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Multi-messenger aspects of cosmic neutrinos*

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Abstract. The recent observation of TeV-PeV neutrinos by IceCube has opened a new window to the high-energy Universe. I will discuss this signal in the context of multi-messenger astronomy. For extragalactic source scenarios the corresponding gamma-rays are not directly observable due to interactions with the cosmic radiation backgrounds. Nevertheless, the isotropic sub-TeV gamma ray background observed by *Fermi*-LAT contains indirect information from secondary emission produced in electromagnetic cascades. On the other hand, observation of PeV gamma rays would provide a smoking-gun signal for Galactic emission. Interestingly, the overall energy density of the observed neutrino flux is close to a theoretical limit for neutrino production in ultra-high energy cosmic ray sources and might indicate a common origin of these phenomena. I will highlight various multi-messenger relations and their implications for neutrino source scenarios.

1. Introduction

The recent discovery of cosmic TeV-PeV neutrinos by the IceCube observatory [2–5] has added an important new pillar to high-energy multi-messenger astronomy. Neutrino emission corresponds to a unique probe of the high-energy Universe. Unlike cosmic rays (CRs), neutrinos are not deflected in cosmic magnetic fields over their long propagation distances and unlike gamma-rays they are not absorbed by pair production via $\gamma\gamma$ interactions with radiation in the source or cosmic radiation backgrounds. In the rather wide energy range from about 10 TeV to 10 EeV neutrinos are thus the only pointing probes that can cover cosmic distances.

The origin of the high-energy neutrino flux is presently unknown. Possible Galactic contributions to super-TeV neutrinos are the diffuse neutrino emission of galactic CRs, the joint emission of galactic PeV sources, and extended galactic structures like the *Fermi Bubbles* or the Galactic halo. Extragalactic source candidates include galaxies with intense star formation, cores of active galactic nuclei (AGN), low-luminosity AGN, blazars, low-power GRBs, cannonball GRBs, intergalactic shocks, and active galaxies embedded in structured regions. We refer to the recent review [6] for a list of references.

High-energy astrophysical neutrinos are expected to be produced by hadronic interactions of high energy CR nucleons with gas ("pp") and radiation ("$p\gamma$"). The individual mesons (mostly pions) produced in these interactions typically carry 20% of the initial CR nucleon energy and produce a high-energy flux of neutrinos via their decay $\pi^+ \to \mu^+\nu_\mu$ followed by $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, and the charge-conjugate processes. In this decay chain each neutrino receives on average 1/4th of the initial pion

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energy. The initial ratio of the three neutrino flavors, $\nu_e : \nu_\mu : \nu_\tau \simeq 1 : 2 : 0$, is then expected to be visible via their oscillation-averaged composition, approximately $\nu_e : \nu_\mu : \nu_\tau \simeq 1 : 1 : 1$. Neutral pions produced in the same hadronic CR interactions are expected to produce a high-energy gamma-rays via the decay $\pi^0 \to 2\gamma$.

The production of high-energy neutrinos is thus intrinsically tied to the presence of CRs and the associated emission of gamma-rays from neutral pion production. In the following sections we will discuss multi-messenger relations between cosmic rays, gamma rays and neutrinos and highlight the implications for various neutrino emission models and future tests.

2. Neutrinos and Cosmic Rays

Hadronic interactions of CRs with gas (pp) or radiation ($p\gamma$) produce a flux of neutrinos with an energy of about 5% of the initial CR nucleon. Hence, the CRs responsible for the observed neutrino flux have corresponding energies reaching 20 PeV (proton) to 1 EeV (iron) depending on composition. This composition-dependent energy range is above the CR "knee" around 3 PeV and the "ankle" around 3 EeV. This region is expected to be the transition region of the spectrum between low-energy Galactic and high-energy extragalactic CRs. It is hence not entirely clear from an energetics point of view if Galactic or extragalactic sources are responsible for the neutrino flux.

