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Detecting High-energy Neutrinos from Microquasars with the ANTARES Telescope

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Abstract The ANTARES project aims at the construction of a neutrino telescope 2500 m below the surface of the Mediterranean sea, close to the southern French coast. The apparatus will consist of a 3D array of photomultiplier tubes, which detects the Cherenkov light emitted by upward going neutrino-induced muons. High-energy neutrinos may be produced in powerful cosmic accelerators, such as, gamma-ray bursters, active galactic nuclei, supernova remnants, and microquasars. We have estimated the event rate in ANTARES of neutrinos coming from these sources, and particularly for a microquasar model, and found that for some of these sources the detection rate can be up to several events per year.

Key words: neutrinos — acceleration of particles — X-rays: binaries

1 INTRODUCTION

A promising challenge for exploring the Universe is the detection of high-energy ($\gtrsim$ 10 GeV) neutrinos. As a matter of fact, the early Universe cannot be probed with high-energy photons due to photon-matter and photon-photon interactions - gamma rays of a few hundred TeV from the Galactic Center cannot survive their journey to the Earth. The weakly interacting nature of neutrinos, and the fact that they are not deflected by magnetic fields, make them unique "probes" for exploring regions at distances larger than 50 Mpc.

Neutrinos may be produced by cosmic accelerators, like those in supernova remnants, active galactic nuclei, microquasars, and gamma-ray bursts. The commonly accepted model of neutrino production in sources is the so called "*astrophysical beam dump*" model, in which neutrinos and photons are produced in pp or $p\gamma$ interactions of accelerated protons with matter or photons via pion decay. Neutrinos escape from the source and travel large distances to the earth, thus delivering information directly from the sites of acceleration.

Another possible source of neutrinos is the annihilation of neutralinos, expected to be gravitationally trapped at the centers of massive bodies such as the Earth, the Sun or the Galaxy, thus contributing to the dark matter quest.

Several projects are now underway to construct large-scale neutrino detectors underwater or under ice, such as Baikal, AMANDA, NESTOR, ANTARES, NEMO, IceCube (Carr 2003, Halzen 2003), with Baikal and AMANDA already running. Those detectors are optimised for

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detecting muons from charged-current reactions of muon neutrinos, but are also sensitive to other neutrino flavours and to neutral-current reactions. Detectors are constructed at large depths where the atmospheric muon flux is significantly reduced compared to that at the surface. Upward-going muons, produced by neutrinos having crossed the Earth, are then recognised as the products of neutrino interactions in or close to the instrumented region.

The technique employed by the neutrino telescopes is dictated by the small neutrino cross section and the large background due to atmospheric muons. Natural Cherenkov radiators, such as water or ice, provide a large active volume at reasonable costs and the indirect detection of neutrinos through muons profits from the increase of the "target" region by the muon range. The Cherenkov light emitted by charged particles in deep water or ice is detected using an array of photomultiplier tubes (PMTs) which are housed, together with some associated electronic components, in a pressure-resistant glass sphere known as an optical module (OM). The muon direction and energy are measured using the arrival times and amplitudes of the PMT pulses. The detector sensitivity increases with energy due to the increase in the hadron-neutrino cross section, the longer muon range and the increase in the amount of emitted Cherenkov light through secondary particles.

2 THE ANTARES DESIGN

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) project started in 1996 and involves physicists, astronomers, sea science experts and engineers from France, Germany, Italy, Russia, Spain, The Netherlands and the United Kingdom. The ANTARES detector will be deployed at about 2500 m depth in the Mediterranean Sea, 37 km off-shore of La Seyne sur Mer, near Toulon (France). The ANTARES location ($42^o\ 50'$ N, $6^o\ 10'$ E) gives an annual sky coverage of about $3.5\,\pi$ sr. ANTARES will look at the whole southern hemisphere, and a significant fraction of the northern hemisphere. The Galactic Centre, an important potential source of high-energy neutrinos, will be visible for 67% of the day. The instantaneous overlap with the AMANDA experiment, located at the South Pole (Ahrens et al., 2002), will be approximatively 0.5π sr, and the total overlap will be $1.5\,\pi$ sr. Hence crosschecks will be allowed over possible point sources.

An intense R&D and Site Evaluation programme has provided the relevant environmental parameters of the detector site. Extensive surveys of the water optical properties have been carried out, along with a detailed analysis of the optical background due to bioluminescence, biofouling on optical modules and light transmission properties.

