Optical follow-up of TXS 0506+056 after the neutrino detection

R. Bachev[1], A. Strigachev[1], A. Kurtenkov[1], B. Spassov[1], Y. Nikolov[1], S. Boeva[1] and E. Semkov[1]
Institute of Astronomy and NAO, Bulgarian Academy of Sciences, 72 Tsarigradsko Shosse, 1784 Sofia, Bulgaria bachevr@astro.bas.bg
(Submitted on 3.07.2020. Accepted on 29.07.2020)

Abstract. TXS 0506+056 is the first blazar, successfully identified as a likely neutrino source. With this work we aim to understand, from the optical variability perspective, how and why this blazar is different from many other similar objects, which have no neutrino emission detected. The object has been monitored for the last 1.5 years on both intra-night and long-term time-scales, primarily with the 60-cm telescope of Belogradchik Observatory, Bulgaria. Our results in the course of this monitoring show "bluer-when-brighter" color changes, significant variability amplitude (almost a magnitude on a month time-scale) and the rare, but prominent intra-night variability. Standard stars have been also calibrated in the field of this object as a part of this work. Our results suggest that the variability behavior is more typical for an LSP (but perhaps not a FSRQ) than for a HSP blazar.
Key words: BL Lacertae objects, individual — TXS 0506+056 — techniques — photometric

Introduction

Blazars are characterized with a non-thermal electromagnetic spectrum and strong temporal variability, produced presumably in a relativistic jet, pointed almost directly towards the observer. Synchrotron and Compton processes within this jet are perhaps responsible for the two broad electromagnetic peaks, observed in their spectra, stretching from radio to VHE γ-rays. The exact physical processes that generate the spectral-energy distribution (SED) of blazars are not firmly established, but invoke relativistic leptons (leptonic processes) and/or relativistic protons (hadronic processes), e.g. (Bottcher & Reimer, 2012). Generally, blazars are divided into classes depending on the location of their peaks (low-spectrum peaked, LSP and high-spectrum peaked, HSP; (Padovani & Giommi, 1995) and on the presence/absence of accretion disk and broad line region signatures (flat spectrum radio quasars, FSRQ and BL Lac – type objects, respectively (Stocke et al., 1991).

An interesting and exciting new opportunity for studying blazars was revealed a few years ago when the IceCube neutrino detector identified the blazar TXS 0506+056 as a likely neutrino source. On September 17, 2017 a 290 TeV neutrino signal ($> 3\sigma$ over the background, *IceCube* event-170922A) was detected from a direction coincident to a degree with the TXS 0506+056 position (IceCube collaboration (2018a), IceCube collaboration (2018b). At the same time, the blazar was in a very high state in the γ-rays. The assumption was that the gamma-ray flare was also accompanied with a significant neutrino production.

So far TXS 0506+056 ($z \simeq 0.34$) is the only blazar, clearly associated with a neutrino event. It is a typical BL Lac type object (classified as HSP or intermediate (Fan et al., 2014), not the closest, not the brightest one, not really distinguished in any other aspect. Why is it, then, this the only object to emit neutrinos? One way to try to answer this question is to explore its optical variability and to compare its characteristics with the typical variability characteristics of blazars of a similar class. In particular, we will search for extreme variability events, especially on intra-night time scales (e.g. Bachev, 2015; Bachev et al., 2017), that could possibly be associated with the neutrino production processes.

Observational data and results

To build the long-term light curve (LC) of TXS 0506+056, the object was observed in four colors ($BVRI$) during about 40 nights, between 2018 Feb and 2020 Apr with 3 telescopes: The 60-cm telescope of Belogradchik observatory, the 2-m RCC telescope of Rozhen observatory (both in Bulgaria) and the 1.3-m telescope of Skinakas observatory (Greece). All telescopes are equipped with CCD cameras and standard filter sets. In addition, multi-color intra-night variability searches were performed during about 20 nights (for a total of more than 60 hours).

Fig. 1 presents the long-term LC of TXS 0506+056 as well as the color changes. The object shows moderate optical variability, typical for a blazar. The amplitude of the variations in all bands is about 1 magnitude ($rms \simeq 0.25$), with a slight increase towards the shorter wavelengths (within the errors). Similar variability was also reported by ASAS–SN for the years 2012–2017 (Franckowiak et al., 2017). No significant color changes are evident from the observations, but the general tendency suggests "bluer-when-brighter" behavior ($R^2 = 0.43$, p-value> 0.99)

