HADRONIC GAMMA-RAY AND NEUTRINO EMISSION FROM CYGNUS X-3

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ABSTRACT

Cygnus X-3 (Cyg X-3) is a remarkable Galactic microquasar (X-ray binary) emitting from radio to γ-ray energies. In this paper, we consider the hadronic model of emission of γ-rays above 100 MeV and their implications. We focus on the joint γ-ray and neutrino production resulting from proton–proton interactions within the binary system. We find that the required proton injection kinetic power, necessary to explain the γ-ray flux observed by AGILE and Fermi-LAT, is $L_P \sim 10^{38} \text{ erg s}^{-1}$, a value in agreement with the average bolometric luminosity of the hypersoft state (when Cyg X-3 was repeatedly observed to produce transient γ-ray activity). If we assume an increase of the wind density at the superior conjunction, the asymmetric production of γ-rays along the orbit can reproduce the observed modulation. According to observational constraints and our modeling, a maximal flux of high-energy neutrinos would be produced for an initial proton distribution with a power-law index $\alpha = 2.4$. The predicted neutrino flux is almost two orders of magnitude less than the two-month IceCube sensitivity at $\sim 1$ TeV. If the protons are accelerated up to PeV energies, the predicted neutrino flux for a prolonged “soft X-ray state” would be a factor of about three lower than the one-year IceCube sensitivity at $\sim 10$ TeV. This study shows that, for a prolonged soft state (as observed in 2006) possibly related to γ-ray activity and a hard distribution of injected protons, Cyg X-3 might be close to being detectable by cubic-kilometer neutrino telescopes such as IceCube.

Key words: gamma rays: general – neutrinos – stars: individual (Cygnus X-3) – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Cyg X-3 was discovered in 1966 (Giacconi et al. 1967) as a bright X-ray source. It is a high-mass X-ray binary located at an estimated distance of about 7–10 kpc (Bonnet-Bidaud & Chardin 1988; Ling et al. 2009). The donor star is known to be a Wolf–Rayet (WR) star (van Kerkwijk et al. 1992) with a strong helium stellar wind (Szostek & Zdziarski 2008), while it is still unclear whether the accreting object is a neutron star or a stellar black hole (Vilhu et al. 2009), even though a black hole scenario is favored (Szostek & Zdziarski 2008; Szostek et al. 2008). The orbital period—detected in infrared (Becklin et al. 1973), X-ray (Parsignault et al. 1972), and γ-ray (Abdo et al. 2009) bands—is very short (4.8 hr), indicating that the compact object is completely enshrouded in the wind of the companion star (orbital distance, $d \approx 3 \times 10^{11}$ cm). Cyg X-3 is known to produce giant radio outbursts (“major radio flares”) up to a few tens of Jy. During these huge flares, milliarcsec-scale observations at cm wavelengths found an expanding one-sided relativistic jet ($v \sim 0.81c$), with an inclination to the line-of-sight of $\lesssim 14^\circ$ (Mioduszewski et al. 2001; Tudose et al. 2010). High-energy γ-rays (HE γ-rays: $>100$ MeV) from Cyg X-3 have been firmly detected by the new generation of space telescopes. AGILE found evidence of transient γ-ray activity from Cyg X-3 in 2009 (Tavani et al. 2009) as confirmed by the Fermi-LAT detections (Abdo et al. 2009). Furthermore, Fermi-LAT could also determine the orbital modulation of the γ-ray emission (Abdo et al. 2009). The photon spectrum (between 100 MeV and 3 GeV) detected by AGILE during the peak flaring activity is well-fitted by a power law with a photon index $\Gamma = 2.0 \pm 0.2$. On the other hand, the average spectrum above 100 MeV measured by Fermi-LAT for two active windows (of about two months each) gives $\Gamma = 2.70 \pm 0.25$. This difference could indicate a fast spectral hardening of the HE emission during the short and intense γ-ray events (lasting $\sim 1$–2 days) detected by AGILE. Nevertheless, the peak γ-ray luminosity detected above 100 MeV by both AGILE and Fermi-LAT corresponds to $L_\gamma \approx 10^{36}$ erg s$^{-1}$. These observations provide direct evidence that extreme particle acceleration occurs in Cyg X-3 in a transient fashion, most likely associated with the relativistic jet ejection and/or propagation. Both AGILE (Tavani et al. 2009; Bulgarelli et al. 2012; Piano et al. 2012) and Fermi (Abdo et al. 2009; Corbel et al. 2012) found the same multi-frequency conditions for the γ-ray activity. In particular, Piano et al. (2012) found that the transient γ-ray emission detected by AGILE is associated with very faint hard X-ray activity$^7$ and generally occurs a few days before intense major radio flares. The γ-ray transient emission is observed when the system is moving into or out of the quenched state, a characteristic state of Cyg X-3 that generally precedes a major radio flare. The quenched state, which has been found to be a key trigger condition for the γ-ray activity, is characterized by a very low or undetectable level of radio flux density and bright soft X-ray emission with a particular X-ray spectrum (the hypersoft spectrum; Koljonen et al. 2010).

