PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Black-hole X-ray binaries in the new era of multi-messenger Astronomy

D. Kantzas,[a,b,*] **S. Markoff,**[a,b] **M. Lucchini**[c] **and C. Ceccobello**[d]

[a] *Anton Pannekoek Institute for Astronomy (API), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands*

[b] *GRavitational AstroParticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands*

[c] *MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[d] *Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, 439 92 Onsala, Sweden*

E-mail: d.kantzas@uva.nl

Since their discovery, cosmic rays (CRs) remain among the most mysterious phenomena of modern physics. The dominant sources, as well as the exact acceleration mechanisms, remain unknown. The CRs up to the "knee", are considered to originate in the shock waves of Galactic supernova remnants, however, due to the lack of a "smoking-gun" TeV counterpart in many cases, this scenario has been recently questioned. In this work, we motivate how the small-scale analogues of active galactic nuclei, namely black-hole X-ray binaries (BHXBs), can potentially contribute to the Galactic CR spectrum. To investigate this idea, we developed a new, multi-zone, lepto-hadronic jet model to take advantage of the entire broadband multiwavelength spectra observed by BHXBs. We statistically apply this model to the first-ever simultaneous radio-to-X-ray spectrum of Galactic BHXB Cygnus X–1 obtained in 2016 (via the CHOCBOX program), and to a quasi-simultaneous dataset of another Galactic BHXB, GX 339–4, during a bright outburst in 2010. In this work, we discuss how the different assumptions on proton acceleration affect both the jet properties and the observed spectrum. In particular, we focus on the GeV-to-TeV regime and discuss its strong dependence on the rest of the multiwavelength spectrum. Finally, we discuss the implication of the results for the next-generation gamma-ray facilities, such as the Cherenkov Telescope Array (CTA), as well as next-generation neutrino detectors, such as KM3NeT, concluding how they can help to constrain the potential BHXB contribution to the Galactic CR spectrum.

*37*th *International Cosmic Ray Conference (ICRC 2021)*
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)1011

1. Introduction

Cosmic Rays (CRs) are elementary particles of astrophysical origin that, despite the decades of research, their exact sources remain unclear. CRs that reach only the "knee" of the observed spectrum, requiring particles of $\sim$ 1 PeV, are most likely of Galactic origin, whereas ultra-high-energy CRs of the order of EeV are of extragalactic origin [1].

The most popular candidate sources of Galactic CRs are supernovae (SNe) and young supernova remnants (SNRs). Based mainly on power arguments, SNRs are considered capable of accelerating particles up to PeV to dominate the Galactic part of the CR spectrum [2, 3]. Such PeV particles can shine up to the TeV-to-PeV regime of the electromagnetic spectrum due to inelastic collisions with the ambient medium or inverse Compton scattering. However, TeV observations of SNRs show a very soft spectrum, or even a cutoff, questioning the SNR paradigm [4]. Moreover, recent PeV observations by the LHAASO collaboration suggest the existence of Galactic PeVatrons of as-yet unidentified nature [5].

Sources that accelerate protons up to high energies of the order of PeV should inevitably be candidate sources of astrophysical neutrinos as well. The same hadronic processes responsible for the γ-ray counterpart lead to the formation of electron and muon neutrinos in the TeV-to-PeV energy band [6]. Consequently, studying the γ-ray profile of a source, assuming that it accelerates protons, is identical to seeking the sources of CRs and neutrinos. Finally, detecting astrophysical neutrinos from a particular source, is strong evidence for efficient proton acceleration in that source.

In the last 15 years, the Galaxy has revealed many new sources of γ-rays than expected. For instance, we have detected γ-rays from mildly relativistic jets launched by accreting stellar black holes in X-ray binaries (BHXBs henceforth). First, the high-mass BHXBs Cygnus X–3 [7] and Cygnus X–1 (Cyg X–1) [8, 9] were detected in the GeV band, and recently, SS 433 was detected up to the TeV γ-ray regime [10]. These sources are observed to launch energetic jets capable of accelerating particles and affecting their ambient medium [11]. It is yet not clear whether these particles can reach some energy of the order of PeV, and what is the nature of these particles (electrons or ions).

