KM3NeT and Fermi bubbles: some predictions

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Abstract

A recent analysis of the Fermi data provided the evidence of the emission of high-energy gamma rays with a high intensity E^{-2} spectrum from two large areas around the Galactic center, spanning 50° above and below the Galactic center. The possible origin of these high-energy gammas from a hadronic mechanism has been proposed making these bubbles promising sources for high-energy neutrino emission. In this work some predictions regarding the detection of high-energy neutrino from Fermi bubbles with the future KM3NeT detector are presented. The preliminary results of Monte Carlo simulations indicates that the discovery of neutrinos from the bubbles will be achieved in about one year.

Keywords: Neutrino telescope, Fermi Bubbles, KM3NeT

1. Introduction

A new era for the high energy astroparticle physics has just started. In fact, in the last years a new generation of high performance high energy gamma detectors, as Fermi [1], HESS [2] and MAGIC [3], has revealed an enormous variety of sources that emit high energy gammas. In particular, from a recent analysis of Fermi LAT data, two large bubbles above and below the Galactic center have been detected [4] as emitters of an intense gamma flux with a energy spectrum $\propto E^{-2}$. The debate about the origin of this gamma emission is very high and both the leptonic and hadronic mechanisms have been proposed. For the understanding of the acceleration mechanism other probes that can complement information from the gamma detection are needed. In particular, the detection of high energy neutrinos, that can be produced only by a hadronic mechanism, can shed light on the origin of the Fermi bubble production mechanisms.

A new generation of km3-scale high energy detectors have been constructed and are proposed. The one km^3 detector IceCube [5], at the South Pole, is taking data in its final configuration since 2010 but data from the complete detector are not yet published. In the Northern hemisphere the KM3NeT consortium [6] has proposed the construction of a large (about 6 km^3) telescope in the Mediterranean sea. From its location KM3NeT will detect upward-going neutrinos from our Galaxy with a very good visibility .

In this work, in the hypothesis that the hadronic mechanism is responsible for the gamma emission, the response of the KM3NeT telescope to neutrinos from Fermi bubbles, deduced from MonteCarlo simulations, will be analyzed. In particular, the number of years required to claim the discovery will be estimated.

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2. The Fermi bubbles

The recent analysis of Fermi Large Area Telescope data has revealed an intense gamma emission from two large areas above and below the Galactic Center. The detected emission has the following characteristics:

- The areas are symmetric with respect to the Galactic Plane extending up to 50 degrees above and below the Galactic Center, with a width of 40 degrees in longitude.
- The gamma emission, measured from $\sim$ 0.5 GeV to $\sim$100 GeV, shows a hard spectrum with slope 2 and an intensity of E^2 dN/dE $\approx 6\ 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}.
- The emission is homogenous in space and intensity within the bubbles and no significant variation was found between the north and the south bubble.
- The gamma emission is spatially correlated with observation in X-ray and Microwave: the edge of the bubbles are correlated with ROSAT X-ray maps at 1.5-2 keV while the inner parts are correlated with the hard-spectrum microwave known as WMAP haze [7, 8].

The gamma ray bubbles could be generated by Inverse Compton scattering of relativistic electrons generated in some large episodes of energy injection inside the Galactic Center (AGN activities or nuclear starburst) [4] or by relativistic electrons that are undergoing stochastic 2nd-order Fermi acceleration by isotropic plasma wave turbulence through the entire bubbles' volume [9]. Emission due to transient recent AGN activities from the GC [10] or Dark Matter [11], or millisecond pulsar [12] have been also proposed.

Currently, all the observed features of the Fermi bubbles are not fully explained by a leptonic mechanism and a hadronic mechanism has been proposed [13]. In Ref. [13] the following scenario is proposed: CR population associated to long time scale star formation in the GC ($\sim 10^{10}$ years), injected into the bubbles by a wind, interacting with the ambient matter produces high energy gamma from π^0 decay. In this model the microwaves are due to synchrotron radiation from secondary electrons. However, the leptonic and hadronic mechanisms require very different galactic diffusion characteristics.

Recently the morphological and spectral characteristics of the WMAP haze have been reviewed [8] with important implications about the possible production scenarios. The authors consider all the proposed models to explain the gamma and the reviewed WMAP haze emission and conclude that hybrid formation scenarios will likely be required.

The detection of high energy neutrinos can disentangle between the hadronic and leptonic models. In fact, only if a hadronic model is totally or partially responsible for the production of gammas from Fermi bubbles will neutrinos also be produced.

