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Galactic sources of high energy neutrinos

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Abstract. The undisputed galactic origin of cosmic rays at energies below the so-called knee implies an existence of a nonthemal population of galactic objects which effectively accelerate protons and nuclei to TeV-PeV energies. The distinct signatures of these cosmic PeVatrons are high energy neutrinos and γ-rays produced through hadronic interactions. While γ-rays can be produced also by directly accelerated electrons, high energy neutrinos provide the most straightforward and unambiguous information about the nucleonic component of accelerated particles. The planned km^3-volume class high energy neutrino detectors are expected to be sensitive enough to provide the first astrophysically meaningful probes of potential VHE neutrino sources. This optimistic prediction is based on the recent discovery of high energy γ-ray sources with hard energy spectra extending to 10 TeV and beyond. Amongst the best-bet candidates are two young shell-type supernova remnants – RXJ 1713.7-4946 and RXJ 0852.0-4622, and perhaps also two prominent plerions - the Crab Nebula and Vela X. Because of strong absorption of TeV γ-rays, one may expect detectable neutrino fluxes also from (somewhat fainter) compact TeV γ-ray emitters like the binary systems LS 5039 and LS I+61 303, and, hopefully, also from hypothetical "hidden" or "orphan" neutrino sources.

1. Introduction

Very High Energy ($E \geq 0.1$ TeV; VHE) neutrinos are unique messengers of nonthermal phenomena in the Universe related to the hadronic interactions of protons and nuclei in cosmic TeVatrons and PeVatrons - Nature's masterly designed machines accelerating particles to TeV and PeV energies. In this regard VHE neutrinos are complementary to γ-rays which are produced both in electromagnetic and hadronic interactions. On the other hand, unlike γ-rays, neutrinos are not fragile; they interact only weakly with the ambient medium - gas, radiation and magnetic fields, and thus carry information about high energy processes occurring in "hidden" regions where the particle accelerators could be located. This concerns, first of all, the regions associated with compact objects - black holes, pulsars, the initial epochs of supernovae explosions, *etc.* The penetrating potential of neutrinos is important not only for extremely dense environments in which γ-rays are dramatically absorbed, but also moderately opaque sources from which we do see γ-rays, but after significant distortion due to internal and external absorption.

Ironically, this nice (from an astrophysical point of view) feature of neutrinos makes, at the same time, their detection extremely difficult. This explains why, over several decades high energy neutrino astronomy has remained essentially a theoretical discipline with many exciting ideas and predictions but without the detection of a single VHE neutrinos source. However, it is expected that, with arrival of the km^3-volume class scale detectors like IceCube and KM3NeT (see e.g. [1, 2]), the status of the field will be changed dramatically. Generally, prediction of VHE

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neutrino fluxes from astrophysical objects contain many assumptions and free parameters and, therefore, often contain large (orders of magnitude!) uncertainties. This leaves a significant freedom in speculations on the "best-bet neutrino sources", and consequently allows a broad spectrum of opinions concerning the prospects for detecting the first astrophysical neutrinos - from very enthusiastic statements to rather careful predictions prevailed by a healthy scepticism (see e.g. [3]).

Presently extragalactic objects like Active Galactic Nuclei (AGN) and sources of Gamma Ray Bursts (GRBs) are believed to be the most likely objects to be detected as neutrino sources, and therefore the driving force of experimental VHE neutrino astronomy (see e.g. [4]). The current models of AGN and GRBs indeed contain many attractive components (concerning the conditions of particle acceleration and their interactions) which make these objects *potentially detectable* sources of VHE neutrinos. On the other hand, the poor understanding of many aspects of the physics of AGN and especially GRBs, as well as the lack of constraints on neutrino productions rates from γ-ray observations (because of intrinsic and intergalactic absorption of VHE γ-rays), formally allow calculations in extreme model-parameter segments which often lead to rather high (over-optimistic) neutrino flux predictions.

The models of potential galactic neutrino sources, in particular the shell type Supernova Remnants (SNRs), Pulsar Wind Nebulae (PWNe), Star Formations Regions and the dense molecular clouds related to them, are robustly constrained by γ-ray observations of the galactic disk in very-high energy ($\geq$ 1 TeV) [5, 6] and ultra-high energy ($\geq$ 100 TeV) [7] domains. Typically, the expected fluxes from these objects are below the detection threshold of the planned neutrino detectors. However, the recent HESS discoveries of several TeV γ-ray sources at the flux level of "1 Crab", which can be interpreted within the hadronic models of gamma-ray emission, sustain a hope that that the first TeV galactic sources will be detected in foreseeable future by km^3-volume class instruments like IceCube and Km3NeT.

2. On the detectability of galactic VHE neutrino sources

The recent performace studies of the km^3-volume scale detectors show that the detection of a persistent point-like (for a typical angular resolution of VHE neutrino detectors the "point-like" source implies an object of angular size $\leq 1^\circ$) neutrino sources for a realistic exposure time (typically, a few years continuous observations) is limited by a flux $F(\geq 1\mathrm{TeV}) \approx 10^{-11}\ \nu/\mathrm{cm}^2\mathrm{s}$ (see e.g. [8, 9, 10, 11]). The corresponding energy flux is $f_{\mathrm{E}} \approx 10^{-10}\mathrm{erg/cm^2s}$ or somewhat less, depending on the spectrum in the most relevant energy band between 1 TeV and 100 TeV. This exceeds, by two orders of magnitude, the minimum γ-ray flux detectable in the same energy band. On the other hand, the sensitivity of the km^3-scale detectors is comparable or better than the minimum detectable energy flux achieved by the Compton Gamma Ray Observatory detectors (COMPTEL, EGRET) in the MeV/GeV γ-ray band. For an isotropic VHE source located at a distance d, the luminosity of TeV neutrinos can be probed at the level

$$L_\nu \simeq 10^{34}(d/1\ \mathrm{kpc})^2\ \mathrm{erg/s}\ . \quad (1)$$

At first glance, this is a quite modest luminosity, at least for a powerful hadronic source located in a dense environment. Indeed, for production of TeV neutrinos in p-p interactions with ambient gas of density $n_0 = n/1\mathrm{cm}^{-3}$, the required total energy in multi-TeV protons is estimated $W_p \simeq t_{\mathrm{pp}} c_{\mathrm{p}\to\nu} L_\nu \simeq 3 \times 10^{48} n_0 d_{\mathrm{kpc}}^2$ erg, where $t_{\mathrm{pp}} \approx 5 \times 10^{14} n_0^{-1}$ s is the radiative cooling time of protons due to inelastic p-p interactions, and $c_{\mathrm{p}\to\nu} \approx 0.1$ is the fraction of average energy of a proton transferred to muon neutrinos. One may conclude that even in a relatively low density environment, $\mathrm{n}_0 \sim 1$, the required total energy can be readily produced in young SNRs through diffusive shock acceleration (see e.g. [12]) or by a powerful pulsar assuming that a major fraction of the spin-down luminosity of the pulsar is converted to an ion-dominated wind (see e.g. [13]). However, these kinds of estimates can be misleading since they are based on a