The future ground-based TeV facility of the Cherenkov Telescope Array (CTA) will be searching for new γ-ray sources in the Milky Way with the Galactic Plane Survey thanks to its increased sensitivity compared to previous facilities like HESS [12]. With this work, we can provide updated estimates on the γ-ray emission of BHXBs that can be incorporated into CTA's plans searching for the missing PeVatrons. To get a robust γ-ray prediction, we consider the entire radio-to-X-ray spectrum emitted by the Galactic jets, and finally, provide self-consistent calculations of the expected neutrino fluxes that could further hint for hadronic acceleration inside the BHXB jets.

2. Lepto-hadronic jet model

To examine how likely is BHXBs to contribute to the low-energy part of the CR spectrum, we study the spectral energy distribution (SED) up to the TeV γ-rays, connecting it to the neutrino counterpart emitted by such sources. Based on the semi-analytical, multi-zone, leptonic jet model of [13], we developed a new lepto-hadronic jet model that takes into account the proton-proton (pp) and proton-photon (pγ) interactions to produce γ-rays via the neutral pion decay [14]. We

PoS(ICRC2021)1011

further included the neutrino fluxes as presented below (see 3.2) to discuss the potential neutrino counterpart.

3. BHXBs as multi-messengers

We examine the first-ever simultaneous radio-to-X-ray spectrum of the prototypical high-mass BHXB Cyg X–1obtained by the CHOXBOX campaign (Cyg X–1 Hard state Observations of a Complete Binary Orbit in X-rays; [14]). By finding the statistically best fit of this spectrum we can predict the γ-ray emission and the neutrino flux.

Cyg X–1 shows two persistent jets that shine in the radio bands via synchrotron radiation of accelerated electrons [15]. The contribution of these electrons in the X-ray spectrum is still debatable, but the X-ray polarization measurements of the *INTEGRAL* satellite suggest that the compact jets shine in the MeV spectrum as well [16–19]. The high fraction of the linear polarization challenges the comptonization models in this energy range, favoring the synchrotron emission from jets. To achieve such an MeV flux with synchrotron radiation we require the accelerated electrons to follow a hard power-law in energy with an index of 1.7.

We furthermore examine the prototypical low mass BHXB GX 339–4 when it went into a bright outburst in 2010. GX 339–4 is a well-studied source but its spectrum is not fully understood yet and has not shown any γ-ray emission so far. We search for the best fit of the quasi-simultaneous spectrum obtained during this outburst in 2010 and predict the γ-ray emission up to the TeV band (Kantzas et al. submitted). In this particular work we show the predicted neutrino fluxes based on the dynamical quantities of the jets that satisfy the entire radio-to-X-ray spectrum (see below).

3.1 The γ-ray spectrum

Cyg X–1 has been detected in the GeV γ-rays [8, 9, 20] but has not yet shown any persistent TeV emission. Recently, the HAWC collaboration presented some upper limits after five years of operation, assuming that the γ-ray spectrum would follow a soft power-law in photon energy. Cyg X–1 though was mostly in the soft state during the operation time of HAWC which means that jets were quenched hence HAWC would not detect any TeV emission from the jets anyway. We plot the best-fit of the spectrum of Cyg X–1 and compare them to the upper limits HAWC has set in the soft state in Fig. 1.

3.2 The neutrino fluxes

There are no astrophysical neutrinos detected to originate in our Galaxy yet. Detecting such a neutrino would strongly favor the hadronic acceleration in a Galactic source and mark this source as a potential CR contributor. To study whether BHXBs and, in particular, if Cyg X–1 and/or GX 339–4 can produce neutrinos, we calculate the intrinsic neutrino fluxes due to pp and pγ collisions inside the jets. We follow the semi-analytical approximation of [23, 24].

