PROCEEDINGS OF SCIENCE

Optical-Infrared Searches for Identifying the IceCube High-Energy Neutrino Sources

Tomoki Morokuma[a,*]

[a] *Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan*

E-mail: tmorokuma@perc.it-chiba.ac.jp

We present our follow-up observations in optical and infrared wavelengths to identify electromagnetic (EM) counterparts of high-energy neutrinos detected with the IceCube experiment. Our observing facilities include a wide range of telescope apertures from small-size (∼ 0.5m) to the largest-size (∼ 8m) in the world. Unique wide-field instruments are also utilized; Hyper Suprime-Cam (1.8 deg^2 field-of-view) on the 8.2-m Subaru telescope and Tomo-e Gozen (20 deg^2 field-of-view) on the 1.05-m Kiso Schmidt telescope. We first aim for searching for candidates of highly variable blazars (including those with red optical colors dominated by their host galaxies rather than blazar components), peculiar supernovae (SNe), and tidal disruption events (TDEs). We also conduct follow-up spectroscopic observations to identify the nature and determine the redshift of the candidates to claim the coincidence of the source with the neutrino detection. We successfully identified the EM counterpart of the high-energy neutrino IceCube-170922A, TXS 0506+056, with quick detection of the rapid near-infrared brightness change with HONIR on the 1.5-m Kanata telescope. After this variability detection in addition to the Fermi/LAT flux increase, world-wide follow-up observations were intensively conducted and the coincidence with the neutrino detection was found. We found that TXS 0506+056 showed a large-amplitude (∼ 1.0 mag) variability in >several-day time scale or longer with the bluer-when-brighter trend, although no significant variability was detected in a time scale of < 1-day. Structure function analyses indicate that TXS 0506+056 is not a special blazar in terms of optical variability.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1559

1. Introduction

Identification of the origin of high-energy (TeV-PeV) neutrinos are important to understand the acceleration mechanisms of high-energy neutrinos and cosmic rays. The IceCube experiment at the South Pole has been detecting high-energy neutrinos. The IceCube collaboration started issuing alerts in 2016 [1] to promote electromagnetic follow-up observations to identify the origin. Follow-up observations in optical wavelengths play key roles in many aspects, including searches for transients possibly related to the neutrino detection, determination of the distances/redshifts to the transients and their host galaxies via spectroscopic observations, and characterization of the transients. Typically, the localization of a neutrino arrival direction is as wide as $\sim$ 1 deg, which can be observed with wide-field telescopes and instruments in optical wavelengths.

Our observing group has been conducting follow-up observations in optical and near-infrared wavelengths with a variety of telescopes with apertures of the primary mirrors from $\sim$ 0.5 m to $\sim$ 8 m spread over the world [2]. Among them, two wide-field imaging instruments, Hyper Suprime-Cam (1.8 deg^2 field-of-view; [3]) on the 8.2-m Subaru telescope and Tomo-e Gozen (20 deg^2 field-of-view; [4]) on the 1.05-m Kiso Schmidt telescope, are so powerful that the entire error region can be covered to search for transient phenomena.

2. Success of Neutrino Source Identification for IceCube-170922A

The IceCube experiment detected a $\sim$ 290 TeV neutrino on September 27, 2017, and issued an alert via GCN [5, 6]. The central coordinate of the neutrino direction for this event was determined to be (RA, Dec) = $(77.43^{+0.95}_{-0.65}, +5.72^{+0.50}_{-0.30})$ [deg] in J2000. We quickly started imaging observations for 7 blazar candidates in the BROS catalog [7] inside the error region with HONIR [8] on the 1.5-m Kanata telescope and towards the entire error region with the Kiso Wide Field Camera (KWFC; [9]) on the 1.05-m Kiso Schmidt telescope.

Among the 7 BROS blazar candidates, rapid near-infrared variability of TXS 0506+056 was detected by comparing the September 23 and 24 HONIR J-band data. Then, the Fermi/LAT data in this region were examined and the recent γ-ray flare was reported [10]. These led to further intensive multi-wavelength follow-up observations of TXS 0506+056, resulting in revealing the detailed SED of TXS 0506+056 as a neutrino source [2, 6].

The redshift of was determined with multiple weak emission lines to be z = 0.3365 with the 10-m GTC [11]. We also took several spectra with Kanata/HOWPol, Nayuta/MALLS, Subaru/FOCAS, and Gemini-S/GMOS and all the spectra are consistent with the GTC result.

We monitored TXS 0506+056 with our observing facilities including the 0.4-m Kyoto telescope, the 0.5-m MITSuME Akeno telescope, Tomo-e Gozen [4] on the 1.05-m Kiso Schmidt telescope, SIRIUS on the 1.4-m Infrared Survey Facility (IRSF), HONIR [8] on the 1.5-m Kanata telescope, and HSC [3] on the 8.2-m Subaru telescope. A large-amplitude ($\sim$ 1.0 mag) variability in >several-day time scale or longer is observed, although no significant variability was detected in a time scale of $<$ 1-day [2]. With the follow-up optical data, the bluer-when-brighter trend are observed as seen in other AGN [2, 12]. Structure function analyses indicate that TXS 0506+056 is not a special blazar in terms of optical variability [2].

