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Microquasar LS 5039: a TeV gamma-ray emitter and a potential TeV neutrino source¹

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Abstract. The recent detection of TeV γ -rays from the microquasar LS 5039 by *HESS* is one of the most exciting discoveries of observational gamma-ray astronomy in the very high energy regime. This result clearly demonstrates that X-ray binaries with relativistic jets (microquasars) are sites of effective acceleration of particles (electrons and/or protons) to multi-TeV energies. Whether the γ -rays are of hadronic or leptonic origin is a key issue related to the origin of Galactic Cosmic Rays. We discuss different possible scenarios for the production of γ -rays, and argue in favor of hadronic origin of TeV photons, especially if they are produced within the binary system. If so, the detected γ -rays should be accompanied by a flux of high energy neutrinos emerging from the decays of π^\pm mesons produced at pp and/or $p\gamma$ interactions. The flux of TeV neutrinos, which can be estimated on the basis of the detected TeV γ -ray flux, taking into account the internal $\gamma\gamma \rightarrow e^+e^-$ absorption, depends significantly on the location of γ -ray production region(s). The minimum neutrino flux above 1 TeV is expected to be at the level of $10^{-12} \text{ cm}^{-2}\text{s}^{-1}$; however, it could be up to a factor of 100 larger. The detectability of the signal of multi-TeV neutrinos significantly depends on the high energy cutoff in the spectrum of parent protons; if the spectrum of accelerated protons continues to 1 PeV and beyond, the predicted neutrino fluxes can be probed by the planned km^3 -scale neutrino detector.

1. Introduction

During the next decade, two km^3 scale underwater/ice neutrino telescopes will start operation, both in the Northern (NEMO/ km^3NeT [1]) and Southern (IceCube [2]) hemispheres. Theoretical and phenomenological studies of recent years show that the sensitivities of these detectors should allow meaningful probes of different nonthermal galactic and extragalactic source populations in high energy neutrinos (see e.g. [3, 4]).

TeV neutrinos are unique carriers of unambiguous information about hadronic processes in cosmic accelerators. They are produced in pp or $p\gamma$ interactions through the decay of secondary charged pions. Since generally these processes also result in TeV γ -rays of a comparable rate,

¹ The material of this paper was one of the highlight topics of the Plenary talk of F.A. Aharonian on the theory of TeV gamma-ray sources at the TAUP05 Conference. Instead of a brief overview of models of all classes of detected gamma-ray sources, in this article we decided to focus on high energy processes in the microquasar LS5039 which presents a great interest for the Astroparticle Physics community in general, and for gamma- and neutrino astronomers, in particular.

the best candidates to be discovered by planned km^3 scale neutrino telescopes are sources of γ -rays with fluxes above 1 TeV at the level of $(3 - 10) \times 10^{-12} \text{ ph/cm}^2\text{s}$.

Presently more than three dozens of sources of both galactic and extragalactic origin are established as TeV γ -ray emitters. Some of them, in particular four galactic objects - RXJ1713.7-3946 and RXJ0852.0-4622 (shell type supernova remnants) and Crab Nebula and Vela X (plerions), as well as three variable extragalactic (BL Lac) objects - Mrk 421, Mrk 501, and 1ES1959+650, do exhibit persistent or episodic fluxes of TeV γ -rays exceeding $J_\gamma(E \geq 1\text{TeV}) = 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$. Thus, if a significant fraction of TeV γ -ray fluxes of these sources are of hadronic origin, and the spectra of parent protons extend to PeV energies, IceCube and NEMO/km3Net should be able to detect the neutrino counterparts of TeV γ -rays.

Moreover, unlike neutrinos, TeV γ -rays are fragile and suffer strong internal and/or external absorption due to interactions with ambient IR/optical photon fields. Therefore, for sources with heavily absorbed TeV emission, the chances of detection of counterpart neutrinos could be quite high, even for relatively weak γ -ray sources with a TeV flux below $10^{-12} \text{ ph/cm}^2\text{s}$. In this regard, the microquasar LS 5039 [5] recently detected in TeV γ -rays by the *HESS* Collaboration [6] is of great interest and a promising source also for neutrino astronomy.

