Propagation of very high energy γ-rays inside massive binaries LS 5039 and LSI +61° 303

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ABSTRACT

Two massive binary systems of the microquasar type, LS 5039 and LSI +61° 303, have been suggested as possible counterparts of EGRET sources. LS 5039 has also been recently detected in TeV γ-rays. Since the massive stars in these binary systems are very luminous, it is expected that high-energy γ-rays, if injected relatively close to the massive stars, should be strongly absorbed, initiating inverse Compton e± pair cascades in the anisotropic radiation from stellar surfaces. We investigate the influence of the propagation effects on the spectral and angular features of the γ-ray spectra emerging from these two binary systems by applying the Monte Carlo method. Two different hypotheses are considered: isotropic injection of primary γ-rays with the power-law spectrum due to e.g. interaction of hadrons with the matter of the wind, and the isotropic injection of electrons, e.g. accelerated in the jet, which comptonize the radiation from the massive star. It is concluded that the propagation effects of γ-rays can be responsible for the spectral features observed from LS 5039 (e.g. the shape of the spectrum in the GeV and TeV energy ranges and their relative luminosities). The cascade processes occurring inside these binary systems significantly reduce the γ-ray opacity obtained in other works by simple calculations of the escape of γ-rays from the radiation fields of the massive stars. Both systems provide very similar conditions for the TeV γ-ray production at the periastron passage. Any TeV γ-ray flux at the apastron passage in LSI +61° 303 will be relatively stronger with respect to its GeV flux than in LS 5039. If γ-rays are produced inside these binaries not far from the massive stars, i.e. within a few stellar radii, then clear anticorrelation between the GeV and TeV energies are produced in the same process by the same population of relativistic particles. These γ-ray propagation features can be tested in the near future by the multiwavelength campaigns engaging the AGILE and GLAST telescopes (>30 MeV) and the Cherenkov telescopes (>100 GeV, e.g. MAGIC, HESS, VERITAS and CANGAROO).

Key words: radiation mechanisms: non-thermal – binaries: close – stars: individual: LS 5039 – stars: individual: LSI +61° 303 – gamma-rays: observations – gamma-rays: theory.

1 INTRODUCTION

Massive binary systems provide very promising conditions for acceleration of particles to relativistic energies and also well-defined conditions for their possible interaction. Therefore, they have been considered for a long time as possible sources of high-energy γ-rays and neutrinos in which acceleration processes can be tested. In fact, some GeV γ-ray sources observed by the EGRET detector (>100 MeV) have been proposed to be related to well-known massive binaries in which non-thermal processes were evident at lower energies, e.g. LSI +61° 303 (2EG J0241+6119; Thompson et al. 1995), Cen X-3 (Vestrand, Sreekumar & Mori 1997), Cyg X-3 (2EG J2033-4112; Mori et al. 1997) and LS 5039 (3EG J1824-1514; Paredes et al. 2000). Early searches of the TeV γ-ray signals from massive binaries have not been very convincing, with the exception of the Cen X-3 binary system (containing a slowly rotating neutron star) which has been reported as TeV γ-ray source by the Durham group (Chadwick et al. 1998, 1999; Atoyan et al. 2002). The turning point came recently with the observations of TeV γ-ray signals from two massive binaries: PSR B1259-63/SS 2883, containing a radio pulsar with the period of 47.8 ms (Aharonian et al. 2005a), and LS 5039, a so-called microquasar possibly containing a solar mass black hole (Aharonian et al. 2005b).
The $\gamma$-ray emission from massive binaries is usually interpreted in terms of the inverse Compton scattering (ICS) model in which thermal radiation coming from the stellar surface is scattered by electrons accelerated in the pulsar wind shock (e.g. Maraschi & Treves 1981) or by electrons moving highly anisotropically in the form of beams or jets (e.g. Bednarek et al. 1990). The binary systems which are considered as an example in this paper, LS 5039 and LSI +61° 303, have been recently discussed in terms of the microquasar inverse Compton model by Bosch-Ramon & Paredes (2004a,b) and Paredes, Bosch-Ramon & Romero (2005). Primary $\gamma$-rays might also be produced in the microquasar scenario of the binary system as a result of the interaction of hadrons, accelerated in the jet, with the matter of the stellar wind (Romero, Christiansen & Orellana 2005). For the review of the $\gamma$-ray production in microquasars, see e.g. Romero (2004) or Paredes et al. (2005).

The problem of the importance of the propagation of TeV $\gamma$-rays inside compact massive binary systems appeared during the early 1980s after the first reports on the possible observation of such $\gamma$-rays (see e.g. Weekes 1988). The optical depths for $\gamma$-rays in the radiation field of the accretion disc around the compact object inside the binary system have been calculated by e.g. Carraminana (1992) and Bednarek (1993), and in the radiation field of the massive star by e.g. Protheroe & Stanev (1987) and Moskalenko, Karakula & Tkaczyk (1993). In the case of very compact binaries, the TeV $\gamma$-rays injected close to the surface of the massive star initiate the IC $e^\pm$ pair cascade. The conditions for which the cascade processes should become important have been considered by Bednarek (1997, section 2) and Dubus (2005, section 6). In general, the product of the massive star luminosity and the square of its surface temperature should be much greater than $\sim 10^{45} \text{erg s}^{-1} \text{K}^2$ [see equation 1 and fig. 3 in Bednarek 1997, hereafter B97]. The $\gamma$-ray spectra which emerge towards the observer from such compact binary systems strongly depend on the phase of the injection place of the primary relativistic particles with respect to the observer. At some phases, significant TeV $\gamma$-ray fluxes are expected, but at other phases only photons with energies extending to a few tens of GeV are able to escape [see detailed calculations of such anisotropic cascades and their application to specific sources, e.g. Cen X-3 and Cyg X-3, in B97, Bednarek (2000) hereafter B00 and Sierpowska & Bednarek (2005) hereafter SB05]. Recently, optical depths of TeV $\gamma$-rays have been calculated for other TeV $\gamma$-ray sources, LS 5039, PSR 1259-63 and LSI +61° 303, without taking into consideration the effects of the IC $e^\pm$ pair cascading (Böttcher & Dermer 2005; Dubus 2005).

