

Prospects for Galactic TeV Neutrino Astronomy

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Abstract. In just the last few years, the catalog of known Galactic TeV gamma-ray sources has grown dramatically, due to the abilities of current air Čerenkov telescopes to measure both the spectrum and morphology of the TeV emission. While these properties can be very well measured, they are not necessarily sufficient to determine whether the gamma rays are produced by leptonic or hadronic processes. However, if the gamma-ray emission is hadronic, there must be an accompanying flux of neutrinos, which can be determined from the observed gamma-ray spectrum. The upcoming km³ neutrino telescopes will allow for a direct test of the gamma-ray production mechanism and the possibility of examining the highest possible energies, with important consequences for our understanding of Galactic cosmic-ray production.

(Based upon M. D. Kistler and J. F. Beacom, “Guaranteed and Prospective Galactic TeV Neutrino Sources,” Phys. Rev. D **74**, 063007 (2006) (astro-ph/0607082) [1].)

1. Neutrino the TeV Sky

Recent years have seen an explosion in the number of detections of TeV gamma-ray sources in our Galaxy. The improved sensitivities and energy reach of air Čerenkov telescopes (ACT), particularly HESS [2], have allowed for an exploration of the richness of these source populations. They include (but are not limited to) shell-type supernova remnants [3, 4], diffuse emission near the Galactic Center [5], and sources without known counterparts at any other wavelength [6]. Yet, even as the list of TeV sources continues to expand, it is still a mystery as to whether the observed gamma rays are produced leptonicly, through the inverse Compton scattering of energetic electrons on ambient photons ($e^- \gamma \rightarrow \gamma e^-$), or hadronically, through neutral pion decay ($\pi^0 \rightarrow \gamma\gamma$).

While an ACT can measure a source spectrum with high precision for $E_\gamma \sim 1 - 10$ TeV, the measurement of gamma rays alone is not sufficient to reveal their true origin. Also, at energies $\gtrsim 10$ TeV, the low statistics of the falling signal spectra make the difficulties of gamma-ray astronomy more pronounced. Fortunately, it is well established that a distinctive feature of a hadronically-produced (pionic) gamma-ray spectrum is an accompanying flux of neutrinos [7]. These neutrinos originate from the decay of charged pions (π^+ , π^-) produced in approximately equal quantities with neutral pions in proton-proton ($p-p$) scattering.

2. Looking Down to See the Sky

Relative to gamma-ray telescopes, the new km³ neutrino telescopes [8, 9] will have several advantages resulting in improved performance at these energies. The rapidly declining atmospheric neutrino background, rising neutrino-nucleon cross section ($\sigma_{\nu N} \sim E_\nu$), and increasing muon range, which leads to a larger effective detector volume ($R_\mu \sim \ln E_\mu$), all help

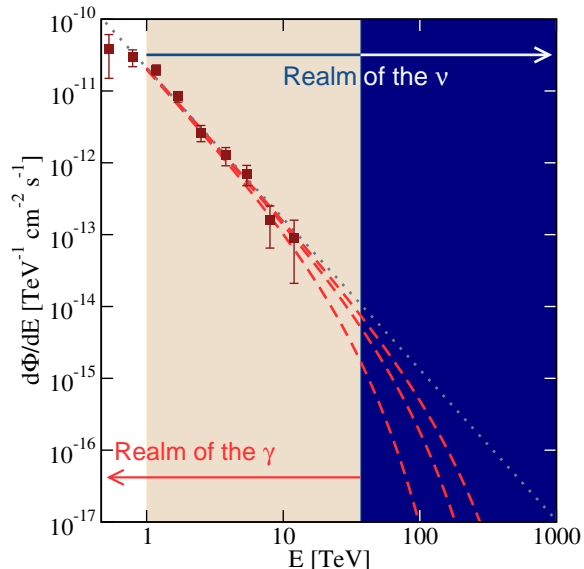


Figure 1. Ranges over which gamma-ray and neutrino observations can measure a source spectrum ($E_\gamma \simeq E_\pi/2$, $E_\nu \simeq E_\pi/4$). Squares are HESS measurements of Vela Jr., fit by a power law (dotted line). Neutrino telescopes can probe higher energies to distinguish between pionic spectra with cutoffs (dashed lines) by measuring the ν_μ -induced muon and shower spectra. Figure adapted from Ref. [1].