2. High Energy Nonthermal Phenomena in X-ray Binaries

In one of the first attempts to classify the potential VHE γ -ray emitters, X-ray binaries were attributed to the category of serendipitous sources, i.e. objects which “do not have any firm *a priori* basis for their selection as candidate VHE γ -ray sources” [7]. Nevertheless, this very class of objects played a very important role in gamma-ray astronomy, in particular initiating in the 1980s a renewed interest in ground based γ -ray observations. But ironically, the same sources ultimately raised questions about the credibility of the results from that controversial period of ground-based γ -ray astronomy. As a result, since the early 1990s X-ray binaries have not been considered as primary targets for VHE γ -ray observations. This pessimistic view was largely supported also by the belief that X-ray binaries should be treated, first of all, as *thermal* sources effectively transforming the gravitational energy of the compact object (a neutron star or a black hole) into thermal X-ray emission radiated away by the hot accretion plasma.

After the discovery of galactic sources with relativistic jets dubbed *Microquasars* [8], the general view on X-ray binaries has dramatically changed; the observations of synchrotron radio flares from microquasars demonstrated non-negligible role of particle acceleration (MeV/GeV electrons) in these accretion-driven objects. The discovery of γ -rays from LS 5039 provides a clear indication that nonthermal phenomena of particle acceleration and radiation in X-ray binaries effectively extend into the TeV and, perhaps, also PeV energy regimes. In this regard, many original ideas and models (see e.g. [9, 10, 11, 12, 13]), which were initiated by the early (wrong ?) claims of TeV and PeV signals from Cyg X-3 and Her X-1 (for a review see [7]), remain very attractive and applicable, after some modifications, to Microquasars as well.

Variable TeV radiation has been predicted from microquasars in different astrophysical scenarios with involvement of both leptonic [14] and hadronic [15] interactions. Gamma-rays of leptonic [16] and hadronic [17, 18] origin associated with termination of jets in the interstellar medium are expected also from extended regions surrounding microquasars.

Hadronic models are attractive in the sense that they predict, from X-ray binaries in general, and from microquasars in particular, significant fluxes of both TeV γ -rays and neutrinos due to proton-proton, photomeson and photo-disintegration processes that may take place in the wind and/or the atmosphere of the normal star, in the accretion disk, and in the jet (see e.g. [9, 10, 11, 12, 13, 19, 20, 21, 22, 23, 24]).

While the models of production of TeV neutrinos demonstrate the feasibility of several different scenarios of particle acceleration and interactions in microquasars, one should not overestimate the prediction power and robustness of calculations of neutrino fluxes based merely

on model assumptions such as (i) the total nonthermal energy of the source, (ii) the efficiency of the particle acceleration, (iii) the energy spectrum and the maximum energy of accelerated protons, (iv) the efficiency of conversion of proton energy into neutrinos. Obviously, the flux predictions based on many model assumptions and parameters does not guarantee any reliable estimate of neutrino fluxes. While this concerns (perhaps, with some exceptions) all astrophysical source populations, in the case of microquasars several model assumptions together result in flux uncertainties as large as orders of magnitude. Moreover, in microquasars particles can be boosted to multi-TeV energies only if the acceleration proceeds at the theoretically highest possible rates allowed by classical electrodynamics. It is not obvious, however, that this should work, from first principles, in microquasars.

The detection of TeV γ -ray emission from LS 5039 has dramatically changed the status of model predictions. First of all, the *HESS* discovery provides the first unambiguous evidence for presence of multi-TeV particles in microquasars. Below we demonstrate that if gamma-radiation is produced within the binary system, then (2) electrons hardly can be accelerated to multi-TeV energies to explain the observed TeV γ -ray signal, and, therefore, (3) the parent particles of γ -rays should be protons or nuclei. If so, (4) γ -radiation should be accompanied by TeV neutrinos with a production rate comparable to the gamma-ray production rate. Furthermore, since the γ -rays suffer unavoidable absorption or cascading, (5) the flux of neutrinos should significantly exceed the observed flux of γ -rays, and therefore (6) can be (marginally) detectable by the km³ class high energy neutrino telescopes.