Note that only calculations by Bednarek and collaborations (B97, B00, SB05) and Dubus (2005) take into account the dimensions of the massive star. Therefore, these can be applied to very compact binaries in which injection distance of the TeV $\gamma$-rays from the centre of massive stars is comparable to their radii, e.g. at the periastron passage of the compact objects in LS 5039 and LSI +61° 303, or in the case of propagation of $\gamma$-rays injected at larger distances but passing close to the surface of the massive stars. The comparison of the exact calculations with the approximate ones, which neglect dimensions of the massive stars, can be found in Dubus (2005).

In this paper, we concentrate on details of the propagation of high-energy $\gamma$-rays injected close to the surface of the massive star, taking into account the effects of cascades initiated through the IC and $e^\pm$ pair production processes. We calculate the $\gamma$-ray spectra emerging to the observer from such anisotropic cascades for two compact massive binaries LS 5039 (already reported in GeV and TeV $\gamma$-rays) and LSI +61° 303 (reported only at GeV energies). Specific cases with the injection of primary $\gamma$-rays (e.g. by relativistic hadrons) or electrons (accelerated in the jet or the shock) with simple power-law spectra and spectral indexes equal to 2 are considered in order to better understand the basic features of such anisotropic cascade processes.

2 THE MASSIVE BINARY SYSTEMS

Both binary systems considered in this paper belong to the class of the non-thermal radio high-mass X-ray binaries showing evidences of collimated relativistic outflows. They are called microquasars due to their supposed similarities to quasars, which show very narrow jets moving with relativistic speeds. In binary systems, jets are launched from the inner parts of accretion discs around compact objects (neutron stars or solar mass black holes).

Here, we consider a simple scenario in which jets are launched along the disc axis. The surface of the disc is in the plane of the binary system, i.e. the jet direction is perpendicular to the plane of the binary system. The schematic picture of such a binary system is drawn in Fig. 1. Relativistic particles, injected in the jet at the distance $z$ from its base, produce $\gamma$-rays. If the injection site of the $\gamma$-rays is relatively close to the massive star, they interact with the stellar radiation, initiating the IC $e^\pm$ pair cascade. The efficiency of such cascades depends strongly on the parameters of the binary systems LS 5039 and LSI +61° 303. These two binaries differ in basic parameters, e.g. their orbital periods are equal to 3.9 and 26.5 d, respectively. However, both of them provide conditions in which cascading effects have to be taken into account when considering $\gamma$-ray production processes.

2.1 The binary system LS 5039

This binary system shows relativistic radio jets on milliarcsecond scales, with the speed of $v \sim 0.3c$ (Paredes et al. 2000). It has also been suggested to be a counterpart of the EGRET source 3EG J1824-1514 localized at $\sim 0.5^\circ$ (Paredes et al. 2005). This source has a relatively flat spectrum above 100 MeV, spectral index $<2$ and the $\gamma$-ray luminosity $\sim 4 \times 10^{33} \text{erg s}^{-1}$. Moreover, the position of LS 5039 is consistent (at the 3$\sigma$ level) with recently detected TeV source HESS J1826–148 (Aharonian et al. 2005a). The spectrum above 250 GeV is also flat with the photon index $2.12 \pm 0.15$, although the luminosity is only $\sim 10^{33} \text{erg s}^{-1}$, about two orders of magnitude less...
than at GeV energies. Recent analysis of the TeV $\gamma$-ray light curve by Casares et al. (2005b), using new orbital parameters, shows possible flux variations of a factor of $\sim$3 with the maximum around the phase $\sim$0.9.

The basic parameters of the binary system LS 5039 have been recently reported by Casares et al. (2005b): the semimajor axis, $a = 3.4 r_\star$, ellipticity, $e = 0.35 \pm 0.04$, the azimuthal angle of the observer with respect to the periastron passage, $\omega = 225^\circ$, radius of the massive star, $r_\star = 9.3^{+0.7}_{-0.6} R_\odot$ and its surface temperature, $T_s = 3.9 \times 10^4$ K. For these parameters, the distance of the compact object from the massive star changes in the range from $r_\gamma = 2.2 r_\star$ at the periastron up to $r_\gamma = 4.5 r_\star$ at the apastron. The estimated inclination angle of the binary system towards the observer depends on the mass of the compact object. It is estimated that $\theta = 24.9 \pm 2.8^\circ$ for the case of the black hole with the mass 3.7 $M_\odot$ and $\sim 60^\circ$ for the neutron star (Casares et al. 2005b). We present the results of numerical calculations for both inclination angles in the case of LS 5039.

2.2 The binary system LSI +61° 303

LSI +61° 303 has been observed as a non-spherical radio source, the structure of which was interpreted as due to relativistic radio jets, the speed of which was $\sim$0.6c, with some hints of its precession (Massi et al. 2004). It has been pointed out (Gregory & Taylor 1978) that this source is connected with the COS B $\gamma$-ray source CG135+01 (Hermes et al. 1977). CG135+01 has also been detected by EGRET (>100 MeV); the source 2EG J0241+6119 has a hard spectrum with photon spectral index 2.05 $\pm$ 0.06 (Kniffen et al. 1997). It was detected by COMPTEL in the energy range $\sim$0.75–30 MeV, spectral index 1.95 $\pm$0.1 (van Dijk et al. 1996). The analysis of different EGRET observations shows evidence of variability (Tavani et al. 1998, confirmed by Wallace et al. 2000) with probable modulation with the orbital period of LSI +61° 303 and the maximum emission near the periastron passage (Massi 2004). The Whipple group (Hall et al. 2003) puts an upper limit on the TeV flux from this source, $\sim10^{-11}$ cm$^{-2}$ s$^{-1}$ above 500 GeV ($<1.3 \times 10^{32}$ erg s$^{-1}$), which is clearly below an extrapolation of the EGRET spectrum.

The basic parameters of the binary system LSI +61° 303 have recently been reported by Casares et al. (2005a): the semimajor axis $a = 5.3 r_\star$, the ellipticity $e = 0.72$, and the inclination of the binary system towards the observer is not well constrained by the observations (Casares et al. 2005a): $25^\circ < i < 60^\circ$ for a neutron star and $\theta < 25^\circ$ for a black hole. We apply the value of $\theta = 30^\circ$. The azimuthal angle of the observer with respect to the periastron passage is $\omega = 70^\circ$, the radius of the massive star $r_\star = 13.4 R_\odot$ and its surface temperature $T_s = 2.8 \times 10^4$ K. For these parameters, the distance of the compact object from the massive star changes in the range from $r_\gamma = 1.5 r_\star$ at the periastron up to $r_\gamma = 9.15 r_\star$ at the apastron. We apply these parameters in our further calculations.