We also build the first-order structure function, SF (Simonetti et al., 1985; see also Bachev et al., 2017), to quantify the variability power on different time-scales for an unevenly spaced time series (Fig. 2, upper panel). The SF is defined, for a magnitude time series $m(t_{\rm i})$,
as $SF(\tau) = \frac{1}{N(\tau)} \sum_{i<j} [m(t_{\rm i}) - m(t_{\rm j})]^2$, where summation is made over all pairs in which $\tau - \Delta\tau/2 < t_{\rm j} - t_{\rm i} \leq \tau + \Delta\tau/2$, $N(\tau)$ denotes a number of such pairs, and $\Delta\tau$ is the width of the time bin. The SF is so to speak a curve of growth of the variability with time. As seen, the most of the variability occurs within the first 1–5 days from any starting point, with only a small increase afterwards. Note that variations due solely to photometric errors in our case will have $\log SF \simeq -1.5$.

The lower panel of Fig. 2 shows the time asymmetry of the LC, defined as the relative difference of the structure functions, build separately for positive and negative slopes of the LC, i.e. $\frac{SF^{+} - SF^{-}}{SF}$ (Kawaguchi et al., 1998). Positive values of the asymmetry mean sharp rises with slow decays and vice versa. A slow, low significance level ($R^2 = 0.22$, p-value$\simeq 0.9$) tendency for a change of the time asymmetry of the light curve with time (from negative to positive) can be noted.

Although significant night-to-night variations of up to 0.2 mag are observed (Fig. 1, 2), the object appears to be not very active on intra-night time scales. During only one night a small increase of ~ 0.06 mag is clearly detected for about 5 hours of observations (Fig. 3).

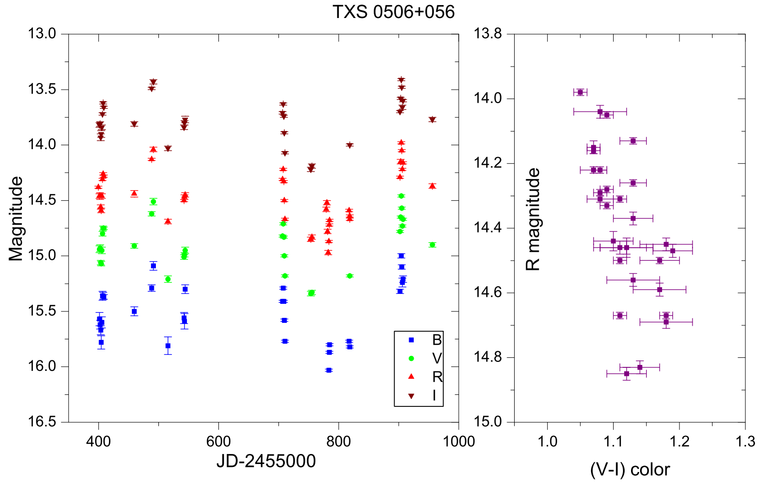

Fig. 1. The long-term LC of TXS 0506+056 between 2018 Feb and 2020 Apr in 4 colors (left panel) and color changes $(V-I)$ vs. R (right panel). Photometric data are available upon request.

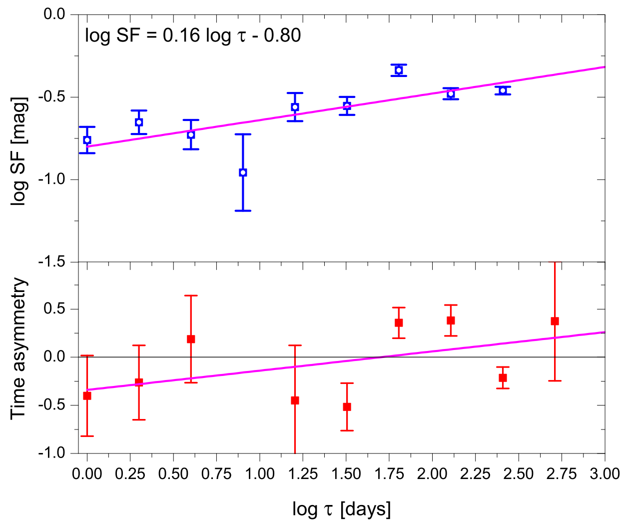

Fig. 2. Upper panel: The R-band structure function of the TXS 0506+056 LC with the best linear fit. Lower panel: Time asymmetry of the LC (see the text) with the best linear fit through data points. Positive values of the asymmetry mean sharp rises with slow decays and vice versa.