3. The case of LS 5039

While the *HESS* discovery of TeV γ -ray emission from LS 5039 does support the early theoretical speculations of acceleration of particles in microquasars to TeV/PeV energies, the reported data do not allow us to relate the γ -ray production region(s) to specific sites of this complex system. The upper limit on the source angular size of about 50 arcsec [6] implies that, for a source distance $d \simeq 2.5$ kpc [25], γ -ray production takes place within a radius ~ 0.6 pc around LS 5039. Although the observed flux does not allow an unequivocal conclusion about the variability of the TeV source [6], hints have been recently reported [25] of a possible correlation of the TeV flux with the 3.9 day orbital period of the binary system. If confirmed by future observations, this would be an indication that TeV γ -rays are produced in a compact region, presumably inside the binary system. In what follows we will assume that γ -rays are produced within $R \sim 10^{13}$ cm, which automatically implies very strong $\gamma\gamma$ absorption. The effect of this absorption should have a strong impact on the detectability of TeV neutrinos from this source, provided that detected γ -rays are of hadronic origin.

TeV γ -ray production generally requires two components: (a) an *effective accelerator* of particles, electrons and/or protons, up to 10 TeV and beyond; (b) an *effective target* (converter). While the most likely site for particle acceleration in LS 5039 is the jet, which with a speed $v = 0.2 c$ and a half-opening angle $\theta \leq 6^\circ$ extends out to 300 mas ($\approx 10^{16}$ cm) [26], the bulk of γ -rays could be produced both inside and outside the jet. In particular, relativistic electrons in the jet can be accelerated through internal shocks [27], and consequently high energy γ -rays can be effectively produced through inverse Compton scattering [28, 14, 5, 29, 30]. However, in the jet of LS 5039, because of close location of the very luminous companion star, the effects of fast radiative cooling may prevent the electrons from reaching multi-TeV energies.

The maximum energy of accelerated electrons is achieved when the acceleration time approaches the cooling time due to radiative (synchrotron and Compton) losses. The acceleration time can be presented in a general form $t_{\text{acc}} = \eta r_L / c \approx 0.11 E_{\text{TeV}} B_G^{-1} \eta$ s, where $r_L = E/eB$ is the Larmor radius, $E_{\text{TeV}} = E/1\text{TeV}$, and $B_G = B/1\text{G}$ is the strength of the ambient magnetic field. The parameter η characterizes the efficiency of acceleration: in the case of extreme accelerators (maximum possible acceleration rate allowed by classical electrodynamics) $\eta \rightarrow 1$,

whereas for shock acceleration in the Bohm diffusion regime $\eta \approx 10(v/c)^{-2}$ (see e.g. [31]). For a star with a temperature $kT = 3.5$ eV and optical luminosity $L_\star \approx 1.2 \times 10^{39}$ erg/s, the energy density of the starlight close to the compact object, $w_r = L_\star/4\pi R^2 c$, varies between 400 and 1600 erg/cm³ at the apastron ($R \approx 2.9 \times 10^{12}$ cm), and at the periastron ($R \approx 1.4 \times 10^{12}$ cm), respectively [25]. The Compton scattering of TeV electrons in the field of $3kT \approx 10$ eV starlight takes place in deep Klein-Nishina regime. While in the Thompson regime ($E_e \ll 0.1$ TeV) the cooling time is inverse proportional to the electron energy, $t_T \approx 0.03 E_{\text{TeV}}^{-1}$ s, in the Klein-Nishina regime the characteristic Compton cooling time can be approximated with a good accuracy, $t_C \approx 34 w_0^{-1} E_{\text{TeV}}^{0.7}$ s, where $w_0 = w_r/500$ erg cm⁻³. From $t_{\text{acc}} = t_C$ one finds

$$E_{e,\text{max}} \simeq 2 [B_G(v/0.2c)^2 w_0^{-1}]^{3.3} \text{ TeV}. \quad (1)$$

Formally, for $B > 1$ G the maximum energy of accelerated electrons can exceed 10 TeV. However, for such a large B -field, the synchrotron losses dominate over the Compton losses. Namely, the condition $t_{\text{acc}} = t_{\text{sy}}$, where $t_{\text{sy}} \approx 400 B_G^{-2} E_{\text{TeV}}^{-1}$ s is the synchrotron cooling time, gives

$$E_{e,\text{max}} \approx 3.8 B_G^{-1/2} (v/0.2c) \text{ TeV}. \quad (2)$$

Equations (1) and (2) imply that electrons could be accelerated to energies exceeding 10 TeV only in an environment with $B \leq 0.1$ G and $w_0 \ll 1$. Such small fields can be realized beyond the binary system, in outer parts of the jet. In this case, γ -rays can be produced through the Synchrotron-self-Compton (SSC) scenario [14], although the contribution from the external (starlight) photons could be still significant even at distances quite far from the binary system. It was recently argued [30] that the inverse Compton on starlight cannot explain the hard TeV γ -ray spectrum, and, therefore, an additional SSC component was proposed to match the *HESS* data. However, the SSC model does not solve the major problem associated with the maximum achievable energy of electrons. In fact, the SSC model requires even higher electron energies than the external Compton model.

