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SEARCH FOR NEUTRINO EMISSION FROM MICROQUASARS WITH THE ANTARES TELESCOPE

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Abstract. Neutrino telescopes are nowadays exploring a new window of observation on the high energy universe and may shed light on the longstanding problem regarding the origin of cosmic rays. The ANTARES neutrino telescope is located underwater 40 km offshore from the Southern coast of France, on a plateau at 2475 m depth. Since 2007 it observes the high energy ($>$ 100 GeV) neutrino sky looking for cosmic neutrino sources. Among the candidate neutrino emitters are microquasars, i.e. galactic X-ray binaries exhibiting relativistic jets, which may accelerate hadrons thus producing neutrinos, under certain conditions. These sources are also variable in time and undergo X-ray or gamma ray outburst that can be related to the acceleration of relativistic particles witnessed by their radio emission. These events can provide a trigger to the neutrino search, with the advantage of drastically reducing the atmospheric neutrino background.

A search for neutrino emission from microquasar during outbursts is presented based on the data collected by ANTARES between 2007 and 2010. Upper limits are shown and compared with the predictions.

Keywords: Neutrinos, Quasars: general

1 Introduction

The ANTARES neutrino telescope (Ageron et al. 2011) is composed of 885 photomultiplier tubes (PMTs) hosted within pressure resistant glass spheres, referred to as optical modules (OMs), that constitute the sensitive part of the detector. The OMs are arranged on 12 lines of 480 m height each, on substructures referred to as storeys, each hosting 3 OMs, spaced by 14.5 m along each line. Lines 1-11(12) host 25(20) storeys. The detector is located 40 km offshore from the coast of Southern France and started taking physics data since January 2007, when it was composed of only five detection lines, and was finally completed to its twelve line configuration in May 2008.

High energy muon neutrinos that interact in the proximity of the detector by charged current interactions are converted into muons that produce Cherenkov light as they displace in water. The space-time distribution of the Cherenkov light signals at the OMs allows the reconstruction of the muon's trajectory which is very close to that of the originating neutrino, allowing a pointing accuracy of less than one degree. The track reconstruction algorithm is based on a likelihood maximization method and provides the direction of the incoming muons, whereas the maximized likelihood is used to define the quality cuts for the event selection. The median angular resolution to a neutrino flux $\propto E_\nu^{-2}$ is $0.5° \pm 0.1°$. The main particle background is due to neutrinos produced by the interaction of cosmic rays with the atmosphere. These neutrinos represent an irreducible background detected with a rate of few per day. Energetic atmospheric muons reach the detector from above giving rise to a much more intense flux of particles detected by ANTARES with a rate of few per second. For this reason, only tracks reconstructed as upgoing and with a sufficient quality are classified as neutrino candidates.

Microquasars are galactic X-ray binaries exhibiting relativistic jets (Mirabel & Rodríguez 1994). Whether hadrons are also accelerated in the jets is still an open question for most systems, since the only microquasar for which hadronic lines have been detected in the jets is SS 433 (Marshall et al. 2002). Arguments in favor of a hadronic composition of the jets can be inferred from their energetics (Heinz 2008). If a fraction of the jet power is tapped for the acceleration of hadrons, these can interact with the X-rays from the disk or the synchrotron photons within the jet and produce neutrinos up to 100 TeV (Levinson & Waxman 2001), that may potentially be detected by neutrino telescopes (Distefano et al. 2002).

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Presented here is a search for neutrino emission from microquasars during X-ray or gamma ray outbursts. By restraining the neutrino search during ejection events, the background due to atmospheric neutrinos is reduced, thus increasing the probability of a discovery. The selection of the candidate microquasars and the outbursting events is presented in § 2. In § 3 the statistical search method is explained and the results are presented. Conclusions and perspectives are drawn in the last section.

2 Outburst selection

In order to define the times in which to look for neutrinos, a multi wavelength study has been performed on the sources under study using X-ray data from RXTE/ASM and Swift/BAT and, in one case, the gamma ray data from Fermi/LAT. When necessary, also results from the literature have been used. The goal is to select those times in which the source is supposed to accelerate relativistic jets, based on its known multi wavelength behaviour (X-ray, gamma and radio). In the following of this section the main selection criteria for the candidate sources are presented.

2.1 Cir X-1

This neutron star binary has an orbital period of 16.6 days (Kaluzienski et al. 1976) and undergoes regular radio flares at periastron, within the phase interval 0.09-0.21 (Murdin et al. 1980; Moin et al. 2011), which is supposed to be due to the enhanced accretion at periastron. Also, during X-ray outburst, the radio core of the source brightens and successively feeds two radio knots of an extended structure at arcsec scale (Fender et al. 2004). Following these features, the time selection for this source has been based on the presence of X-ray outbursts observed with the RXTE/ASM telescope, which have been eventually extended in order to include the periastron phase, when sufficiently close.

