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VHE Gamma-rays from galactic binaries

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Abstract. The discovery of TeV gamma-rays in some X-ray binaries provides clear evidence of very efficient acceleration of particles to multi-TeV energies in these systems. The observations demonstrate the richness of non-thermal phenomena in compact galactic objects containing relativistic outflows or winds produced near black holes and neutron stars. Also, recently detected gamma-ray sources have been proposed to be associated with massive binary stars. I review here some of the main observational results on the non-thermal emission from X-ray binaries as well as some of the proposed scenarios to explain the production of high and very high-energy gamma-rays.

Key words. X-ray: binaries; gamma-rays: observations; gamma-rays: theory

1. Introduction

The current catalog of Very High Energy (VHE, $E > 100$ GeV) gamma-ray sources detected with the Imaging Atmospheric Cherenkov telescopes contains more than 80 objects. The number of extragalactic sources is 28, most of them being blazars, whereas the number of galactic sources is 54, which are classified as supernovae remnants (SNRs), pulsars, pulsar wind nebulae (PWNe), binaries, miscellaneous, diffuse sources and unidentified sources. Online catalogues of TeV sources can be found in http://www.mppmu.mpg.de/~rwagner/sources/ and http://tevcat.uchicago.edu/. The category of binaries is particularly interesting because its emission at TeV energies is variable, and in some cases periodic. The variable/periodic TeV emission is also observed at other wavelengths and has been associated with the binarity. The other types of galactic VHE sources - PWN, SNR, extended unidentified sources - show no hints of variability. The type of binaries detected at TeV energies are high-mass X-ray binaries (HMXB) consisting of the donor star, an O or B star of mass in the range 8–40 $M_{\odot}$, and a compact companion (neutron star or black hole). Up to now, no low-mass X-ray binary has been detected at VHE, suggesting that the bright primary star in HMXB plays an important role in the production of high-energy photons. Some properties of these systems and an individual description of them have also been discussed in Paredes (2008). Binary systems of massive stars have also been proposed as sources of gamma-rays (Benaglia & Romero 2003), and there are hints at present that one such system, Eta Carinae, has recently been detected in the GeV band by *AGILE* (Tavani et al. 2009)

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2. TeV binaries

At present, among the VHE sources detected with the Cherenkov telescopes, there are three X-ray binaries. These binaries, PSR B1259−63 (Aharonian et al. 2005a), LS I +61 303 (Albert et al. 2006) and LS 5039 (Aharonian et al. 2005b), have a bright high-mass primary star, which provides a huge UV photon field for inverse Compton scattering, and a compact object as companion star. All of them have been detected at TeV energies in several parts of their orbits and show variable emission and hard spectrum. The emission is periodic in the systems LS 5039 and LS I +61 303, with a period of 3.9078±0.0015 days and 26.8±0.2 days respectively (Aharonian et al. 2006; Albert et al. 2009), consistent with their orbital periods (Casares et al. 2005a,b; Aragona et al. 2009).

These two sources also share the distinction of being the only two known high-energy emitting X-ray binaries that are spatially coincident with sources above 100 MeV listed in the Third EGRET catalog (Hartman et al. 1999). LS 5039 is associated with 3EG J1824−1514 (Paredes et al. 2000) and LS I +61 303 with 3EG J0241+6103 (Kniffen et al. 1997).

In the case of PSR B1259−63 the periodicity has not been yet determined because the long orbital period (3.4 years) requires extensive monitoring during several years with the Cherenkov telescopes. The source was not detected by EGRET.

Another high-mass X-ray binary, Cygnus X-1, was observed with MAGIC during a short-lived flaring episode, and strong evidence (4.1σ post-trial significance) of TeV emission was found (Albert et al. 2007). These TeV measurements were coincident with an intense state of hard X-ray emission observed by *INTEGRAL*, although no obvious correlation between the X-ray and TeV emission was found (Malzac et al. 2008). The detection occurred around the superior conjunction of the compact object, when the highest gamma-ray opacities are expected. After computing the absorbed luminosity that is caused by pair creation for different emitter positions, it has been suggested that the TeV emitter is located at the border of the binary system (Bosch-Ramon et al. 2008). A recent study of the opacity and acceleration models for the TeV flare can explain qualitatively the observed TeV spectrum, but not its exact shape (Zdziarski et al. 2009).

