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Reevaluation of the prospect of observing neutrinos from Galactic sources in the light of recent results in gamma ray and neutrino astronomy

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A B S T R A C T

In light of the recent IceCube evidence for a flux of extraterrestrial neutrinos, we revisit the prospect of observing the sources of the Galactic cosmic rays. In particular, we update the predictions for the neutrino flux expected from sources in the nearby star-forming region in Cygnus taking into account recent TeV gamma ray measurements of their spectra. We consider the three Milagro sources: MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 and calculate the attainable confidence level limits and statistical significance as a function of the exposure time. We also evaluate the prospects for a kilometer-scale detector in the Mediterranean to observe and elucidate the origin of the cosmic neutrino flux measured by IceCube.

1. Introduction

If supernova remnants are indeed the sources of the highest energy Galactic cosmic rays [1], the IceCube neutrino detector is expected to detect a flux of neutrinos accompanying the observed cosmic ray flux. Fermi has recently established the presence of pions in two supernova remnants thus unambiguously indicating the acceleration of cosmic rays [2]. However, their energies do not reach the PeV range and therefore the "PeVatrons" that are the sources of the cosmic rays in the "knee" region of the spectrum, and above, remain unidentified. Generic PeVatrons produce pionic gamma rays whose spectrum extends to several hundred TeV without a cutoff. Their predicted flux should be within reach of the present generation of ground-based gamma ray telescopes but has not been identified so far.

The highest energy survey of the Galactic plane to date has been performed by the Milagro detector. In particular, the survey in the 10 TeV band has revealed a subset of sources located within nearby star-forming regions in Cygnus and in the vicinity of Galactic latitude $l = 40^{\circ}$. Subsequently, directional air Cherenkov telescopes were pointed at some of the sources [3,4], revealing them as PeVatron candidates with gamma-ray fluxes following an E^{-2} energy spectrum that extends to tens of TeV without evidence for a cutoff. Interestingly, some of the sources cannot be readily associated with known supernova remnants, or with any non-thermal sources observed at other wavelengths. These are likely to be molecular clouds illuminated by the cosmic-ray beam accelerated in young remnants located within about 100 pc. Indeed one expects that multi-PeV cosmic rays are accelerated only over a short time period when the shock velocity is high, i.e., between free expansion and the beginning of its dissipation in the interstellar medium. The high-energy particles can produce photons and neutrinos over much longer periods when they diffuse through the interstellar medium to interact with nearby molecular clouds [5]. An association of molecular clouds and supernova remnants is expected in star-forming regions. Note that any confusion between pionic with synchrotron photons is unlikely to be a problem in this case.

Assuming that the Milagro sources are indeed cosmic-ray accelerators, the equality of the production of pions of all three charges dictates the relation between pionic gamma rays and neutrinos and basically predicts the production of a $\nu_\mu + \bar{\nu}_\mu$ pair for every two gamma rays seen by Milagro. The calculation can be performed in more detail with approximately the same outcome [6,7]. For average values of the source parameters it was anticipated that the completed IceCube detector should confirm sources in the Milagro sky map as sites of cosmic-ray acceleration at the 3σ

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level in less than one year and at the 5σ level in three years. This assumes that the source extends to 300 TeV, i.e., approximately 10% of the energy of the cosmic rays near the knee in the spectrum. There are intrinsic ambiguities of an astrophysical nature in this estimate that may reduce or extend the time required for a 5σ observation [7], most prominently the exact location where the sources run out of energy. Also, the extended nature of some of the Milagro sources represents a challenge for IceCube observations that are optimized for point sources. For other previous analyses of galactic sources of high-energy neutrinos at IceCube, we refer also to Refs.[8,9].

IceCube searches have revealed positive fluctuations from these sources in the 8 years of AMANDA data and in 4 out of 5 years of data collected with the partially deployed IceCube detector. On the other hand, the first extraterrestrial neutrino flux observed [10] by IceCube consists of 28 events (more below) with no event originating from the nearby star-forming region in Cygnus. This fact, together with the availability of new information from gamma ray telescopes, has motivated us to revisit the calculation of the neutrino flux in Ref. [7] for some of the sources. In particular we will update the information on MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 [11,12], 3 of the 6 sources used in the IceCube stacking analysis based on references [7,6,13].

Note that recently a lot of work has been done to try to explain the IceCube results in terms of point sources. For example, in Ref. [14] the authors discuss the possibility to explain the IceCube data, and in particular an hot spot of 7 shower events, with 24 TeV unidentified sources of our Galaxy. Among the sources considered, there are also the two Milagro sources, MGRO J1908+06 and MGRO J2031+41, assumed to be Galactic hypernova remnant. Note that MGRO J2019+37 is, instead, identified as pulsar wind nebulae (PWN). The conclusion of the analysis is that only 3.8 of the IceCube events may originate from the TeV unidenfied sources, conclusion obtained by comparing the spatial distribution of the IceCube events and the one from the unidentified sources. In Ref. [15], instead, numerous Galactic sources are examined and for them the shower event rates and muon event rates are calculated. For example, Vela Jr. (RX J0852.04622) is a southern-sky source, that could be observed as muon tracks by an km^3 Northen hemisphere detector and through cascade events by the IceCube detector. Using both the muon tracks and cascades, it could be possible to better identify the specific source, pinning down its characteristics. In particular both the location (through muon events) and the source spectrum (through cascade events) could be reconstructed with precision.

