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Interferometric Monitoring of a Potential Neutrino-Emitting Blazar PKS 0735+178: a Connection between Neutrino Events and Radio Flares?

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Abstract. The blazar PKS 0735+178 is a promising candidate for emitting high-energy neutrinos through a relativistic jet. In early December 2021, multiple neutrino observatories, including IceCube, detected neutrino events with energies ranging from GeV to TeV in the direction of the source. Following these detections, multi-wavelength flares were observed, ranging from radio to gamma rays. However, the nature of the neutrinos remains uncertain. We conducted very long baseline interferometry (VLBI) follow-up observations of the blazar PKS 0735+178 with the Korean VLBI Network (KVN) simultaneously at 22, 43, 86, and 129 GHz from December 2021 to November 2023. Our observations revealed a core-dominated jet on milli-arcsecond scales, with core flux density continuously increasing across all KVN frequencies. We explored synchrotron self-absorption (SSA) spectral properties by calculating the turnover frequency and peak flux density. The turnover flux density increased over time, while the turnover frequency and spectral index showed no substantial change. This behavior suggests the formation of a shock in the jet associated with the IceCube neutrino event. The angular size of the SSA region aligns with expectations for equipartition conditions between the energy densities of the radiating particles and magnetic fields, suggesting near equipartition in source energy. Our magnetic field strength estimates imply that the leptonic process likely dominates over the hadronic process in the radio synchrotron emission.

1. Introduction

The initial discovery of neutrino flux at 30 TeV to PeV energies by the IceCube observatory marked the beginning of neutrino astronomy (IceCube Collaboration 2013), after the first detections of extraterrestrial neutrinos from the Sun and the supernova SN 1987A. The isotropic distribution of the observed neutrinos suggests that a significant fraction is of extragalactic origin (Ahlers et al. 2016). Despite many discoveries and studies, however, the nature of astrophysical neutrinos remains largely unknown.

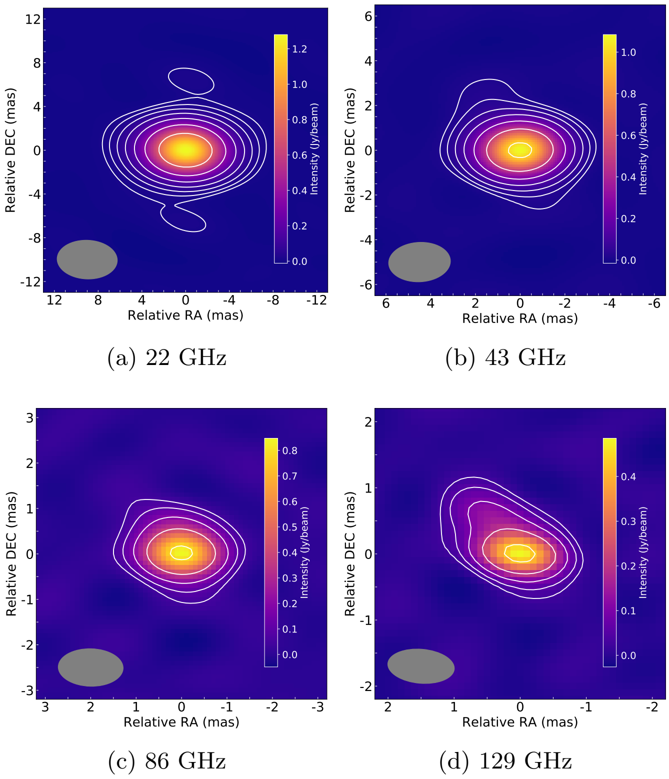
Blazars, a subclass of active galactic nuclei, are among the most promising sources of high-energy neutrinos. It was firstly reported that a neutrino event detected by the IceCube observatory in 2018 was spatially consistent with TXS 0506+056 (IceCube Collaboration et al. 2018). So far, numerous blazars have been suggested as potential neutrino candidates. Interestingly, these sources are radio-bright and detected via very long baseline interferometry (VLBI). This implies that relativistic jets from blazars may contribute crucially to the production of high-energy neutrinos (e.g., Plavin et al. 2023).

PKS 0735+178 is a blazar with a redshift of $z = 0.45 \pm 0.06$ (Nilsson et al. 2012). In early December 2021, multiple neutrino events were detected by the IceCube (IceCube Collaboration 2021), Baikal-GVD (Dzhilkibaev et al. 2021), Baksan (Petkov et al. 2021), and KM3NeT (Filippini et al. 2022) neutrino observatories, all spatially associated with the position of the source. The IceCube neutrino event (IceCube-211208A) was followed by multi-wavelength flares in the source, observed in the radio (Kadler et al. 2021), optical (Zhirkov et al. 2021), X-ray (Santander & Buson 2021), and gamma-ray (Garrappa et al. 2021) bands. The multi-wavelength flares have motivated various studies on the broadband spectral energy distribution (SED) of PKS 0735+178 using hadronic models (e.g., Sahakyan et al. 2023; Acharyya et al. 2023; Prince et al. 2024; Bharathan et al. 2024).