3 OPTICAL DEPTHS FOR $\gamma$-RAYS

The optical depths for $\gamma$-rays (for the process $\gamma + \gamma \rightarrow e^+e^-$) in the radiation field of the massive star, determined by the radius of the star and its surface temperature, are calculated in the general case, i.e. for an arbitrary place of injection of $\gamma$-ray photons with arbitrary energies and angles of propagation (see also B97, B00, SB05). This approach allows us to calculate the optical depths even for the primary $\gamma$-rays injected at the surface of the massive star. Therefore, it can be applied for studies of the cascade processes initiated by $\gamma$-ray photons since secondary $\gamma$-rays can appear, in principle, everywhere inside the binary system. In fact, the optical depths for the $\gamma$-rays propagating in the thermal radiation of these massive stars can be obtained by simple rescaling of the earlier calculations for the massive star in Cen X-3 (shown e.g. in B00; Fig. 2), since they are proportional to the fourth power of the surface temperature and the square of the radius of the massive star. Also, a shift in energy proportional to the surface temperature is necessary. Note that in the case of cascade processes discussed in this paper, primary particles propagating at specific direction can contribute to the final $\gamma$-ray spectra escaping at other directions. Therefore,
for easier analysis of the obtained results, we show here the optical depths for γ-rays injected at the distance of the periastron and the apastron passages of the compact object around the massive stars in LS 5039 [Figs 2(a) and (b)] and LSI +61° 303 [Figs 2(c) and (d)], as a function of the photon energy and their arbitrary injection angles, α, measured from the direction defined by the centres of the companion stars, towards the massive star.

As expected, the optical depths strongly depend on the injection parameters (photon energy, angles of propagation) and the parameters of the massive star. The optical depths reach the maximum corresponding to the peak in the blackbody spectrum of soft photons. The maximum optical depth shifts to larger photon energies with decreasing angle α (provided that α is smaller than the angle β, interpreted by the massive star observed from the distance of the injection place). The optical depths are lower for α > 10°. In this case γ-rays propagate only toward the surface of the massive star [see full thick curves in Figs 2(a) and (c)]. γ-rays with energies around 1 TeV, injected at the periastron distance in LS 5039, 2.2 σ, are absorbed (τ > 1) for most of the propagation directions, except a small cone with the angular extension of ~40°. At the apastron distance, 4.5 r*, the escape cone increases to ~60°. Only within such small cones, γ-rays with ~1 TeV energy have a high chance of escape without absorption. The optical depth for γ-rays in LSI +61° 303 is typically lower due to the significantly lower surface temperature of the massive star. At the periastron distance, 1.5 r*, the escape cone for ~1 TeV γ-rays is also ~40°, very similar to the periastron distance in LS 5039, due to the closer location of the injection place. However, at the apastron distance, 9.15 r*, most of ~1-TeV γ-rays escape from the binary system without absorption, except γ-rays moving towards the massive star within the cone with the angle ~80°.

In LS 5039, the angles between the observer (at the inclination angle 25°) and the direction defined by the stars are ~110° for the periastron passage and ~70° for the apastron passage. For such geometry, the optical depths towards the observer are larger than unity for γ-rays with energies in the range ~0.03–20 TeV, for the periastron passage, and ~0.2–2 TeV, for the apastron [see Figs 2(a) and (b)]. These calculations of the optical depths are generally consistent with that obtained by Dubus (2005).

In LSI +61° 303, the observer is located at the angle of ~80° at the periastron passage and ~100° at the apastron passage. In this case, the optical depths are larger than unity for γ-rays with energies in the range ~0.1–10 TeV for the periastron passage, but always lower than unity for the apastron, provided that they are injected towards the observer [see Figs 2(c) and (d)].

4 THE CASCADE γ-RAY SPECTRA

Since the optical depths for high-energy γ-rays in the radiation fields of the massive stars in binary systems LS 5039 and LSI +61° 303 are large, the total γ-ray spectra, emerging from the binary systems towards the observer, are determined by the primary γ-ray spectra (if such are produced e.g. by hadrons accelerated in the jet) and by the γ-ray spectra produced in the IC e± pair cascades occurring in the radiation of the massive star. However, since the place of injection of primary γ-rays or primary electrons is different from the centre of the massive star (the source of isotropic soft radiation), the IC e± pair cascade in fact occurs in the anisotropic radiation field. IC e± pair cascades of this type have already been considered by us under two extreme assumptions. In the first approximation, local isotropization of the secondary cascade e± pairs by the random component of the magnetic field inside the stellar wind and the jet is assumed (see B97, B00). In the second approach, we follow the paths of secondary cascade e± pairs in the magnetic field which has a structure that is described by a specific model (see SB05). In the present work, we apply the first approach. Note that the IC e± pair cascade considered in this work does not take into account the synchrotron losses of e± pairs and assumes that secondary e± pairs radiate secondary γ-rays locally, i.e. at their production site. The conditions for this type of cascade are determined in Bednarek (B97, see section 2). For completeness, and due to some different details of the scenario considered in this paper, we discuss below some important conditions for IC e± pair cascades occurring in the radiation field of the massive star.

Leptons injected into the radiation of the massive star (primary electrons and secondary e± pairs from the cascade) are immersed in the stellar wind and/or in the plasma outflow along the jet. Therefore, the efficiency of the ICS process is determined by the relative importance of the IC cooling time-scale with respect to the characteristic escape time-scale, determined by the advection time-scale of e± pairs with the stellar and/or jet outflows. The IC cooling time of leptons (the Thomson regime) in the radiation of the massive star can be estimated from

\[ \tau_{IC} = m_e c / \sigma_T \approx 4 \times 10^8 r^2 / \left( T_{4\gamma} T_{4 \gamma} \right) \text{s}, \]  

where \( m_e \) and \( T_\gamma \) are the rest mass and the Lorentz factor of leptons, \( \sigma_T = (3/4)c \sigma_T \) is the energy loss rate on ICS of leptons, \( c \) is the velocity of light, \( \sigma_T \) is the Thomson cross-section, \( U_{rad} = \frac{1}{2} \gamma B^2 T_\gamma^4 / r^2 \), \( \sigma_{SB} \) is the Stefan–Boltzmann constant, \( T_\gamma = 10^4 T_4 \) K and \( R = r r_* \) are the surface temperature of the massive star and the distance from the centre of the massive star (in units of its radius), respectively. The characteristic escape time-scale of leptons from their creation (acceleration) place, identified with their advection time-scale with the jet or the wind plasma flow, is

\[ \tau_{esc} = R / V = 33 r_{12} T_{12} / v \text{s}, \]  

where \( v = V / c \) is the velocity of the jet (or the stellar wind). It is assumed that typical radii of the massive stars are of the order of \( r_* = 10^{12} r_{12} \) cm. By comparing equations (1) and (2), we estimate the minimum Lorentz factor of leptons above which they cool locally:

\[ \gamma_{\min} > 1.2 \times 10^7 v / \left( T_{4\gamma} r_{12} \right). \]  