At very high energies (VHE γ-rays: $>250$ GeV), Cyg X-3 was observed by the MAGIC telescope for about 70 hr between 2006 March and 2009 August. These observations

$^7$ The γ-ray activity has been detected—always during soft X-ray spectral states—when the 15–50 keV count rate detected by the Swift/Burst Alert Telescope (BAT) was lower than 0.02 counts cm$^{-2}$ s$^{-1}$ (∼0.091Crab).
correspond to different X-ray/radio spectral states and also show periods of enhanced $\gamma$-ray emission (Aleksić et al. 2010). No TeV $\gamma$-rays from Cyg X-3 have been detected and the upper limits on the integrated $\gamma$-ray flux above 250 GeV are $2.2 \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$ (Aleksić et al. 2010). We notice that the lack of evidence for detectable TeV emission from Cyg X-3 may be due to the strong absorption of these photons (through $\gamma\gamma$ absorption on ultraviolet (UV) stellar photons from the WR star) or due to the limited time of observation. If $\gamma$-ray emission from Cyg X-3 is caused by hadronic interactions, our knowledge regarding the source would be greatly improved by the detection of HE neutrinos. For proton–proton (pp) interactions, the emitted photons and neutrinos can have comparable intensities. In this case, HE photons can be absorbed and neutrinos can freely escape from the source. Neutrinos carry invaluable information about the existence (or absence) of energetic protons and shed light on the location of the $\gamma$-ray production region.

Recently, the IceCube collaboration reported on searches for neutrino sources at energies above 200 GeV in the Northern sky of the Galactic plane (including Cyg X-3), using data collected by the South Pole neutrino telescope, IceCube, and AMANDA (Abbasi et al. 2013). Interestingly, it turns out that during this period Cyg X-3 was observed both close to $\gamma$-ray flaring activity as well as in different X-ray/radio states. A maximum likelihood test using a time-dependent version of the unbinned likelihood ratio method was applied to the IceCube data. As a result, no evidence for a signal was found in the neutrino sample. The 90$\%$ confidence level upper limits on the differential muon neutrino flux from Cyg X-3 for the $E^{-2}$ and $E^{-3}$ spectra are: $dN/dE \leq 7 \times 10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ and $dN/dE \leq 5 \times 10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$, respectively (Abbasi et al. 2013).

In this paper we focus on the hadronic scenario for HE emission from the microquasar Cyg X-3. We assume that the jet of Cyg X-3 accelerates both leptons and hadrons to HEs. The accelerated protons escape from the jet and, interacting with the hadronic matter of the WR star, produce $\gamma$-rays and neutrinos. By normalizing our model with the $\gamma$-ray emission of Cyg X-3 at its peak (using AGILE data) and considering the MAGIC upper limits (that we interpret in terms of a strong $\gamma\gamma$ absorption on the stellar photons), the corresponding flux of HE neutrinos is calculated and compared with the IceCube sensitivity.