Interestingly, the overall energy density of the observed neutrino flux is close to a theoretical limit for neutrino production in the sources of ultra-high energy (UHE) CRs [7]. The neutrino and CR nucleon (N) emission rates Q (in units of $\mathrm{GeV}^{-1}\mathrm{s}^{-1}$) are related via

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{1}{4}\frac{f_\pi K_\pi}{1+K_\pi} E_N^2 Q_N(E_N)\,, \tag{1}$$

where $f_\pi \leq 1$ is the pion production efficiency in hadronic interaction and neutrino and CR nucleon energy are related as $E_\nu \simeq 0.05 E_N$. The factor K_π corresponds to the ratio of charged to neutral pions, which can be approximated as $K_\pi \simeq 2$ for pp and $K_\pi \simeq 1$ for $p\gamma$ interactions.

After production in hadronic interactions the flux of neutrinos is not further affected by absorption mechanisms and only subject to redshift losses. In the following we assume a flat universe dominated by vacuum energy with $\Omega_\Lambda \simeq 0.7$ and cold dark matter with $\Omega_\mathrm{m} \simeq 0.3$ [8]. The Hubble parameter at earlier times is then given by its value today of $H_0 \simeq 70$ km s^{-1} Mpc^{-1} and the relation $H^2(z) = H_0^2\,(\Omega_\Lambda + \Omega_\mathrm{m}(1+z)^3)$. The observable diffuse neutrino flux from a homogeneous distribution of extragalactic sources with co-moving density $\mathcal{H}(z)$ can then be readily estimated as (see, e.g. Ref. [9]

$$\phi_\nu(E_\nu) = \frac{1}{4\pi}\int_0^\infty \frac{\mathrm{d}z}{H(z)}\mathcal{H}(z) Q_\nu((1+z)E)\,. \tag{2}$$

The local emission rate density of UHE CRs depend on spectrum and composition. For an E^{-2} flux of protons it can be estimated as $E_p^2 Q_p(E_p)\mathcal{H}(0) \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ [9]. Hence, using Eq. (2) the diffuse neutrino flux can be estimated as

$$E_\nu^2 \phi_\nu(E_\nu) \simeq \frac{\xi_z f_\pi K_\pi}{1+K_\pi}(2-4)\times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}\,, \tag{3}$$

where we define the evolution factor (assuming constant f_π)

$$\xi_z = \int_0^\infty \mathrm{d}z \frac{(1+z)^{-\Gamma}}{\sqrt{\Omega_\Lambda + (1+z)^3\Omega_\mathrm{m}}}\frac{\mathcal{H}(z)}{\mathcal{H}(0)}\,. \tag{4}$$

For a spectral index $\Gamma = 2$ and no source evolution ($\mathcal{H}(z) = \mathcal{H}(0)$) this evolution factor is $\xi_z \simeq 0.5$, whereas evolution following the star-formation rate [10, 11] gives $\xi_z \simeq 2.4$.

Since the pion production efficiency is limited, $f_\pi \leq 1$, the estimate (3) provides a theoretical upper limit on neutrino production, the *Waxman-Bahcall* (WB) bound [7] (see also Ref. [12]). It is intriguing that the observed flux [2–5] is very close to this upper limit. This might be just by chance, or it could indicate a deeper multi-messenger relation. It is important to keep in mind that the observed neutrino flux does not directly relate to UHE CRs with energies above EeV and for proton-dominated scenarios that we assumed in the previous estimate an extrapolation over two orders of magnitude is required.

Neutrino fluxes close to the WB bound would require very efficient CR production with optical thickness $\tau_{p\gamma/pp} \gg 1$, such that $f_\pi \simeq 1$, i.e. CR reservoirs [13] such as starburst galaxies [14, 15] or clusters of galaxies [16–18]. Interestingly, the energy density of Galactic CRs require a similar energy density. Assuming that 1% of the kinetic energy of 10^{51} erg of a supernova (SN) explosion is converted to CRs and assuming normal galaxies with densities $\mathcal{H}_0 \simeq 10^{-3}\mathrm{Mpc}^{-3}$ and a SN rate of 10^{-2} yr^{-1} we arrive at $E_p^2 Q_p(E_p) \simeq 10^{44}\,\mathrm{erg\,Mpc}^{-3}\,\mathrm{yr}^{-1}$. This coincidence together with the saturation of the WB bound has let to speculations that Galactic and extragalactic CRs might be produced in the same transient sources [13].