For example, in the case of the massive star in LS 5039, where \( T = 3.9, r_{12} = 1 \) and \( v = 0.5 \), leptons with the Lorentz factors above \( \gamma_{\min} > 25 r \) cool locally before escaping from the binary system.

Leptons with Lorentz factors \( \gamma_{\min} \) produce γ-ray photons with energies

\[ E_\gamma \approx (4/3) \gamma_{\min}^2 \approx 10^3 r^2 v^2 / \left( T_{4\gamma} r_{12} \right) \text{MeV}, \]

where typical energies of photons coming from the massive stars are \( \epsilon = 3 k_B T_\gamma \approx 2.6 \times 10^{-6} T_4 \) eV. We conclude that spectra of γ-ray photons produced in the cascade (assuming local cooling of leptons) are correct above energies given by equation (4). For the parameters of the massive stars in LS 5039 and LSI +61° 303, escaping γ-ray spectra are correct above ~10 MeV, provided that the production of γ-rays occurs inside the jet and within \( r \approx 30 r_* \) from the centre of the massive star. For the stellar wind region, the limits on the low-energy cut-offs in the cascade γ-ray spectra are about two orders of magnitude lower due to much lower stellar wind velocities with respect to the plasma velocity in the jet.

However, for the Lorentz factors above ~10, scattering of soft photons occurs in the Klein–Nishina (KN) regime. We approximate the IC cooling time of leptons in the KN regime by

\[ \tau_{IC}^{KN} = m_e c / \sigma_T \approx 8 \times 10^{-6} r^2 v / T_{4\gamma} \text{s}, \]

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where $\gamma_{\text{KN}/T} \approx m_e c^2 / \epsilon \approx 2 \times 10^4 / T_4$. By comparing the escape time-scale, $\tau_{\text{esc}}$, with the IC cooling time-scale in the KN regime, $r_{\text{KN}}$, we obtain the upper limit on the Lorentz factor of leptons able to cool locally:

$$\gamma_e < \gamma_{\text{max}} \approx 4 \times 10^4 r_{\text{in}} T_4^2 / (r v).$$

(6)

Therefore, we conclude that leptons with energies $\sim 10$ TeV should be able to cool locally within a very small field radii from the surface of the massive stars in LS 5039 and LSI $+61^\circ$ 303.

In the calculations shown below, we assume that synchrotron energy losses of leptons can be neglected with respect to the IC losses. This is correct provided that the surface magnetic fields of the massive stars fulfill the condition

$$B_s < 40 T_4^2 G$$

(7)

obtained from the comparison of the synchrotron and IC energy losses of leptons in the Thomson regime. The simple limit given by equation (7) is valid under the assumption of the $B \propto r^{-2}$ magnetic field dependence on the distance from the stellar surface. It neglects the inner dipole part of the magnetic field in which $B \propto r^{-1}$. Therefore, the real upper bound on the surface magnetic field is a factor of 2–3 larger than given by equation (7). For the massive stars in LS 5039 and LSI $+61^\circ$ 303, these upper bounds (equation 7) are $\sim 620$ and $\sim 320$ G. In the KN regime, i.e. for $\gamma_e \gg 10^4$, the limit on the magnetic field is more restrictive due to the decrease of the cross-section. It has been discussed in detail by B97 (see their fig. 4).

Under conditions specified above (neglected synchrotron losses of leptons and their local isotropization), we study the features of the $\gamma$-ray spectra emerging from the binary system, due to the propagation effects in the radiation of their massive companions, assuming that primary particles, i.e. electrons or $\gamma$-rays, are isotropically injected somewhere along the jet. We consider the primary particles with the power-law spectra and spectral index equal to 2 due to the equally distributed power per decade. The high-energy cut-off in these primary spectra is assumed at 10 TeV (to be consistent with the observations of $\gamma$-ray spectra from LS 5039 up to $\sim 4$ TeV; Aharonian et al. 2005b). These initial spectra of particles are normalized to unity. The spectral index equal to 2 is also motivated by a relatively flat GeV $\gamma$-ray spectra observed from these two sources. The jets in microquasars move with much lower velocities (Doppler factor $D \sim 1$) than those observed in active galactic nuclei. Therefore, the effects of relativistic beaming can be neglected in the first approximation.

4.1 LS 5039

Let us at first consider the case of isotropic injection of primary electrons at the base of the jet, i.e. $z \approx 0$. In fact, $\gamma$-rays have to be injected at some distance from the accretion disc at which the disc radiation can be neglected with respect to the stellar radiation. The distance from the base of the jet at which the above condition can be fulfilled is estimated by comparing the energy density of the disc radiation with the energy density of the stellar radiation. These radiation fields are defined by the surface temperature of the massive star and the maximum temperature on the surface of the disc (at the disc inner radius, $T_\text{in}$). We approximate the accretion disc radiation by the model of Shakura & Sunyaev (1973) in which the disc radiation from its surface can be approximated by the blackbody radiation with some temperature gradient. The following condition has to be approximately fulfilled:

$$T_4^4 / r^2 \approx T_\text{in}^4 (r_{\text{in}} / z)^2,$$

(8)

where $r_{\text{in}}$ is the disc inner radius. From this condition, we estimate that above

$$z \approx r_{\text{in}} (T_\text{in} / T_4)^2$$

(9)

the massive star radiation dominates over the accretion disc radiation. For typical parameters of the considered binary systems $T_4 \approx 3 \times 10^4 K$, $r = 10$, the accretion disc inner radius $r_{\text{in}} = 10^7$ cm, and $T_\text{in} = 10^4 K$ (limited by the condition that the disc thermal luminosity has to be lower than the observed X-ray luminosity from these binary systems, $<10^{34}$ erg s$^{-1}$), we estimate that above $z > 10^7$ cm ($\sim 0.1 r_\star$) from the base of the jet, stellar radiation dominates over accretion disc radiation. This condition is valid in the Thomson regime. However, for the IC scattering process occurring in the KN regime, stellar radiation starts to dominate even at lower distances from the inner part of the disc, due to a significantly larger temperature in the inner disc than on the stellar surface. These same arguments also concern possible disc corona which has density energy comparable to the energy density of radiation from the surface of the disc, but the characteristic temperature (average photon energies) is larger. The conditions for absorption of $\gamma$-ray photons in the radiation of the massive star are more favourable with respect to the radiation of the accretion disc, due to a larger angular extension of the stellar disc with respect to the inner part of the accretion disc.