This paper is organized as follows. In Section 2 the model for the production of hadronic $\gamma$-rays is described and in Section 3 the spectra of $\gamma$-rays and neutrinos produced in pp interactions are calculated; the results are presented in Section 4. The discussion and conclusions are presented in Sections 5 and 6.

2. THE MODEL

The origin of HE $\gamma$-rays from microquasars can be interpreted within both leptonic and hadronic scenarios. The jet in the microquasars is a powerful particle accelerator (electrons and/or protons), and the photon field and/or wind from a companion star can be a target for $\gamma$-ray production. In the leptonic scenario, HE $\gamma$-rays are produced from inverse Compton (IC) scattering of soft seed photons (from the companion star and from the accretion disk) by energetic electrons. In the case of Cyg X-3, the leptonic scenario has been extensively discussed in the literature (Dubus et al. 2010; Zdziarski et al. 2012; Piano et al. 2012). In particular, Piano et al. (2012) applied this scenario to the AGILE observations of Cyg X-3 in flaring states, showing how a leptonic scenario can explain the spectral shape at GeV energies as well as the hard X-ray emission at $\sim$100 keV observed during the transient $\gamma$-ray activity.

By considering a hadronic scenario, since protons are characterized by a longer cooling time than electrons, we can assume that protons are accelerated well above 10 TeV. The detection of a periodic TeV $\gamma$-ray signal (which could be evidence for the production of TeV photons in a binary system) would provide additional information on the problem of distinguishing leptonic and hadronic contributions. If accelerated in the presence of a strong cooling photon background, electrons would possibly produce VHE $\gamma$-rays by IC scattering. On the other hand, hadrons would produce VHE $\gamma$-rays by interaction with a suitable gaseous target. After escaping from the jet, protons can interact both with the X-ray photon field from the accretion disk (pp interaction) as well as with the hadronic component of the stellar wind (pp interaction). In both cases, a significant flux of TeV $\gamma$-rays and neutrinos is predicted: while the $\gamma$-rays are absorbed (depending on the energy), the neutrinos escape from the region with negligible absorption. The emerging flux of HE neutrinos can significantly exceed the $\gamma$-ray observed flux (approximately $\exp(\tau)$ times higher, where $\tau$ is the optical depth of $\gamma\gamma$ absorption). For example in the case of the microquasar LS 5039, the flux of HE neutrinos can be as large as $1.6 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ for energies greater than 1 TeV, above the sensitivity threshold of experiments in the Mediterranean Sea (Aharonian et al. 2006). Therefore the binary systems could have a high flux of HE neutrinos, which can be detected by the current generation of detectors.