The nature of the compact object is well determined in only two sources. In the case of Cygnus X-1 it is a black hole and, in the case of PSR B1259−63, a neutron star. For LS I +61 303 and LS 5039 there is no strong evidence yet supporting either the black hole nor the neutron star nature of the compact objects. Some of these sources have also been detected at MeV and GeV energies by instruments onboard the Compton Gamma-ray Observatory (CGRO), like COMPTEL and EGRET (as commented above), or by the two current spatial missions *AGILE* and *Fermi*. A summary of the sources detected with these instruments can be found in Table 1. A common characteristic of these four sources is that all of them are radio emitters, producing non-thermal radiation. These sources, with the exception of PSR B1259−63, show elongated radio structures of synchrotron origin. It is possible that PSR B1259−63 has this kind of structure but has not yet been detected with the present sensitivity and resolution of the instruments available in the southern hemisphere.

Some properties of these systems are individually described below.

2.1. Cygnus X-1

Cygnus X-1 is the brightest persistent HMXB in the Galaxy, radiating a maximum X-ray luminosity of a few times 10^{37} erg s^{-1} in the 1–10 keV range. At radio wavelengths the source displays a $\sim$15 mJy flux density and a flat spectrum, as expected for a relativistic compact (and one-sided) jet ($v > 0.6c$) during the low/hard state (Stirling et al. 2001). A transient relativistic radio jet was observed during a phase of repeated X-ray spectral transitions in an epoch with the softest 1.5–12 keV X-ray spectrum (Fender et al. 2006). Arc-minute extended radio emission around Cygnus X-1 was

Table 1. X-ray binaries with gamma-ray emission

Instrument	PSR B1259−63	LS I +61 303	LS 5039	Cygnus X-1
COMPTEL (1–30 MeV)	–	yes	GRO J1823−12	yes
EGRET (> 100 MeV)	–	3EG J0241+6103	3EG J1824-1514	–
AGILE (30 MeV–50 GeV)	–	yes	–	–
Fermi (30 MeV–300 GeV)	–	yes	yes	–
HESS (> 100 GeV)	yes	not visible	periodic	–
MAGIC (> 60 GeV)	not visible	periodic	–	yes
VERITAS (> 100 GeV)	not visible	yes	–	–

also found using the VLA (Martí et al. 1996). Its appearence was that of an elliptical ring-like shell with Cygnus X-1 offset from the center. Later, as reported in Gallo et al. (2005), such structure was recognised as a jet-blown ring around Cygnus X-1. This ring could be the result of a strong shock that develops at the location where the pressure exerted by the collimated jet, detected at milliarcsec scales, is balanced by the ISM. The observed thermal Bremsstrahlung radiation would be produced by the ionized gas behind the bow shock.

2.2. PSR B1259−63

PSR B1259−63 is the first variable galactic source of VHE gamma-rays discovered. This is a binary system containing a Be main sequence donor, known as LS 2883, and a 47.7 ms radio pulsar orbiting it every 3.4 years in a very eccentric orbit with $e = 0.87$ (Johnston et al. 1994).

The radiation mechanisms and interaction geometry in this pulsar/Be star system were studied in Tavani & Arons (1997). In a hadronic scenario, the TeV light-curve, and radio/X-ray light-curves, can be produced by the collisions of high energy protons accelerated by the pulsar wind and the circumstellar disk (Neronov & Chernyakova 2007). A very different model is presented in Khangulyan et al. (2007), where it is shown that the TeV light curve can also be explained by IC scenarios of gamma-ray production.

