MASTER optical observations of the blazar TXS0506+056 during the IC170922A

V. M. Lipunov[1,2*], K. Zhirkov[1,2], V. G. Kornilov[1,2], E. Gorbovskoy[2], N.M. Budnev[3], D. A. H. Buckley[4], R. Rebolo[5], M. Serra[5] , R. Podesta[6], C.Francile[6], V. Topolev[1,2], N. Tiurina[2], O. A. Gress[2,3], P. Balanutsa[2], A. Chasovnikov[1,2], D. Vlasenko[1,2], E. Minkina[1,2], A. Gabovich[7], G. Antipov[2], A. Kuznetsov[2], V. Vladimirov[2], S.Svertilov[8], F.Podesta[6], V.Grinshpun[1,2], A. Tlatov[9], D.Cheryasov[2], V.Senik[2]

1 Lomonosov Moscow State University, Physics Department, Vorobievy Hills, 1, Moscow 119991, Russia

2 Lomonosov MSU, SAI, Universitetsky, 13, Moscow 119234, Russia

3 Irkutsk State University, 20, Gagarin, Irkutsk 664003, Russia

4 South African Astrophysical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa

5 Instituto de Astrofísica de Canarias, Lactea, E38205, LaLaguna, Tenerife, Spain

6 Observatorio Astronomico Felix Aguilar(OAFA), San Juan National University, Avda Benavides s/n, Rivadavia, El Leonsito, Argentina;

7 Blagoveschensk State Pedagogical University, Lenin, 104, Amur, Blagoveschensk 675000, Russia

8 Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics (SINP MSU), Vorobievy Hills, 1, Moscow, 119991, Russia

9 Kislovodsk Solar Station PulkovoObservatory, Gagarina 100, Kislovodsk 357700, Russia

**E-mail: lipunov@sai.msu.ru*

We present MASTER Global Robotic Net (Lipunov et al. 2010) earliest optical alert observations of IceCube-170922A error box. We discovered fast variability of blazar TXS 0506+056 27 sec after notice time (73s after the trigger time) at 2017-09-22 20:55:43 UT by MASTER-Tavrida robotic telescope. MASTER found the blazar TXS 0506+056 to be in the off-state after one minute and then switched to the on-state no later than two hours after the event. The effect is observed at a 50-sigma significance level. We also analysed own unique 16-years light curve of blazar TXS 0506+056 (518 data set).

Keywords: Gamma-ray burst

1. Introduction

High energy cosmic neutrinos sources are still mysterious. MASTER Global Robotic Net (Lipunov et al. 2010)[19] starts Ice Cube alert and follow up observations a few years ago. On 22 September 2017 the robotic telescope of the MASTER global network automatically imaged the error box of the high-energy neutrino event IceCube-170922A (Kopper et al. 2017). Observations were carried out 27 seconds after receiving the alert, i.e., 73 seconds after the IceCube-170922A neutrino event was detected by the IceCube observatory at the South Pole (Lipunov et al. 2018a) [23]. Observations started at 84 degree zenith distance (MASTER has fully opened roof as alert telescope).

We calibrated these images using the Gaia (Brown et al. 2018) catalog as the source of reference stars, and found the BL Lacertae type blazar TXS 0506+056 (IceCube et al. 2017) to be in the off-state after one minute and then switched to the on-state no later than two hours after the event. The effect is observed at *delta* m =0.790+-0.016 (a 50-*sigma* significance level) [27].

IceCube registered events with error regions, whose sizes are currently comparable to one square degree. Therefore finding a blazar within the error box of a VHE neutrino event cannot be considered sufficient to prove that blazars are actually progenitors of these particles. Detecting some non-standard event from the supposed source at a time close to the neutrino event is required. For example, a blazar emitting gamma and cosmic rays and showing a sharp flux variation near the neutrino detection time would provide compelling evidence of the association of the neutrino event with a known astrophysical object. The first candidate object for an astrophysical neutrino event was the blazar TXS 0506+056 (IceCube et al. 2017) [14,15] found inside the error box of the IceCube-170922A neutrino event. This blazar turned out to be located at a distance of $\tilde{3}$.7 billion light years (its redshift is z = 0.3365+/- 0.0010) (Paiano et al. 2018) [29].

