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A Galactic Halo Origin of the Neutrinos Detected by IceCube

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Abstract

Recent IceCube results suggest that the first detection of very high energy astrophysical neutrinos have been accomplished. We consider these results at face value in a Galactic origin context. An outflow emission scenario from both the Fermi bubble and broader halo region are considered. We motivate that such an intensity of diffuse neutrino emission could be Galactic in origin if it is produced by cosmic ray transport via a Galactic outflow into the halo region. This scenario requires cosmic ray transport within the outflow/halo environment to be different to that inferred locally within the disk and that activity in the central part of the Galaxy accelerates cosmic rays to trans-"knee" energies before they escape into an outflow. The presence of a large reservoir of gas in a very extended halo around the Galaxy, recently inferred from X–ray observations, implies that relatively modest acceleration power of 10^{39} erg s^{-1} in PeV energy cosmic rays may be sufficient to explain the observed neutrino flux. Such a luminosity is compatible with that required to explain the observed intensity of cosmic rays around the "knee".

Keywords:

1. Introduction

The recently reported detection of 28 neutrinos with energies in excess of $\approx$ 30 TeV, on an expected background of $10.6^{+5.0}_{-3.6}$ events, by the IceCube collaboration is strongly suggestive that the age of very high energy (VHE) neutrino astronomy has begun. A purely atmospheric origin for the detected events has thus been rejected at the 4 σ level [1, 2]. Data have been accumulated from some 662 days of observation of the full sky. Furthermore, although limited in statistics, the neutrino distribution indicates a broadly isotropic distribution of arrival directions of these neutrinos [2, 3].

Such an excess of events corresponds to a diffuse energy flux of neutrinos in the energy interval 0.1-1 PeV, for all three flavours, at the level:

$$E_\nu^2 \frac{dN}{dE_\nu} \approx 30 \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (1)$$

with a spectral slope which is estimated to be close to flat (i.e. $\alpha \approx 2$ for $dN/dE_\nu \propto E_\nu^{-\alpha}$) in this representation.

The size of this energy flux is of primary concern in the following discussion. This energy flux amounts to a little over 10 Crab, which in terms of both Galactic and extragalactic γ-ray energy fluxes is considered bright. It is therefore worth bearing in mind that we might consider ourselves somewhat both fortunate and surprised that such large astrophysical flux exists.

The origin of the neutrinos detected by IceCube presently remains unknown. Both Galactic [3, 4, 5] and extragalactic [6, 7] scenarios of their production have been proposed, with a tendency to disfavor Galactic models other than those involving a connection with the Fermi bubble structures. These structures, whose existence were only recently disclosed both in γ-rays and radio [8, 9], extend well outside the Galactic plane region and may well house a significant population of cosmic ray (CR) particles.

Generally, two classes of scenarios can be envisaged in an attempt to explain the apparently isotropic neutrino flux detected by IceCube. The observed flux level (Eq. 1) might either result from the superposition of discrete sources or be truly diffuse on some scale. Indeed, insight into the problems facing the origin of this emission may be obtained through the consideration specifically of one of these scenarios.

Assuming that some fraction of the neutrino flux is not actually diffuse on the largest scales, originating instead from the Galactic plane region, an indication of the expected neutrino detection rate can be derived from the γ-ray emission flux from this region, some $\Omega_d \sim 0.1$ sr in size. The level of very high energy γ-rays allowed from the Galactic plane, as was considered in [10], the MILAGRO observations [11] which partially covered this region provide a basis for determining its multi-TeV gamma-ray brightness. Using these observations to determine the corresponding neutrino flux brightness from the Galactic plane, the expected detection rate of neutrinos from the region can be determined. Specifically, the MILAGRO observations from this region, whose median photon energy was estimated to be 15 TeV, motivate a photon energy flux at the level,

$$E_\gamma F_\gamma^{\rm d} = \Omega_{\rm d} E_\gamma^2 \frac{dN}{dE_\gamma} \approx 70 \text{ eV cm}^{-2} \text{ s}^{-1}. \tag{2}$$

For the highly optimistic scenario in which the spectrum of parent protons continues with an E^{-2} spectral shape up to a cutoff energy of 30 PeV, the corresponding neutrino detection rate expected from the Galactic plane region is obtained by convolving the parent CR flux with the IceCube effective area. For the effective area, we adopt a monotonic function of the form

$$A_{\rm eff}^{\nu} \approx A_0 \left(\frac{E}{\rm TeV}\right)^{\gamma} e^{-(E_b/E)} \text{ m}^2. \tag{3}$$

with A_0 =1, 0.9, 0.4, γ =0.4, 0.4, 0.5, and E_b =117 TeV, 155 TeV, 170 TeV for ν_e, ν_μ, and ν_τ, respectively. This parameterisation is found to fit well, within an accuracy of $\sim$ 20%, the published all–sky effective area for the three different neutrino species shown in fig. 7 of [2]. Thus, overall, a total of $\sim$1 event per year is predicted from the Galactic plane region, with >30 TeV energy neutrinos dominating the contribution to this rate.