2.3. LS I +61 303

This source is located at a distance of 2.0±0.2 kpc (Frail & Hjellming 1991). It contains a rapidly rotating B0 Ve star with a stable equatorial shell, and a compact object of unknown nature with a mass between 1 and 5 $M_\odot$, orbiting it every 26.5 d (Hutchings & Crampton 1981; Casares et al. 2005a). Quasi-periodic radio outbursts monitored during 23 years have provided an accurate orbital period value of $P_{\rm orb}$=26.4960±0.0028 d (Gregory 2002). The orbit is eccentric ($e \simeq 0.72$) and periastron takes place at phase 0.23±0.02, assuming T_0= JD 2,443,366.775 (Casares et al. 2005a). Grundstrom et al. (2007) obtained new orbital parameters, revealing an eccentricity of 0.55 and a periastron at phase 0.30±0.01. However, the Balmer lines used in their study are known to be contaminated by the stellar wind. New radial velocities measurements reported recently by Aragona et al. (2009) give improved orbital elements for LS I +61 303 and for LS 5039.

An orbital X-ray periodicity has been found using *RXTE*/ASM archival data (Paredes et al. 1997). Simultaneous X-ray (*RXTE*/PCA) and radio observations of LS I +61 303 over the 26.5 day orbit showed a significant offset between the peak of the X-ray and radio flux. The X-ray outbursts, starting around phase 0.4 and lasting up to phase 0.6, peak almost half an orbit before the radio ones (Harrison et al. (2000) and references therein). Similar results have recently been

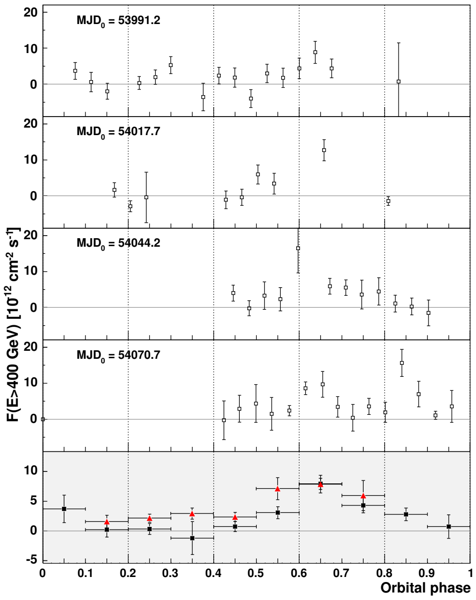

Fig. 1. VHE (E >400 GeV) gamma-ray flux of LS I +61 303 for four orbital cycles and the average (lowermost panel) as a function of the orbital phase. Data published previously (Albert et al. 2006) are shown in red. Figure from Albert et al. (2009).

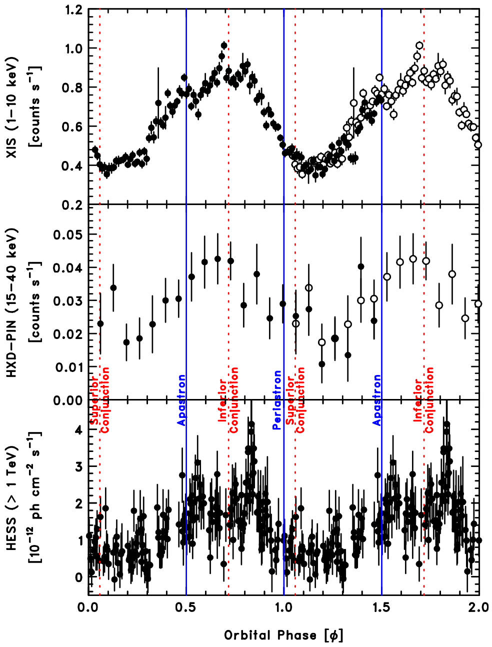

Fig. 2. X-ray and TeV light curves of LS 5039 versus the orbital phase. The *Suzaku* count rate in the 1–10 keV band is at the top and in the 14–40 keV band is in the middle panel (Takahashi et al. 2009). The HESS data (Aharonian et al. 2006) are at the bottom. Figure from Takahashi et al. (2009).

obtained at higher energies with *INTEGRAL* data (Hermsen et al. 2006). The maximum of the radio outbursts varies between phase 0.45 and 0.95. Massi et al. (2004) reported the discovery of an extended jet-like and apparently precessing radio emitting structure at angular extensions of 10–50 milliarcseconds. VLBA images obtained during a full orbital cycle show a rotating elongated morphology (Dhawan et al. 2006), which may be consistent with a model based on the interaction between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion (Dubus (2006); see nevertheless Romero et al. (2007) for a critical discussion of this scenario).