Thus, any evidence of γ -ray production inside the binary system, e.g. detection of a periodic component of TeV radiation would be a strong argument in favor of the hadronic origin of these energetic photons. The extension of hard γ -ray spectrum above several TeV requires acceleration of protons to ≥ 100 TeV. Within the inner parts of the jet, with a radius $R_{\text{jet}} \sim 10^7 - 10^8$ cm, a magnetic field $B \geq 10^5$ G could be sufficient to boost protons up to very high energies. The maximum energy is determined by the condition $r_L \leq R_{\text{jet}}$, which gives $E_p \leq 3 \times 10^{15} (R_{\text{jet}}/10^8 \text{ cm})(B/10^5 \text{ G})$ eV. Although these protons are not sufficiently energetic to interact with the starlight photons, they can trigger photomeson processes on X -ray photons in the accretion disk. These interactions may lead to copious production of high energy neutrinos, neutrons, γ -rays and electrons. While neutrons and neutrinos escape the source without significant suppression, the electromagnetic fraction of the energy is effectively reprocessed, and escape the source mainly in the form of hard X -rays and low energy γ -rays. For example, if the luminosity of the accretion disk at UV band exceeds 10^{35} erg s⁻¹, all γ -rays above several tens of GeV will be converted into e^\pm pairs before they can leave the source. Hence, the synchrotron radiation of the last generation of electrons will lead to a hard γ -ray spectrum $\propto E^{-1.5}$, extending to ~ 100 MeV. Interestingly, observations of LS 5039 performed by the COMPTEL telescope do show [32] a statistically significant signal of MeV γ -rays with a photon index 1.6 ± 0.2 and a total energy flux between 1 MeV and 30 MeV of about 9×10^{-10} erg/cm²s. If this radiation is indeed related to LS 5039, it would imply a pronounced maximum in the spectral energy distribution at the level of 6×10^{35} erg s⁻¹.

Thus, speculating that this radiation is initiated by photomeson interactions (of protons with energy ≥ 100 TeV) close to the inner part of the accretion disk, one can estimate the expected flux of TeV muon neutrinos at the level of $\sim 10^{-10}$ cm⁻²s⁻¹, provided that the

charged pions decay before interacting with the ambient dense plasma and radiation. In the lab frame, the decay time of charged pions responsible for TeV neutrino production is $t_{\pi^\pm} = (E_\pi/m_\pi c^2) \tau_{\pi^\pm} \approx 2.5 \times 10^{-3} (E_\pi/10 \text{ TeV}) \text{ s}$. On the other hand, the cooling time of π^\pm due to inelastic πp and $\pi\gamma$ interactions depends on the ambient gas n_p and photon n_x densities: $t_{\pi p} \sim 10^{-3} (n_p/10^{17} \text{ cm}^{-3})^{-1} \text{ s}$, and $t_{\pi\gamma} \sim 5 \times 10^{-3} (n_x/10^{20} \text{ cm}^{-3})^{-1} \text{ s}$. For typical parameters characterizing LS 5039, the number density of X-ray photons and the plasma density in the region $R \geq 10^7 \text{ cm}$ do not exceed 10^{20} cm^{-3} and 10^{17} cm^{-3} , respectively. Therefore charged pions decay to μ and ν_μ before interacting with the ambient photons and protons. The production of neutrinos from the subsequent muon decay also proceed with high probability as long as the magnetic field does not exceed $B \sim 10^6 \text{ G}$. This follows directly from the comparison of the decay time of muons, $t_\mu = (E_\mu/m_\mu c^2) \tau_\mu \simeq 0.2 (E_\mu/10 \text{ TeV}) \text{ s}$, with their synchrotron cooling time $t_{\text{sy}} \approx 0.07 (B/10^6 \text{ G})^{-2} (E_\mu/10 \text{ TeV})^{-1} \text{ s}$.

