High energy neutrinos from pulsar wind nebulae

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Abstract. Several Pulsar Wind Nebulae have been detected in the TeV band in the last decade. The TeV emission is typically interpreted in a purely leptonic scenario, but this usually requires that the magnetic field in the Nebula be much lower than the equipartition value and the assumption of an enhanced target radiation at IR frequencies. In this work we consider the possibility that, in addition to the relativistic electrons, also relativistic hadrons are present in these nebulae. Assuming that part of the emitted TeV photons are of hadronic origin, we compute the associated flux of $\sim 1-100$ TeV neutrinos. We use the IceCube non-detection to put constraints on the fraction of TeV photons that might be contributed by hadrons and estimate the number of neutrino events that can be expected from these sources in IceCube, ANTARES and in KM3Net.

1. Introduction

Pulsar Wind Nebulae (PWN) are diffuse nebulae of non-thermal radiation associated with the presence of a highly spinning, strongly magnetised neutron star. The central star of a PWN might be detected as a pulsar or not, in both cases it must emit what is called a pulsar wind, namely a relativistic magnetised outflow, mainly made of electron-positron pairs. Confinement of this outflow by the surrounding Supernova Remnant or by the interstellar medium leads to the formation of a termination shock, at which the wind is slowed down to non-relativistic bulk speed and particles are accelerated to a power-law (or broken power-law) distribution. The interaction of these highly energetic leptons with the ambient magnetic field and with the radio and IR background radiation is thought to be at the origin of the nebular emission, from radio wavelengths to the TeV band. Several PWNe have been discovered in radio, optical, and X-ray bands, with the Crab as the youngest and most energetic source. In this work, we consider the possibility that part of the TeV emission is due to the decay of neutral pions produced in nuclear collisions. The same process that produces the neutral pions and subsequently the TeV photons would also generate charged pions that decay into neutrinos of similar energy.

2. Neutrino Telescopes

High-energy neutrinos interact with nucleons present in the detector producing secondary particles, which travel faster than the speed of light in the sea or ice and therefore induce the emission of Cherenkov light. These photons are detected by optical sensors deployed in sea or ice. In the following we briefly describe the basic characteristics of each telescope considered in this work.

IceCube, located at the geographic South Pole, is a cubic-kilometer particle detector buried in
the Antarctic ice. In its final detector configuration, the digital optical modules are arranged on 86 vertical strings of 60 sensors each, spread over depths between 1450m and 2450m with vertical distances of 17 m between sensors.

The ANTARES detector is currently the only deep sea high energy neutrino telescope, which is operating in the Northern hemisphere. The telescope covers an area of about 0.1 km$^2$ on the sea bed, at a depth of 2475 m, 40km off the coast of Toulon, France.

KM3Net is the future generation of underwater neutrino telescopes. The infrastructure will consist of three so-called building blocks, each made of 115 strings of 18 optical modules, that have 31 photo-multiplier tubes each. KM3Net is made of KM3Net/ARCA (Toulon, France) and KM3Net/ORCA (Capo Passero, Sicily).

3. Astrophysical events
To compute the neutrino fluxes that would be expected from the TeV detected PWNe in IceCube based on conversion of the whole photon flux in a corresponding number of neutrinos [1]. We then discuss the most promising sources in detail and the implications of their non-detection by IceCube in terms of more refined predictions for ANTARES and KM3Net [2]. Relativistic protons may produce TeV $\gamma$-rays either by photo-meson production or inelastic nuclear collisions. The relation between the neutrino and photon flux is:

$$\int_{E_{\nu}^{\text{min}}}^{E_{\nu}^{\text{max}}} dN_{\nu}/dE_{\nu} = \int_{E_{\gamma}^{\text{min}}}^{E_{\gamma}^{\text{max}}} dN_{\gamma}/dE_{\gamma}$$  \hspace{1cm} (1)