We want to stress, however, that the three Milagro sources that we are going to consider in this paper will give as main channel in IceCube muon tracks, since they are located in the Northern hemisphere. For this reason, this is the main event signal that we are going to calculate. We will not consider shower events in a Northern hemisphere detector for these three Milagro sources. Our main scope is to consider the muon tracks and analyzing the possibility that these sources could be detected or not in less than 10 years at IceCube. However, we will instead consider a Northern hemisphere detector under the hypothesis of testing an hot spot recently revealed by IceCube, as described in the following.

As mentioned above, recently, IceCube has presented the first evidence for an extraterrestrial flux of very high-energy neutrinos, some with PeV energies. IceCube has thus become the latest entry in an extensive and diverse collection of instruments attempting to pinpoint the still enigmatic sources of cosmic rays. Analyzing data collected between May 2010 and May 2012, 28 neutrino events were identified with in-detector deposited energies between 30 and 1200 TeV. Among the 28 events, 21 are showers whose energies are measured to better than 15% but whose directions are determined to 10–15° only. None show evidence for a muon track accompanying the neutrino. If of atmospheric origin, the neutrinos should be accompanied by muons produced in the air shower in which they originate. For example, the probability that a PeV atmospheric neutrino interacting in IceCube is unaccompanied by a muon is of order 0.1%. The remaining seven events are muon tracks. With the present statistics, these are difficult to separate from the competing atmospheric background. Fitting the data to a superposition of an extraterrestrial neutrino flux on an atmospheric background yields a cosmic neutrino flux of

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} = 3.6 \times 10^{-11}\ \mathrm{TeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \tag{1}$$

Of those 28 events, a hot spot of 7 shower events is evident at RA = 281° and dec = 23° close to the Galactic center although its significance is only 8% according to the test statistic defined in the blind analysis of the IceCube data. On the other hand, the highest energy event does reconstruct to within 1 degree of the Galactic center and, assuming an isotropic distribution, only 0.7 events are expected in the area of the sky covered by the seven showers. We will speculate that PeVatrons producing cosmic rays in the 10^{15}—10^{17} energy range are the origin of these neutrinos. It is not unreasonable to expect that PeVatrons cluster in the direction of the Galactic center corresponding to the largest concentration of mass along the line of sight. The star-forming region near the Galactic center itself is likely to be distant to be observed individually. We will investigate the opportunities for a kilometer-scale detector in the Northern hemisphere to elucidate the origin of the IceCube flux by observing muon neutrinos which allow for sub-degree angular reconstruction.

In Section 2 we update the gamma ray spectra from the three Milagro sources: MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 and the calculation of the associated neutrino event rates in IceCube. In Section 3 we study the attainable confidence level limits and statistical significance which IceCube can set as a function of the exposure time considering different values of the source parameters. We also estimate the prospects for a kilometer-scale detector in the Mediterranean to observe and elucidate the origin of the cosmic neutrino flux measured by IceCube. We briefly summarize our conclusions in Section 4.

2. Point sources

2.1. Neutrino flux

We start by updating the information on 3 of the 6 MILAGRO sources considered in past IceCube analyses. The parameters in Table 1 refer to the parametrization reported in Refs. [11,12], where the γ-ray flux in the TeV energy range is parametrized in terms of a spectral slope α_γ, an energy $E_{cut,\gamma}$ where the accelerator cuts off, and a normalization k_γ as

$$\frac{dN_\gamma(E_\gamma)}{dE_\gamma} = k_\gamma \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\frac{E_\gamma}{E_{cut,\gamma}}\right) \tag{2}$$

Table 1
Best-fit values for MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41, as reported in Refs. [11,12] from the ARGO-YBJ and the Milagro experiments. For the MGRO J2031+41 source, we report the values for a power law fit (a) and a power law with cut-off fit (b).

Source	K [$\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$]	$E_{norm,i}$ [TeV]	$\alpha_{\gamma,i}$	$E_{cut,\gamma,i}$ [TeV]
MGRO J2019+37	$7^{+5}_{-2} \times 10^{-14}$	10	$2.0^{+0.5}_{-1.0}$	29^{+50}_{-16}
MGRO J1908+06	$6.1^{+1.4}_{-1.4} \times 10^{-13}$	4	$2.54^{+0.36}_{-0.36}$	–
MGRO J2031+ 41$^{(a)}$	$2.1^{+0.6}_{-0.6} \times 10^{-14}$	10	$3.22^{+0.23}_{-0.18}$	–
MGRO J2031+41$^{(b)}$	$5^{+157}_{-3} \times 10^{-14}$	10	$2.7^{+0.7}_{-3.3}$	$21^{+\infty}_{-18}$