Modelling the electromagnetic and neutrino flux for the IceCube candidate source TXS 0506+056

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Half a Century of Blazars and Beyond
Torino, Italy, June 2018
Outline

- TXS 0506+056 - the first high-energy neutrino source?
- LEHA - a lepto-hadronic one-zone emission model
- Proton-synchrotron solutions for TXS 0506+056
- Mixed lepto-hadronic solutions for TXS 0506+056
- Conclusions
TXS 0506+056 - the first high-energy neutrino source?
Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu
The H.E.S.S. array of imaging atmospheric Cherenkov telescopes was used to carry out follow-up observations of a high-energy neutrino detected by IceCube on 22 September 2017 at 20:54:30.43 UTC. H.E.S.S. observed the region around the IceCube best fit position (RA=77.43 deg, Dec=-5.72 deg; GCN circular #21916) in two consecutive nights for about 1h each. First observations started 23 September 2017 at 01:05 UTC (about 4h after the neutrino detection). A second set of observations were obtained the following night (24 September 2017 at 03:10 UTC). A preliminary on-site calibration and analysis searching for a point-like gamma-ray source from within the 90% uncertainty region of the neutrino event IceCube-170922A revealed no significant detection. H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes for the detection of very-high-energy gamma-ray sources and is located in the Khomas Highlands in Namibia. It was constructed and is operated by researchers from Armenia, Australia, Austria, the Czech Republic, France, Germany, Ireland, Netherlands, Japan, Poland, South Africa, Sweden, UK, and the host country, Namibia.
TXS 0506+056 - first high-energy neutrino source?

H.E.S.S. follow-up of IceCube-170922A

ATel #10787; Mathieu de Naurois for the H. E. S. S. collaboration on 27 Sep 2017; 14:33 UT

Credential Certification: Fabian Schassler (fabian.schassler@cern.ch)

Subjects: VHE, Neutrinos

Referred to by ATel #: 10799, 10817, 10830, 10833, 10844

The H.E.S.S. array of imaging atmospheric Cherenkov telescopes was triggered by observations of a high-energy neutrino detected by IceCube on 22 Sep 2017 UTC. H.E.S.S. observed the region around the IceCube best position (RA=05h06m, Dec=-5.72 deg; GCN circular #21916) in two consecutive nights observations started 23 September 2017 at 01:05 UTC (about 4h after the best position). Second set of observations were obtained the following night (24 Sep 2017).

A preliminary on-site calibration and analysis searching for a point-like source within the 90% uncertainty region of the neutrino event IceCube-170922A did not find a detection. H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes of very high energy gamma-ray sources and is located in the Khomas Hochland, Republic, France, Germany, Ireland, Netherlands, Japan, Poland, South Africa, the host country, Namibia.

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration on 28 Sep 2017; 10:10 UT

Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27).

Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/−0.5)E-7 photons
TXS 0506+056 - first high-energy neutrino source?

H.E.S.S. follow-up of IceCube-170922A

ATel #10787; Mathieu de Naurois for the H. E. S. collaboration
on 27 Sep 2017; 14:33 UT

Credential Certification: Fabian Sch"{a}tzer (fabian.schatzer@ totalitarian.de)

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; Razmik Mirzoyan for the MAGIC Collaboration
on 4 Oct 2017; 17:17 UT

Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10842

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After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are detected from this blazar.

Indeed, the LAT 0.1-300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons sr^-1 s^-1.
TXS 0506+056 - first high-energy neutrino source?

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H.E.S.S. follow-up of IceCube-170922A

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

VERITAS follow-up observations of IceCube event 170922A

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

Subjects: X-ray, Gamma Ray, >GeV, TeV, Neutrinos, AGN, Blazar, Quasar

Referred to by ATEL #: 10861
TXS 0506+056 - first high-energy neutrino source?

- IceCube alert for track-like VHE event (EHE sample) - most likely astrophysical muon neutrino, $E > 100$ TeV - on 22 sept. 2017

- Arrival direction $< 0.1$ deg from the position of the BL Lac object TXS 0506+056 (constrained in about 1 deg$^2$)

- TXS 0506+056 was in a high state (flux up to 6 times that of low state seen with Fermi-LAT) from April - October 2017; detected also with AGILE

- First detection of VHE emission with MAGIC from 28 sept. to 4 oct.; detected also with VERITAS

- Recent redshift measurement $z = 0.3365 \pm 0.0010$ (Paiano et al. 2018 -> poster !)