2.2 GX 339−4, H1743−322, IGR J17091−3624 and Cyg X-1

The time selection for these black hole binaries has been based on the known disc-jet coupling relation between X-ray and radio for this type of sources (Belloni 2010). Namely, during hard X-ray states a steady jet is normally observed with a Lorentz factor ~ 2, whereas during transitions between hard and soft states, when the source transits through the hard and soft intermediate states, a discrete ejection is observed with a higher Lorentz factor. Following this pattern, hard X-ray states and transitional states have been selected for the neutrino search. As these two cases refer to two different physical scenarios, two separate neutrino searches have been performed during hard states and transitional states respectively.

Whereas the identification of transitional states needs detailed X-ray analyses and has been based on results found in the literature, the selection of hard states has been performed by selecting X-ray outbursts in the Swift/BAT daily averaged light curve. The resulting time selection for GX 339−4 is shown in Fig. 1 as an example. The classification of X-ray states for Cyg X-1, instead, has been based on the mapping of the X-ray states with respect to the position of the source in the flux-hardness diagram of RXTE/ASM as found by (Grinberg et al. 2012).

2.3 Cyg X-3

This source has been observed emitting high energy gamma rays by both AGILE (Tavani et al. 2009) and Fermi/LAT (Abdo et al. 2009). The gamma ray emission is associated to its ultra soft X-ray states which in turn is related to giant radio outburst. The gamma ray data between 30 MeV and 30 GeV from Fermi/LAT have been analyzed using the procedure in (Abdo et al. 2009). Outbursting periods in gamma rays have been selected for the neutrino search.

3 Search in ANTARES data

An unbinned likelihood method based on a likelihood ratio test statistic has been adopted to analyze the neutrino sky maps relative to each neutrino search and define whether they are compatible with the background of atmospheric neutrinos or with the presence of a neutrino source on top of it. For each neutrino search, both the number of background events and their angular distribution have been estimated from the data. A high number of background-only pseudo experiments has been generated by randomizing the directions of the

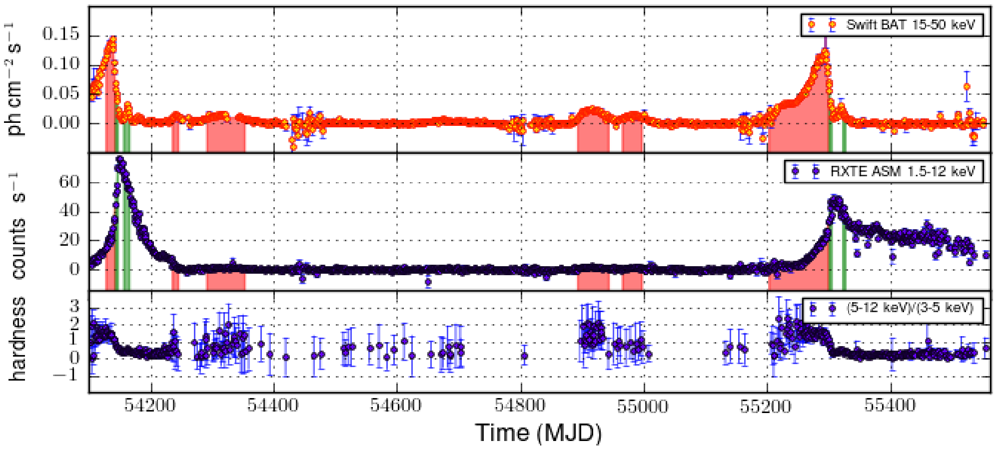

Fig. 1. X-ray light curves of GX 339−4 between 2007 and 2010, from Swift/BAT (top) and RXTE/ASM (middle). The lower panel shows the hardness ratio HR2 from ASM. The filled areas refer to the periods selected for the neutrino search: in red during the hard state and in green during the hard to soft transition. A separate neutrino search is performed on red and green areas.

selected neutrino events in the data, in order to reproduce all possible background fluctuations. Also, the effect of neutrino signals has been studied by injecting up to 30 signal events in the background only pseudo sky maps, distributed around the source according to the ANTARES point spread function. The results of the pseudo experiments have been used to optimize the quality cuts in order to maximize the probability of a discovery supposing a neutrino flux $\propto E_\nu^{-2}$. The analysis has been carried on in a blind fashion, i.e. the quality cuts and the criteria for a discovery or an evidence have been defined before looking at the actual neutrino directions in the data.