2.4. LS 5039

LS 5039 is a high-mass X-ray binary containing a compact object of unknown mass, 1.5–10 $M_{\odot}$ depending on the binary system inclination, which is an unknown parameter. The neutron star or black hole orbits an O6.5V((f)) star every 3.9 days in an eccentric orbit with e = 0.35, and is located at 2.5 kpc (Casares et al. 2005b). The radio emission of LS 5039 is persistent, non-thermal and variable, but no strong radio outbursts or periodic variability have been detected so far (Ribó et al. 1999, 2002). VLBA observations allowed for the detection of an elongated radio structure, interpreted as relativistic jets (Paredes et al. 2000). The discovery of this bipolar radio structure, and the fact that LS 5039 was the only source in the field of the EGRET source 3EG J1824−1514 showing X-ray and radio emission, allowed us to propose the physical association of both sources (Paredes et al. 2000). A theoretical discussion of the radio properties of LS 5039 can be found in Bosch-Ramon (2009).

X-ray observations of LS 5039 with the *Suzaku* satellite, covering one and half orbits, show strong modulation over the orbital period of the system that is closely correlated with the TeV gamma-ray light curve (see Figure 2) (Takahashi et al. 2009). This seems to indicate a synchrotron origin for the X-rays, and that the electrons producing the synchrotron radiation are also responsible for the TeV emission via IC scattering. However, whereas the TeV periodicity is mainly explained by the photon-photon pair production and anisotropic IC scattering, the X-ray modulation seems to be produced by adiabatic losses dominating the synchrotron and IC losses of electrons (Takahashi et al. 2009). To avoid heavy absorption, it is required that the gamma-ray emission be produced at the periphery of the binary system (Khangulyan et al. 2008; Bosch-Ramon et al. 2008), although a scenario accounting for electromagnetic cascading has been also considered (Sierpowska-Bartosik & Torres 2007; Khangulyan et al. 2008).

Two incompatible scenarios have been proposed to explain the acceleration mechanism that powers the relativistic electrons. In the first one electrons are accelerated in the jet of a microquasar powered by accretion (Paredes et al. 2006). In the second one they are accelerated in the shock between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion (Dubus 2006).

3. A new TeV binary candidate: HESS J0632+057

HESS J0632+057 was discovered by the HESS telescope array as a point-like source in Monoceros (Aharonian et al. 2007). Its energy spectrum is consistent with a power-law with photon index of 2.53 and flux normalisation of 9.1×10^{-13} cm^{-2} s^{-1} TeV^{-1}. No evidence of flux variability was found. Three different sources - the *ROSAT* source 1RXS J063258.3+054857, the EGRET source 3EG J0634+0521 and the star MWC 148 - were suggested as possible associations with HESS J0632+057.

Later X-ray observations with *XMM-Newton* revealed a variable X-ray source, XMMU J063259.3+054801, which is positionally coincident with the massive B0pe spectral type star MWC 148 (HD 259440) and compatible in position with HESS J0632+05 (Hinton et al. 2009). The X-ray spectrum is hard, and can be fitted with an absorbed power-law model with a 1 keV normalization of $(5.4 \pm 0.4) \times 10^{-5}$ keV^{-1} cm^{-2} s^{-1}, a photon index of 1.26±0.04 and a column density of $(3.1 \pm 0.3) \times 10^{21}$ cm^{-2}. The spectral energy distribution (SED) of HESS J0632+057, assuming that the sources associated at different spectral bands are the real counterparts, looks similar to that of the TeV binaries LS I +61 303 and LS 5039. In Figure 3 is shown the SED of HESS J0632+057, together with a one-zone model developed by Hinton et al. (2009) and adapted to the new data by Skilton et al. (2009).