3.2.1 Neutrino spectra

In Fig. 2 we plot the intrinsic fluxes of electron (left) and muon (right) neutrinos and anti-neutrinos based on the best fit parameters for the dynamical quantities of the jets of Cyg X–1

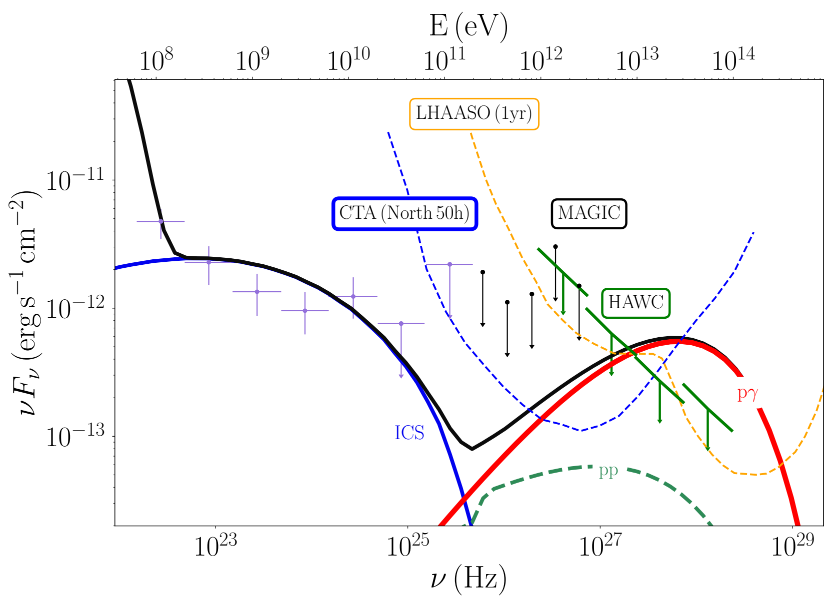

Figure 1: The predicted spectral energy distribution of Cyg X–1 in the GeV-to-TeV energy band. The physical jet parameters are those of [14]. We also include here the 5 yr upper limits set by the HAWC collaboration while the jets of Cyg X–1 were quenched (the so-called soft state) just for comparison [21]. The rest of the depicted data are the *Fermi*/LAT data from [20] and the 7 yr upper limits of the MAGIC collaboration [22].

[14]. We see that the two different physical processes contribute to different parts of the neutrino spectrum. In particular, pp interactions produce a relatively softer distribution covering the lowest part, whereas pγ interactions lead to a more sharp distribution in the highest energies.

Each jet segment contributes to the intrinsic neutrino flux. In Fig. 3 we integrate the entire intrinsic muon neutrino flux of Cyg X–1 and plot it against the most sensitive upper limits derived so far by the IceCube collaboration [25].

We further plot the predicted intrinsic neutrino flux of GX 339–4 in Fig. 4. Both neutrino fluxes of Cyg X–1 and GX 339–4 are significantly below the upper limits derived by IceCube and thus more sensitive detectors such as KM3NeT/ARCA are required [26].

3.2.2 Total neutrino fluxes

We calculate the rate of muon and electron neutrinos and anti-neutrinos of both Cyg X–1 and GX 339–4 utilizing the following expression:

$$R = \int 4\pi \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} A_{\mathrm{eff}}(E_\nu)\, \mathrm{d}E_\nu, \qquad (1)$$

where $\mathrm{d}\Phi_\nu/\mathrm{d}E_\nu$ is the neutrino differential flux, A_{eff} is the effective area of the detector, and we integrate between energies of 0.1 TeV and 10 PeV. We use the effective areas of IceCube [25, 29], ANTARES [30] and the simulated effective area of KM3NeT/ARCA [26].

As we show in Table 1, IceCube would be able to detect of the order of 0.7 neutrinos per year coming from Cyg X–1 when it launches its jets. Facilities such as KM3NeT/ARCA that is currently under construction in the Mediterranean sea, will detect about 0.9 neutrinos per year. Although KM3NeT/ARCA is more sensitive than IceCube when observing the southern hemisphere, Cyg X–1