In this study, we present the results from a study on a physical connection between the IceCube neutrino event and radio flares from the jet of PKS 0735+178. We investigated the source spectra and properties of the magnetic field by using simultaneous multi-frequency radio observational data. Details about the observations, data reduction, and data acquisition are described in Sect. 2. Our main results are presented in Sect. 3. Conclusions and future works are given in Sect. 4.

2. Observations and data

PKS 0735+178 was observed with the KVN (PI: S. Kim) for 10 hours per epoch, from 2021/12/27 to 2023/11/19 (MJD 59575–60267). The observing frequencies are 21.244–22.268 GHz, 42.744–43.768 GHz, 85.744–86.768 GHz, and 128.744–129.768 GHz, in left-handed cir-



(a) 22 GHz (b) 43 GHz

(c) 86 GHz (d) 129 GHz

Fig. 1: Total intensity images of the jet in PKS 0735+178 observed at (a) 22 GHz, (b) 43 GHz, (c) 86 GHz, and (d) 129 GHz with the KVN on 2022/10/16. The beam size at the bottom-left corner in each image is 5.4 × 3.7 mas at 89 deg, 2.7 × 1.8 mas at -87 deg, 1.4 × 0.8 mas at 89 deg, and 1.0 × 0.5 mas at 85 deg, from (a) to (d), respectively. The lowest total intensity contours are 0.01, 0.03, 0.05, and 0.03 Jy beam^{-1}, with map peaks of 1.26, 1.06, 0.85, and 0.49 Jy beam^{-1}, from (a) to (d), respectively. The contours increase by a factor of two from the lowest total intensity.

cular polarization (LCP). KVN observations provide the longest baseline length of 478 km, corresponding to angular resolutions of 5.8, 3.0, 1.5, and 1.0 mas at 22, 43, 86, and 129 GHz, respectively (see Fig. 1). The KVN data were recorded with a total bandwidth of 512 MHz divided evenly for each frequency band, at a recording rate of 8 Gbps. Compact and bright sources of OJ 287 and 0420-014 were observed as calibrators.

The KVN data were correlated by the DiFX (Distributed FX; Deller et al. 2011) software correlator in Daejeon, Republic of Korea (Lee et al. 2014). For the post-correlation data calibration, we used a Python pipeline with the ParselTongue interface implemented in the NRAO Astronomical Image Processing System (AIPS; Greisen 2003), based on the KVN pipeline developed by Hodgson et al. (2016). We applied a frequency phase transfer (FPT) technique to 86/129 GHz data to improve the detections at these high frequencies by transferring phase solutions from lower to higher frequencies (Rioja & Dodson 2011; Algaba et al. 2015).

After the data calibration, we imaged the source using the CLEAN task in the interferometric imaging software DIFMAP (Shepherd 1997). Fig. 1 presents the total intensity images of PKS 0735+178 jet. We fitted circular two-dimensional Gaussian models to CLEAN images using the MODELFIT task in DIFMAP. The uncertainties of the Gaussian components were calculated following Jorstad et al. (2017).

To investigate the long-term variation in the KVN core flux density of PKS 0735+178 before and after IceCube-211208A, the KVN data were complemented by additional data from a KVN monitoring program, the Interferometric Monitoring of Gamma-ray Bright AGNs (iMOGABA; Lee et al. 2016), for 2013/01/16–2020/03/06 (MJD 56308–58914). We used the calibrated 43 GHz very long baseline array (VLBA) data for the source as part of the BEAM-ME monitoring program to obtain information about the core components (e.g., flux density and size) from 2021/12/14 to 2023/11/25 (MJD 59562–60273), with a total of 22 epochs (see Jorstad et al. 2017, for more in details). The gamma-ray data at 0.1–100 GeV were obtained from the Fermi-LAT Light Curve Repository (Abdollahi et al. 2023).

3. Results

Our VLBI imaging and model-fitting results using KVN data reveal that the jet of PKS 0735+178 is resolved on milli-arcsecond (mas) scales, with a bright and compact core at the upper end of the jet. The core size exceeds the minimum resolvable size (see Lobanov 2005, for the equation) in all epochs. The core flux density dominates the synchrotron emission on mas scales, comprising over 97% of the total CLEAN flux density at all frequencies. Our results indicate a compact core-dominated structure.