TXS 0506+056 blazar was registered in the gamma-ray active state several months before the neutrino event. Detection of high-energy particles (175Gev) began one week after, and the optical, x-ray, and gamma-ray emission was observed with low temporal resolution and showed no appreciable variations near the detection time . Therefore although when combining the available data suggested that TXS 0506+056 was a very promising high energy neutrino source optical candidate, the temporal resolution of multi-messenger data did not provide conclusive evidence at the time and the object remained just a likely, but still debatable, candidate . In this letter we report conclusive detection of light variation of the blazar TXS 0506+056 just several minutes after the neutrino event, which ended no later than after two hours. For comparison, nearest ASAS-SN, Kiso/KWFC and Kanata/HONIR optical observations do not show the same decrease in optical brightness (because they started 18 hours after MASTER observations when effect disappeared. Although the blazar was in the gamma-ray active state, this state started several months before the neutrino event. Detection of high-energy particles (175Gev) began one week after, and the optical, x-ray, and gamma-ray emission was observed with low temporal resolution and showed no appreciable variations near the detection time. Therefore although when combining the available data suggested that TXS 0506+056 was a very promising high energy neutrino source optical candidate, the temporal resolution of multi-messenger data did not provide conclusive evidence at the time and the object remained just a likely, but still debatable, candidate . In this letter we report conclusive detection of light variation of the blazar TXS 0506+056 just several minutes after the neutrino event, which ended no later than after two hours. For comparison, nearest ASAS-SN, Kiso/KWFC and Kanata/HONIR optical observations do not show the same decrease in optical brightness (because they started 18 hours after MASTER observations when effect disappeared.

2. MASTER alert optical observations of IceCube-170922A error box

MASTER Global Robotic Net, as the leader of early gamma-ray burst observations (Troja et al. 2017; Ershova et al. 2020, Lipunov et al. 2016, Lipunov et al. 2017, Gorbvoskoy et al. 2016)[10,11,18,20,21,32] has an almost 20-year long experience with real-time rapid pointings to GRB alerts within the first minute of the alert . In 2015 MASTER started actively participation in the program of fast optical support of major physical and astrophysical experiments, such as detection of very high energy neutrinos (ANTARES (Dornic et al. 2015[9]; Gress et al. 2019[12]), IceCube (Aartsen et al. 2017)[1] , Baksan (Lipunov et al. 2019a)[25], gravitational waves (LIGO/VIRGO collaboration (Abbott et al. 2016)[2], and Fast Radio Bursts (FRB (Lipunov et al. 2018b)[24]). The favorable arrangement of MASTER sites makes it possible to inspect all gravitational-wave error boxes. MASTER made the crucial contribution to the optical support of the first gravitational-wave event GW 150914 by inspecting the most part of the error box (Abbott et al. 2016, Lipunov et al. 2017)[3,21]. On 17 August 2017 MASTER, together with 5 other telescopes, performed the first ever optical localization of a gravitational-wave source independently discovered Kilonova from GW 170817 (Abbot et al. 2017, Lipunov et al. 2017)[3,22].

At the 22nd of September, 2017, MASTER received an alert from IceCube event and MASTER-Tavrida telescope acquired the first three images, starting from 2017-09-22 20:55:43UT 27 sec after notice time (i.e.73s after the trigger time). The field of view of the MASTER telescope has a size of four square degrees (Lipunov et al. 2010)[19] and fully covers the final field of view of IceCube (Lipunov et al. 2020[27]).

MASTER limiting magnitude was 19.0m at 180-second frames, despite the large zenith distance (84 degrees). Hence the TXS 0506+056 blazar at the time of the alert was a 15.12 +- 0.01 magnitude object in all three frames acquired over $\tilde{1}5$ minutes (the light curve is shown in Fig. 2). There was the faintest blazar brightness over the full period of this alert. After 2 hours, at 2017-09-22 23:11:36 UT, the flux from the blazar increased in brightness by a factor of two and reached 14.33m+-0.01m. We emphasize that here in the text we give the averaged values for the triples of frames in the first minutes and after two hours (compare[27]). Hence our observations show at an extremely high confidence level of 50 sigma that within