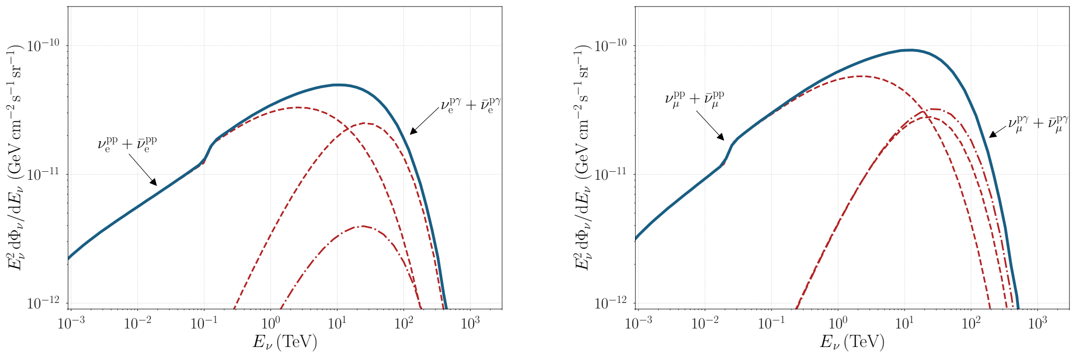

Figure 2: The intrinsic neutrino spectra of Cyg X–1. We plot on the left the electron neutrino and anti-neutrino distributions derived from both pp and pγ processes. On the right plot, we show the muon neutrino and anti-neutrino distributions.

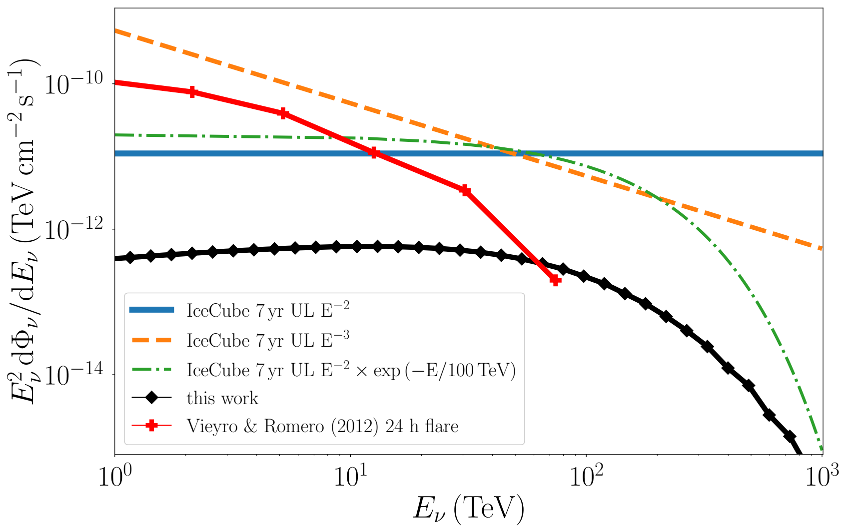

Figure 3: The total muon neutrino and anti-neutrino flux of the jets of Cyg X–1 multiplied by the square of the energy. We compare to the IceCube upper limits based on three different model assumptions as shown in the legend [25]. We also compare our results to the previous work of [27].

is observable from the northern hemisphere for which both these two detectors have almost the same sensitivity. The neutrino rates of GX 339–4 are significantly lower making it hard for current and future facilities to anticipate any persistent neutrino emission from this source.

4. Summary

CR sources remain one of the long-standing open questions. In this work, we discuss whether BHXBs could potentially contribute to the CR spectrum, at least up to the "knee" where the Galactic sources are likely to dominate.

PoS(ICRC2021)1011

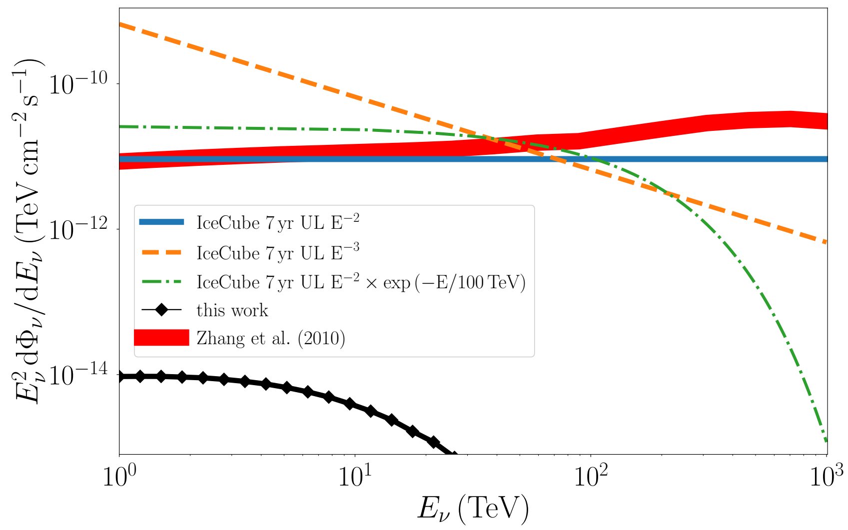

Figure 4: The total muon neutrino and anti-neutrino flux of the jets of GX 339–4 multiplied by the square of the energy. We compare to the IceCube upper limits based on three different model assumptions as shown in the legend [25]. We also compare our results to the previous work of [28].