Hadronic models based on pp interactions require acceleration of protons in the inner jet up to the energies of $10^{16}$ eV in order to produce a significant flux of HE $\gamma$-rays and neutrinos. On the other hand, models based on pp interactions can explain the observed $\gamma$-ray flux by requiring lower energies for accelerated protons. Production of HE neutrinos from pp interaction in Cyg X-3 have been discussed in Baerwald & Guetta (2013): the expected number of neutrinos—assuming the IceCube sensitivity—during 61 days is 0.02, corresponding to a non-detectable flux. An alternative hadronic scenario for the production of $\gamma$-rays from Cyg X-3 was discussed in Piano et al. (2012), within the jet-wind interaction model. They found that the constraints on the energetics of the system are physically reasonable: the required jet kinetic power is lower than the Eddington accretion limit for the source, and the resulting spectral shape is consistent with the observed spectrum above 100 MeV. In our model we assume that the energy budget in the jet is dominated by the kinetic energy of an $e^{-}p$ plasma and it contains a significant population of protons. These particles are accelerated along the jet propagation (e.g., via shock acceleration) and can reach very HEs; in the binary frame this energy is even higher (multiplied by the Lorentz factor of the jet). Due to the slowly cooling of the protons in the jet, their maximum energy will likely be limited by the size of acceleration region: the Larmor radius ($r_L$) of the protons should be contained in the acceleration region $r_L \leq R_{jet}$ where $R_{jet}$ is the jet radius and $r_L = E_{in}/eB$, where $e$ is the elementary charge. Depending on the efficiency of acceleration, the magnetic field ($B$), and the jet radius ($R_{jet}$), the proton maximum energy ($E_{in}$) can be as large as 100 TeV. However, the accelerated protons can escape from the jet at some distance from the compact object since the magnetic field gets weaker. In the case where this occurs in a binary system, the protons interact with the dense wind of
the WR star, producing neutral and charged pions via inelastic hadronic scattering. The neutral pions subsequently decay into γ-rays, while muon and electron neutrinos (νμ, νe) are produced by the decays of π± (e.g., π+ → μ+ + νμ → e+ + νe + νμ + δν). If we define Λp as the luminosity of relativistic protons, the corresponding luminosity of γ-rays is Lγ ≈ ζcppLp where ζcpp is the energy transfer efficiency from relativistic protons to secondary particles (for simplicity it is assumed that the escape time of protons from the binary system is longer than the cooling time). Similarly, expressing the acceleration power of protons in terms of the total jet power, Lp ≈ ξLjet, one finds the following relation between jet power and γ-ray luminosity, Lγ ≈ ζcppLjet = ξLjet, where ξ is the acceleration efficiency and ζcpp is the efficiency of γ-ray production. Assuming ccpp ≈ ξ ≈ 10% (ξ ≈ 10^-2), and a peak γ-ray isotropic luminosity above 100 MeV of Lγ ≈ 10^36 erg s^{-1}, the corresponding jet power is Ljet ≈ 10^38 erg s^{-1}, which is an order of magnitude lower than the Eddington accretion limit for the system (assuming that the compact object in Cyg X-3 is a black hole with a mass of M_*=10 M_⊙, where M_⊙ is the solar mass) and it is consistent with the average bolometric luminosity of the hypersonof soft state, L_{bol}^{HYS} ≈ 1.2 × 10^{38} erg s^{-1} (Koljonen et al. 2010). Furthermore, as demonstrated by Cerutti et al. (2011), it is unlikely that the HE γ-rays have a coronal origin (unless the corona is unrealistically extended): the observed γ-ray emission is linked to the physics of the jet and created outside the γ-ray photosphere (at distances greater than 10^9–10^{10} cm from the compact object).

Fermi–LAT observations of the source revealed a γ-ray orbital modulation (Abdo et al. 2009) coherent with the orbital period (t_mod =4.8 hr). The folded emission above 100 MeV is characterized by a sharp maximum in correspondence to the superior conjunction of the system (compact object behind the WR star, with respect to the line of sight). The γ-rays appear to be approximately in antiphase with the X-ray modulation, a fact that may be linked to the different physical origins of the two components. The modulated γ-rays are produced only if the protons are confined in the binary system in timescales less than ξ t_mod; otherwise the protons will escape from the binary system. Since the cooling time for pp interactions is t_{pp} ≈ 10^{15} N_s s (N = n_H/1 cm^{-3}), from the relation t_{pp} = ξ t_mod, the condition for γ-ray modulation is satisfied only for densities (n_H) larger than ≲ 6 × 10^{12} cm^{-3} (assuming ξ ≈ 10^{-2} and t_mod = 4.8 hr). Accordingly, this condition is satisfied, especially near superior conjunction, because of an increase of the density along the orbit (anisotropic wind) or due to protons interacting with clumps (regions where the density is significantly higher than the average value; Araudo et al. 2009). At other phases along the orbit, the density of the wind should be significantly lower and since this change of density causes the change of luminosity of produced γ-rays, this results a modulation of the γ-ray signal.

