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Multiwavelength Observations of the Blazar PKS 0735+178 in Spatial and Temporal Coincidence with an Astrophysical Neutrino Candidate IceCube-211208A

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We report on multiwavelength target-of-opportunity observations of the blazar PKS 0735+178, located 2.2 degrees away from the best-fit position of the IceCube neutrino event 211208A. The source was in a high-flux state in the optical, ultraviolet, X-ray, and GeV gamma-ray bands around the time of the neutrino event, exhibiting daily variability in the soft X-ray flux. The X-ray data from Swift-XRT and NuSTAR characterize the transition between the low-energy and high-energy components of the broadband spectral energy distribution, and the gamma-ray data from Fermi-LAT, VERITAS, and H.E.S.S. require a spectral cut-off near 100 GeV. Both measurements provide strong constraints on leptonic and hadronic models. We analytically explore a synchrotron self-Compton model, an external Compton model, and a lepto-hadronic model. Models that are entirely based on internal photon fields face serious difficulties in matching the observed spectral energy distribution (SED). The existence of an external photon field in the source would instead explain the observed gamma-ray spectral cut-off in both leptonic and lepto-hadronic models, and it would allow a proton jet power that marginally agrees with the Eddington limit in the lepto-hadronic model. A numerical lepto-hadronic model with external target photons reproduces the observed SED and is reasonably consistent with the neutrino event despite requiring a high jet power.

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1. Introduction

The distribution of arrival directions of the astrophysical neutrinos detected with the IceCube Neutrino Observatory [1] suggests an extragalactic origin involving very many individual sources, besides a recently identified Galactic contribution [2]. Despite strong evidence for TeV neutrino emission from the nearby active galaxy NGC 1068 [3, 4], and the coincident detection in 2017 of a 200-TeV neutrino event from TXS 0506+056 with temporally correlated gamma-ray flaring activity [5], there is no firm identification of the source class that produces the bulk of the diffuse neutrino emission in the TeV band.

Here we present results of multi-band observations of the blazar PKS 0735+178 contemporaneous with or immediately following the IceCube astrophysical neutrino candidate IceCube-211208A. An earlier study [6] explored the connection between PKS 0735+178 and IceCube-211208A on the basis of *Fermi*-LAT, SWIFT (UVOT and XRT), and optical observations of the blazar. A similar study including NuSTAR data was performed recently [7]. We present, in addition, TeV-band data obtained with the Very Energetic Radiation Imaging Telescope Array System (VERITAS) and the High Energy Stereoscopic System (H.E.S.S.) that indicate a cut-off around 100 GeV in the gamma-ray spectrum. Acknowledging that the association between the neutrino event and the blazar PKS 0735+178 may well be spurious, we interpret the broadband SED of the source in the context of both leptonic and lepto-hadronic models, and discuss whether the neutrino event could have originated from the blazar. This proceedings paper provides a brief synopsis of the findings presented in an extended publication that will appear in the Astrophysical Journal [8].

2. Data

IceCube-211208A was detected as a track-like event with an energy $E_\nu \approx 171$ TeV and a 50.2% probability of being astrophysical [1] on December 8, 2021 [9]. The gamma-ray blazar PKS 0735+178 (redshift $z = 0.45$) is located immediately outside of the 90% error region (2.13°; statistical error only) for the neutrino event, 2.2° away from the best-fit position. Subsequent observations of PKS 0735+178 revealed flaring states in the radio band [10], optical band [11], X-ray band [12–14], and GeV gamma-ray band [15].

We triggered NuSTAR observations on December 11 and 13, 2021, and found the X-ray spectrum to be harder than that seen with SWIFT-XRT [14]. In addition, VERITAS and H.E.S.S. performed ToO observations that yielded upper limits above 100 GeV. We present the SED in Figure 1. The VERITAS upper limit at 330 GeV is particularly relevant. After correction for absorption by extragalactic background light (EBL) [16] for the nominal redshift $z = 0.45$ [17], the flux limit is about a factor of ten below the log-parabola extrapolation of the *Fermi*-LAT spectrum. This finding suggests that either the redshift is misestimated, or there is an intrinsic cut-off at 100 GeV in the emission spectrum, or the source becomes optically thick at 100 GeV, on account of pair production on ambient hard-X-ray photons.