VERITAS observed HESS J0632+057 during three differents epochs obtaining no significant evidence for gamma-ray emission (Acciari et al. 2009). The flux upper limits for energies above 1 TeV are shown in Figure 4, where the data from HESS has also been plotted. The HESS detection and the VERITAS non detection seems to point to a long-term gamma-ray variability. This seems to happen also in the X-ray band, when comparing the *XMM-Newton* data (Hinton et al. 2009) and *Swift* data taken contemporaneously with VERITAS (Acciari et al. 2009). The absence of radio emission in this area, based on the NRAO VLA Sky Survey (NVSS) catalog (Condon et al. 1998), seemed to indicate that any possible radio counterpart should be either faint and/or variable. This suspicion has been confirmed very recently. Radio observations carried out in 2008 with the VLA at 5 GHz and GMRT at 1280 MHz have found a faint and unresolved source at the position of MWC 148 (Skilton et al. 2009). While the radio flux density at the lower frequency is not variable, there is a significant flux variability on month timescales at 5 GHz. The TeV variability, as well as the X-ray and the radio variability clearly associated with MWC 148, gives suport to the idea proposed by Hinton et al.

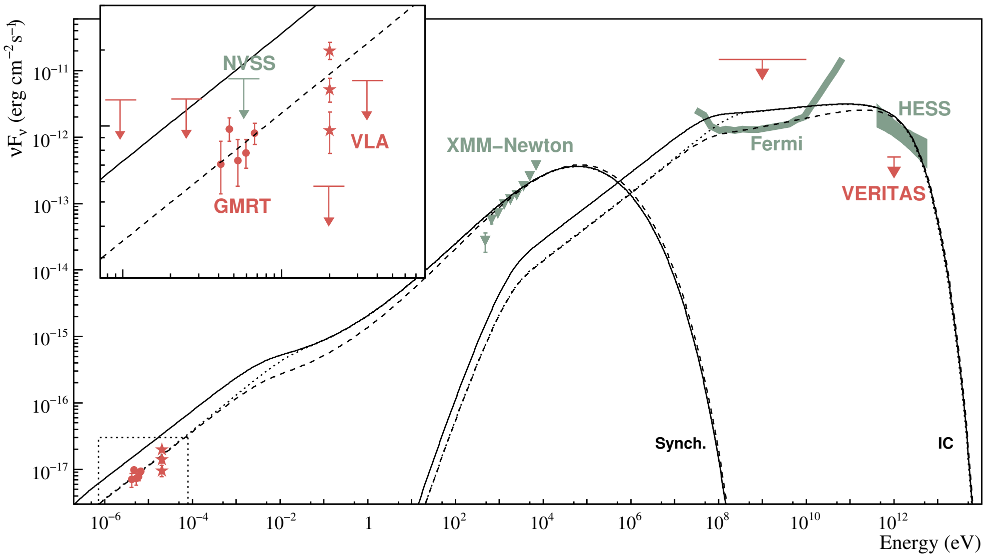

Fig. 3. Spectral energy distribution of HESS J0632+057. The different curves show a one-zone model. Figure from Skilton et al. (2009).

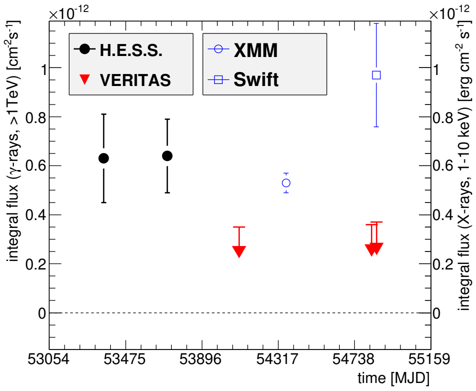

Fig. 4. HESS (Aharonian et al. 2007) and VERITAS (Acciari et al. 2009) light curve of HESS J0632+057 above 1 TeV. X-ray data from *XMM-Newton* and *Swift* are also shown. Figure from Acciari et al. (2009).