- No determination of the black hole mass
Available data

**SWIFT UVOT**: V/U/B/W1/M2/W2 - flat spectrum  
(27/9/2017)

**Fermi-LAT**: 2.06 ± 0.08 (15 - 27/9/2017)

**archival data**  
(SSDC)

**SWIFT XRT**: power-law with index 2.58 ± 0.09  
(27/9/2017)

**NuStar**: power-law with index 1.59 ± 0.08  
(29/9/2017)

PRELIMINARY (FPMA)
LEHA - a lepto-hadronic one-zone emission model
LEHA - a lepto-hadronic one-zone emission model
the “LEHA” code

stationary one-zone LEpto-HAdronic model for BL Lac objects

- models all emission processes due to e- and p+ interactions in the source

- we usually impose physical constraints:

  -- power-law spectra with same index for p+ and e- (co-acceleration)

  -- spectral breaks from synchrotron cooling.

  -- max. p+ energy from comparison of acceleration and cooling time scales

  \[ \text{\rightarrow 7 free parameters} \]

  -- verify variability time scale constraint:
  \[ \frac{R}{\delta} \leq c \frac{\Delta t_{\text{obs}}}{(1+z)} \]

  -- verify jet power requirements
  \[ L_j \approx 2 \pi R^2 \beta c \Gamma^2 (u_B + u_e + u_p) + 2 L_r \]
Monte Carlo treatment of proton-photon interactions with the *Sophia* code (*Mücke et al. 2000*)

- treatment of all photopion production channels with resulting particle spectra (including $\nu$ spectra…)
- explicit treatment of unstable particles (muons, pions, Kaons…)

Bethe-Heitler pair production (analytical) : *Kelner & Aharonian* (2009)

Leptons and gammas from proton-photon interactions have very high energies

$\rightarrow$ generate **synchrotron-pair cascades** through interactions with photon field

*Mücke et al. 2000*
Some applications of LEHA

Systematic exploration of hadronic solutions for PKS 2155-304 and Mrk 421 during low states & predictions for the CTA

Proton-synchrotron and mixed lepto-hadronic solutions for extreme blazars

Exploration of neutrino spectra for
Centaurus A, PG 1553+113, PKS 2155-304
(astro-ph 1610.00255)

Lepto-hadronic models for the high-redshift
BL Lac object PKS 1424+240
Proton-synchrotron solutions for TXS 0506+056
a hadronic (proton-synchrotron) interpretation for TXS 0506+056

$$\delta = 30, \ R = 4.2 \times 10^{16} \ cm, \ B = 3 \ G, \ \gamma_{p,\text{max}} = 1.7 \times 10^9, \ L_{\text{jet}} = 2.9 \times 10^{47} \ erg/s$$

Number of IceCube $\mu$-neutrinos expected for 6 month high state : $\sim 0.03$

Poisson probability for detection of 1 muon-neutrino : $\sim 3\%$
### systematic exploration of proton-synchrotron solutions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>0.3365</td>
</tr>
<tr>
<td>$\delta$</td>
<td>30 - 50</td>
</tr>
<tr>
<td>$R_{\text{src}}$ [1e16 cm]</td>
<td>0.3 - 9.7</td>
</tr>
<tr>
<td>$\tau_{\text{var}}$ [days]</td>
<td>0.03 - 1</td>
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<tr>
<td>$B$ [G]</td>
<td>0.2 - 7.1</td>
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<tr>
<td>$\gamma_{\text{e, min}}$</td>
<td>200</td>
</tr>
<tr>
<td>$\alpha_{\text{e,1}} = \alpha_{\text{p,1}}$</td>
<td>2</td>
</tr>
<tr>
<td>$\alpha_{\text{e,2}} = \alpha_{\text{p,2}}$</td>
<td>3</td>
</tr>
<tr>
<td>$\gamma_{\text{p, min}}$</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma_{\text{p, max}}$</td>
<td>2.3e+08 - 1.7e+09</td>
</tr>
<tr>
<td>$u_{\text{p}}/u_B$</td>
<td>10 - 1038</td>
</tr>
<tr>
<td>$L_{\text{jet}}$ [1e46 erg s^-1]</td>
<td>4 - 170</td>
</tr>
</tbody>
</table>

Scan of $v_{p,\text{syn}}$ in log-steps of 0.1 and Doppler factor in steps of 5.