to amplify the diminished flux. As the background quickly becomes negligible, the detection of *any* high energy neutrinos from a source could significantly indicate a hadronic production mechanism. Measurement of the energies of neutrino-induced muons and showers (related to the original charged pion energy) can probe the source proton spectrum in a manner complementary to gamma-ray observations [10] (which effectively measure the neutral pion spectrum) and permit a study of spectral features in the highest energy regime, especially an expected cutoff. The sensitivities of these two independent approaches, including the regime where they coincide, are illustrated in Fig. 1.

High rates of down-going muons (from atmospheric cosmic-ray showers) force a neutrino telescope to search for up-going muons resulting from neutrino interactions. IceCube is well-situated to utilize the high angular resolution of these ν_μ -induced muons in observing northern-sky sources. However, a detector is needed in the northern hemisphere to accurately locate southern-sky neutrino sources. Together, IceCube and a km³ Mediterranean detector will provide full-time coverage of the entire sky. The ability to accurately measure neutrino-induced muon spectra greatly improves the prospects for detecting sources, as the harder source spectra dominate the atmospheric background above ~ 1 TeV. While muon tracks have better angular resolution ($\lesssim 1^\circ$ [11]), neutrino *showers* ($\sim 10^\circ$ in water [12]), which measure the ν_e and ν_τ fluxes [13], more faithfully trace the spectrum. The combined observations from these detectors can be used to study complex objects, by: (1) Discovering neutrino sources through the good resolution resolution ($\lesssim 1^\circ$) of ν_μ -induced muons; (2) Confirming agreement with gamma-ray observations in the low energy regime; (3) Examining previously unexplored energies using muons and showers together.

3. Where the Sources Have No Name

Utilizing recent gamma-ray spectra of Galactic TeV sources, the corresponding neutrino fluxes can be found (assuming only that the *measured* spectra are pionic). Using the predicted neutrino flux, along with the neutrino-nucleon cross section [14] and the average muon energy loss [15], we can calculate the spectra of detectable neutrino-induced muons and showers in a km³ detector. We refer the interested reader the Ref. [1] for details on these calculations (see also Refs. [7, 16]).

The shell-type SNR Vela Jr. (RX J0852.0–4622) is one of the most interesting known TeV sources. This source is very bright in gamma rays ($d\Phi/dE = 21 \times 10^{-12} (E/\text{TeV})^{-2.1} \text{ TeV}^{-1} \text{ cm}^{-2}$

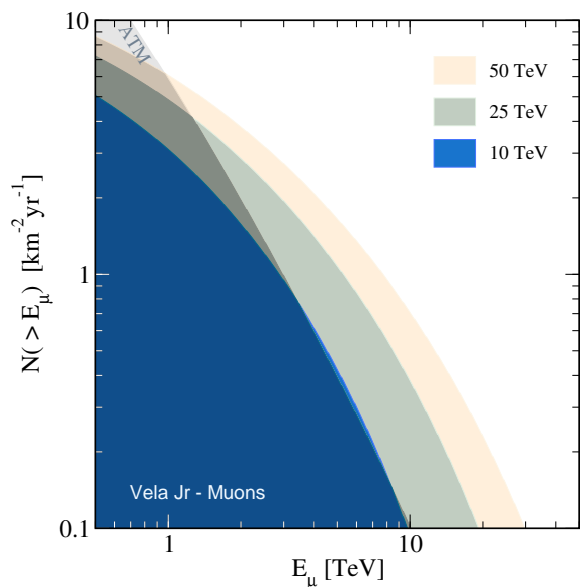


Figure 2. *Vela Jr. (RX J0852.0–4622) – Muons:* Integrated $(\nu_\mu + \bar{\nu}_\mu)$ -induced muon rates above a given measured muon energy. The curves, from top to bottom, correspond to neutrino spectrum exponential cutoffs of 50, 25, and 10 TeV, respectively. The shaded region corresponds to the expected atmospheric background in a 7 deg^2 bin. Rates are for one year of operation in a km^3 Mediterranean detector. Figure adapted from Ref. [1].