source	flavor	IceCube	ANTARES	KM3NeT/ARCA
Cyg X–1	ν_μ	0.7	0.005	0.9
	ν_e	0.002	0.0008	0.3
GX 339–4	ν_μ	1.4×10^{-7}	0.00008	0.008
	ν_e	6.2×10^{-7}	0.00009	0.004

Table 1: The neutrino rate in yr^{-1} for Cyg X–1 and GX 339–4 for the various detectors.

To do this, we indirectly study whether BHXBs can accelerate particles up to PeV energies. CRs that carry energy of the order of PeV interact with the ambient medium and give rise to secondary particles (in case of protons). A γ-ray observation, along with a neutrino counterpart would strongly favor the assumption that BHXBs may be considered PeVatrons.

To further constrain our assumptions regarding the proton acceleration inside the jets launched by stellar BHs, we study the canonical case of Cyg X–1 and the prototypical low mass BHXB GX 339–4. For the case of Cyg X–1, we use the simultaneous radio-to-X-ray spectrum to find the best fit of the SED and extract the physical jet parameters. We find that protons may gain energy of the order of 1 PeV following a hard power-law distribution. Such energetic particles can shine in the TeV regime of the electromagnetic spectrum, where CTA will be able to either confirm or reject such a scenario. Finally, in case of efficient hadronic acceleration, we predict that the jets of Cyg X–1 may be point-like neutrino sources that emit 0.7 (0.9) neutrinos per year that can potentially be detected by IceCube (KM3NeT/ARCA).

The aforementioned neutrino emission would be detected as a point-like source in the sky. We plan to account for the escape of particles from the accelerating region and the CR diffusion along the Galaxy in a following work to constrain the diffuse emission of Cyg X–1 and GX 339–4 and eventually, the whole jetted BHXB population.

References

[1] L.O. Drury, *Origin of cosmic rays*, *Astroparticle Physics* **39-40** (2012) 52.

[2] A.M. Hillas, *Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays?*, *Journal of Physics G: Nuclear and Particle Physics* **31** (2005) R95.

[3] P. Blasi, *The origin of galactic cosmic rays.*, *Astronomy & Astrophysics Review* **21** (2013) 1 .

[4] F. Aharonian, R. Yang and E. de Oña Wilhelmi, *Massive stars as major factories of Galactic cosmic rays*, *Nature astronomy* **3** (2019) 561.

[5] Z. Cao, F.A. Aharonian, Q. An, Axikegu, L.X. Bai, Y.X. Bai et al., *Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources*, *Nature* **594** (2021) 33.

[6] K. Mannheim and R. Schlickeiser, *Interactions of cosmic ray nuclei*, *A&A* **286** (1994) 983.

[7] M. Tavani, A. Bulgarelli, G. Piano, S. Sabatini, E. Striani, Y. Evangelista et al., *Extreme particle acceleration in the microquasar cygnus x-3*, *Nature* **462** (2009) 620.

[8] S. Sabatini, M. Tavani, P. Coppi, G. Pooley, M.D. Santo, R. Campana et al., *gamma-ray observations of Cygnus X-1 above 100 MeV in the hard and soft states*, *ApJ* **766** (2013) 83.

[9] D. Malyshev, A.A. Zdziarski and M. Chernyakova, *High-energy gamma-ray emission from Cyg X-1 measured by Fermi and its theoretical implications*, *MNRAS* **434** (2013) 2380.

[10] A. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. Álvarez, R. Arceo et al., *Very-high-energy particle acceleration powered by the jets of the microquasar SS 433*, *Nature* **562** (2018) 82.

[11] I.F. Mirabel and L.F. Rodriguez, *Sources of relativistic jets in the galaxy*, *Annual Review of A&A* **37** (1999) 409.

[12] CTA, *Design Concepts for the Cherenkov Telescope Array*, *Experimental Astronomy* **32** (2011) 193.

