other processes which contribute to gamma-ray emission. It is common to distinguish between the hadronic process, i.e., the π^0 decay, and leptonic processes such as synchrotron emission and inverse Compton scattering. The typical gamma-ray energy spectrum for a source can be divided in two parts. The low-energy range is dominated by synchrotron emission. Inverse Compton emission and neutral pion decay contribute to the high-energy part of the spectrum, usually up to tens of TeV. The detection of TeV gamma-rays from a specific source is considered the first hint for a possible neutrino emission, however there is no way to distinguish a-priori whether the photons detected are of leptonic or hadronic origin. Many theoretical models are trying to explain the spectral energy distribution for several candidate sources of cosmic rays. These models strongly depend on source parameters, such as the magnetic field and the proton density, which can only be inferred. For hadronic models, it is clear that the detection of a signal of astrophysical neutrinos could constrain the interval of allowed parameters assumed. While cosmic rays are deflected by Galactic and extra-Galactic magnetic fields, and gamma-rays interact with the cosmic microwave background, neutrinos point back to their source.

2. Neutrino astronomy with ANTARES

The detection of astrophysical neutrinos was first proposed in the 1960's by the Russian physicist Moisei Aleksandrovich Markov [104]. He suggested to "install detectors deep in a lake or sea water and determine the direction of the charged particles with the help of Cherenkov radiation". The idea is that neutrinos emitted by an astrophysical source interact with matter via charged current interactions and create leptons[1]. While travelling in the water, these leptons emit Cherenkov radiation.

This concept was adapted by the ANTARES collaboration to build the first neutrino telescope in the Mediterranean Sea. ANTARES is a three-dimensional array of 885 photomultiplier tubes looking 45° downward and distributed along 12 detection strings. An illustration of ANTARES is shown in Figure 3.

The detector performance is expressed in terms of the angular resolution and the acceptance, and is obtained by simulations. For the data analysed in this work, assuming a neutrino flux proportional to E_ν^{-2}, the angular resolution derived from simulations is 0.46 ± 0.10 degrees. The effective area, i.e. the equivalent area of a 100% efficient detec-

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[1] Neutral current interactions are also possible, however they are not considered in this work.

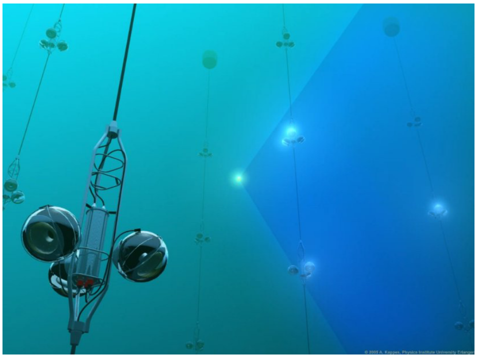

Figure 3.: Illustration of the ANTARES detector. Credits to Alexander Kappes.

tor, increases with the neutrino energy and is roughly 0.1, 1 and 10 m^2 at 1, 100 and 10000 TeV respectively.

3. My work

During my four years with ANTARES, I was involved in the search for point-like sources of astrophysical neutrinos. The presence of an excess of cosmic neutrinos above the background is tested by looking for clusters of events in a given direction. Therefore, a good angular resolution is necessary.

The analysis presented in this thesis is based on four years of data collected from January 2007 to December 2010. The total observation time equals 813 days.

Neutrino candidates were selected by applying three different cuts. First, only tracks reconstructed as upgoing are selected. Cuts on the reconstruction quality variables, β and Λ, are then applied in order to reject misreconstructed atmospheric muons. These cuts were chosen in order to optimise the discovery potential, i.e., the neutrino flux needed to have a 50% chance of discovering the signal with a 5σ significance level assuming an E_ν^{-2} spectrum. The final sample consists of 3058 neutrino candidates. Simulations predict 358±179 atmospheric muons and 2408±72 atmospheric neutrinos.