In conclusion, we consider the injection of the primary $\gamma$-rays and electrons at the base of the jet assuming that it occurs at the distance $z > 0.1 r_\star$, which is very close to the base of the jet with respect to the dimensions of the massive star.

Although primary $\gamma$-rays and soft photons from the massive star are injected isotropically, their places of injection are located at different parts of the binary system (the jet or the compact object for primary $\gamma$-rays and the massive star for soft photons). Therefore, primary $\gamma$-rays in fact develop an IC $e^\pm$ pair cascade in the non-isotropic radiation field. The spectra, which emerge from the binary system, depend on the location of the observer with respect to direction defined by the location of the injection and the centre of the massive star (the angle $\alpha$ measured from the outwards direction defined by the place of injection and the centre of the massive star). We calculate the angle-dependent spectra of $\gamma$-rays escaping from the binary system by applying the Monte Carlo method (details are described in B00). Such a method allows us to include the redistribution of directions of secondary cascade $\gamma$-rays with respect to the direction of their parent primary $\gamma$-rays, which is due to the isotropization of secondary cascade $e^\pm$ pairs and their preferable head-on interactions with soft photons arriving from a specific direction on the sky (i.e. inside the stellar disc limb). The parameters of $\gamma$-ray photons produced in the cascade (their energies and the escape angles $\alpha$) are sorted at a specific range of the cosine angles, $\cos \alpha$, with a width of $\Delta \cos \alpha = 0.1$.

We show the spectra of primary $\gamma$-rays which escape from the radiation field of the massive star without absorption (Fig. 3a), the spectra of $\gamma$-rays produced as a secondary cascade products (Fig. 3b) and the sum of these two, i.e. the total $\gamma$-rays spectra (Fig. 3c), for primary $\gamma$-rays injected at the distance $z \approx 0$ along the jet, and for two locations of the compact object on its orbit, at the periastron distance from the massive star (2.2$r_\star$, upper figures in Fig. 3) and at the apastron distance (4.5$r_\star$, bottom figures). Simple absorption effects of primary $\gamma$-rays, for both distances of the place of injection from the massive star, are very strong (see Fig. 3a). Primary $\gamma$-rays with energies in the range of between a few tens of GeV and a few TeV are completely absorbed (the exact range depends strongly on the observation angles), provided that the observation angles lie within the hemisphere containing the massive star. However, these strong
Figure 3. Differential γ-ray spectra (multiplied by the square of photon energy) escaping from the binary system at a specific range of the cosine angles α, measured with respect to the direction defined by the injection place and the centre of the massive star. The range of Δ cos α (with the width 0.1) is centred on 0.95 (full curve), 0.55 (dashed), 0.15 (dot-dashed), −0.25 (dotted) and −0.65 (triple-dot-dashed). γ-rays are produced in the cascade initiated by primary γ-rays with the power-law spectrum and spectral index 2 which are injected isotropically close to the base of the jet (z ≈ 0 ≪ r*, but sufficiently far away from the accretion disc), and at two distances from the massive star 2.2r* (upper figures, corresponding to the periastron passage of the compact object) and 4.5r* (bottom figures, corresponding to the apastron passage). (a) Spectra of primary γ-rays escaping without interaction. (b) Spectra of secondary γ-rays produced in the IC cascade. (c) Total spectra of γ-rays escaping from the binary system [the sum of spectra shown in (a) and (b)].

deficits of γ-rays (between 0.1 and 1 TeV) are partially fulfilled by the secondary cascade γ-rays (see Fig. 3b). The secondary γ-rays contribute also to the total γ-ray spectrum below ~10 GeV escaping in the outwards directions, i.e. for α > 90° (Fig. 3b). Total γ-ray spectra (Fig. 3c) strongly depend on the observation angle. They show strong deficit above ~100 GeV (a dip of up to two orders of magnitude) and the excess (up to a factor of 2) with respect to the shape of the primary power-law spectrum for large angles α. However, they become more similar to the injected γ-ray spectrum for small α. As expected, γ-ray spectra escaping from the binary system for the injection places located at larger distances from the massive star (at the apastron passage) are less modified by the cascading processes than those produced at the periastron passage.

The secondary γ-ray spectra produced by primary γ-rays injected at the apastron passage show decline above a few TeV (Fig. 3b). This is due to the high-energy cut-off in the spectrum of primary particles at 10 TeV and due to the average larger interaction angles between primary γ-rays and soft photons from the massive star at the apastron passage.

In Fig. 4, we also show the γ-ray spectra produced in the cascade for the periastron and the apastron distances assuming that the injection place is located at the distance of z = 5r* from the base of the jet in order to have impression how significant are the γ-ray spectra on the production site in the jet. General features of these γ-ray spectra are quite similar to the case of injection at the base of the jet (z ≈ 0). Therefore, if the injection of primary γ-rays occurs with similar acceleration efficiency and spectrum along the jet within a few stellar radii from the base of the jet, then the angular distribution of γ-rays (and their spectra) formed in the cascade process shows quite similar features in relation to the direction defined by the injection place and the massive star. Note, however, that the γ-ray spectra towards the observer located in a fixed direction with respect to the plane of the binary may look very different for these two injection places; we will discuss this in Section 5.

As a second scenario, we consider the injection of primary electrons in the specific region of the jet. As above, we consider two locations for the injection place along the jet: the base of the jet (Figs 5a and b) and the distance z = 5r* from the base of the jet (Fig. 4). The distance of the injection place from the massive star is ~5.5r* at the periastron (upper figures) and ~6.7r* at the apastron (bottom figures).