- Satisfactory solutions for B-field values $0.5 \text{ G} < B < 10 \text{ G}$

- Minimum jet power $4\text{e46 \text{ erg/s}}$

- Accommodates variability down to below day-scale
proton-synchrotron solutions: expected neutrino rate

- minimum and maximum expected rates for IceCube:
  \[0.003 - 0.053 \, \mu\text{-neutrinos} / \text{year}\]

- Poisson probabilities for finding 1 \(\mu\)-neutrino / 6 months given the flux estimations from the model:
  \[0.1\% - 2.6\%\]

-> Proton-synchrotron solutions are not favorable for a direct link with the IceCube event.
Mixed lepto-hadronic solutions for TXS 0506+056
starting with a pure SSC interpretation

$\delta = 20, \ R = 2.7\times10^{16} \ cm, \ B = 0.2 \ G, \ N_p = 0, \ L_{\text{jet}} = 2\times10^{43} \ erg/s$

Start from this solution, increase $\gamma_{\text{min,e}}$ (here =100), and add a hadronic component that is limited by the NuStar spectrum $\rightarrow$ maximum hadronic contribution
a lepto-hadronic interpretation for TXS 0506+056

\[ \delta = 20, \ R = 2.7 \times 10^6 \text{ cm}, \ B = 0.2 \text{ G}, \ \gamma_{e, \text{min}} = 500, \ \gamma_{p, \text{max}} = 3.4 \times 10^8, \ \mathcal{L}_{\text{jet}} = 6.0 \times 10^{47} \text{ erg/s} \]

Number of IceCube \( \mu \)-neutrinos expected for 6 month high state: \( \sim 0.18 \)

Poisson probability for detection of 1 muon-neutrino: \( \sim 15\% \)
systematic exploration of mixed lepto-hadronic solutions

Tested four values for B-field and 3 values for Doppler factor.

-> satisfactory solutions for B-field values 0.1 G < B < 1 G

-> minimum jet power 2e47 erg/s

-> accommodates variability down to below day-scale

-> far out of equipartition
mixed lepto-hadronic solutions: expected neutrino rate

- minimum and maximum expected rates for IceCube:
  
  0.19 - 1.23 $\mu$-neutrinos / year

- Poisson probabilities for finding 1 $\mu$-neutrino / 6 months given the flux estimations from the model:
  
  9% - 33%

- Keep in mind that the lepto-hadronic scenario, the hadronic contribution and neutrino flux can be arbitrarily low, depending on $\gamma_{e,\text{min}}$
Conclusions

- The SED of TXS 0506+056 is rather well constrained (especially in X-rays).

- Proton-synchrotron scenario: good solutions for broad-band SED, but difficult to account for IceCube event.

- Mixed lepto-hadronic scenario: good solutions for broad-band SED; accounts well for Ice Cube event.

- Waiting for more details on Ice Cube events and on VHE data…

Thank You!
LEHA simulates **synchrotron-pair cascades** triggered by:

- $\gamma$-$\gamma$ absorption of proton-synchrotron photons, muon synch. photons, photons from $\pi^0$

- $e^+ e^-$ pairs from Bethe-Heitler, leptons from $\pi^+$, $\pi^-$

Repeat over $\sim 3$ generations.
Fermi light curve
hadronic parameter space for HBLs

hadronic model - time-scales

Fig. 6. SEDs for PKS 2155-304 with two hadronic models where proton synchrotron emission (left figure) or muon-synchrotron emission (right figure) dominates the TeV spectrum. These solutions correspond to a spectral index of $n_1 = 2.1$ and 1.9, a magnetic field with $\log B_\text{[G]} = 0.3$ and 0.7, and an emission region of size $\log R_{[\text{cm}]} = 9 \times 10^{16}$ and $1.5 \times 10^{16}$, respectively. See Fig. 2 for a description of the different curves. The dataset is described in the text.
High-energy neutrinos from PKS 2155-304?

Hadronic models produce very-high-energy neutrino flux, peak around $10^{17} - 10^{19}$ eV.

-> Out of reach for IceCube / KM3Net? Need to evaluate detectability with GRAND, etc. …


emitting region dense, cascades important

emitting region less dense, cascades less important

B=80 G

B=2G