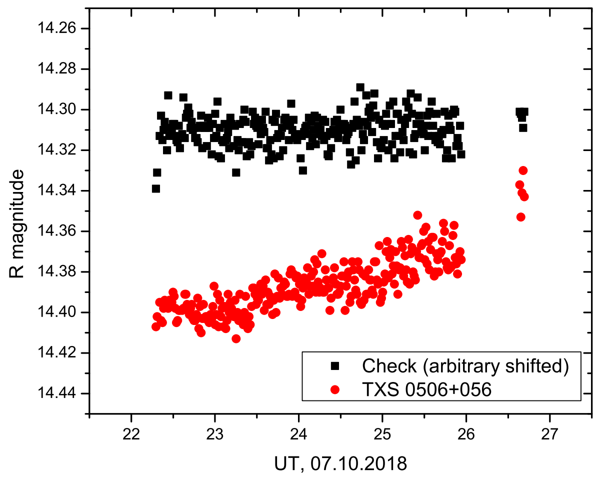

Fig. 3. A rare example of clearly detected small-scale intra-night variability of TXS 0506+056, observed for 5 hours with the 2-m Rozhen telescope during the night of Oct 7, 2018.

In addition, to facilitate further photometric studies of this interesting object, we calibrate secondary standard stars in the field. Calibration is made based on standards in the field of S5 0716+714 (Ghisellini et al., 1997; Villata et al., 1998) as well as on selected Landolt standards, (Landolt, 1992). Fig. 4 shows the comparison stars and their magnitudes are given in Tab. 1.

Table 1. BVRI magnitudes of the calibrated secondary standards from Fig. 4. The errors are due to our photometrical uncertainty only.

Band	A (err)	B (err)	C (err)	D (err)
B	15.11 (0.02)	16.61 (0.06)	15.22 (0.02)	15.63 (0.02)
V	14.48 (0.01)	15.75 (0.02)	14.61 (0.01)	15.23 (0.01)
R	14.07 (0.01)	15.30 (0.01)	14.24 (0.01)	14.94 (0.01)
I	13.70 (0.01)	14.89 (0.02)	13.95 (0.01)	14.63 (0.02)

Discussion and conclusions

Recently Padovani et al. (2019) argued that TXS 0506+056 is actually not a BL Lac type object, but is intrinsically a FSRQ, with a hidden broad line

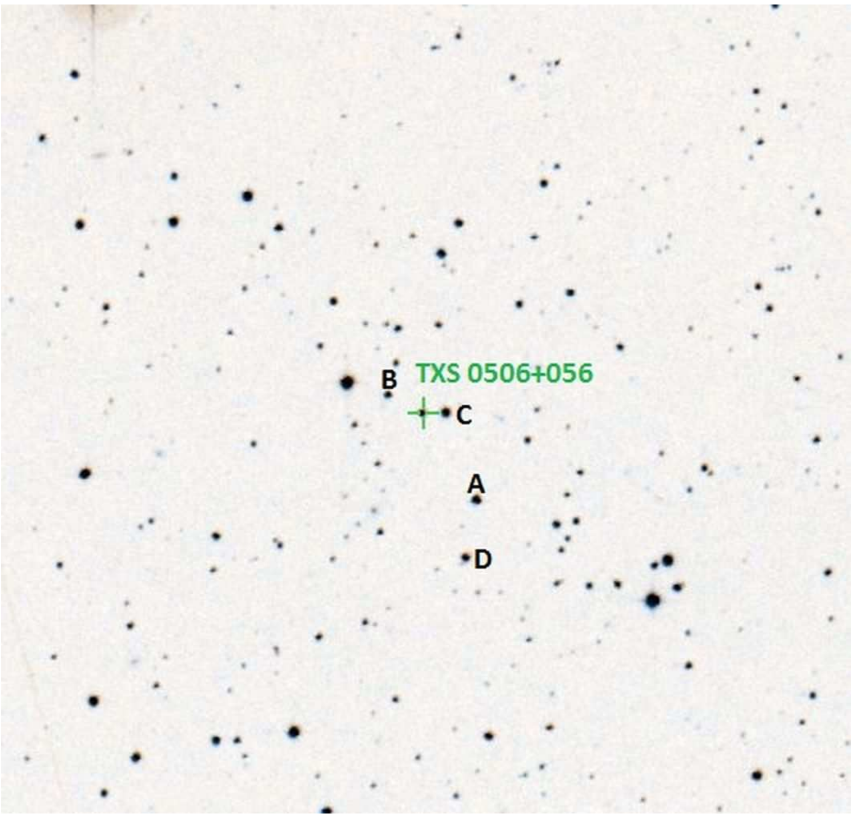

Fig. 4. A chart of TXS 0506+056 field with calibrated secondary standards. The field is 10x10 arcmin. North is up and east is to the left.

region (BLR). They based their arguments on the radio/O II and emission-line ratios, the Eddington rate, the position along the so called "blazar sequence", etc., all of which makes the object to appear more typical for a FSRQ. In this work we reconsider their claims from the perspective of the optical variability of TXS 0506+056.