After the true neutrino directions in the data have been unveiled and the likelihood method applied on them, none of the searches ended up producing a significant result, thus the 90% confidence level upper limits on the neutrino fluences have been calculated supposing an E_ν^{-2} neutrino flux. The preliminary results are shown in Table 1. The search that was less compatible with the background-only hypothesis is the one relative to the state transitions of H1743−322. The total livetime of this search is relatively low, only 5.1 days, whereas a neutrino has been detected 2.3° away from the source, which is more than four times the detector's angular resolution, i.e. the result is compatible with the background-only hypothesis.

Table 1. Summary of the preliminary results on the neutrino searches for the outbursting microquasars under study. The columns report the values of the test statistic (TS) and the number of signals fitted by the likelihood method (n_{sig}), the livetime of the search in days, the number of selected neutrinos in the whole sky map (representing the amount of background), the distance of the closest neutrino to the source, the number of expected background neutrinos within 3° from the source and the 90% C.L. upper limit on the neutrino fluence in GeV cm^{-2}, respectively.

	TS	n_{sig}	livetime	$N_{\nu,bg}$	closest ν	$N_{bg}^{exp}(< 3°)$	fluence u.l.$^{90\%\mathrm{C.L.}}$
H1743−322(TS)	0.41	0.66	5.1	27	2.3°	0.04	30.3
Cyg X-1 (HS)	0.0016	0.08	174.4	638	1.4°	0.86	14.1
Cir X-1	0	0	100.5	256	5.7°	0.35	16.9
GX 339−4 (HS)	0	0	147.0	484	2.8°	0.66	10.9
GX 339−4 (TS)	0	0	4.9	14	11 °	0.02	19.7
H1743−322 (HS)	0	0	84.6	447	4.6°	0.61	9.1
IGR J17091−3624	0	0	8.5	40	12 °	0.05	21.3
Cyg X-1 (TS)	0	0	30.9	182	6.4°	0.27	6.0
Cyg X-3	0	0	16.6	149	6.9°	0.20	5.7

Also, the 90% upper limits on the energy flux in neutrinos have been calculated and compared with the flux predictions from (Distefano et al. 2002). To adhere the model's scenario, a neutrino flux with an exponential cutoff at 100 TeV has been considered. This is shown in Fig. 2. The limits obtained are very close to the predictions in the cases of GX 339−4 and Cyg X-3, although it is not yet possible to constrain the model. Nevertheless, future ANTARES data and improvements in the analysis technique will allow constraints of this model at least for these two sources.

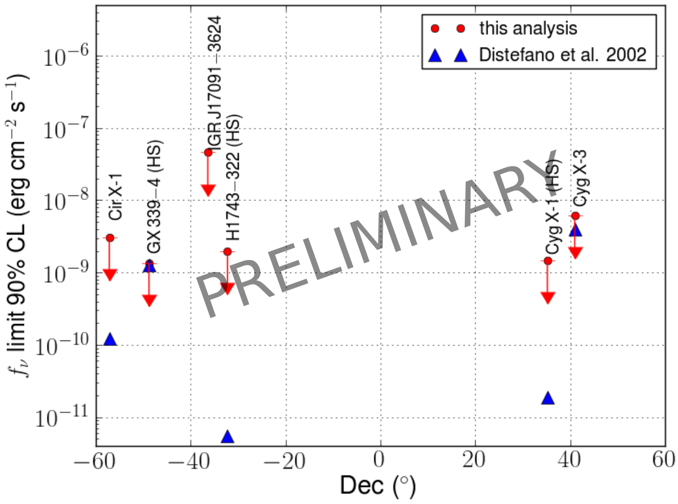

Fig. 2. Feldman-Cousins 90% confidence level upper limits on the energy flux in neutrinos f_ν obtained from this analysis, considering a flux $\propto E^{-2}\exp(-E_\nu/100\ \text{TeV})$, compared with the expectations from Distefano et al. (2002). The model expectation for IGR J17091−3624 is not included in the plot since no infrared measurements were found to calculate it.

4 Conclusions

An analysis of the data collected by ANTARES between 2007 and 2010 has been presented to put in evidence a neutrino emission from outbursting microquasars. Time cuts have been defined in order to restrain the neutrino search to those periods in which the source was thought to be accelerating a relativistic jet, by using the X-ray light curves from RXTE/ASM and Swift/BAT, and the gamma ray light curve of Fermi/LAT in the case of Cyg X-3 . The analysis of ANTARES data has been performed using a likelihood method based on a likelihood ratio test, optimized for discovery. Upper limits on the neutrino fluences are shown and the comparison with the model's prediction from (Levinson & Waxman 2001) indicate that future ANTARES data will allow to put constraints on the model's parameters.

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