The synchrotron peak frequency is loosely constrained by the rather flat optical/UV spectrum. Nominally, the highest energy flux is observed at a few 10^{14} Hz, or abourt 1 eV, with UVOT data suggesting an optical/near-UV flux that is a slowly declining function of frequency. Beyond the

[1]https://gcn.gsfc.nasa.gov/notices_amon_g_b/136015_21306805.amon

near-UV band, there are no measurements up to 300 eV, where XRT data indicate a flux a factor of 30 below that at 3 eV, indicating that the cut-off energy is below 100 eV, and likely far lower based on the slowly declining UV spectrum. The measured soft and hard X-ray spectra fully constrain the tail of the synchrotron emission and the beginning of the high-energy component of the SED, respectively. The transition occurs at a few keV.

Day-scale variability in the GeV-band gamma-ray flux is evident, but there is no evidence of spectral variability. The soft X-ray flux exhibited daily variability, but no hard X-ray variability was observed between the two NuSTAR observations on December 11 and 13. Given the daily variability, the SED on December 13 is the focus of our modeling.

3. Discussion

The radius of the emission region is constrained by the soft X-ray variability, and to a lesser degree by that in gamma-rays, to $R \lesssim 10^{16}$ cm. The size estimate permits turning the observed synchrotron flux at the νF_ν peak into the photon energy density in the emission zone,

$$U' = \epsilon' n'_{\ln\epsilon} \approx \frac{5\times 10^{-3}\ \mathrm{erg\,cm^{-3}}}{D_{25}^4\, R_{16}^2}\,, \tag{1}$$

where we denote the radius of the emission zone as $R' = R_{16}\,(10^{16}$ cm) and the Doppler factor as $D = 25\,D_{25}$. Primed quantities are measured in the jet frame, and $n_{\ln\epsilon}$ stands for the photon density per logarithmic energy interval. This is the photon field that Inverse-Comption emission and potentially neutrino emission is produced with.

The synchrotron spectrum seems to roll over at a few 10^{14} Hz in frequency, and we write the peak photon energy as $\epsilon_{\rm peak} = \epsilon_{\rm peak,eV}$ eV. There has to be a Synchrotron-self-Compton (SSC) contribution to the SED. Since the Thomson limit applies, the ratio between the inverse-Compton (IC) and the synchrotron peak frequencies (100 GeV$/\epsilon_{\rm peak}$) gives the square of the peak Lorentz factor of electrons, leading to

$$\gamma_{\rm peak} \approx \frac{3\times 10^5}{\sqrt{\epsilon_{\rm peak,eV}}}\,. \tag{2}$$

The synchrotron peak frequency and the peak Lorentz factor of electrons constrain the magnetic-field strength in the emission zone,

$$B' D \approx (10^{-3}\ \mathrm{G})\,\epsilon^2_{\rm peak,eV}\,. \tag{3}$$

The optical/UV synchrotron emission appears to be roughly as bright in νF_ν as is the GeV-scale gamma-ray emission, indicating that the energy densities in the photon field and in the magnetic field must be comparable. That requires a very high cut-off frequency of the synchrotron emission or an emission zone that is very much larger than 10^{16} cm. As the UVOT data suggest $\epsilon_{\rm peak,eV} \approx 1$, and the source radius cannot be made arbitrarily large, on account of the day-scale variability, the SSC model has difficulty reproducing a 100-GeV cut-off in the gamma-ray spectrum. We present a best-fit SSC model and the observed SED in Fig. 1. To be noted from the figure is the deficit in the SSC spectrum of gamma rays around 10 GeV.