If the sources of UHE CRs are responsible for the neutrino emission it might be possible to cross-correlate these events [19]. The strong interaction of UHE CRs with the cosmic microwave background (CMB) limit the survival length to 200 Mpc above the Greisen-Zatsepin-Kuzmin [20, 21] (GZK) cutoff at around 50 EeV. UHE CR sources that appear at larger distance will still be visible by their neutrino emission, but not in UHE CRs. We can make a simple estimate what fraction of neutrinos would be expected to correlate with the local population of UHE CRs which can be sampled by the observed UHE CR arrival direction: The Hubble horizon at about 4.4 Gpc is about 20 times larger than the GZK horizon. That means that we only expect that about one neutrino out of 20 should correlate with local sources. In comparison, the most recent event sample of the high-energy starting event (HESE) analysis [5] comprises 53 events with a signal-to-background ratio close to 1. Hence, we expect only 1-2 of these events to correlate to local UHE CR sources and thus with the arrival direction of observed UHE CR events. This estimate is consistent with the absence of strong cross-correlations in a dedicated analysis of this data [19].

3. Neutrinos and gamma-rays

Hadronic interactions of CRs will not only produce charged pions that on decay release a flux of high-energy neutrinos, but also neutral pions that decay via $\pi^0 \to 2\gamma$. The production rates are simply related by

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4} E_\gamma^2 Q_\gamma(E_\gamma)\,, \tag{5}$$

where the gamma-ray and neutrino energies are related as $E_\gamma \simeq 2E_\nu$. This relation does not depend on the pion production efficiency and thus the gamma-to-neutrino multi-messenger relation is less affected by the mechanisms that lead to the initial production of pions, except for the relative charged-to-neutral pion rate K_π already introduced earlier.

However, the production rate described by Eq. (5) is not necessarily the emission rate of the sources. In particular, sources that efficiently produce neutrinos via $p\gamma$ interactions require a strong photon target spectrum. The gamma-rays produced via neutral pion decay can in this case undergo e^+e^- pair production before they escape. These leptons can scatter with the same background photons via inverse-Compton scattering or emit synchrotron emission in magnetic fields. The electromagnetic emission initiated by hadronic interactions might thus look much different from the initial production spectrum (5), although the total energy is conserved.

The situation is less complicated for optically thin sources, in particular those sources that are dominated by pp interactions. In this case the gamma-rays described by Eq. (5) are expected to correspond to the source emission spectrum. The pion production efficiency via *pp* interactions does only weakly depend on the CR energy and the neutrino and gamma-ray spectra are expected to follow the (time-integrated) CR spectrum, cf. Eq. (1), typically a broken power-law up to a maximal energy limited by the CR source type.

However, once released from distant sources it is inevitable that high-energy gamma rays interact with cosmic radiation backgrounds, in particular the CMB. The pair production interaction length of PeV gamma rays in the CMB is of the order of 10 kpc, which makes it impossible to observe this emission over extragalactic distances. However, pair production and subsequent inverse-Compton scattering of the high energy leptons will lead to electromagnetic cascades that shift the initial radiation into the sub-TeV gamma-ray band and supplement the direct sub-TeV emission of the source. The observed gamma-ray background in this energy region provides hence a general upper limit on the diffuse hadronic emission [22], which also applies to the production of cosmogenic neutrinos produced via the GZK interaction [23–26].

These general considerations allow to constrain various extragalactic source scenarios of the TeV-PeV neutrino flux. As discussed earlier, hadronic γ-ray and neutrino emission produced in *pp* sources, e.g., in starburst galaxies [14] is expected to follow the parent CR spectrum and can thus be extrapolated as a power-law to lower energies. It was shown in Ref. [27] that an unbroken power-law emission with a spectral index much softer than $\Gamma \simeq 2.2$ would be inconsistent with the isotropic diffuse gamma-ray background (IGRB) inferred by *Fermi* [28]. This places some tension on *pp* scenarios since the best-fit power-law index of the TeV-PeV neutrino data is significantly softer, $\Gamma \simeq 2.50 \pm 0.09$ [4].