Following the prescription described in [14], in the hypothesis that the source is transparent to gamma emission and that the mechanisms responsible for the gamma emission is hadronic, it is possible to estimate the neutrino spectrum from the measured gamma-ray spectrum. In particular, assuming that the bubble gamma-ray spectrum is $E^2\Phi_\gamma \approx 6 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} and the solid angle of the two simulated bubbles is 0.69 sr, we estimated a neutrino flux of $E^2\Phi_\nu \approx 1 \cdot 10^{-7}$ GeV cm^{-2} s^{-1}. Moreover, we assume an energy cutoff at about 50-100 TeV in the neutrino spectrum that is consistent with the observed cutoff in the Cosmic Ray spectrum at about 1 PeV.

3. The detector

The proposed KM3NeT telescope, that will be located into the Mediterranean sea, will be the ideal instrument for the observation of neutrino from Fermi bubbles. In order to investigate the detector capability for the detection of muon neutrinos from Fermi bubbles a Monte-Carlo simulation has been performed.

The KM3NeT consortium, funded by the EU, has the aim to develop a deep-sea research infrastructure hosting a multi-cubic-kilometer scale high energy neutrino detector in the Mediterranean sea. During the Design Study [15] design concepts and the technical solutions have been investigated. During the Preparatory Phase a final design concept has been defined and currently the collaboration is approaching the construction phase.

The KM3NeT detector [16] will consist of a 3D array of Optical Modules (OM) attached to a vertical structure (Detection Unit, DU). An array of DUs will constitute a detector building block. The DUs, which will be anchored to the sea floor and kept vertical by buoys, consist of horizontal bars equipped with 2 OMs one at each end. In the DU adjacent bars are oriented orthogonally to each other. The DUs will be connected to shore by an electro-optical cable. The OM consists of a 31 3" PMTs inside a pressure-resistant glass sphere. For the aim of this work a detector of 308 DU (two building blocks of 154 DUs) at a distance of 180m has been simulated. The DU consists of 20 bars with 6 m length and vertically spaced by 40 m (40 OM per DU).

4. Monte Carlo simulation and results

The simulation chain comprises the generation of neutrinos from the bubble regions, the muon and neutrino atmospheric background, the ^{40}K background simulation, the generation of Cherenkov light, and the digitization of the PMT signals. Optical properties of the sea water and PMT characteristics are taken into account in the simulation of the photon arrival time. The simulations were performed with the ANTARES codes [17] modified for a km3-scale detector and Multi-PMT OMs.

From the simulated arrival time of Cherenkov photons and PMT position it is possible to reconstruct the muon track directions that are almost identical to that of muon neutrinos. The reconstruction algorithm is based on a likelihood fit that uses probability density functions for the photon arrival time on the PMT. In addition to the positions and track directions, the number of hits used in the last fit of the reconstruction algorithm (N_{hit}) and a quality parameter Λ is given as output. The Λ parameter is determined from the likelihood and from the number of compatible solutions found by the algorithm and is used to reject badly reconstructed events.

The MC neutrinos from Fermi bubbles have been generated homogeneously in two circular regions of radius 19° around two positions in the sky at the following equatorial coordinates: $\delta = -15°$ and RA $= 243°$ for the north bubble and $\delta = -44°$ and RA $= 298°$ for the south bubble in the energy range $10^2 \leq E_\nu \leq 10^8$ GeV. In Fig. 1 the generated up-going tracks are plotted in galactic coordinates. In Fig.1 the edges (points) of the two bubbles, as in ref. [4] Table 1, are also reported. The difference in the yield of Fig. 1 is due to the visibility of a detector located at the Capo Passero latitude (36° 16' N) with 2π downward coverage. The average visibility is of 58% of the time for the north bubble and of 80% for the south bubble.

The same MC events can be differently weighted to reproduce the neutrino energy spectrum. Two neutrino energy spectra have been considered: a pure exponential spectrum with slope 2 ($\Phi_\nu = \Phi_0 \times E^{-2}$) and a spectrum with 100 TeV cutoff energy ($\Phi_\nu = \Phi_0 \times E^{-2} \times e^{-\mathrm{E}/100\mathrm{TeV}}$). The flux normalization factor is irrelevant in the calculation of the discovery fluxes and was fixed to $\Phi_0 = 10^{-7}$ GeV^{-1} s^{-1} cm^{-2}.