The search is based on a likelihood ratio method. The null hypothesis is represented by the background only case (only atmospheric muons and neutrinos in data). The alternative hypothesis refers to the case where in addition to the background a signal is also present with a flux proportional to E_ν^{-2}.

The sensitivity of the analysis was evaluated with the generation of pseudo-experiments to simulate the signal and the background. Thus, it was possible to derive the simulated distributions of the test statistic for the two hypotheses. A discovery is claimed when the observed test statistic exceeds a critical value. This value is determined from the distribution of the test statistic for the background only case for the 3σ (or 5σ) confidence level.

Two alternative searches were performed. In the candidate list search, the presence of an excess of signal events was tested at the location of 51 a-priori defined candidate sources. In the full-sky search, I looked for an excess of signal over the background anywhere in the visible sky.

For the first time within the ANTARES collaboration, an estimate of the neutrino energy, i.e. the number of hits, has been included in the likelihood, in order to improve the discrimination between signal and background. The inclusion of the number of hits in the likelihood reduces the number of events (thus, the signal) needed for a 5σ discovery by $\sim$ 25% as shown in Figure 7.21.

In addition to these two searches, the algorithm has been tested in the presence of extended sources and neutrino fluxes described by an exponential cut-off functions. Simulations show that for a source with Gaussian extension $\sigma_{\mathrm{source}} = 1^{\circ}$, the flux needed for a 5σ discovery is roughly 1.4 higher compared to point-like sources. Assuming a neutrino flux parametrised by an exponential cut-off function (with cut-off energy $E_{\mathrm{cutoff}} = 1\mathrm{TeV}$) yields a discovery probability a factor 2 higher compared to the standard E_{ν}^{-2} case

Models of neutrinos emission for three Galactic sources, RX J1713.7-3946, Vela X and the Crab Nebula, were also tested. For RX J1713.7-3946 and Vela X the extension of the source was also taken into account. For this purpose, a convolution of the point spread function and the source extension has been included in the likelihood calculation. The results of this convolution is shown in Figure 7.22 for both RX J1713.7-3946 and Vela X. The source extension was directly derived from gamma-rays data published by the H.E.S.S. collaboration.

Results

In both the full-sky and the candidate list search, no significant excess of signal events was found. In the full-sky search the most significant cluster is located at $(\alpha, \delta) = (-46.5^{\circ}, -65.0^{\circ})$ where 5(9) events were found within 1(3) degrees of these coordinates. The value of the test statistic associated with this cluster is 13.1. This translates to a (post trial) p-value, i.e. the probability to obtain a test statistic at least as extreme as the one actually observed, of 2.6%.

In the candidate list search the most signal-like source is HESS J1023-575 where the fit yields 2 signal events. The post trial p-value of this cluster is 41%. Upper limits at 90% confidence level were then derived using the Feldman and Cousins prescription, assuming a neutrino flux proportional to E_{ν}^{-2}. These limits are shown in Figure 8.6 were they are compared with other published limits from various experiments. For some sources in the Southern sky, the limits obtained are the most restrictive ones. In this hemisphere the larger neutrino telescope IceCube, located at the South Pole, is sensitive to ultra high-energy neutrinos, $E_{\nu} > 1$ PeV, while in this analysis 80% of the signal events have 4 TeV $< E_{\nu} < 700$ TeV.

Upper limits were also derived assuming the different models discussed in Chapter 2 for RX J1713.7-3946, Vela X and the Crab Nebula. As an example, Figure 8.8 (bottom) shows the results obtained for the Crab Nebula. The limits obtained are quite above the predictions. This is mainly due to the low visibility of the Crab Nebula at the ANTARES site. More promising are the limits obtained for RX J1713.7-3946 and Vela X, as discussed in Chapter 8.

Although no excess of signal events was found, the work presented in this thesis is a step toward the first detection of TeV neutrinos from astrophysical sources. Perphaps the

ANTARES detector is too small to achieve such a discovery; however, with IceCube already running and KM3NET in construction the future of neutrino astronomy is bright. Let's just wait and see.