Considering an internal photon field with energy density as given in Eq. 1, p-γ interactions of PeV-scale protons can yield a neutrino flux commensurate with one detected neutrino per month

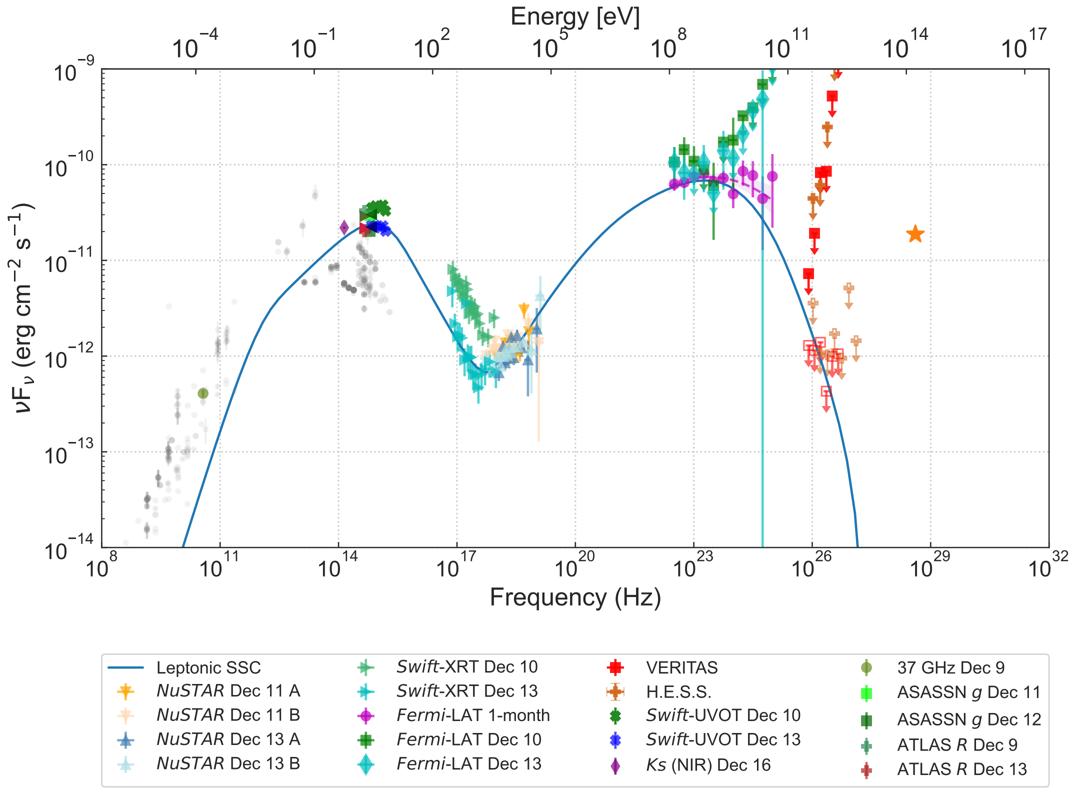

Figure 1: The broadband SED and a best-fit one-zone SSC model. For the TeV-band data, open symbols indicate the measured flux and filled symbols refer to the de-absorbed flux. Flux points in grey reflect archival data. The star at 170 TeV marks the neutrino flux corresponding to one observed event in eight months of observing time.

only, if the proton acceleration power, and hence the jet luminosity, vastly exceed the Eddington luminosity [18].

The featureless optical spectrum of PKS 0735+178 suggests that it may be a BL Lac. It has been noted in BL Lacs that the jet may pass through a region harboring a significant jet-external photon field [19]. In the jet frame the external photons would be in the keV band and have an energy density much higher than that of the synchrotron photons. If only 1% of the observed soft-UV flux were rescattered in a pc-scale central region, then one neutrino event in a month of high source activity would be in marginal agreement with the Eddington limit. We performed a numerical analysis using a state-of-the-art code [20] and confirmed the analytically derived findings that are presented above.

4. Summary

Based on extensive follow-up observations across the electromagnetic spectrum, we analysed the state of the blazar PKS 0735+178 in the context of a potential association with a VHE neutrino event that was seen with IceCube in December 2021. We analytically demonstrated that the observed SED of the blazar, especially the gamma-ray cutoff in the TeV data, constitutes a challenge to a simple one-zone SSC model. It may be explained by an SSC/EC scenario, which naturally provides the observed 100-GeV cut-off through Klein-Nishina suppression and γ-γ pair absorption. The potential association with the neutrino event could be explained with a lepto-hadronic scenario that likewise must involve an external photon field, otherwise there would be no agreement between the Eddington limit on the jet luminosity and the observed IceCube neutrino rate.

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