The ANTARES telescope will detect the Cherenkov light emitted by secondary particles produced in neutrino interactions in sea water or rock below the sea bed. The detector, illustrated in Fig. 1, consists of a 3-dimensional array of OMs arranged in 12 lines made of mechanically resistant electro-optical cables. The lines will be anchored at the sea bed at distances of about 70 m one from each other, and tensioned by buoys at the top. Each line has a total length of about 450 m, of which about 350 m will be equipped with 75 optical modules arranged in triplets (storeys, see Fig. 1), and oriented at 120° in azimuth apart from each other and at an angle of 45° below the equator, in order to be mostly sensitive to neutrinos which have crossed the Earth. The vertical distance between adjacent storeys will be 14.5 m. The whole apparatus will be connected to the onshore station by a 40 km long electro-optical cable (EOC), deployed in October 2001. The EOC terminates with a junction box, which transmits power and sends the data to the shore station, where they are recorded.

3 EXPECTED PERFORMANCE

The ANTARES scientific programme is mainly devoted to the detection of neutrinos of astrophysical origin produced in point-like sources or coming from a distribution of sources in

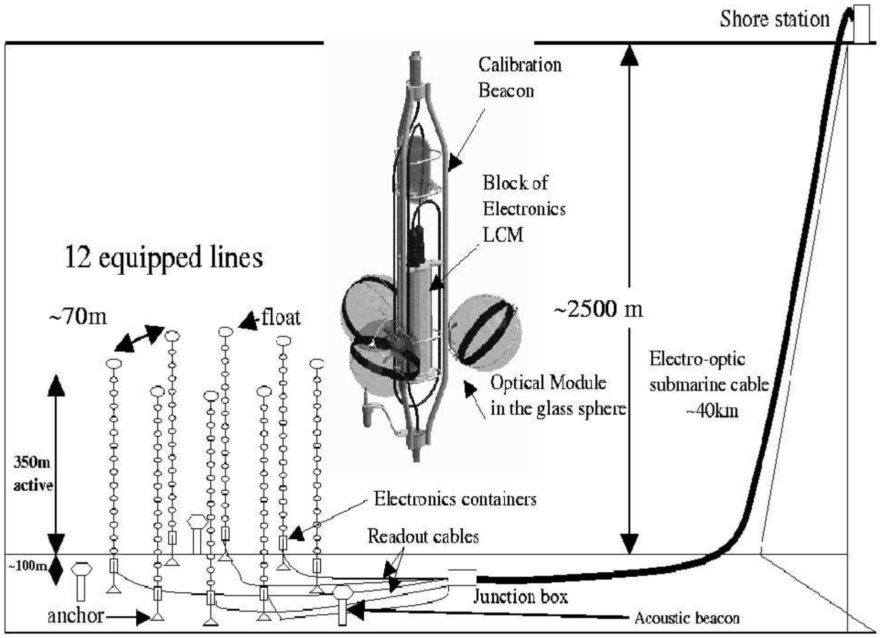

Fig. 1 Schematic view of the ANTARES detector.

the whole sky which produces a diffuse flux. The neutrino signal can be detected above the background due to atmospheric neutrinos at energies greater than 10–100 TeV, as a result of the harder neutrino spectrum expected from cosmic accelerators compared to neutrinos from cosmic ray interactions in the atmosphere.

The important parameters which characterize a neutrino telescope are the effective area, the angular resolution and the energy resolution. In particular, the effective area is crucial because it determines the event rate in a detector. In fact, for point-like sources at a declination δ producing a differential flux of neutrinos $\frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu}$, the event rate is given by

$$N_\mu(\delta) = \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_\nu A_\nu^{eff}(E_\nu, \delta) \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu} \, , \tag{1}$$

where $E_{\min}$ and $E_{\max}$ are the minimum and maximum energies of neutrinos for the considered flux, respectively. A_ν^{eff} is the sensitive area "seen" by ν's producing detectable μ's when entering the Earth. The effective area depends on the neutrino energy, the efficiency of reconstruction and selection cuts.

In Fig. 2 we display the neutrino effective area as a function of the neutrino energy. The figure shows the effective area for a uniform event distribution (circles) and for three different angular ranges of the arrival directions. In particular, the downward triangles refer to arrival directions closer to the vertical one, whereas the upward triangles refer to directions closer to the horizon. The dependence on the arrival direction is due to the Earth's opacity. The effective area increases rapidly up to about 1 PeV. Above this energy, the effective area for a uniform event distribution saturates because of the balance between the increase of the hadron-neutrino cross section and the Earth's absorption. The latter strongly decreases the effective area of the detector for events around the vertical. A similar trend has been observed also in the AMANDA-II detector (Ahrens et al., 2004).