[13] S. Markoff, M.A. Nowak and J. Wilms, *Going with the Flow: Can the Base of Jets Subsume the Role of Compact Accretion Disk Coronae?*, *ApJ* **635** (2005) 1203.

[14] D. Kantzas, S. Markoff, T. Beuchert, M. Lucchini, A. Chhotray, C. Ceccobello et al., *A new lepto-hadronic model applied to the first simultaneous multiwavelength data set for Cygnus X–1*, *MNRAS* **500** (2020) 2112.

[15] A. Rushton, J. Miller-Jones, R. Campana, Y. Evangelista, Z. Paragi, T. Maccarone et al., *A weak compact jet in a soft state of Cygnus X-1*, *MNRAS* **419** (2012) 3194.

[16] P. Laurent, J. Rodriguez, J. Wilms, M. Cadolle Bel, K. Pottschmidt and V. Grinberg, *Polarized Gamma-Ray Emission from the Galactic Black Hole Cygnus X-1*, *Science* **332** (2011) 438 [1104.4282].

[17] E. Jourdain, J. Roques, M. Chauvin and D. Clark, *Separation of two contributions to the high energy emission of Cygnus X-1 polarization measurements with INTEGRAL SPI*, *ApJ* **761** (2012) 27.

[18] J. Rodriguez, V. Grinberg, P. Laurent, M.C. Bel, K. Pottschmidt, G. Pooley et al., *Spectral State Dependence of the 0.4-2 MeV Polarized Emission in Cygnus X-1 Seen with INTEGRAL/IBIS, and Links with the AMI Radio Data*, *ApJ* **807** (2015) 17.

[19] F. Cangemi, T. Beuchert, T. Siegert, J. Rodriguez, V. Grinberg, R. Belmont et al., *Potential origin of the state-dependent high-energy tail in the black hole microquasar Cygnus X-1 as seen with INTEGRAL, arXiv preprint arXiv:2102.04773* (2021) .

[20] R. Zanin, A. Fernández-Barral, E. de Oña Wilhelmi, F. Aharonian, O. Blanch, V. Bosch-Ramon et al., *Gamma rays detected from Cygnus X-1 with likely jet origin*, *A&A* **596** (2016) A55.

[21] A. Albert, R. Alfaro, C. Alvarez, J.R.A. Camacho, J.C. Arteaga-Velázquez, K.P. Arunbabu et al., *HAWC Search for High-mass Microquasars*, *ApJ Letters* **912** (2021) L4.

[22] M.L. Ahnen, S. Ansoldi, L. Antonelli, C. Arcaro, A. Babić, B. Banerjee et al., *Search for very high-energy gamma-ray emission from the microquasar Cygnus X-1 with the MAGIC telescopes*, *MNRAS* **472** (2017) 3474.

[23] S. Kelner, F.A. Aharonian and V. Bugayov, *Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime*, *Physical Review D* **74** (2006) 034018.

[24] S. Kelner and F. Aharonian, *Energy spectra of gamma rays, electrons, and neutrinos produced at interactions of relativistic protons with low energy radiation*, *Physical Review D* **78** (2008) 034013.

[25] M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Search for Sources of Astrophysical Neutrinos Using Seven Years of IceCube Cascade Events*, *ApJ* **886** (2019) 12.

[26] S. Adrián-Martínez, M. Ageron, F. Aharonian, S. Aiello, A. Albert, F. Ameli et al., *Letter of intent for KM3NeT 2.0*, *Journal of Physics G: Nuclear and Particle Physics* **43** (2016) 084001.

[27] F.L. Vieyro and G.E. Romero, *Particle transport in magnetized media around black holes and associated radiation*, *A&A* **542** (2012) A7.

[28] J.F. Zhang, Y.G. Feng, M.C. Lei, Y.Y. Tang and Y.P. Tian, *High-energy neutrino emission from low-mass microquasars*, *MNRAS* **407** (2010) 2468.

[29] M.G. Aartsen, R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J. Aguitar et al., *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, *Science* **342** (2013) .

[30] ANTARES Collaboration collaboration, *First all-flavor neutrino pointlike source search with the ANTARES neutrino telescope*, *Phys. Rev. D* **96** (2017) 082001.