Figure 4. As in Fig. 3 but for the injection distance along the jet z = 5r*. The distance of the injection place from the massive star is ~5.5r* at the periastron (upper figures) and ~6.7r* at the apastron (bottom figures).

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The case of isotropic injection of primary electrons with the power-law spectrum differs from the previously considered case of isotropic injection of primary $\gamma$-rays because electrons have a tendency towards more frequent production of the first generation of cascade $\gamma$-rays in the direction towards the massive star (the effect of non-isotropic radiation and kinematics of the IC process). Therefore, $\gamma$-ray spectra which escape from the binary system in this second scenario resemble the secondary cascade $\gamma$-ray spectra produced in the case of the injection of primary $\gamma$-rays [compare Figs 3(b) and 4(b) with Fig. 5]. Escaping $\gamma$-ray spectra strongly depend on the viewing angle $\alpha$ not only in the TeV range ($>100$ GeV) but also in the GeV range (see Fig. 5). Moreover, the $\gamma$-ray fluxes expected in these two energy ranges are strongly anticorrelated (large TeV flux is accompanied by low GeV flux, and vice versa). This is due to the fact that at directions of the large optical depths, the energy converted from primary electrons in the IC process to the TeV $\gamma$-rays is redistributed to the GeV energies. In directions where the optical depths are low, the energy of TeV $\gamma$-rays is not so efficiently degraded in the cascade process to lower energies. As a result, relatively large TeV fluxes are accompanied by small GeV fluxes.

4.2 LSI $+61^\circ$ 303

The binary system LSI $+61^\circ$ 303 differs in some aspects from LS 5039. Although both binaries contain massive stars with similar radii, the surface temperature of the star in LSI $+61^\circ$ 303 is a factor of $\sim 0.7$ lower, which results in a radiation energy density that is a factor of $\sim 4$ lower. Also, the distance of the compact object from the massive star in LSI $+61^\circ$ 303 changes in a larger range, from 1.5$r_\star$ to 9.15$r_\star$. Therefore, primary $\gamma$-rays injected in the jet propagate through the radiation field, which varies with a larger amplitude which has a full orbital period than LS 5039. Due to this effect, $\gamma$-ray spectra escaping towards the observer from LSI $+61^\circ$ 303 for the case of injection of both primary $\gamma$-rays and electrons change more significantly with the observation angle $\alpha$. As an example, we show the $\gamma$-ray spectra for the case of injection of primary $\gamma$-rays at the base of the jet, i.e. for $z = 0$ (Fig. 6), and at the distance $z = 3r_\star$ from the base of the jet (Fig. 7). $\gamma$-ray spectra for the periastron passage of the injection place are quite similar to those expected from LS 5039 [compare the results in the upper Figs 3(c) and 4(c) with the upper Figs 6(c) and 7(c)]. The effects of the lower surface temperature of the massive star in LSI $+61^\circ$ 303 and the distance at the periastron passage almost compensate. However, at the apastron passage and at the base of the jet, the absorption dips (above $\sim 100$ GeV) are much lower in the case of LSI $+61^\circ$ 303 [compare the bottom Figs 6(c) and 7(c) with the bottom Figs 3(c) and 4(c)]. Even at the apastron passage of the compact object in LSI $+61^\circ$ 303 and at the distance of injection place from the base of the jet $z = 3r_\star$, $\gamma$-ray spectrum above $\sim 100$ GeV should still vary by a factor of $\sim 5$ with the angle $\alpha$ (see Fig. 7c). Note that secondary cascade $\gamma$-ray spectra produced by primary $\gamma$-rays, which are injected at large distance from the massive star (at the apastron passage and at $z = 3r_\star$), show strong cut-offs after $\sim 2$ TeV. This is the result of a relatively weak absorption of primary $\gamma$-rays with energies above a few TeV, combined with the kinematics of the IC scattering process for the case of strongly anisotropic radiation field of soft photons from the massive star.

$\gamma$-ray spectra emerging from the binary system LSI $+61^\circ$ 303 in the case of injection of primary electrons at the periastron distance are very similar to the spectra expected from LS 5039 [Figs 5(a) and (c) with Figs 8(a) and (c)]. The absorption features are only slightly stronger. $\gamma$-ray spectra, produced by electrons injected farther from the base of the jet, e.g. at the distance $z = 3r_\star$, are still strongly influenced by the cascade effects showing strong dependence on the observation angle in the GeV and TeV energy ranges (see Fig. 8c). However, at the apastron distance, the $\gamma$-ray spectra look different. They show strong dependence on the observation angle in the GeV energy range but relatively weak dependence in the TeV energy range (e.g. Fig. 8b). $\gamma$-ray spectra produced at the apastron passage, but at distances from the base of the jet of the order of a few stellar radii, do not depend strongly on $z$ [see Figs 8(b) and (d)], since electrons injected at such a distance still propagate in quite similar radiation fields. In fact, for the apastron passage of the compact object in LSI $+61^\circ$ 303 (at 9.15$r_\star$), the distance of the place of injection along the jet ($z = 3r_\star$) is located at the
Figure 6. Differential $\gamma$-ray spectra escaping from the binary system at a specific range of the cosine angle $\alpha$ (as in Fig. 3) but for the binary system LSI +61° 303. The injection place of primary $\gamma$-rays is at the distance of the periastron passage ($R = 1.5r_\star$, upper figures) and the apastron passage ($9.15r_\star$, bottom figures) close to the base of the jet ($z \approx 0 \ll r_\star$). The primary $\gamma$-rays spectra which escape without absorption are in (a), secondary cascade $\gamma$-ray spectra in (b), and the sum of (a) and (b), total escaping $\gamma$-ray spectra are in (c).

Figure 7. The $\gamma$-ray spectra produced by primary $\gamma$-rays (as in Fig. 6) but for the injection place of primary $\gamma$-rays and the distance $z = 3r_\star$ from the base of the jet. The distance of the injection place from the massive star is $\sim 3.35r_\star$ at the periastron (upper figures) and $\sim 9.6r_\star$ at the apastron (bottom figures).