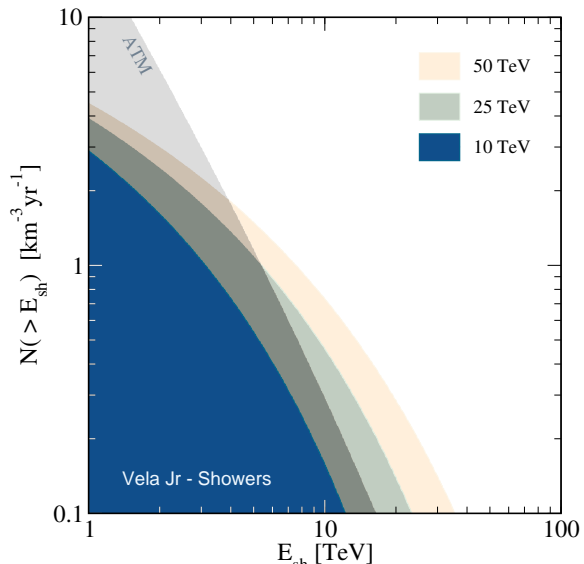


Figure 3. *Vela Jr. (RX J0852.0–4622) – Showers:* Integrated neutrino-induced shower rates above a given measured shower energy, with signals as in Fig. 2. Note that a different energy scale is used for showers, as measurable shower events are assumed to have a 1 TeV energy threshold. Background rates are for a circle of 10° radius, corresponding to the shower angular resolution in a km^3 Mediterranean detector. Rates are for one year of operation. Figure adapted from Ref. [1].

s^{-1}), with well-defined regions of gamma-ray emission [3]. Shell-type SNRs are considered to be the most likely sites of Galactic cosmic-ray acceleration [17]. We calculate the expected neutrino-induced muon rate assuming a pionic spectrum with several neutrino spectrum exponential cutoffs (50, 25, and 10 TeV), as shown in Fig. 2. The brightness of the source may also make it possible to observe appreciable numbers of showers, which more directly trace the neutrino flux (since $\sim 100\%$ of the $\nu_{e,\tau}$ energy goes into the cascade). Fig. 3 shows the rate of showers for one year of observation, compared to the irreducible atmospheric background. IceCube might also be used to effectively increase the shower volume (since shower events must be located within the detector) in measuring the $\nu_e + \nu_\tau$ flux.

Though we only discuss Vela Jr. in detail here, many Galactic gamma-ray sources may be producing neutrinos. A more complete list is given in Ref. [1]. Recent calculations have also been presented in Refs. [10, 18, 19], which all now agree well with those of Ref. [1].

4. Conclusions: Still Haven't Found What We're Looking For

The upcoming km^3 detectors will reach the scale necessary to examine Galactic TeV sources and deliver the first direct evidence concerning their gamma-ray production mechanisms. Combined, IceCube and a km^3 Mediterranean detector will provide continuous, all-sky coverage and can be used together to detect neutrino-induced muons and showers from TeV sources. The good angular resolution for muon events can be used to precisely locate a source in neutrinos. Showers,

and contained muon events, provide accurate reconstruction of the source spectrum at energies beyond the reach of gamma-ray telescopes. Neutrino measurements would provide important information concerning the production of cosmic rays in the Galaxy, which is expected to dominate the cosmic-ray spectrum past the knee at $\sim 3 \times 10^{15}$ eV (with extragalactic neutrino measurements providing information at the highest energies e.g. Ref. [20]).

In summary, the prospects for the near-term first discoveries of Galactic TeV neutrino sources are very good. Importantly, this conclusion is empirically based on measured gamma-ray spectra. It must be noted that measured muon energy spectra should be used to discriminate against the quickly falling atmospheric neutrino backgrounds. For example, a single event near 10 TeV from a source direction is almost certainly signal, while an event near 1 TeV has a much higher probability of being background. Due to the amplifying factors of neutrino cross section and muon range, neutrino detectors have better reach to the highest energies in the source spectra, as compared to gamma-ray telescopes, which can make precise measurements at lower energies. This complementarity should be exploited in order to help solve the long-standing puzzles of the origin of the Galactic cosmic rays and gamma rays.

Acknowledgments

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