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VLBI as a key to neutrino production in blazars

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Abstract

Observational information on high-energy astrophysical neutrinos is being continuously collected by the IceCube observatory. However, their sources were still unknown until recently. We adress the problem of the astrophysical neutrinos' origin in a statistical manner. It is found that AGNs positionally associated with IceCube events have stronger VLBI cores than the rest of the sample. This result is significant with the probability of a chance coincidence of $4 \cdot 10^{-5}$ (4.1σ). We select five strong blazars as highly probable associations for neutrinos above 200 TeV: 3C 279, NRAO 530, TXS 1308+326, PKS 1741-038, and PKS 2145+067. There are at least 70 more bright AGNs that emit neutrinos of lower energies starting from TeVs. Moreover, we find radio flares at frequencies above 10 GHz around neutrino arrival times for several VLBI-selected AGNs on the basis of RATAN-600 monitoring. The most pronounced example of such behavior is PKS 1502+106. We conclude that AGNs with bright Doppler-boosted jets may explain the entire IceCube astrophysical neutrino flux as derived from muon-track analyses. High-energy neutrinos can be produced in parsec-scale AGN jets in interactions of relativistic protons with self-Compton photons, or photons emitted close to the accretion disk. Radio-bright blazars associated with neutrinos have very diverse gamma-ray properties suggesting that gamma-rays and neutrinos may be produced in different regions of AGN and not directly related. A small jet viewing angle is, however, required to detect either of them.

1 Introduction

Extraterrestrial neutrinos with TeV and higher energies have been convincingly observed by the IceCube experiment since 2012. Indications to the astrophysical high-energy neutrino flux were also found by the ANTARES and Baikal–GVD (Gigaton Volume Detector) experiments. Despite these observations, the origin of energetic astrophysical neutrinos remains unknown. Since the arrival directions of the neutrinos do not demonstrate any significant Galactic anisotropy, their origin in extragalactic sources is often assumed. Active galactic nuclei (AGN) were discussed as potential neutrino emitters long before the neutrino detection. Further interest in this class of sources was sparked by the observation of a γ-ray flare of the blazar TXS 0506+056 in a directional and, to a certain precision, temporal coincidence with the neutrino event 170922A detected by IceCube. This event was supplemented by an excess of lower-energy neutrinos from the same direction found in the archival data.

The aim of this work is to present direct observational evidence that blazars are a major origin of astrophysical neutrinos. Furthermore, we are able to distinguish between central parsecs and outer parts of active galaxies with the help of very-long-baseline interferometric (VLBI) radio observations.

2 Correlation of Neutrino Detections and Blazars

We analyze a set of 57 published IceCube events with neutrino energies above 200 TeV directional errors less than 10 deg^2. It is found that AGNs directionally coincident with neutrino events within statistical and systematic errors have, on average, higher historic VLBI flux density compared to other AGNs in the all-sky complete flux density-limited sample of 3388 sources [1]. We estimate the significance of this correlation by Monte-Carlo simulations and find the probability to observe the excess as a random fluctuation to be $7 \cdot 10^{-4}$. This includes a correction for multiple trials related to the unknown value of the IceCube systematic error in arrival directions. The five particular brightest sources that dominate the observed correlation are 3C 279, NRAO 530, TXS 1308+326, PKS 1741−038, and PKS 2145+067.

We additionally analyze information about IceCube muon-track events from 2008-2015 with energies from a fraction of a TeV to a few PeVs. The corresponding dataset was made available in 2020 and is shown in Figure 1. This allows us to demonstrate that the neutrino-blazar association holds for the entire high-energy spectrum, both above and below 200 TeV [2]. The combined post-trial significance of directional correlations found in these two independent analyses, at lower and higher energies, corresponds