More generally, as shown in [10, 12], this result demonstrates a simple but nevertheless robust rule–of–the–thumb: a neutrino flux at the level corresponding in γ-rays to 1 Crab (i.e. $F_\gamma(> 1 \text{ TeV}) > 10^{-11} \nu \text{ cm}^{-2} \text{ s}^{-1}$) yields a detection rate of about 1 neutrino per flavor per year in a detector whose size is one cubic kilometer. For typical spectra of astrophysical sources, the count rate is dominated by $\approx$ 10 TeV neutrinos, and decreases at larger energies. This implies that a quite large number of discrete neutrino sources with fluxes at the Crab level (or, equivalently, an unreasonably large number of significantly weaker sources) are required to explain IceCube data. If neutrinos are produced through inelastic proton–proton interactions, a γ-ray flux of the same order of magnitude is also expected from such sources. Thus, the scarce number of very high energy γ-ray sources detected by current instruments at the Crab flux level seems to rule out this possibility. In the same context, a detailed investigation has been recently performed to assess the possible contribution to the neutrino flux from unidentified TeV sources in our Galaxy [13] and the results from this study are in line with the simple considerations made above.

It is here argued that a Galactic origin of these neutrinos remains a viable option if one assumes that they are produced in the Galactic halo. This model assumes that the neutrinos result from PeV CR interactions, after their escape from the Galactic disk, with the diffuse ambient gas of non-negligible density present. For a more detailed description of this model see [14].

2. Galactic Outflow Emission

If diffuse on larger angular scales than the Galactic plane, the detection of surprisingly bright neutrino emission at PeV energies can have important implications with regards their Galactic ejection and escape at multi-PeV energies. Indeed, in the following section we consider a departure from the constant intensity assumption for CR throughout the Galaxy, with Galactic activity from/near the central region, either the central blackhole itself [15] or that from a nearby central starburst region [16], powering fast CR acceleration and advection into the Galactic halo region. It is worth highlighting that CR which enter an advective flow are not expected to return to the disk region, and therefore, with regards spallation constraints on their propagation time, can be considered to have effectively escaped [17].

Fermi Bubbles: recent ejection from the Galactic center in the last few Myr into the Fermi bubble region may have deposited a fresh population of CR which have not had time to diffusively escape from the region. Such a scenario apparently fits in with recent dynamic modelling of the Fermi bubble structures [18].

With constraints on the possible multi-TeV γ-ray flux from this region being placed by extrapolations from Fermi satellite measurements, an optimistic estimate of the number of neutrinos expected from the Fermi bubble regions may be obtained.

Adopting an energy flux of 100 GeV γ-rays from the Fermi bubble regions at a level of $E_\gamma^2 \frac{dN}{dE_\gamma} \approx$ 300 eV cm^{-2} s^{-1} sr^{-1}, and accounting for their larger angular size with $\Omega_{\rm FB}/\Omega_{\rm d} \approx 8$, the results for the Galactic plane region can be scaled up by a factor of 4 to obtain the expected rates from these regions. Thus, potentially a rate of ∼6 events per year would be expected to arrive from these regions at energies > 30 TeV, in agreement with similar calculations by others [19, 5].

Using the above result, an optimistic estimation for the neutrino luminosity from the Fermi bubble regions is, $L_\nu = 3\times10^{36}$ erg s^{-1}. However, the long pp cooling time in the region well outside the Galactic plane, for which we adopt $n_p = 10^{-2}$ cm^{-3}, and large scale height of 10 kpc, result in an energy transfer efficiency of CR power into neutrinos, with $t_{\rm esc}/t_{pp} = (3\times10^7)/(4\times10^9) = 0.008$. Thus, overall, a proton luminosity with a value of $L_p \approx 10^{39}$ erg s^{-1} is required. Such a luminosity, though large, is comparable to that required by hadronic origin scenarios used to explain the existence of Fermi Bubble regions at GeV energies [20].

Galactic Halo: beyond the Fermi bubbles, the diffuse γ-ray background [21] sits at a level of only a factor of a few lower than the Fermi bubble emission flux, and appears isotropic. The origin of this emission remains unclear. Furthermore, a dominant component of Fermi bubble emission beyond the observed boundaries, with a weaker observed brightness, would be swamped by this background.

With regards a target for pp collisions within the halo, recent new observational evidence now suggests that the "missing baryons problem" may be solved by the presence of a dominant component of baryons in the halo [22]. These baryons may provide an important target for Galactic CR in the halo. Assuming $10^{11}\ M_\odot$ of baryonic material exists within the halo and is contained within 100 kpc, a mean density of $\bar{n}_p = 10^{-3}$ cm^{-3} is expected.