Protons can also interact effectively with the ambient cold plasma, close to the base of the jet and/or throughout the entire jet. In what follows we assume that the base of the jet is located close to the inner parts of the accretion disk, i.e., the jet axis z is taken normal to the orbital plane, with $z_0 \sim 30 R_S$ ($R_S \simeq 3 \times 10^5 (M_{\text{BH}}/M_\odot) \text{ cm}$ is the Schwarzschild radius). If the magnetic field drops as $B \propto z^{-1}$, the condition of the confinement of protons in the jet, $r_L \leq R$, where $R = \theta z$ is the radius of the jet at a distance z , implies $E_{\text{max}} \propto Bz = \text{constant}$. Thus, one may expect acceleration of protons to the same maximum energy E_{max} over the entire jet region. However, if there is a faster drop of B with z , the protons at some distance z_t from the compact object will start escaping the jet. If this happens within the binary system, i.e. $z_t \leq 10^{12} \text{ cm}$, protons interacting with the dense wind of the optical star will result in additional γ -ray and neutrino production outside the jet.

If the jet power is dominated by the kinetic energy of bulk motion of cold e - p plasma, the baryon density of the jet n_{jet} can be estimated from the condition $L_{\text{jet}} = \pi R_{\text{jet}}^2(z) n_{\text{jet}}(z) m_p v^3/2$. The efficiency of γ -ray production in the jet is $\rho_\gamma = L_\gamma/L_p = \sigma_{pp} f_\pi \int_{z_0}^{z_t} n_{\text{jet}}(z) dz \leq 1$, where L_γ is the luminosity of VHE γ -rays and L_p is the power of accelerated protons. Here, $\sigma_{pp} \approx 40 \text{ mb}$ is the cross-section of inelastic pp interactions, and $f_\pi \approx 0.15$ is the fraction of the energy of the parent proton transferred to a high energy γ -ray photon. Given the recent estimate of the black hole mass in LS 5039 $M = 3.7_{-1.0}^{+1.3} M_\odot$ [25], we set $z_0 \simeq 3 \times 10^7 \text{ cm}$. For the profile of the number density we adopt a power law-form, $n_{\text{jet}} = n_0 (z/z_0)^{-s}$, where $s = 0$ corresponds to a cylindrical geometry, $s = 2$ to a conical jet, and $s \sim 1$ is an intermediate case. Expressing the acceleration power of protons in terms of the total jet power, $L_p = \kappa L_{\text{jet}}$, one finds the following requirement for the jet power,

$$L_{\text{jet}} \approx 2 \times 10^{37} \frac{L_{\gamma,34}^{1/2} (v/0.2c)^{3/2}}{\sqrt{C(s)} (\kappa/0.1)} \text{ erg s}^{-1}, \quad (3)$$

where κ is the acceleration efficiency and $L_{\gamma,34} = L_\gamma/10^{34} \text{ erg s}^{-1}$. The parameter $C(s)$ characterizes the geometry/density profile of the jet. For $s = 0, 1, 2$, one has $C(s) = z_t/z_0$, $\ln(z_t/z_0)$, and 1, respectively. The case of cylindrical jet provides the highest efficiency of γ -ray production. However, since $L_\gamma \leq 1/30 L_{\text{jet}}$ (assuming $\approx 10\%$ efficiency of proton acceleration, and taking into account that the fraction of energy of protons converted to γ -rays cannot exceed 30%) the γ -ray production cannot be extended beyond $z_t \sim 10^4 z_0 \sim 3 \times 10^{11} \text{ cm}$. The case of a conical jet corresponds to the minimum efficiency of γ -ray production, and thus the largest kinetic power of the jet. In this case the bulk of γ -rays are produced not far from the base. Finally, in the intermediate case, TeV γ -rays are produced in equal amounts per decade of length of the jet, until the jet terminates.

If γ -rays are indeed produced in pp interactions, one would expect production of high energy neutrinos with a rate close to the γ -ray production rate, $Q_{\nu_\mu}(E) = \zeta Q_\gamma(E)$, where ζ varies