Figure 8. As in Fig. 5 but for LSI +61° 303. $\gamma$-ray spectra are calculated for the injection place of primary electrons at the periastron distance (i.e. at $1.5r_\star$ – a and c), at the apastron distance (i.e. at $9.15r_\star$ – b and d) and at the distance from the base of the jet $z = 0$ (a and b) and $z = 3R_\star$ (c and d).
distance of only 9.63$r_\star$ from the massive star (i.e. very similar to the apastron distance). Therefore, TeV $\gamma$-ray fluxes observed from LSI $+$61° 303 at the apastron passage should be relatively larger with respect to their GeV fluxes in comparison to the expectations from the massive binary LS 5039, in which the TeV fluxes should be significantly lower than their corresponding GeV fluxes.

5 PHASE-DEPENDENT $\gamma$-RAY SPECTRA AND LIGHT CURVES

The location of the observer is different with respect to the orbital plane of the binary systems in LS 5039 and LSI $+$61° 303. The inclination angles of the binary systems are probably quite similar, i.e. 25° in the case of LS 5039 (assuming that the compact object is a black hole) and 30° in the case of LSI $+$61° 303. However, the azimuthal angles of the observer’s location, measured with respect to the periastron passage, are 225° in LS 5039 and 70° in LSI $+$61° 303. Therefore, phase-dependent $\gamma$-ray spectra and $\gamma$-ray light curves expected from these two binary systems should have different features.

Below, we show the $\gamma$-ray light curves from these binaries at the GeV energies (1–10 GeV) and the TeV energies (>100 GeV), based on the calculations of the IC $e^\pm$ pair cascades occurring inside the radiation field of their massive stars. The phase-dependent spectral features of the $\gamma$-ray emission are also discussed.

5.1 LS 5039

We have calculated the $\gamma$-ray luminosities escaping towards the observer as a function of the phase of the place of injection of primary particles in the jet launched from the compact object in LS 5039. The light curves are obtained for two energy ranges, the GeV range (1–10 GeV) and the TeV range (>100 GeV), in the case of isotropic injection of primary $\gamma$-rays [Figs 9(a) and (c)] and primary electrons [Figs 9(b) and (d)], with the power-law spectra and spectral index 2 (as discussed in Section 4.1). We consider the injection regions at the base of the jet, $z = 0$ (full curves) and at the distance $z = 5r_\star$ (dashed curves) along the jet and two inclination angles of the observer $\theta = 25°$ [Figs 9(a) and (b)] and $\theta = 60°$ [Figs 9(c) and (d)].

In order not to complicate the geometry too much, only the case of perpendicular propagation of the jet with respect to the plane of the binary system is considered. The calculations of the $\gamma$-ray spectra for the jets aligned at some angle to the plane of the binary system are straightforward. They will be discussed in another work.

If the primary particles are injected at the base of the jet, then the $\gamma$-ray power in the GeV energy range varies by a factor of $\sim$2 and in TeV energy range by a factor greater than $\sim$10 for $\theta = 25°$ [see Figs 9(a) and (b)]. The maximum in TeV $\gamma$-ray light curve occurs at the phase $\sim$0.6 and corresponds to the minimum in the GeV $\gamma$-ray light curve. Therefore, based on these cascade calculations we predict clear anticorrelation between the GeV and TeV $\gamma$-ray fluxes. The level of variability of the GeV fluxes is larger in the case of injection of primary electrons in comparison to the injection of primary $\gamma$-rays since the primary (unabsorbed) $\gamma$-rays also contribute to the predicted total $\gamma$-ray light curve. Therefore, GeV $\gamma$-ray light curve is quite smooth for the case of the injection of primary $\gamma$-rays. This feature might give some insight into the production mechanism of primary particles ($\gamma$-rays or electrons) allowing to distinguish which particles are accelerated, hadrons (responsible for the primary $\gamma$-rays) or electrons? If primary particles are injected farther from the base of the jet, then the amplitude of the $\gamma$-ray emission drops in both energy ranges [see dashed curves in Figs 9(a) and (b)]. However, the level of variability is still larger in the case of injection of primary electrons.

The $\gamma$-ray light curves for the observer located at larger inclination angle, i.e. $\theta = 60°$, show significantly larger variability than for $\theta = 25°$. For example, the $\gamma$-ray power can change by almost an order of magnitude in the GeV energy range and by two orders of magnitudes in the TeV energy range for the case of injection of primary $\gamma$-rays (see Fig. 9d). Therefore, in principle the level of $\gamma$-ray variability might help to distinguish between different interpretations of the observational data concerning the inclination of the binary system in LS 5039 and put some insight on the nature of the compact object.

In Figs 10 and 11, we show the $\gamma$-ray spectra which escape to the observer for a few selected phases (time from the periastron divided by the orbital period) of the compact object in all the above-considered scenarios for the case of the inclination of the binary system equal to $\theta = 25°$ and 60°, respectively. The cascade $\gamma$-ray
spectra produced by primary particles injected at the base of the jet drop suddenly above a few tens of GeV, reach the minimum at a few 100 GeV and become flat (spectral index <2) at higher energies. Between ~0.1 and 1 TeV, the spectral index does not change significantly with the phase of the injection place. The TeV γ-ray deficit is larger for the injection of primary electrons and for larger inclination angles. However, the spectral indexes in the GeV and TeV energies are close to two in spite of such a large difference in the level of emission. These features are generally consistent with the observations of LS 5039 in the GeV and TeV energy ranges. The spectra look completely different for the place of injection that is farther along the jet. For example, at the distance of 5*r_⋆ from the base of the jet and θ = 25°, the total cascade γ-ray spectra are almost independent from the phase of the compact object in the case of injection of primary γ-rays (see Fig. 10b). However, for larger inclination angles of the binary, e.g. θ = 60°, a small absorption feature starts to appear at TeV energies when the compact object is at the periastron. In the case of injection of primary electrons, the TeV γ-ray spectra are on a similar level but differ significantly in the GeV energies. This GeV spectrum is flatter than in the case of injection of primary γ-rays (spectral index close to ~1.5 versus a slightly flatter than 2), due to the lack of domination of the GeV spectrum by the primary γ-rays. These weak dependences of the γ-ray spectra in the TeV energies are due to small differences in the angles between the observer and the injection place of the primary particles farther from the base of the jet (e.g. considered here z = 5*r_⋆) for different phases of the binary system. Note, however, that these angles show stronger differences for larger inclination angles of the binary system (compare Figs 10 and 11).