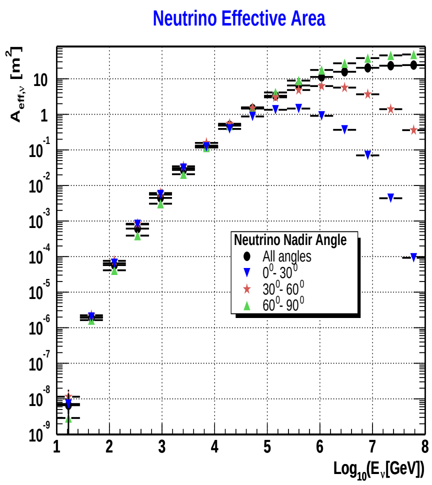

Fig. 2 Effective area vs neutrino energy after quality cuts: circles are for a uniform event distribution, whereas the other curves are for specific neutrino arrival directions.

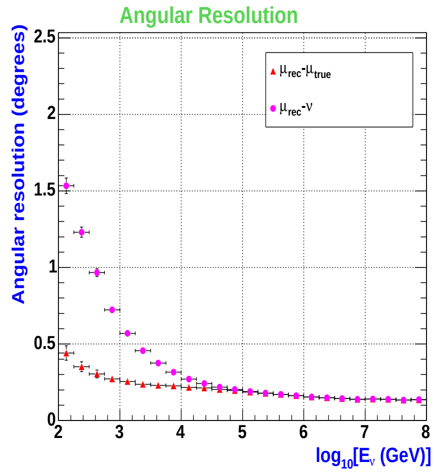

Fig. 3 Median angle of the distributions of the angle betwen the reconstructed muon and the simulated muon (triangles) or the simulated neutrino (circles) versus neutrino energy.

The intrinsic angular resolution of the telescope, defined as the median angular separation between the true and the reconstructed muon track, has been estimated from simulation. In Fig. 3 the median value of the distribution of the angle between the reconstructed and simulated muon is shown by triangles, while the circles represent the median angle between the reconstructed muon and the parent neutrino as a function of the neutrino energy. At smaller energies the angle between the reconstructed muon and the parent neutrino direction is dominated by the kinematics of the charged current interaction. The improvement of the angular resolution with increasing energy results in an increase of the signal to noise ratio for neutrino astrophysics studies at energies greater than $\approx 10\,\mathrm{TeV}$. At these energies, the pointing accuracy is only limited by the intrinsic angular resolution with a limiting value of 0.15° .

The energy resolution in ANTARES and the methods of reconstructing muon energy and parent neutrino spectra are discussed in Romeyer et al. (2003). The muon energy, E_μ, is determined from the muon range at small energies and from the Cherenkov intensity due to radiative energy losses at high energies. The resulting energy resolution is about a factor ~ 2 above 1 TeV.

4 SENSITIVITY TO MICROQUASARS

Microquasars have recently been considered as galactic candidates for emission of high energy neutrinos. The observation of relativistic radio jets from some sources (Mirabel, 2004) has stimulated the idea that processes of neutrino production by relativistic particles, similar to those believed to occur in active galactic nuclei (AGNs), can be considered.

Recently, Levinson & Waxman (2001) have proposed a model for neutrino production in microquasars, similar to the AGN proton initiated cascade model of Mannheim et al. (1992). The authors argue that hadrons can be accelerated up to $\sim 10^{16}\,\mathrm{eV}$ in the inner part of the jet by internal shocks. Pions are produced in collisions of hadrons with external X-ray photons, and with the synchrotron photons from the jet produced by leptons accelerated in this same shock. The neutrino fluxes, expected in the energy range 1–100 TeV, are very high, especially from persistent sources, e.g., $\sim 10^3$ neutrino event rates in a $1\,\mathrm{km}^2$ neutrino detector in the case of SS433. In a subsequent paper, Distefano et al. (2002) estimated the expected neutrino event