3. Near-Future Prospects

After the IceCube-170922A event, two TDEs are identified to be likely sources of the two neutrinos; AT2019dsg at $z = 0.051$ for IceCube-191001A [13] and AT2019fdr at $z = 0.267$ for IceCube-200530A [14]. Given the typical optical luminosity of possible neutrino sources such as TDEs [15] and SNe [16] and the expected higher redshifts of $z \sim 0.5 - 1$ for a typical singlet neutrino [17], 4m or 8m-class optical telescopes are required to discover in imaging, and classify and identify those types of transients in spectroscopy, as tried for IceCube-170922A with DECam on the 4m Blanco telescope with which a source SN is searched for [18]. Currently, Hyper Suprime-Cam (HSC, 1.8 deg^2 field-of-view) on the 8.2-m Subaru Telescope has the largest survey power while the Rubin/LSST (6.5-m-effective primary mirror and 9.6 deg^2 field-of-view) will start its operation soon. Spectroscopic identification of apparently faint transients at $z \sim 1$ is not easy but not impossible with the current 8-m class telescopes [19]. Spectroscopy with 30m-class telescopes will enable us to effectively identify them.

A blind spectroscopic survey with high-multiplicity spectrographs on > 4-m telescopes such as Prime Focus Spectrograph (PFS) on the 8.2-m Subaru Telescope [20] and the Dark Energy Spectroscopic Instrument (DESI) on the 4-m Mayall telescope [21] will be another solution. These instruments can cover the IceCube error region effectively. The number of the transients within the region is roughly a few hundreds [22] and can be simultaneously observed with these powerful instruments.

However, chance coincidence of transients unrelated to the neutrino event always will be a problem when we want to pin down the source of the neutrino [23]. Interacting SNe are rarer than Type Ia SNe and normal core-collapse SNe, but the number density is still an order of 10 deg^{-2} up to $z \sim 1$ discovered with 8m-class telescopes. Then, better localization (~ 0.1 deg^2 for a singlet) or closer source (i.e., smaller volume) would be expected to identify the source with smoking-gun evidence. TDEs are as rare as < 1 deg^{-2} and PFS or DESI specetroscopic survey for transients enables us to identify a TDE as a neutrino source. For a multiplet neutrino event, the expected redshift to a source is as low as $z \sim 0.15$ [23] and such chance coincidence is smaller than unity even for intearacting SNe. For such closer transients, 4m-class telescope imaging capability is deep enough.

This work is supported by Grant-in-Aid of the Ministry of Education, Science, Culture, and Sport for Transformative Research Areas (A), "Multimessenger Astrophysics", JP23740143, JP25800103, JP16H02158, JP18H04575, JP15H02075, JP16H06341, JP18H05223, JP17K14253, JP17H04830, JP26800103, JP19H00693, JP17H06363, JP17H06362, JP24103003, JP1805458, and JP19K14772. This work was partly supported by ICRR, NAOJ, and PIRE. The data is partly processed using the Gemini IRAF package. This work is also supported by Toray Science Foundation (FY2023-2025). This work was also based in part on data collected at the Subaru Telescope, which is operated by the NAOJ, and at the international Gemini Observatory (NOIRLab/AURA/NSF).

References

[1] M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *The IceCube realtime alert system*, *Astroparticle Physics* **92** (2017) 30 [1612.06028].

[2] T. Morokuma, Y. Utsumi, K. Ohta, M. Yamanaka, K.S. Kawabata, Y. Inoue et al., *Follow-up observations for IceCube-170922A: Detection of rapid near-infrared variability and intensive monitoring of TXS 0506+056*, *PASJ* **73** (2021) 25 [2011.04957].

[3] S. Miyazaki, Y. Komiyama, S. Kawanomoto, Y. Doi, H. Furusawa, T. Hamana et al., *Hyper Suprime-Cam: System design and verification of image quality*, *PASJ* **70** (2018) S1.

[4] S. Sako, R. Ohsawa, H. Takahashi, Y. Kojima, M. Doi, N. Kobayashi et al., *The Tomo-e Gozen wide field CMOS camera for the Kiso Schmidt telescope*, in *Ground-based and Airborne Instrumentation for Astronomy VII*, C.J. Evans, L. Simard and H. Takami, eds., vol. 10702 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 107020J, July, 2018, DOI.

[5] C. Kopper and E. Blaufuss, *IceCube-170922A - IceCube observation of a high-energy neutrino candidate event.*, *GRB Coordinates Network* **21916** (2017) 1.