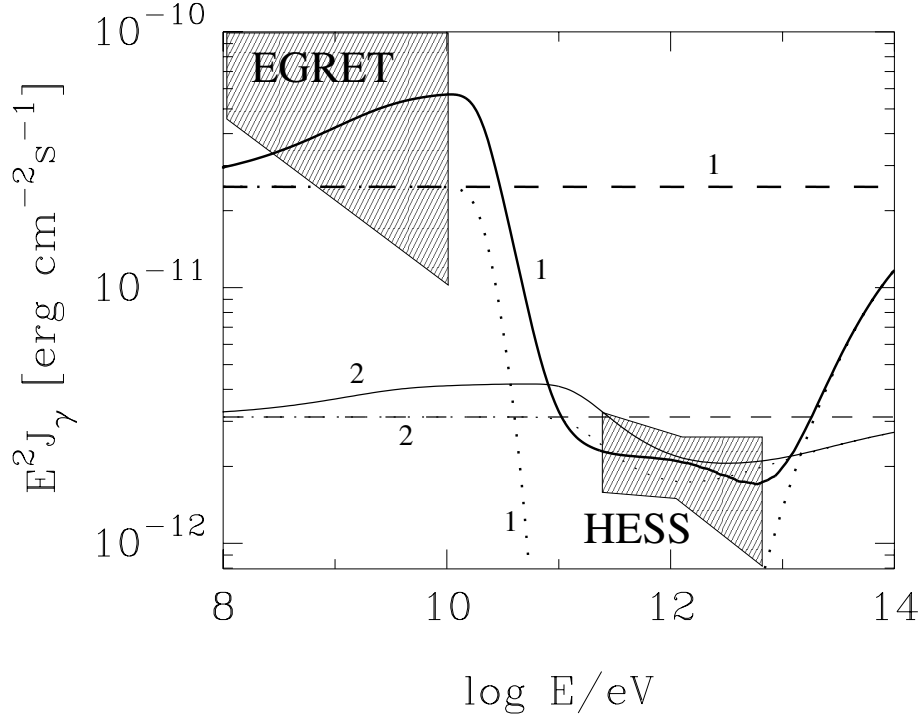


Figure 1. Time averaged γ -ray spectra of LS 5039 formed due to absorption (dotted lines) and cascading (solid lines) in the anisotropic radiation field of the normal companion star. Curves 1 and 2 correspond two different assumptions on the location of the γ -ray production region in the jet: at $z = 10^8$ cm (1), and $z = 10^{13}$ cm (2). Dashed curves correspond to the primary γ -ray injection rates chosen in a way that the calculated cascade spectra match the observed γ -ray flux around 1 TeV. The shaded regions indicate the ranges of MeV/GeV (EGRET) and TeV (HESS) γ -ray fluxes [6].

between 0.5 and 2 depending on the shape of the proton spectrum. However, since γ -rays are subject to energy-dependent absorption [6], both the energy spectrum and the absolute flux of neutrinos, $J_{\nu_\mu}(E) \simeq \zeta J_\gamma(E) \exp[\tau(E)]$, could be quite different from the detected γ -rays, $J_\gamma(E) \approx 1.2 \times 10^{-12} E_{\text{TeV}}^{-2.1} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ [6]. The optical depth $\tau(E)$ depends significantly on the location of the γ -ray production region, and therefore varies with time if this region occupies a small volume of the binary system. This may lead to time modulation of the energy spectrum and the absolute flux of TeV radiation with the orbital period [33, 34]. However, the $\gamma\gamma$ interactions generally cannot be reduced to a simple effect of absorption. In fact, these interactions initiate high energy electron-photon cascades, supported by the inverse Compton scattering and $\gamma\gamma$ pair production processes. The cascades significantly increase the transparency of the source. The spectra of γ -rays formed during the cascade development significantly differ from the spectrum of γ -rays that suffer only absorption. This is shown in Fig. 1. Three processes have been included in calculations - photon-photon pair production, inverse Compton scattering and synchrotron radiation of electrons. The calculations of the electromagnetic cascade developed in the photon and magnetic field are based on the method similar to the one described in Ref [35]. Because of the orbital motion, both the absolute density and the angular distribution of the thermal radiation of the star relative to the the position of the compact object (microquasar) vary with time. In calculations we take into account the effect of the anisotropic (time-dependent) distribution of target photons on the Compton scattering and pair-production cross-sections [36]. In Fig. 1 we show the γ -ray spectra averaged over the

orbital period.