(2009) that HESS J0632+057 is likely a new gamma-ray binary. However, further observations are necessary to determine the binarity of MWC 148.

4. Wolf-Rayet binaries

Massive hot stars can generate strong winds with high mass-loss rates at the level of 10^{-5} $M_{\odot}$ yr^{-1}. These winds strongly affect the environment and shocks are expected to form, especially in binary systems, where the winds collide. In some cases, the colliding wind region can be resolved at radio wavelengths (Contreras et al. 1997; Dougherty et al. 2005; Linder 2008). Such region presents non-thermal radiation of synchrotron origin, indicating the presence of relativistic electrons. The existence of relativistic particles in an environment with a dense photon field makes inverse Compton losses unavoidable, and hence several authors have suggested that colliding wind binaries should be high-energy sources (Eichler & Usov 1993; Benaglia et al. 2001; Benaglia & Romero 2003). Based on specific radio information for some Wolf-Rayet (WR) binaries, some detailed models have recently been developed (Pittard & Dougherty 2006; Reimer et al. 2006; Reimer & Reimer 2009). Two of these systems, WR 146 and WR 147, have been observed with the MAGIC telescope. Although the obtained results are com-

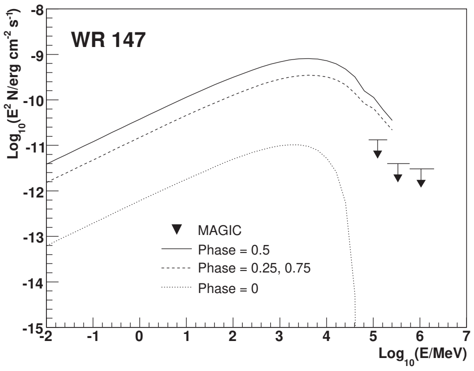

Fig. 5. The expected spectral energy distribution from inverse Compton interactions at the colliding wind of WR 147 (Reimer et al. 2006) and the upper limits obtained with MAGIC (Aliu et al. 2008).

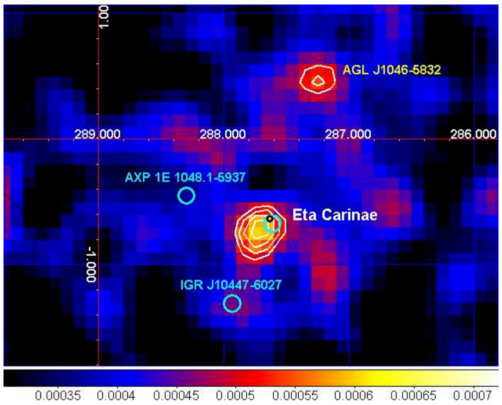

Fig. 6. *AGILE* integrated sky map of η Car region at energies > 100 MeV (Tavani et al. 2009). The small black circle marks the optical position of η Car, the cyan circles mark the *INTEGRAL* sources (Leyder et al. 2008) and the white contours mark the *AGILE* source 1AGL J1043−5931, associated with η Car. The source 1AGL J1046−5832 is associated with the radio pulsar PSR B1046−58.

patible with background fluctuations, these are the first experimental limits on these objects (Aliu et al. 2008). In Figure 5 the MAGIC upper limit fluxes of WR 147, together with the IC spectra computed for different orbital phases by Reimer et al. (2006), are shown. The long orbital period (1350 yr, Setia Gunawan et al. (2001)) of this system makes it unlikely that gamma-ray attenuation produces any distinctive feature in the spectrum. However, anisotropic IC scattering can produce flux variations that can allow one to estimate system parameters such as the inclination (Reimer & Reimer 2009). In this context, MAGIC data point to a high inclination for the WR 147 system.