3. PRODUCTION AND ABSORPTION OF GAMMA-RAYS

In binary systems the production of γ-rays (of both leptonic and hadronic origin) is accompanied by strong absorption of these photons. Depending on both their energy and the site of HE production, the emitted γ-rays can be absorbed by interactions with the X-ray photons from the corona/disk complex or with the UV photon field from the companion star. We discuss below the production of γ-rays from pp interaction as well as the opacity of photon absorption.

3.1. Production of Gamma-Rays and Neutrinos from pp Interaction

Hadronic inelastic scattering, between HE protons (accelerated in the jet) and cold protons from the WR wind, is responsible for the production of secondary γ-rays and neutrinos. The fluxes of produced particles are calculated using the analytical approximation derived in (Koljonen et al. 2006), obtained from numerical simulations of pp interactions with the publicly available code SIBYLL. The analytical formulae provide a very good description of the flux and energy distribution of secondaries for energies above 100 GeV. The formula for γ-rays also includes the contribution of η meson decay, in addition to that of π^0, with an overall accuracy of the order a few percent.

At energies below 0.1 TeV and down to the rest energy of the π-meson, the fluxes of γ-rays and neutrinos are modeled with delta function approximation as suggested by (Koljonen et al. 2006), namely the fluxes are given by:

$$\Phi_i(E_i) = \frac{cA_i\kappa_{\text{BH}}}{4\pi D^2K_\gamma} \int_0^\infty \frac{\sigma_{pp}(E_i)N_p(E_i)}{\sqrt{E_{\gamma}^2 - m_{\pi}^2c^2}} dE_\pi$$  \hspace{1cm} (1)

for both particle type i (i = γ, ν), E_{ν,γ} = E_i/(1 - r_i) + (1 - r_i)(m_π^2c^4/4 E_i) where r_i = 0, r_i = (m_μ/m_π^2)^2, A_γ = 2, and A_ν = (1 - r_γ)^{-1}. In Equation (1) K_γ is the mean fraction of proton kinetic energy transferred to pions, c is the speed of light in a vacuum, D is the distance from the source, \kappa is the free parameter to match the results of Monte Carlo simulations (Koljonen et al. 2006), ζcpp is the pp inelastic interaction cross section, E_i = m_p c^2 + E_γ/K_γ and m_p, m_μ, m_π are the proton, muon, and pion masses, respectively.

3.2. Absorption of Gamma-Rays

The produced γ-rays can be absorbed by interactions with UV stellar photons from the companion star. In the calculations below, we take into account this absorption by using the opacity averaged over the injection angles:

$$\tau_d(E_\gamma, r) = \int_0^\infty \int_0^{\epsilon_{\text{min}}} n(\epsilon_0, r')\sigma_{\gamma\gamma}(\epsilon_0, E_\gamma) d\epsilon_0 d\epsilon_0'$$  \hspace{1cm} (2)

where \epsilon_0 is the energy of the companion star’s photons, \epsilon_{\text{min}} is the threshold of pair production, \epsilon_{\text{min}} = m_e^2 c^2/E_\gamma, E_\gamma is the energy of the γ-ray, m_e c^2 is the electron rest energy, and \sigma_{\gamma\gamma}(\epsilon_0, E_\gamma) is the cross section for photon–photon pair production (Gould & Schrédé 1967). The distribution of stellar photons is assumed to have a blackbody spectrum peaking at the star’s effective temperature (T_{eff}):

$$n(\epsilon_0, r) = \frac{2\pi \epsilon_0^2}{(hc)^2} \frac{1}{e^{\epsilon_0/kT_{\text{eff}}} - 1} \frac{R_*^2}{r^2}$$  \hspace{1cm} (3)

where h and k are the Planck and Boltzmann constants, respectively, and R_* is the radius of the companion star. For Cyg X-3 we adopt the following values: T_{eff} = 10^5 K, and R_* = 6 × 10^{10} cm.