Moreover, the total extra-galactic gamma-ray background (EGB) above 50 GeV is expected to be largely dominated by the emission of AGN (see, e.g., Ref. [29]). In a recent analysis of pixel-by-pixel photon count statistics [30] it was estimated that blazars comprise about $86^{+16}_{-14}\%$ of the total EGB intensity. This places even stronger bounds on *pp* scenarios that are expected not to coincide with AGN [31]. Recently, it was argued that limits derived from the cross-correlation of *Fermi* gamma-rays with galaxy catalogues exclude the *pp* scenarios with soft emission and weak redshift evolution [32]. Other electromagnetic emission bands can also become important in constraining *pp* emission scenarios, for instance radio emission of galaxy clusters [18].

The situation for $p\gamma$ scenarios is somewhat different. Firstly, the production spectrum of gamma-rays and neutrinos are obtained via a folding of the initial CR spectrum and the photon target spectrum. For typical target spectra present in astrophysical sources these emission spectra are not well described as power laws. Hence, from the spectral fit of the IceCube data in the TeV-PeV range we can not make a simple extrapolation towards lower energies. However, even the cascade emission associated with gamma rays emitted in the TeV-PeV is already at a level of 10% in the 0.1–1 TeV gamma-ray range. Thus, a careful decomposition of the IGRB into contributions of known populations can also constrain this emission scenario.

However, the presence of strong photon target fields in $p\gamma$ sources is also expected to enhance the gamma-ray opacity with respect to pair production. In fact, a high pion production efficiency of more than 0.01, which can be motivated by the high neutrino intensity at around 10 TeV [33], implies that $p\gamma$ sources are opaque to 1–100 GeV gamma rays. Depending on the low energy tail of the photon target spectrum this opacity can also extend into the TeV-PeV gamma-ray region and hence these sources would not be constrained by either direct observation by *Fermi* or indirect emission in the IGRB. Neutrinos could be the unique messenger of high-energy processes for these sources.

The arguments in the previous paragraphs focused on the emission of gamma-rays from extragalactic sources, which are strongly attenuated by the cosmic radiation backgrounds. However, with the limited angular resolution and statistics of the neutrino observation it is possible that extended emission from Galactic sources can contribute to the data (see, e.g., the study [34]). These emission includes the diffuse gamma-ray emission of the Galactic Plane [35], quasi-diffuse emission from the sum of Galactic sources, or extended emission from *Fermi Bubbles* [36, 37] or Galactic halo [38]. Exotic contributions like decaying heavy dark matter could also produce an extended emission in gamma-rays and neutrinos (see the recent review [6] for a list of references).

The observation of PeV gamma-rays with an attenuation length of about 10 kpc via pair production with CMB photons would be a *smoking gun* for this Galactic production [39, 40]. Various CR observatories already provide strong TeV-PeV gamma-ray limits, in particular KASCADE-Grande [41]. Studies of the isotropic diffuse high-energy gamma-ray emission in the near future with the HAWC observatory [42] and the far future with the air shower arrays LHAASO [43] or HiSCORE [44] can greatly improve the present limits. However, all these experiments are located in the Northern Hemisphere and have only a limited view of the Galactic Center region or the *Fermi Bubbles*.

4. Conclusions

The recent observation of TeV-PeV neutrinos has added an important new pillar to multi-messenger astronomy. Presently, the observed neutrino events have limited angular resolution and statistics and the underlying source population remains elusive, see e.g. Ref. [45]. However, multi-messenger relations between cosmic rays and gamma rays can already provide hints and constraints for possible source scenarios.

Presently, one particularly puzzling observation is the particularly high intensity of the IceCube observation in the (10–100) TeV range, which is indicated by a recent combined data analysis [4]. The underlying source population is required to have a high CR luminosity and pion-production efficiency while at the same time it has to avoid strong limits implied by the observed level of the extragalactic gamma-ray background seen by *Fermi*.

The continued observation of the neutrino flux with IceCube will help to identify possible substructures in the spectrum that provide indirect evidence of the source emission type. An improved study of neutrino flavor composition will provide an important test of astrophysical neutrino emission and atmospheric background models. Subdominant contributions from Galactic emission could become evident by the manifestation of anisotropies or the detection of hadronic PeV gamma-ray emission.

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