where $E_{\gamma}^{\text{min}}$ ($E_{\nu}^{\text{min}}$) and $E_{\gamma}^{\text{max}}$ ($E_{\nu}^{\text{max}}$) are the minimum and maximum photon (neutrino) energies respectively. We are aware that is a simplistic approximation as most of the multiwavelength photon emission from PWNe seems to be due to leptonic processes rather than hadronic ones. However this provides the most optimistic estimate of the hadronic contribution to the TeV photon fluence measured by the TeV telescopes, and will be used as such. We estimate the neutrino flux in the energy range $1 - 100$ TeV, which is the range in which IceCube, and ANTARES are operating and we assume the same range also for KM3Net. The total number of expected astrophysical events in a year of operation of a neutrino telescope is given by

$$N = \int_{T_{1 \text{TeV}}}^{T_{100 \text{TeV}}} \frac{dN_{\gamma}}{dE_{\gamma}} \left[ A(E_{\nu}, \delta) d[2E_{\nu}] \right]$$  \hspace{1cm} (2)

where $T$ is the exposure time of one year, $dN_{\gamma}/dE_{\gamma}$ is the TeV spectrum, $A(E_{\nu}, \delta)$ is the effective area of the considered neutrino telescope, as a function of the neutrino energy $E_{\nu}$ and of the source declination, $\delta$. $A(E_{\nu}, \delta)$ is the effective area for the IceCube [3], ANTARES [4] and KM3Net/ARCA [5] detector respectively.

4. Atmospheric events
The main component for the background is the flux of atmospheric neutrinos, which is caused by the interaction of cosmic rays, high energy protons and nuclei, with the Earth’s atmosphere. Decay of charged pions and kaons produced in cosmic ray interactions generates the flux of atmospheric neutrinos and muons. Their energy spectrum is about one power steeper than the spectrum of the parent cosmic rays at Earth, due to the energy dependent competition between meson decay and interaction in the atmosphere. The spectral index for such power law is typically $\xi = 2.7$. For the following estimates, we do not consider the additional atmospheric component due to the decay of heavier mesons, since this becomes relevant only for $E > 100$
TeV. The atmospheric neutrino flux is expressed as a power law

$$\frac{d\Phi_\nu}{dE_\nu d\Omega} = C_\nu E_\nu^{-\beta}$$

(3)

where $C_\nu$ is a scale factor derived through Monte Carlo computations or experimental data, while $\beta \simeq \xi + 1$. The number of background neutrinos can be estimated as:

$$BG = \int_{T_\text{eV}}^{100\ T_\text{eV}} T \frac{d\Phi_\nu}{dE_\nu d\Omega} A(E_\nu, \delta) dE_\nu d\delta d\Omega$$

(4)

where $T$ is the exposure time of one year, $A(E_\nu, \delta)$ is the relative effective area and $\frac{d\Phi_\nu}{dE_\nu d\Omega}$ is the atmospheric neutrino flux [6] [7].

5. Conclusions

The existing upper limits on the neutrino flux derived from IceCube non-detection do not allow us to put constraints on the hadronic content of the Crab pulsar wind. However, with the next generation neutrino telescopes we will be likely able to probe the presence of relativistic hadrons in the Crab Nebula: with a factor of ten larger sensitivity, TeV neutrinos should be detectable from Crab, in 5-10 years of integration with KM3Net/ARCA, almost independently of the pulsar wind parameters, in the case of cold hadrons; they should also be detectable for a power law distribution of hadrons, if these carry more than 20% of the pulsar wind energy.

The second source we considered, Vela, turns out to be the best candidate PWN to be detected in neutrinos. Even taking into account the IceCube non-detection, the revised number of expected neutrinos still suggests that the source can be detected by ANTARES in a few years of integration and promptly by KM3Net/ARCA. We also mentioned the difficulties associated with a fully leptonic interpretation of the $\gamma$-ray flux from this source: namely the requirement that the nebular magnetic field be on average a factor 5 below the estimated equipartition field and the presence of an enhanced IR background. Taking into account all this, Vela really appears to be a promising neutrino source.

A detectable neutrino flux is also expected from MSH15-52, while for the remaining potentially promising sources in our list, the IceCube constraints strongly reduce the perspectives of detection with the KM3Net detector.

It is important to note that the KM3Net/ARCA predictions were derived without considering the effect of the efficiency of the apparatus and the selection and reconstruction criteria.

The Cherenkov Telescope Array will likely increase the number of PWNe detected at TeV energy to several hundreds, probably providing an essentially complete account of TeV emitting PWNe in the Galaxy.

References

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