Cosmic rays entering the atmosphere produce extensive air showers that contain high energy muons. Although the

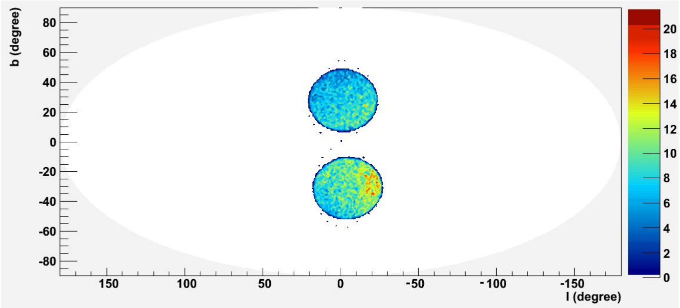

Figure 1: Number of MC events generated up-going in galactic coordinates. The number of generated events is reported in arbitrary units. The measured [4] bubble edges are also reported (points).

sea water above the detector serves as a shield, many such muons reach the detector. Since the atmospheric muons come from above, in a neutrino telescope we will look for up-going tracks. However, fake atmospheric muons reconstructed as up-going remain one of the main background sources in a neutrino telescope.

For the aim of this work atmospheric muons have been generated with the MUPAGE package [20]. MUPAGE provides a parameterized description of the underwater flux of atmospheric muons including also multi-muon events. A muon samples has been generated at a depth of 3400m with a total energy threshold of $E_{\rm b} \geq 10$ TeV ($E_{\rm b}$ is the sum of the energy of single muon in the bundle) corresponding to a live time of about 2 days.

Large numbers of charged pions and kaons are produced in cosmic ray interactions in the atmosphere. Their subsequent decays produce neutrinos, resulting in a large flux of atmospheric high energy neutrinos. They are an irreducible background for the detection of neutrinos of cosmic origin. The MC atmospheric neutrino background have been generated in the energy range $10^2 \leq E_\nu \leq 10^8$ GeV and zenith angle $0° \leq \theta \leq 180°$. The events were weighted to reproduce the conventional atmospheric neutrinos from charged mesons decay (Bartol) [18] ($\Phi_\nu \propto \mathrm{E}^{-3.7}$ at high energies). A prompt contribution from charm decays according to the highest prediction of the Recombination Quark Parton Model [19] is included. In the present analysis this background represents the main source of background.

From the simulated number of expected events from signal $\langle n_s \rangle$ and background $\langle n_{back} \rangle$ it is possible to calculate the flux required to claim the discovery of the bubbles. A neutrino source can be considered discovered if the number of events detected has a probability of $5.7 \cdot 10^{-7}$, 5σ of a normalized Gaussian, at a 50% of confidence level to be background.

The best discovery potential is obtained with cuts in Λ, $\mathrm{N_{hit}}$ and $\mathrm{R_{bin}}$ ($\mathrm{R_{bin}}$ is the angular distance between the reconstructed event and the center of each bubbles) that minimize the Model Discovery Potential (MDP) [21] MDP= $\frac{N_\alpha(\langle n_{back} \rangle)}{\langle n_s \rangle}$ (α is the significance level) and hence minimize the discovery potential flux.

$$\Phi_\alpha = \Phi_0 \cdot \mathrm{MDP} = \Phi_0 \cdot \frac{N_\alpha(\langle n_{\rm back} \rangle)}{\langle n_{\rm s} \rangle} \quad (1)$$

N_α is the number of events from signal that exceed the background with a significance α.

	years	N_α	$n_{\rm back}$
3σ	0.4	35	127
5σ	1.0	105	426

Table 1: Number of years required to detect a neutrino flux from bubbles of $\Phi_\nu E^2 = 10^{-7} e^{-\mathrm{E}/100\mathrm{TeV}} GeV cm^{-2} s^{-1}$ with 3σ and 5σ of significance at 50% C.L.The number of neutrinos from signal and background are also reported.

In Tab. 1 the number of years needed to claim the discovery (5σ 50% C.L.) and the evidence (3σ 50% C.L.) for an expected neutrino spectrum of $\Phi_\nu E^2 = 10^{-7} e^{-\mathrm{E}/100\mathrm{TeV}}$ GeV cm^{-2} s^{-1} is reported.

The 5σ discovery for a pure exponential E^{-2} neutrino spectrum is expected in about 1 month of data taking.

5. Conclusions

The discovery of an intense gamma flux from two large areas around the Galactic center, the Fermi bubbles, has triggered the work here presented. In fact the future detector KM3NeT, thanks to its location in the Mediterranean sea and to its large volume, is the ideal instrument to observe neutrinos from the Fermi bubbles.

Predictions of discovery of neutrino from Fermi bubbles with the KM3NeT detector have been presented. These predictions are based on Monte-Carlo calculations that simulate the neutrino emitted from the Fermi bubbles and the detector response. Preliminary results indicate that the KM3NeT telescope can give a response on the mechanisms responsible for the gamma emission mechanisms in a rather short time. In fact, we should obtain a first evidence of the presence of these sources in few months and claim the discovery in about 1 year. Even the non observation of neutrinos can set severe upper limits on the neutrino models and constraints on the production mechanisms.

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