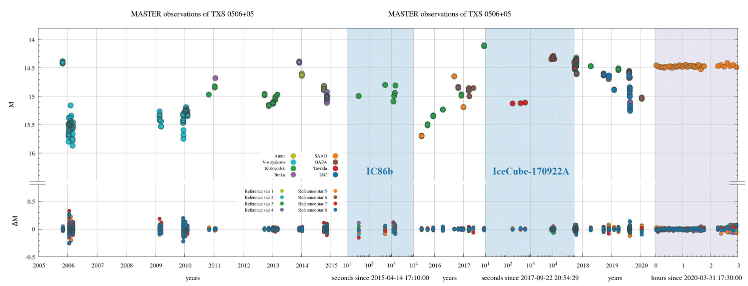

Fig. 1. MASTER light curve of the TXS 0506+056 blazar for the 16 years. Archive light curve of the TXS 0506+056 blazar based on observations made by MASTER Global Net robotic telescope of from 2005 until now (red point). Below we see the photometry of 8 reference stars, to the pink and blue panels represent three very narrow episodes in time. The first of these is April 2015 when IceCube IC86b saw a 3.5 sigma excess of the neutrino flux over the background (IceCube 2017) . The second is the 22 September 2017 event (IceCube 2017). Logarithmic time is shown in seconds from the neutrino trigger. It is easy to easily see the rapid change in the luminosity of the blazar in $\tilde{2}$ times. Finally, the third episode is a uniform blazar monitoring timeline in the first quarter of 2020. With these new observations, the total number of observations submitted reached 518 (See the photometry table) [27]

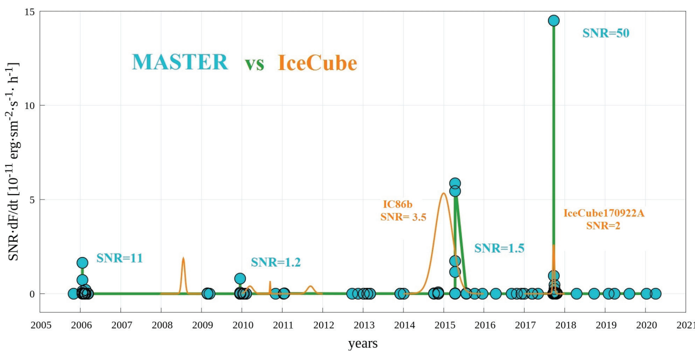

Fig. 2. MASTER optical variability rate history for blazar TXS0506+056. Flux deriviation the multiplied by the signal-to-noise ratio (blue). The orange curves schematically show the Gaussian analysis of the archive data of IceCube [27].

several minutes of the neutrino event, the blazar was in an anomalously extinguished state. This conclusion was fully confirmed during the two days after the alert, when the MASTER-SAAO robotic telescope joined the blazar observation campaign

(Lipunov et al. 2018)[23,24]

To undestand, was it a unique event for the TXS 0506+056 blazar or no, we analysed 518 2x2 square-degrees images in MASTER Global Robotic Net database, starting from 2005, when we had only one MASTER I telescope located near Moscow (Lipunov et al. 2010[19], MASTERVostryakovo)[27]. All MASTER telescopes has identical equipment, that gives us possibility to make photometry in one system (Lipunov et al. 2010, 2019b)[19,26].

Fig. 1 shows our photometry of the blazar over the last 16 years. We chose 8 Gaia catalog stars, having the brightness and color similar to those of the blazar, as photometric reference stars, and estimated the errors of individual photometric measurements from the scatter of the magnitudes of these reference stars. We also checked these stars for rapid and long-term variability and found them to be quite stable. We found three times when the brightness of the blazar varied $\tilde{0}$.5m more than 1-3 significance level. The first such time was in 2006, when IceCube neutrino observatory was not yet operating. The second time was in April 2015 (substantial increase of neutrino signal IC86b). The MASTER observation date is in April but statistically close to Gaussian IceCube half year window 9/2014 to 3/2015. And the third time was in September 2017, when the IceCube-170922 (IC86C) event occurred[27].

The event of September 22, 2017 has outstanding characteristics in terms of flux derivation and signalto- noise ratio. Recently, we conducted detailed blazar monitoring over several nights at the right end of Fig. 2. As we see in the usual state, the blazar is stable at times of several hours and even days with an accuracy of $\tilde{0}$.02 mag. This means that the instability we discovered on 22 September 2017, a few minutes after the neutrino alert, has a reliability of 50 sigma by this criterion(Fig. 2). This result shows the power of fast alert observations of sources of ultrahigh energy particles.

The event of September 22, 2017 has outstanding characteristics in terms of flux derivation and signal-to- noise ratio. Recently, we conducted detailed blazar monitoring over several nights. In the usual state, the blazar is stable at times of several hours and even days with an accuracy of $\tilde{0}$.02 mag. This means that the instability we discovered on 22 September 2017, a few minutes after the neutrino alert, has a reliability of about 40 sigma, and by this criterion. This result shows the power of fast alert observations of sources of ultrahigh energy particles.