A multi-wavelength light curve analysis reveals a connection between the IceCube neutrino event and gamma-ray and radio flares in PKS 0735+178. Fig. 2 shows the gamma-ray and radio light curves of this source. We identified a temporal coincidence between IceCube-20211208A and a rapid gamma-ray flare peaking on 2021/12/17 (MJD 59566). Following the neutrino event, the core flux density increased (e.g., from 0.8 to 1.5 Jy at 22 GHz). The increase in both radio and gamma-ray flux densities provides strong observational evidence that PKS 0735+178 is a highly probable neutrino-emitting blazar.

We investigated the synchrotron spectrum of PKS 0735+178 using the KVN data. For this, a curved power-law model was applied to the data, with the form $S = S_{\rm m}\,(\nu/\nu_{\rm m})^{\alpha \ln(\nu/\nu_{\rm m})}$ (Algaba et al. 2018), where $\nu_{\rm m}$ is the turnover frequency in GHz, α is an optically thin spectral index (i.e., $\alpha < 0$) at $\nu > \nu_{\rm m}$, and $S_{\rm m}$ is the peak flux density at $\nu = \nu_{\rm m}$, in the unit of Jy. As seen in Fig. 3, our model recognizes curvature in the observed spectrum at lower frequencies (e.g., at $\nu < 40$ GHz), due to synchrotron self-absorption (SSA). In the time evolution of spectral parameters, the turnover flux density ($S_{\rm m}$) increased by a factor of four from ∼0.4 Jy to ∼1.5 Jy. This behavior suggests the formation of a new shock in the jet, consistent with the shock-in-jet model, where

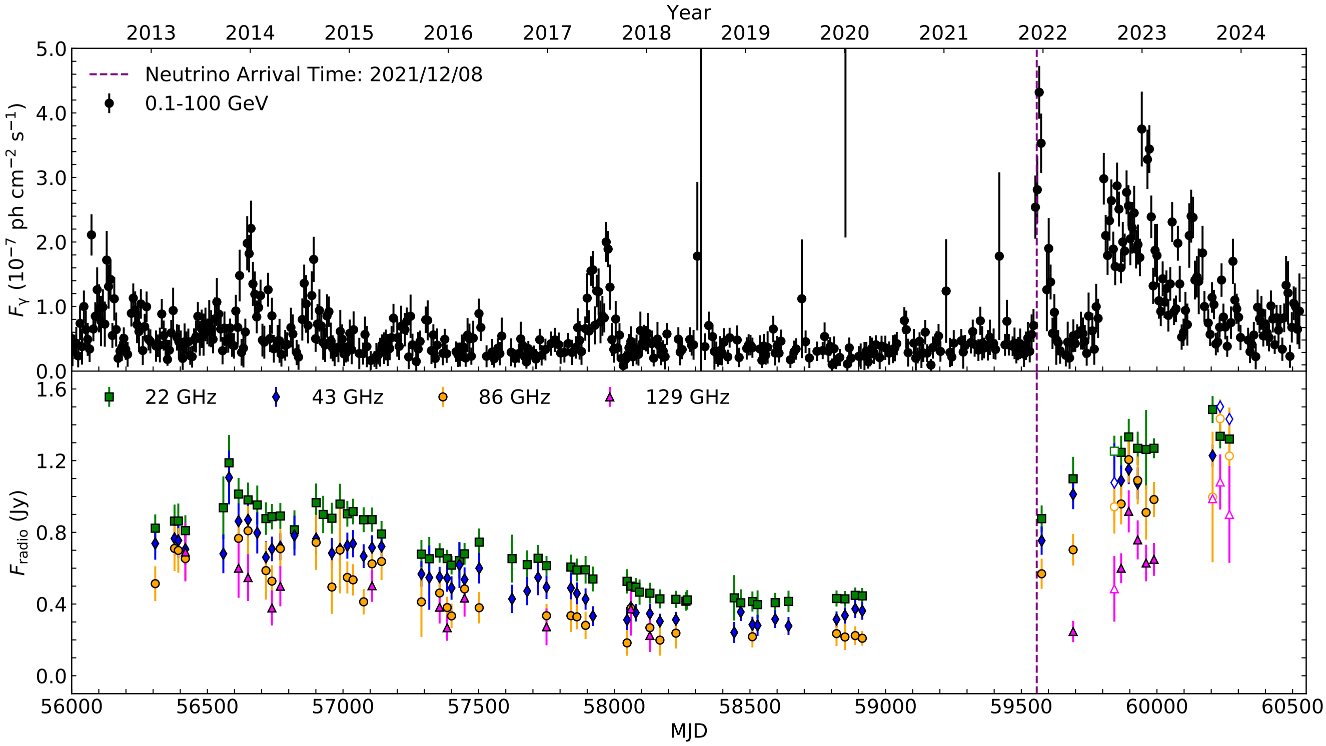


Fig. 2: Light curves from PKS 0735+178. The period is from 2013/01/16 to 2023/11/19 (MJD 56308–60267). The upper and lower panels show the gamma-ray at 0.1–100 GeV and radio (22/43/86/129 GHz) light curves, respectively. The radio light curves at different frequencies are shown with different colors and symbols (see the label). The filled and unfilled symbols indicate the core and single-baseline flux density, respectively. The purple vertical line marks the arrival time of IceCube-211208A.