With the level of the diffuse flux being dictated by the target material distribution, we adopt a profile of the form

$$r\frac{dN}{dr} \propto \left(\frac{1.0}{1.0+(r/r_0)}\right)^{\beta}. \quad (4)$$

The observed brightness from CR interactions with such a distribution is dictated by the column depth of material along different lines of sight convolved with the radial distribution of the CR. Adopting an r^{-1} CR distribution for the region $r < r_0$, a flat surface brightness would be expected for the case of a conical outflow, with the decrease in CR flux being compensated by the increase in column depth with distance (ie. r) from the Galactic center. Beyond r_0, the observed brightness would be expected to decrease. With regards the total emission from shells for this set-up, however, this would be expected to increase for shells out to r_0, with emission from larger shell radii plateauing due to the emitting volume growing with r^2. It should therefore be borne in mind that the Fermi bubbles may be only the tip of an iceberg whose true size has yet to be revealed due to the current limits in sensitivity. Indeed, recent analysis suggesting an energy dependence of the bubble morphology [23] lends credence to the idea that the present bubble boundaries are dictated by instrument sensitivity.

Assuming that the origin of the full observed neutrino flux comes from a region with average distance $d_s \approx$ 100 kpc away, the observed energy flux translates into a source luminosity of

$$L_\nu = 4\pi d_s^2 E_\nu F_\nu = 8\times10^{38}\ \text{erg s}^{-1}. \quad (5)$$

Furthermore, provided that $t_{pp} < t_{\rm esc}$, the target can act as an energy dump and the observed neutrino flux spectral shape will reflect that output by the source. Thus, for $K_\nu \approx 0.5$, a comparable level efficiency factor is also expected, and the corresponding CR luminosity required to power the system is $L_{\rm CR} \approx 10^{39}$ erg s^{-1}. This value is comparable to estimations of the CR source power required to support the CR population between the "knee" and "ankle" regions [24]. Indeed, the suggestion of a single source of this magnitude powering the CR population above the "knee" was made previously in [25].

3. Future Detection

At an energy of ∼1 PeV, the diffuse CR energy flux sits at a level of, $E_{\rm CR}^2 dN/dE_{\rm CR} \approx 2\times10^5$ eV cm^{-2} s^{-1}sr^{-1}. Assuming that the γ-ray flux associated with the diffuse neutrino flux is diffuse on the largest scales, it is expected to be at a level of $E_\gamma^2 dN/dE_\gamma \approx 30$ eV cm^{-2} s^{-1}sr^{-1}, the photon fraction level of diffuse high energy radiation at PeV energies is therefore $\gamma/p \sim 10^{-4}$. At lower energies, this ratio decreases even further due to the rapid growth in the CR energy flux. The search for the presence of a γ-ray component in CR air-shower experiments via their muon-poor signature presently places a constraint on a diffuse PeV γ-ray flux approximately at this level [26, 27]. Future searches for this component by IceTop and IceCube collectively are expected to allow a more sensitive probe of this component [28].

With regards dedicated γ-ray observatories, in the near future the HAWC detector will provide a promising probe for the diffuse scenario, with a capability to detect Crab level diffuse fluxes ($F_\gamma(>1$ TeV$) > 10^{-11}\gamma$ cm^{-2} s^{-1}) from regions less than ∼15° in size

[29]. Cherenkov telescope experiments such as HESS also have the possibility to probe a diffuse background component through their studies of electromagnetic air showers [30]. Though unable to discern between electrons and photons, at multi-TeV energies, the cooling times of the electrons are extremely short, which severely limits their diffusive propagation distance. For this reason, at multi-TeV energies, electrons from nearby sources are not expected to be detected at Earth, and thus the electromagnetic showers seen by HESS are most likely photons. With regards a detection of diffuse fluxes, at energies beyond ~20 TeV, the presence of a diffuse electromagnetic background at the level detected by IceCube should be within reach. Although the fluxes at such energies may not be feasibly detected with present generation instruments, next generation instruments such as CTA may well offer sufficiently sensitivity. In this same vein of next generation instruments, LHAASO [31] also hold great potential for probing diffuse Galactic scenarios even further. Thus, presently, several promising methods exist for discerning the origin of the neutrinos, providing complementary additional information for future arrival directions studies.

4. Conclusion

An investigation of possible Galactic origin scenarios to explain the observation of multi-TeV to PeV neutrinos reported by IceCube is carried out. On dimensional grounds, the Galactic halo is motivated to be a potentially significant source of high energy neutrinos provided that sufficient target material exists out at these large radii.

Consideration of constraints from diffuse γ-ray flux measurements from the Fermi bubble region by the Fermi satellite, even with extreme extrapolations into the multi-TeV domain, are demonstrated to yield an insufficient neutrino flux to account for the excess of neutrinos observed. An origin of the emission from the more extended Galactic halo region, however, cannot be ruled out and may have a physical basis if the neutrino emission is connected to an advected CR population. Such a scenario would justify the violation of the uniform CR hypothesis usually adopted.

Future detection of diffuse γ-rays from the Galactic halo highlighted as a means of testing such a Galactic halo hypothesis.

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