3. Discussion

We find for the adopted set of Hubble cosmological parameters (Planck Collaboration et al. 2016)[4] H0 = 67.8 km/s/Mpc (the Hubble constant), $Omega_m = 0.308$, $\Omega_\Lambda = 0.692$ (the matter and vacuum density) that several minutes after the neutrino event the optical isotropic luminosity of the blazar was L_{opt} $4.3 * 10^{45}$ erg/s and after two hours it returned to the typical level within several weeks of the neutrino event, $9.7 * 10^{45}$ erg/s (we include galactic absorbtion AB=0.4 (Schlegel et al. 1998)[31]). The generally accepted picture (Schlegel et al. 1998)[31] is that blazar radiation arises from relativistic jet directed toward us. The boosted jet gamma factor is moderate Γ 10. In the shock wave at the front of the jet there is an acceleration of protons to ultrahigh energies, which in turn collide with target photons and generate pion production. The decay of pions, in turn, gives rise to a muon neutrino which registers an IceCube detection and high gamma photons detected by the Fermi gamma-ray observatory.

During the period within $\tilde{2}$ weeks around the neutrino event detection time the $0.1 - 100$ Gev gamma-ray luminosity was $1.3 * 10^{47}$ erg/s (IceCube et al 2017). Note that the neutrino luminosity of the quasar was equal to about $4 * 10^{47}$ erg/s, which is appreciably higher and, evidently, closer to the gamma-ray luminosity. However, this is not surprising because neutrinos and gamma-ray emission have the same source of energy — that of high-energy protons accelerated by the central supermassive black hole.

The event that we discovered, namely the decrease of the brightness of the TXS 0506+056 blazar near the neutrino detection time, provides complementary and very compelling evidence for the link between the blazar and the IceCube-170922 neutrino event. We analyzed archival data (MASTER unique 518 photometry data for 16 years), which we found to be consistent with this fact. We also propose a hypothesis explaining the anti correlation of the optical and neutrino flux. An increase in neutrino flux means that up to half of the protons disappear. If we assume that these protons produce synchrotron optical radiation, then any increase in neutrino luminosity will lead to a decrease in the optical brightness of the blazar.

MASTER and Lomonosov Space Observatory are supported by Lomonosov Moscow State University Development program (equipment). VL, PB are supported by RFBR grant 19-29-11011. NB is supported by FZZE-2020-0017).

References

1. Aartsen M. et al., 2017, A&A 607, A115
2. Abbott B.P. et al. 2016, ApJL, 826, 13A
3. Abbot B. P. et al. 2017, ApJL, 848 (2), L12
4. Planck Collaboration et al. 2016, A&A, 594, A13
5. Ageron M.et al. 2011, NIMPh, 656, 11
6. Balkanov V. et al. 2002, NuPhS, 110, 504B
7. Boliev M.M. et al. 2018, PPN , 49 (4), 585
8. Brown A.G.A. et al. 2018, A&A, 616, A1
9. Dornic D. et al. 2015, ATel, 7987, 1
10. Ershova O. et al. 2020, ARep, 64 (2), 126
11. Gorbovskoy et al. 2016, MNRAS, 455, 3312
12. Gress O. et al. 2019, RMxAA, 51, 89
13. Hayakava S., Yamamoto Y. 1963, PThPh, 30, 71
14. IceCube Collaboration et al. 2017, Sci, 361, eaat1378
15. IceCube Collaboration. 2017, Sci, 361, 147
16. Kopper C.et al. 2017, GCN Circ, 21916, 1
17. Kornilov V. et al. 2012, ExpAst, 33, 173

18. Laskar et al. 2019, ApJ, 884, 121
19. Lipunov V. et al. 2010, AdAst, 2010, 30L
20. Lipunov V. et al. 2016, MNRAS, 455, 3312
21. Lipunov V. et al. 2017, MNRAS , 465 (3), 3656
22. Lipunov V. et al. 2017, ApJL, 850, 1L
23. Lipunov V.M. et al. 2018a, GCN Circ, 22942, 1
24. Lipunov V. et al. 2018b,ATel, 11902, 1
25. Lipunov V. et al. 2019a, GCN Circ, 26539, 1
26. Lipunov V. et al. 2019b, ARep, 63,293
27. Lipunov V. et al. 2020, ApJ, 896L, 19L
28. ORiordan M., Pe'er A., McKinney J. C. 2017, ApJ, 843, 2, id. 81
29. Paiano S. et al. 2018, ApJ, 854, L32
30. Paliya V.S.et al. 2020, a-ph: 20034.060112v2 , https://arxiv.org/abs/2003.06012
31. Schlegel D., Finkbeiner D., Davis M. 1998, ApJ, 843, 525
32. Troja et al., 2017a, Natur, 547, 425T