- The relatively small variability amplitude on long time scales (Fig. 1) seems more typical for a BL Lac object (e.g. Bachev, 2018; Anjum et al., 2020), instead for a FSRQ. In addition, the "bluer-when-brighter" color behavior also suggests a BL Lac (e.g. Gaur et al., 2012b).
- On the other hand, the fact that the most of the variability occurs on time scales of just several days (Fig. 2), suggests probably an LSP, not an HSP type object, as the later would typically show only slow, minor activity in the optical. Understandably, the "blue" part of the synchrotron peak (located in the optical region for LSP's) is expected to vary faster, due to the faster evolution of the higher-energy electrons.
- Although we find intra-night variability only on rare occasions (Fig. 3), such is practically absent in HSPs (Gaur et al., 2012a). Actually, rapid variability on such short time scales is frequently observed only in very few LSP/FSRQ objects (Bachev et al., 2012).

An interesting point to comment is the possibility (if real) of a change of the time asymmetry sign of the LC with the time scale (Fig. 2, lower panel). A possible interpretation can be based on radial dependence of the energy injection/loss times. The characteristic loss time for a relativistic particle is $\propto 1/B^2$ (or $\propto 1/r^4$, where r is the radial distance along a conical jet). Assuming an almost constant energy injection time (particle acceleration due to magnetic reconnections, shocks, etc.), then close to the jet base the variations will be generally fast, with a negative time asymmetry (slow rise – fast drop) and vice versa for the outer jet.

To conclude, our optical variability monitoring suggests indeed that TXS 0506+056 is perhaps not a typical HSP-type object, due to its significant variations on short time scales. We cannot confirm, however its FSRQ nature, as these objects frequently show larger variability amplitudes. The question is still open. To further facilitate photometric studies of TXS 0506+056, we calibrated secondary standards in the field (Fig. 4).

Acknowledgments: This research was partially supported by the Bulgarian National Science Fund of the Ministry of Education and Science under grants DN 18-10/2017, DN 18-13/2017, KP-06-H28/3 (2018) an KP-06-PN38/4 (2019). The Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology – Hellas, and the Max-Planck-Institut für Extraterrestrische Physik.

References

Anjum A., Stalin C. S., Rakshit S., Gudennavar S. B., Durgapal A., 2020, *MNRAS 494, 746*
Bachev R., 2015, *MNRAS 451, L21*
Bachev R., 2018, *Bulgarian Astronomical Journal, 28, 22*
Bachev R., Popov V., Strigachev A., et al., 2017, *MNRAS 471, 2216*

Bachev R., Semkov E., Strigachev A., Gupta A. C., Gaur H., Mihov B., Boeva S., Slavcheva-Mihova L., 2012, *MNRAS 424, 2625*
Böttcher M., Reimer A., 2012, Radiation Processes, *in Relativistic Jets from Active Galactic Nuclei, Eds. M. Böttcher, D. Harris, H. Krawczynski; Wiley-VCH*
Fan J.-H., Bastier D., Yang J.-H., Liu Y., Hua T-X., Yuan Y.-H., Wu D.-X., 2014, *RAA 14, 1135*
Franckowiak A., Stanek K. Z., Kochanek C. S., Thompson T. A., Holoien T. W.-S., Shappee B. J., Prieto J. L., Dong Subo, 2017, *ATel# 10794*
Gaur H., Gupta A. C., Strigachev A., Bachev R., Semkov E., Wiita P. J., Peneva S., Boeva S., et al., 2012a, *MNRAS 420, 3147*
Gaur H., Gupta A. C., Strigachev A., Bachev R., Semkov E., Wiita P. J., Peneva S., Boeva S., et al., 2012b, *MNRAS 425, 3002*
Ghisellini G. et al., 1997, *A&A 327, 61*
IceCube collaboration, 2018a, *Science 361, 147*
IceCube collaboration, 2018b, *Science 361, id. eaat1378*
Kawaguchi T., Mineshige S., Umemura M., Turner E. L., 1998, *ApJ 504, 671*
Landolt A. U., 1992, *AJ 104, 340*
Padovani P., Giommi P., 1995, *ApJ 444, 567*
Simonetti J.H., Cordes J.M., Heeschen D.S., 1985, *ApJ, 296, 46*
Stocke J. T., Morris S. L., Gioia I. M., Maccacaro T., Schild R., Wolter A., Fleming T. A., Henry J. P., 1991, *ApJS 76, 813*
Villata M. et al., 1998, *A&AS 130, 305*