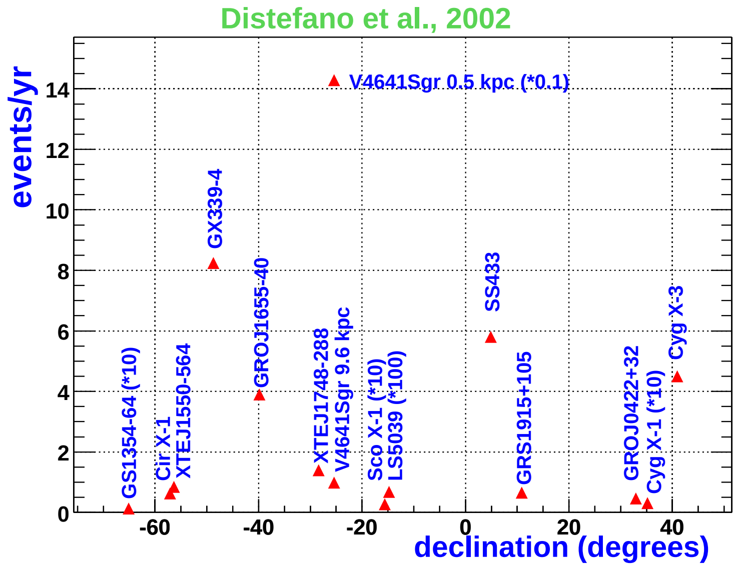

Fig. 4 Event rate from known microquasars in ANTARES.

rates in a 1 km^2 detector from the large population of known microquasars, assuming that relativistic protons take 10% of the jet power. The authors conclude that some microquasars with persistent activity, particularly SS433 and GX339–4, should produce more than 100 neutrino events per year in such a 1 km^2 detector, while microquasars with episodic activity, e.g. Cyg X-3 or GRO J1655–40, might yield a few neutrino events per long-duration flare. Therefore smaller detectors such as AMANDA-II (Ahrens et al., 2004) or ANTARES might observe a small number of neutrino events from microquasars. We have calculated the predicted number of events in ANTARES for some selected sources by convolving the neutrino fluxes given in Distefano et al. (2002) with the ANTARES effective area. In Fig. 4 we show the expected event rate in one year in ANTARES against the source declination. Four or five of the microquasars considered can produce a significant event rate, given an atmospheric neutrino background of the order of 0.5 events per year in 1° around the source. About 6–8 events per year are expected for the two persistent sources, SS433 and GX339–4. In particular, GX339–4 will be always visible for ANTARES and is never seen by AMANDA, whereas SS433 is seen by both detectors (11.5 h per day for ANTARES and 24 h per day for AMANDA) and therefore provides a cross-check. Regarding SS433, one should mention that AMANDA-II has placed a 90% c.l. upper limit of 1.24 events (based on zero events observed), whereas the Distefano et al. prediction is 1.07 events (Ahrens et al., 2004).

As clearly shown in Fig. 4, most of the sources will produce in ANTARES an event rate per year not larger than one. For the source V4641 Sgr, two sets of parameters have been adopted: small distance (0.5 kpc) and large angle of sight (63°), which corresponds to the one shown in the figure, or larger distance (9.6 kpc) with a jet directed toward our line of sight (9°). The latter leads to a much higher neutrino detection rate, about ~ 100 events per year.

Recently, Romero et al. (2003) have proposed a new mechanism for neutrino production from microquasars containing early-type stars. The authors argue that the relativistic hadrons accelerated in the jet can also interact with the dense matter of the wind of the massive star, thus producing neutrino fluxes larger (by a factor 3) than the atmospheric neutrino background in the energy range 1–10 TeV. A comparison between the neutrino fluxes predicted by the Distefano et al. model and the Romero et al. model has been extensively discussed at this conference (Torres et al., 2004).

5 SUMMARY AND CONCLUSIONS

The ANTARES neutrino telescope is foreseen to be fully deployed by 2007. The project has now entered the construction and deployment phase for a 0.1 km^2 scale detector. The assembly and deployment of the first full line will be performed at the beginning of 2005. The R&D phase of the project, which started in 1996, is now completed. During this phase a detailed assessment of the main requirements for an undersea neutrino telescope was made. After the installation of the electro-optical cable and the junction box, a prototype string and a string dedicated to environmental parameter measurements have been deployed, operated and recovered. A large bulk of data was acquired and analysed, helping to identify and solve some problems.

As far as the detection capability of ANTARES is concerned, it has been found that the highest detection rates are obtained for galactic sources, especially young supernova remnants and microquasars. For the latter ones, we have taken a theoretical model, which has been recently published by Distefano et al. (2002), and calculated the event rates in ANTARES for 14 visible sources. We have found that only two microquasars, i.e. SS433 and GX339–4, can produce in ANTARES an appreciable detection rate in one year, about 6–8 events. Moreover, SS433 is visible both by ANTARES and AMANDA telescope, and therefore for this source a crosscheck is possible. Other microquasars, taken into account by Distefano et al. (2002), do not produce in ANTARES an event rate per year larger than one.

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