5. Eta Carinae (η Car)

η Car is one of the most remarkable objects of our Galaxy. It is a very massive star ($\sim$ 100 $M_{\odot}$) showing strong mass outflow eruptions (e.g., Davidson & Humphreys (1997)). Extensive spectral observations of η Car yield a period of 2020±4 days, giving strong support to a binary scenario (Damineli et al. 2008). The system would be highly eccentric ($e \sim 0.9$), with an O star companion of $\sim 30\ M_{\odot}$. *INTEGRAL* detected very hard X-ray emission from η Car in the 22–100 keV energy range, with a luminosity of 7×10^{33} erg s^{-1} (Leyder et al. 2008).

The Carina region was observed with EGRET in the past, with no positive detection above 100 MeV. The gamma-ray satellite *AGILE* has observed extensively this region, reporting the detection of a gamma-ray source (1AGL J1043−5931) consistent with the position of η Car, which is well within the 95% confidence radius gamma-error box (see Figure 6). The average gamma-ray flux (> 100 MeV) is $(37 \pm 5) \times 10^{-8}$ ph cm^{-2} s^{-1}, which corresponds to an average gamma-ray luminosity of 3.4×10^{34} erg s^{-1} for a distance of 2.3 kpc (Tavani et al. 2009). The *AGILE* gamma-ray light curve was roughly constant during all the observations, although a few day timescale gamma-ray flare was detected a few months before periastron. This can be seen in Figure 7, where the *AGILE* data are superimposed to the *RXTE* X-ray light curve.

The association of 1AGL J1043−5931 with η Car, if confirmed, would imply the first evidence of > 100 MeV gamma-ray emission from a colliding wind system. The results obtained by *AGILE* seems to agree with what is expected from IC and neutral pion processes in

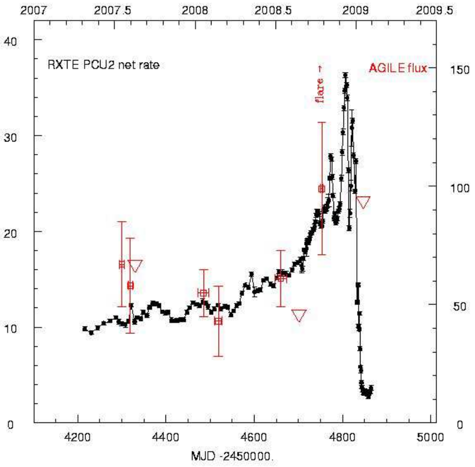

Fig. 7. 1AGL J1043−5931 light curve obtained by *AGILE* at > 100 MeV (red empty squares and triangles (2σ upper limit)) and RXTE X-ray light curve (2–15 keV) (black filled squares) (Tavani et al. 2009). The *AGILE* fluxes are at the right axis scale and in units of 10^{-8} ph cm^{-2} s^{-1}.

colliding wind binaries (Benaglia & Romero 2003; Reimer et al. 2006).

6. Conclusions

The populations of the VHE gamma-ray binaries is limited to very few sources. However, it is expected that this situation may change in the coming years, not only because of the increasing sensitivity of the Cherenkov telescopes like MAGIC II and H.E.S.S. II, but also because new candidates are emerging. The most promising of them is HESS J0632+057, although it is necessary to prove the binary nature of MWC 148 before considering it a member of the TeV binary group. There is also the possibility that other binaries not belonging to the XRB class may be sources of VHE. The well known source η Car has been detected recently at high energies, > 100 MeV, by *AGILE*, and it is a good candidate to also be a TeV emitter. Other types of binary massive stars, like Wolf-Rayet stars, include several systems that could be VHE sources. All these results increase the expectations for the detections of new types of binaries at HE and VHE.

DISCUSSION

ANDRZEJ ZDZIARSKI's Comment: We do not know any class of binaries that would for sure be accreting and would emit high energy gamma rays in the way of LS 5039 and LS I +61 303. I would be really very surprised if those sources are shown to accrete.

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