a flare originates from a shock wave traveling through the relativistic jet (Marscher & Gear 1985). However, it should be cautioned that the turnover frequency (ν_{m}) and spectral index (α) remain unvarying within their uncertainties, which may be affected by the sparse data coverage.

The SSA region is close to the equipartition state, where the energy densities of the radiating particles and the magnetic fields are balanced. Based on our finding that $< \nu_{\mathrm{m}} > \approx 43$ GHz, we assume the size of the SSA region (d_{m}) is similar to the 43 GHz VLBA core size. We derived the size of the SSA region under equipartition conditions, d_{eq}, assuming that the magnetic field strength in the SSA region (B_{SSA}) is comparable to that under equipartition conditions (B_{eq}), i.e., $B_{\mathrm{SSA}} \approx B_{\mathrm{eq}}$, for the ΛCDM cosmology (Scott & Readhead 1977; Readhead et al. 2021). It should be noted that we corrected a typographical error in the expression (Kiehlmann et al. 2024). We found that sizes of the SSA region, i.e., d_{m} and d_{eq}, are comparable in most epochs.

The comparison of the size between d_{m} and d_{eq} enabled us to explore the particle composition of the jet. Estimating B_{eq} requires η, the ratio of the energy density carried by protons and electrons to the energy density of the electrons (i.e., $\eta = 1$ and 1836 for the leptonic and hadronic jets, respectively). Assuming a

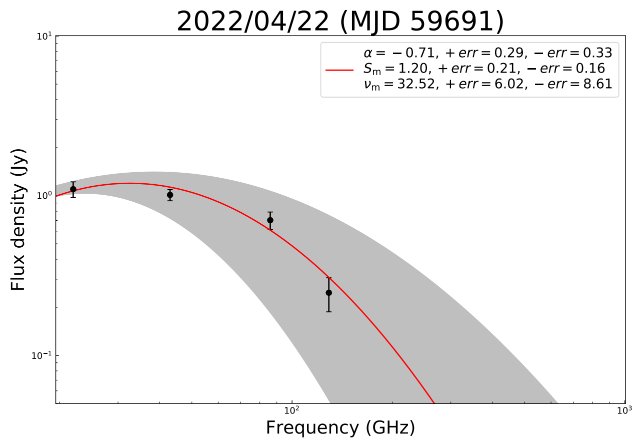


Fig. 3: Result of the spectral fitting to the KVN data on 2022/04/22 (MJD 59691). The black points indicate the observed data with errors. The red solid line represents the best-fit curved power-law spectrum. The error region on the fitted spectrum is plotted as the filled gray region. The fitted parameters (i.e., α, S_{m}, and ν_{m}) are labeled in the top right corner.

Doppler factor of 19.492 ± 2.513 (Weaver et al. 2022), we estimated that $B_{\mathrm{SSA}} < 0.13$ G through the SSA spectra (see Kim et al. 2022, for more details on the method). Under the equipartition state ($B_{\rm SSA} \approx B_{\rm eq}$), upper limits on the ratio of the energy densities were obtained to be $\eta < 200$, except for $\eta < 1000$ on 2023/10/16 (MJD 60233). Our results suggest that the radio synchrotron emission is probably dominated by the leptonic process, which is consistent with previous studies (e.g., Sahakyan et al. 2023; Abdollahi et al. 2023; Prince et al. 2024; Bharathan et al. 2024).

4. Conclusions and future works

In this work, we studied the neutrino-blazar connection for PKS 0735+178 based on the results from the simultaneous multi-frequency VLBI observations at 22–129 GHz. Our results indicate that a new shock wave may have formed in the jet of the source, linked to the IceCube neutrino event. Additionally, the synchrotron emission region appears to be in an equipartition state following the neutrino event. This jet environment enabled us to estimate the particle composition, indicating a leptonically dominated jet. We conclude that hadronic emission is less dominant in the radio synchrotron emission, consistent with previous SED studies of the source. However, we cannot rule out a contribution from the hadronic emission, given the probable correlation between X-ray and neutrino emissions (e.g., Prince et al. 2024). We will investigate cross-correlations of multi-wavelength light curves from radio to gamma-ray bands, including the X-ray band.

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