This absorption depends strongly on the geometry. It depends on the relative location of the γ-ray source, the companion star, and the line of sight to the observer. We calculated the opacity, which depends on the distance from the companion star (r), by averaging over the injection angles. This is illustrated in Figure 1, where the opacity is calculated from Equation (2) for r = R_*, 5R_*, and 10R_*. The VHE γ-rays produced very
For comparison, the opacity of gamma–photon interaction at the shape. However this opacity will vary depending on the distance; of VHE photons would be hardened compared to its intrinsic 

angles) calculated for different distances from the companion star for the Cyg X-3 system.

(A color version of this figure is available in the online journal.)

Figure 1. Opacity of photon–photon pair production (averaged over injection angles) calculated for different distances from the companion star for the Cyg X-3 system.

Figure 2. Hadronic modeling of the γ-ray flaring spectrum detected by AGILE assuming different indices of the initial proton energy distribution. The blue, red, and black solid lines correspond to power-law indices α = 2.4, 2.5, and 2.7, respectively; the dashed line corresponds to α = 2.3.

(A color version of this figure is available in the online journal.)

As one can see, the minimum power-law index which can reproduce the observed data corresponds to α = 2.4 (blue solid line), since for lower power-law indices the predicted flux of γ-rays is larger than the γ-ray data (blue dashed line in Figure 2). Moreover, softer proton spectra fit the data better (see the red and black lines in Figure 2, calculated for α = 2.5 and 2.7, respectively).

Figure 3(a) shows the γ-ray fluxes calculated for the proton energy distributions given by Equation (4) with α = 2.4, 2.5 and 2.7 (blue, red, and black colors, respectively). The dashed lines corresponds to the unabsorbed flux of γ-rays, instead the corresponding absorbed spectra are depicted with solid lines. As one can see, in all cases the predicted unabsorbed flux of γ-rays at TeV energies is larger than the upper limits (ULs) derived from MAGIC observations. However, taking into account the absorption of γ-rays, our model is in agreement with the observed data in MeV/GeV and TeV energies. For example, in the case of a proton index of α = 2.4 (which is related to the highest γ-ray flux), assuming that the γ-rays are produced at the distance r = R⋆, the density of the stellar photon field is so high that the absorbed γ-ray spectrum is lower than the MAGIC ULs (blue solid line in Figure 3(a)). Similar results are obtained for values of α = 2.5 with r = 1.4R⋆ (red line in Figure 3(a)), and for α = 2.7 with r = 4R⋆ (blue line in Figure 3(a)). We remark that the values presented here correspond to the maximum distances from the star where the γ-rays can be created: for closer distances, the absorption is higher and the predicted flux will be smaller.

Neutrinos are produced together with the γ-rays, but unlike the γ-rays they escape from the region without any absorption. In Figure 3(b) we show the resulting neutrino fluxes from Cyg X-3 corresponding to the γ-ray models of Figure 3(a). Since the minimum power-law index obtained from the γ-ray observations corresponds to α = 2.4, the predicted flux of neutrinos can be considered as a maximum flux during the γ-ray activity of the microquasar (this is shown by the filled area in Figure 3(b)). This predicted flux of HE neutrinos is compared with the IceCube sensitivities expected for different exposure times: two-month (61 days) and one-year (365 days) exposure times (red and blue dashed lines in Figure 3(b), respectively). The effective area for the 40-string configuration (Abbasi et al. 2011) has been scaled to the 86-string
configuration \(^8\) (full string configuration). The maximum predicted flux of neutrinos is almost two orders of magnitude less than the 61 day IceCube sensitivity, in agreement with the absence of a detectable neutrino signal from Cyg X-3 from the current IceCube observations (Abbasi et al. 2013). Nevertheless, we can assume that relativistic particles inside the jet can be accelerated far above 100 TeV, reaching PeV energies (supposing that Cyg X-3 is a Galactic “Pevatron”). Accordingly, if the cut-off energy in the proton spectrum (see Equation (4)) is at 10 PeV, the predicted flux of HE neutrinos is slightly lower than the IceCube sensitivity for the one-year exposure time (solid blue line in Figure 3(b)). Therefore, future detection of HE neutrinos from Cyg X-3 is possible if the particles in the jet are accelerated up to ultra HEs.