The solid curves show the cascade spectra, the dotted curves are the spectra of γ -rays which the observer would see due to the pure absorption effect (i.e. in the case of effective suppression of the cascade), and the dashed curves indicate the injection spectra. Two different locations of γ -ray production region have been assumed: (i) close to the base of the jet $z \leq 10^8$ cm, and (ii) well above the base of the jet, $z = 10^{13}$ cm. All curves are averaged over the orbital period of the system, taking into account the recent data concerning the geometry of the system [25]. The cascade spectra are normalized to the reported range of TeV fluxes. They correspond to the production rate (luminosity) of $0.1 - 10$ TeV γ -rays between 10^{34} (corresponding to the dashed curve 2 for $d = 2.5$ kpc) and $8 \times 10^{34} \text{ erg s}^{-1}$ (dashed curve 1). Figure 1 shows that the cascade γ -rays calculated for $z = 10^8$ cm agree quite reasonably with the low energy (MeV/GeV) data as well, given the large statistical uncertainties and the fact that the EGRET and *HESS* observations are from different epochs.

Since muon neutrinos should be produced with about the same rate as TeV γ -rays, the dashed curves can be used to estimate the neutrino flux expected from the source: $J_{\nu_\mu}(> 1 \text{ TeV}) = 1.6 \times 10^{-11}$ and $1.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ for the cases (i) and (ii), respectively. The flux of neutrinos could be, in principle, higher if there is suppression of the cascade, as indicated by the dotted curves. This could happen if the magnetic field within the binary system exceeds 30 G. Although the energy density of this field $B^2/8\pi \approx 35 \text{ erg cm}^{-3}$ is significantly less than the energy density of the radiation field, due to the Klein-Nishina effect, the cooling of the electrons is dominated by synchrotron radiation in the energy interval $E \approx 100 \text{ keV} - 10 \text{ MeV}$. The flux observed by COMPTEL [32] provides an upper bound on the energy released via synchrotron radiation, and consequently sets an upper bound on the expected TeV neutrino flux around $J_{\nu_\mu}(> 1 \text{ TeV}) = 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$.

Table 1. Number of ν_μ events with $E > 1$ TeV expected in 1 yr of observation. We took into account that during propagation ν_μ 's will partition themselves equally between ν_μ 's and ν_τ 's due to maximal mixing [40].

Experiment	ANTARES		NEMO	
E_{max} [TeV]	$\Gamma = 1.5$	$\Gamma = 2.0$	$\Gamma = 1.5$	$\Gamma = 2.0$
10	0.20	0.11	6.0	3.0
100	0.26	0.15	8.3	5.0

Future experiments in the Mediterranean Sea, such as ANTARES [37], NESTOR [38], and NEMO [1] can provide meaningful probes of very high energy neutrinos from LS 5039. The most advanced project is ANTARES, with construction beginning in the fall 2005 and completion expected by early 2007. This detector will have an instrumented area $> 0.06 \text{ km}^2$, with an angular resolution better than 1.0° (0.2°) at energies larger than 100 GeV (100 TeV). In Table 1 we show event rates expected for ANTARES assuming a power-law neutrino spectrum, $dN_{\nu_\mu}/dE \propto E^{-\Gamma}$, with energy cutoff $E_{\text{max}} = 10 \text{ TeV}$ and 100 TeV , and $\Gamma = 1.5$ and 2 . We used a realistic Monte Carlo simulation to account for the detector response. We also compensated for the fraction of the day in which the source is visible through upward-going muon tracks by ANTARES, which amounts to about 55% duty cycle (for details see [39]). For all four combination of parameters Γ and E_{max} we assume the same energy flux of neutrinos above 0.1 TeV , $F_E = 10^{-10} \text{ erg/cm}^2 \text{ s}$. Note that this is comparable with the energy flux corresponding to the dashed curve 1 in Fig. 1, and a factor of 5 less than the upper bound on the ν_μ -flux set by COMPTEL data. For a 1° search cone, the atmospheric neutrino background is at the level of 0.05 yr^{-1} ; consequently in the most optimistic scenario the full lifetime of the experiment will be required to achieve a 5σ discovery. As we also show in Table 1, more promising data samples

will be obtained by NEMO. The larger sensitivity and low background ($\approx 1 \text{ yr}^{-1}$) will allow NEMO to probe a broad range of plausible fluxes.

In summary, our estimates of the neutrino flux associated with recent *HESS* discovery of TeV γ -rays from the direction of the microquasar LS 5039 show that the upcoming neutrino experiments will be sensitive to this flux, provided that the observed TeV γ -rays are produced in the inner parts of the jet, and that the spectrum of the accelerated parent protons extends to PeV energies.

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