[6] IceCube Collaboration, M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, *Science* **361** (2018) eaat1378 [1807.08816].

[7] R. Itoh, Y. Utsumi, Y. Inoue, K. Ohta, A. Doi, T. Morokuma et al., *Blazar Radio and Optical Survey (BROS): A Catalog of Blazar Candidates Showing Flat Radio Spectrum and Their Optical Identification in Pan-STARRS1 Surveys*, *ApJ* **901** (2020) 3 [2008.00038].

[8] H. Akitaya, Y. Moritani, T. Ui, T. Urano, Y. Ohashi, K.S. Kawabata et al., *HONIR: an optical and near-infrared simultaneous imager, spectrograph, and polarimeter for the 1.5-m Kanata telescope*, in *Ground-based and Airborne Instrumentation for Astronomy V*, S.K. Ramsay, I.S. McLean and H. Takami, eds., vol. 9147 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 91474O, Aug., 2014, DOI.

[9] S. Sako, T. Aoki, M. Doi, N. Ienaka, N. Kobayashi, N. Matsunaga et al., *KWFC: four square degrees camera for the Kiso Schmidt Telescope*, in *Ground-based and Airborne Instrumentation for Astronomy IV*, I.S. McLean, S.K. Ramsay and H. Takami, eds., vol. 8446 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 84466L, Sept., 2012, DOI.

[10] Y.T. Tanaka, S. Buson and D. Kocevski, *Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.*, *The Astronomer's Telegram* **10791** (2017) 1.

[11] S. Paiano, R. Falomo, A. Treves and R. Scarpa, *The Redshift of the BL Lac Object TXS 0506+056*, *ApJL* **854** (2018) L32 [1802.01939].

[12] S. Hwang, M. Im, Y.C. Taak, I. Paek, C. Choi, S. Shin et al., *Medium-band Observation of the Neutrino Emitting Blazar, TXS 0506+056*, *ApJ* **908** (2021) 113 [2011.14049].

[13] R. Stein, S.v. Velzen, M. Kowalski, A. Franckowiak, S. Gezari, J.C.A. Miller-Jones et al., *A tidal disruption event coincident with a high-energy neutrino*, *Nature Astronomy* **5** (2021) 510 [2005.05340].

[14] S. Reusch, R. Stein, M. Kowalski, S. van Velzen, A. Franckowiak, C. Lunardini et al., *Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino*, *PRL* **128** (2022) 221101 [2111.09390].

[15] K. Murase, S.S. Kimura, B.T. Zhang, F. Oikonomou and M. Petropoulou, *High-energy Neutrino and Gamma-Ray Emission from Tidal Disruption Events*, *ApJ* **902** (2020) 108 [2005.08937].

[16] K. Murase, T.A. Thompson, B.C. Lacki and J.F. Beacom, *New class of high-energy transients from crashes of supernova ejecta with massive circumstellar material shells*, **84** (2011) 043003 [1012.2834].

[17] Icecube Collaboration, M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *Multiwavelength follow-up of a rare IceCube neutrino multiplet*, *A&A* **607** (2017) A115 [1702.06131].

[18] R. Morgan, K. Bechtol, R. Kessler, M. Sako, K. Herner, Z. Doctor et al., *A DECam Search for Explosive Optical Transients Associated with IceCube Neutrino Alerts*, *ApJ* **883** (2019) 125 [1907.07193].

[19] T. Morokuma, K. Tokita, C. Lidman, M. Doi, N. Yasuda, G. Aldering et al., *Subaru FOCAS Spectroscopic Observations of High-Redshift Supernovae*, *PASJ* **62** (2010) 19 [0911.1258].

[20] N. Tamura, N. Takato, A. Shimono, Y. Moritani, K. Yabe, Y. Ishizuka et al., *Prime Focus Spectrograph (PFS) for the Subaru telescope: overview, recent progress, and future perspectives*, in *Ground-based and Airborne Instrumentation for Astronomy VI*, C.J. Evans, L. Simard and H. Takami, eds., vol. 9908 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 99081M, Aug., 2016, DOI [1608.01075].

[21] DESI Collaboration, B. Abareshi, J. Aguilar, S. Ahlen, S. Alam, D.M. Alexander et al., *Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument*, **164** (2022) 207 [2205.10939].

[22] T. Morokuma, M. Doi, N. Yasuda, M. Akiyama, K. Sekiguchi, H. Furusawa et al., *The Subaru/XMM-Newton Deep Survey (SXDS). V. Optically Faint Variable Object Survey*, *ApJ* **676** (2008) 163 [0712.3108].

[23] S. Yoshida, K. Murase, M. Tanaka, N. Shimizu and A. Ishihara, *Identifying High-energy Neutrino Transients by Neutrino Multiplet-triggered Follow-ups*, *ApJ* **937** (2022) 108 [2206.13719].