In the previous discussion only the \(\gamma\)-ray data from AGILE observations are used. However, the derived conclusions are valid also for the \(\gamma\)-ray spectrum obtained by Fermi-LAT during a prolonged \(\gamma\)-ray activity of the microquasar (Abdo et al. 2009). The predicted flux of HE neutrinos, related to the \(\gamma\)-ray activity detected by Fermi-LAT, will be slightly lower than the ones presented in Figure 3(b), since the Fermi-LAT photon index for the average emission from Cyg X-3 above 100 MeV is \(\Gamma = 2.7\) (Abdo et al. 2009), instead of the value \(\Gamma = 2.0\) determined by AGILE in the range 100 MeV–1 GeV.

5. DISCUSSION

Hadronic \(\gamma\)-ray emission from Cyg X-3, discussed and presented in the previous sections, requires an effective acceleration of hadrons (protons) in the jet of the microquasar. The total energy of the protons (for \(\alpha = 2.4\)) corresponds to \(W_p \approx 1.74 \times 10^{39}\) erg, assuming the number density of the wind to be \(n_H = 6 \times 10^{12}\) cm\(^{-3}\). The kinetic power of protons in the jet \((L_p = W_p t_p)\) would be \(L_p = 1.04 \times 10^{38}\) erg s\(^{-1}\), consistent with the hypersot tral state bolometric luminosity. This flux of \(\gamma\)-rays would be accompanied by the flux of HE neutrinos and, for a proton injection power \(L_p = 1.04 \times 10^{38}\) erg s\(^{-1}\), the predicted neutrino flux is \(f_{0 \text{ TeV}} \approx 9.1 \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\) at 10 TeV (solid line in Figure 3(b)). Furthermore, the minimum detectable neutrino flux for a neutrino point source with a generic \(E^{-2}\) spectrum, after one year of operation, is \(f_{\text{sens}} = 2.72 \times 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) at 5\(\sigma\) significance (Ahrens et al. 2004). We then obtain \(f_{0 \text{ TeV}} / f_{\text{sens}} \approx 0.3\). This estimate shows that only quite a hard proton injection rate (of index \(\alpha < 2.4\)) extending up to 10 PeV can produce a detectable flux of HE neutrinos from Cyg X-3. The flux of HE neutrinos depends, not only on the proton injection rate (which may be time variable), but also on the duration of the HE activity of the source. It is known that the microquasar Cyg X-3 emits \(\gamma\)-rays only under specific X-ray conditions: namely, during bright soft X-ray spectral states coincident with \textit{minima} of the hard X-ray light curve (Tavani et al. 2009; Abdo et al. 2009; Corbel et al. 2012; Piano et al. 2012). In principle, these states could last several months (Abdo et al. 2009) or even longer, with a strong probability of emitting \(\gamma\)-rays. These prolonged episodes of minimal hard X-ray emission (and corresponding maximal soft X-ray emission) might imply a significant increase of neutrino emission which can be detected by IceCube under favorable conditions. Interestingly, the hard X-ray light curve as detected by Swift/BAT (15–50 keV; see Figure 4), shows such prolonged activity. Namely, the gray region of the plot indicates a prolonged period (MJD: \(\sim 53749–54136\), between 2006 and 2007 February) in which Cyg X-3 is found to be in a soft state most of the time (\(\sim 70\%\) (Swift/BAT count rate \(\lesssim 0.02\) counts cm\(^{-2}\) s\(^{-1}\)). Therefore, if the conditions for \(\gamma\)-ray emission discussed by Piano et al. (2012) are valid, we deduce that in that period Cyg X-3 was characterized by a quasi-continuous emission of \(\gamma\)-rays and possibly detectable neutrinos. Unfortunately neither AGILE nor Fermi (nor sensitive neutrino detectors) were operational in 2006 to test this picture. In the future, such a possible prolonged active state accompanied by a quasi-continuous emission of \(\gamma\)-rays (of hadronic origin) might reach a neutrino flux close to detection by instruments such as IceCube.