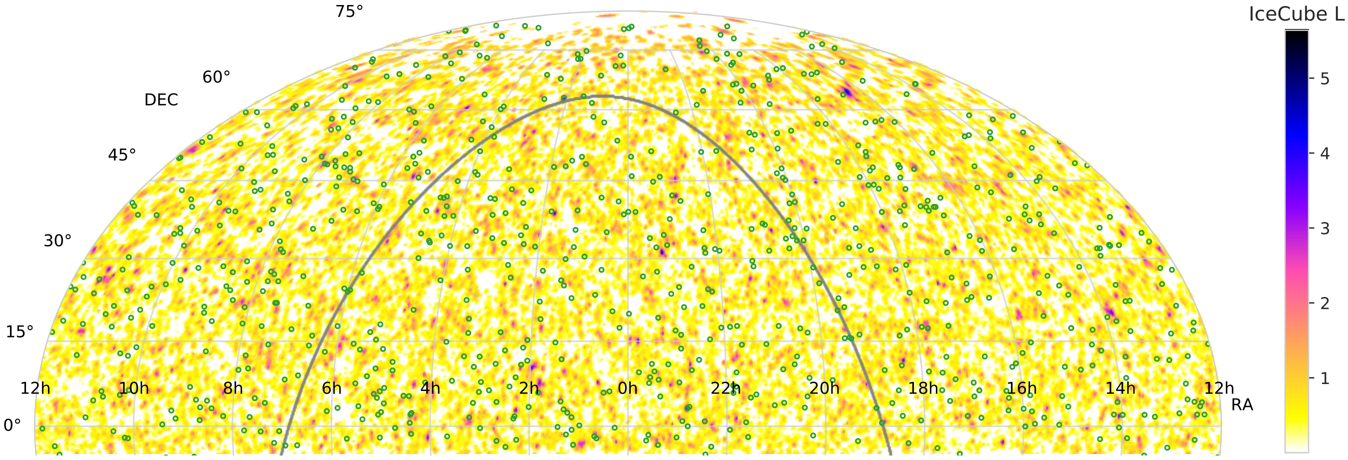

Figure 1. Sky map in equatorial coordinates of the IceCube local likelihood logarithms denoted here as L. Darker areas with larger L indicate higher probabilities to have an astrophysical neutrino point source in this direction. All sky north of $\delta = -5°$ is displayed in equatorial coordinates. Radio AGNs from the complete 8 GHz VLBI sample down to the flux density of 0.33 Jy are shown as green circles. The grey line represents the Galactic plane.

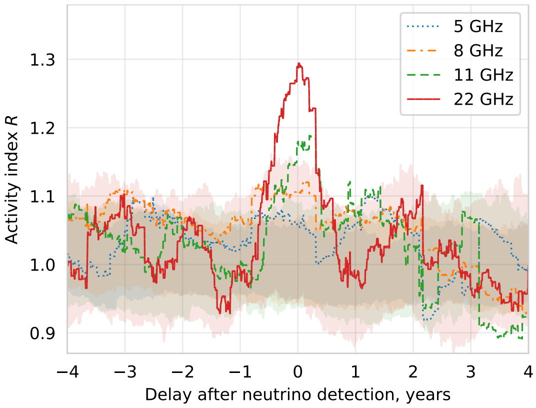

Figure 2. Ratio of RATAN-600 flux densities averaged over a 0.9 yr window to the average flux density outside it. Each point of the curve represents this ratio averaged across all AGNs inside neutrino error regions versus the time delay between a 0.9 yr window center and the corresponding IceCube event. Filled areas correspond to curves of the same color and indicate pointwise 68% intervals of Monte-Carlo realizations for randomly shifted neutrino event positions.

to a chance probability of $p = 4 \cdot 10^{-5}$ (4.1σ). Notably, the lower-energy associations were found on statistical and not on event-by-event grounds. It implies that the sources are numerous and most of them do not stand out individually in the seven-years IceCube sample. We expect that even in future studies with larger statistics, any analysis focused only on the brightest spots in the neutrino map would miss most of the sources. Many actual neutrino sources still remain outside of our flux-limited sample, including distant or less beamed blazars. Overall, we explain at least 1/4 of the astrophysical muon neutrino flux, as derived from IceCube track data, by the VLBI-selected blazars brighter than 0.15 Jy. This is consistent with the entire neutrino flux at these energies being produced in central parsecs of radio-bright blazars.

For the first time, our study invokes the statistical power of radio observations to the problem of high-energy neutrino origin. We estimate systematic errors of IceCube directions and account for them in the analysis. The found systematic errors on the level of 0.5–0.7 are compatible with the sparse published information. VLBI turns out to be the key to the high-energy neutrino associations.

Further, in [1] we use the data from the RATAN-600 total radio flux density monitoring of VLBI-selected AGN and demonstrate that periods of increased emission at frequencies above 10 GHz correlate with neutrino detections (Figure 2). This result remains significant even when the four sources singled out by the average historic VLBI-flux-density analysis are removed from the sample. This means that other fainter AGNs from the VLBI-selected sample are also neutrino emitters. In particular, the strongest flux density enhancement at the time of a neutrino event is observed for PKS 1502+106. This is a probable source of the 2019-07-30 IceCube event but is not among the five strongest objects discussed above.

3 Astrophysical Implications

Altogether, our results indicate that a major fraction of the observed astrophysical neutrinos from TeVs to PeVs are produced in central parsec-scale regions of radio-bright blazars. These potential neutrino sources are found to have γ-ray fluxes that differ by several orders of magnitude. This is expected if the neutrino production region is opaque to energetic γ-rays due to pair-production cascades.

The presence of the neutrino-blazar association at this wide range of energies puts strong constraints on our understanding of the neutrino production mechanism. In particular, high-energy target photons are required to produce observed neutrinos in $p\gamma$ interactions, which is the most probable channel of neutrino production in blazars. In radio-loud blazars, these target photons may be provided by the X-ray self-Compton radiation: it inevitably accompanies the synchrotron radiation of non-thermal electrons observed in the radio band from the parsec-scale jet. High-energy neutrino emission and gamma radiation may be, to an extent, independent and produced in different zones of the central parsecs in blazars. This explains the lack of association between gamma-ray loud blazars and IceCube neutrinos reported in numerous previous studies.

Future studies will help to verify and clarify the relation between radio blazars and high-energy neutrinos. The results of the present work can be tested with the full collected IceCube dataset. Since 2020, IceCube alerts are followed by immediate radio observations by VLBA and RATAN-600. Independently, a set of probable high-energy neutrino emitters is continuously monitored by the same instruments. In the nearest future, the study will be extended to Baikal-GVD neutrino candidate events. Further ahead, KM3NeT and PONE in neutrinos, eASTROGAM, AMEGO, and SRG in keV to GeV photons will supplement these studies with important multimessenger information.

This URSI GASS 2021 Summary Paper is prepared on the basis of our two publications [1, 2].

References

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