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\(8\) The real effective area related to the 86-string IceCube configuration for a point source may be marginally different, but so far no public data are available.
6. CONCLUSIONS

Effective particle acceleration in a microquasar jet makes these objects strong sources of MeV–TeV \(\gamma\)-rays. These \(\gamma\)-rays can be produced via leptonic interactions (e.g., IC scattering of low energy photons by relativistic electrons), as well as via hadronic processes (e.g., \(pp\) or \(\gamma p\) interactions). In the case of hadronic interactions, the flux of \(\gamma\)-rays is accompanied by emission of HE neutrinos. Therefore, these sources are an interesting target for observations with HE neutrino detectors.

In this paper we investigated the possibility of detecting HE neutrinos from Cyg X-3 within a hadronic model of emission. We discussed a simplified picture of hadronic \(\gamma\)-ray production, namely we assumed that the protons are effectively accelerated by the jet up to 100 TeV energies (the maximum energy achieved by protons depends on the magnetic field and on the size of the jet). These protons can escape from the jet and interact with cold protons in the wind of the companion star. From these inelastic collisions, neutral and charged pions are produced with subsequent substantial neutrino emission. In this scenario, the effective production of \(\gamma\)-rays occurs only if the surrounding matter (number) density is larger than \(\approx 6 \times 10^{12} \text{ cm}^{-3}\) (corresponding to a cooling time \(\ll \xi_{\text{mod}}\), with \(\xi \approx 10^{-8}\)). This condition is expected to be satisfied for Cyg X-3 at a superior conjunction where the modulated \(\gamma\)-ray emission along the orbit reaches its maximum (Abdo et al. 2009). The absorption of \(\gamma\)-rays (by UV stellar photons from the WR star) does not affect the propagation of photons at MeV/GeV energies (unlike the TeV \(\gamma\)-rays), therefore the minimum index of the initial proton energy distribution can be derived from the Cyg X-3 \(\gamma\)-ray flares to be \(\alpha \gtrsim 2.4\) (from AGILE data). The spectrum of \(\gamma\)-rays and HE neutrinos can be then calculated. Taking into account the absorption of TeV \(\gamma\)-rays as deduced from the MAGIC upper limits, we can constrain the distance from the companion star where the \(\gamma\)-rays should be created. Within this distance, the absorption modifies the spectrum at TeV energies. The injection rate of protons should be \(L_p \approx 10^{38} \text{ erg s}^{-1}\) in order to explain the observed spectrum of \(\gamma\)-rays. The required power is physically reasonable: it is consistent with the bolometric luminosity during the hypersoft spectral state (correlated to the \(\gamma\)-ray transient activity, Piano et al. 2012), and it is lower than the Eddington accretion limit for a stellar black hole mass in Cyg X-3. Together with \(\gamma\)-rays, HE neutrinos are produced, escaping the region without any absorption. We found that a maximal neutrino flux (expected during the \(\gamma\)-ray activity of Cyg X-3) corresponds to an accelerated proton distribution with \(\alpha = 2.4\). In the case of short exposure time (two months), the predicted flux of HE neutrinos is almost two orders of magnitude less than the 61-day IceCube sensitivity. Only when assuming that protons are accelerated up to 10 PeV energies with a spectrum harder than \(\alpha = 2.4\), would the predicted neutrino flux be detectable by the IceCube full-string sensitivity (with a one-year exposure time). Whether a proton spectrum harder than \(\alpha = 2.4\) can be produced in Cyg X-3 in a time variable fashion not in contradiction with TeV upper limits is an open question that will be investigated in future observations. Long term observations of Cyg X-3 with IceCube combined with GeV and TeV observations can give important information about emission of neutrinos from microquasars, providing invaluable constraints on the hadronic particle density in relativistic jets. These considerations show how Cyg X-3 is a crucially interesting source, not only for radio-to-\(\gamma\)-ray observations, but also for new-generation neutrino detectors.

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