5.2 LSI +61° 303

The features of the γ-ray light curves and phase-dependent spectra expected from the binary system LSI +61° 303 are qualitatively similar to those discussed above for the binary system LS 5039 (see Figs 12 and 13). However, there are also some significant differences. For example, the maximum in the TeV γ-ray light curve of LSI +61° 303 is broader and appears at the phase ~0.2–0.5. The level of variability at TeV energies is smaller (variable by a factor less than ~10). The anticorrelation between the GeV and the TeV

Figure 10. γ-ray spectra which escape from the binary system LS 5039 towards the observer at the inclination angle θ = 25° for different locations of the injection place of the source of primary particles (a and b–γ-rays, and c and d–electrons) defined by the azimuthal angle measured from the periastron: ω = 0° (full curve), 90° (dashed), 180° (dot–dashed), and 270° (dotted), and at the distance from the base of the jet z = 0r_⋆ (a and c) and z = 5r_⋆ (b and d).

Figure 11. As in Fig. 10 but for the inclination angle of the binary system θ = 60°.
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Figure 12. As in Fig. 9 but for the binary system LSI $+61^\circ$ 303 (for the inclination $\theta = 30^\circ$). Primary $\gamma$-rays (a) and primary electrons (b) are injected at the distance from the base of the jet $z \approx 0r_\star$ (full curves) and $z \approx 3r_\star$ (dashed curves).

Figure 13. As in Fig. 10 but for LSI $+61^\circ$ 303. Primary $\gamma$-rays (a and b) and primary electrons (c and d) are injected at the distance from the base of the jet $z \approx 0r_\star$ (a and c) and $z = 3r_\star$ (b and d).

6 CONCLUSIONS

We have performed the Monte Carlo simulations of the propagation of high-energy $\gamma$-rays inside compact massive binaries of the microquasar type, applying as an example parameters of LS 5039 (recently observed in TeV $\gamma$-rays and suggested as a counterpart of the EGRET source) and LSI $+61^\circ$ 303 (similar parameters to LS 5039 and also suggested as a counterpart of the EGRET source). In both the sources, the optical depths for TeV $\gamma$-rays are greater than unity for most of the propagation directions, provided that the injection place of primary particles ($\gamma$-rays or electrons) is relatively close to the base of the jet launched from the inner part of the accretion discs around compact objects. Therefore, these primary particles initiate IC $e^\pm$ pair cascades in the anisotropic radiation of the massive stars. We have calculated the $\gamma$-ray spectra produced in such cascades and investigated their basic features. It is concluded that the absorption dips in TeV $\gamma$-ray spectra emerging towards the observer are not so drastic as predicted in the earlier papers, e.g. by Böttcher & Dermer (2005) and Dubus (2005). This is clearly seen by comparing $\gamma$-ray spectra calculated with pure absorption [e.g. Figs 3(a), 4(a), 6(a) and 7(a)] with the corresponding total $\gamma$-ray spectra produced in the cascade processes inside the binary system [Figs 3(c), 4(c), 6(c) and 7(c)]. These less pronounced dips are due to the redistribution of energy in the primary spectrum of $\gamma$-rays from the region above $\sim 1$ TeV to 0.1–1 TeV energy range. Since the soft radiation field created by the massive stars in these two binaries is quite similar during periastron passages of their compact objects, the $\gamma$-ray spectra produced in the cascade processes do not differ significantly in the case of LS 5039 and LSI $+61^\circ$ 303. However, the propagation effects are responsible for essential differences at the apastron passage, since LSI $+61^\circ$ 303 is more extended (the apastron distance in LSI $+61^\circ$ 303 is a factor of $\sim 2$ larger than in LS 5039).

Let us concentrate at first on the features of $\gamma$-ray emission from LS 5039. The $\gamma$-ray luminosity from this source observed in the GeV energy range [assuming that the identification with the EGRET
source by Paredes et al. (2000) is correct is about two orders of magnitude larger than observed in TeV energy range (Aharonian et al. 2005b). However, spectra reported in these two energy ranges are quite similar (spectral index close to 2). These spectral features can be naturally explained by the propagation effects considered in this paper, i.e. IC $e^\pm$ pair cascading processes, inside the binary system. The primary $\gamma$-rays or electrons could be injected with a simple power-law spectrum (and spectral index close to 2), relatively close to the base of the jet. The $\gamma$-ray luminosity expected in this propagation model at GeV energies (1–10 GeV) should vary by a factor of $\sim$2–3, and at TeV energies (>100 GeV) by a factor of $\sim$10 with the orbital period of the binary system LS 5039. In fact, possible variation of the TeV signal by a factor of $\sim$3 has been recently suggested by Casares (2005), although not statistically significant (Aharonian et al. 2005b). Moreover, we show that, due to the propagation (IC $e^\pm$ pair cascade) effects, the maximum in the TeV $\gamma$-ray light curve should occur at phase $\sim$0.6 (measured as an azimuthal angle from the periastron passage; see Fig. 1). This seems to be inconsistent with the recent suggestion by Casares et al. (2005b) who reanalysed the HESS data with the new orbital parameters and concluded that the maximum of TeV emission occurs at the phase $\sim$0.9. This discrepancy does not allow us to put any definitive conclusions since the error bars in TeV $\gamma$-ray light curve, shown by Casares et al. (2005b), are very large. However, if real, it can give some information on the efficiency of acceleration process of the primary particles occurring in the jet (possibly linked with the efficiency of the accretion process) with the phase of the compact object on its orbit around the massive star.

Based on the propagation calculations, it is concluded that $\gamma$-ray spectra produced in such IC $e^\pm$ pair cascades should show clear anticorrelation between the fluxes in the GeV and TeV energy ranges (see the light curves in Fig. 9). We also investigated the dependence of the propagation effects on the distance of the injection place from the base of the jet. If primary particles are injected already at the distance of a few stellar radii from the base of the jet (the case of $z = 5r_\star$ is discussed), then $\gamma$-ray fluxes expected from LS 5039 do not vary strongly enough to explain relative luminosities in the GeV and TeV energy ranges. Either a more complex shape for the spectrum of primary particles injected into the jet is required, e.g. composed of at least three different power laws, or two different populations of primary particles are needed, or the origin of different parts of $\gamma$-ray spectra in different regions of the jet has to be postulated. Moreover, the shape of the $\gamma$-ray spectra escaping towards the observer depends also on the inclination angle of the binary system which is not well known at present (estimated on $25^\circ$ for the case of a solar mass black hole and on $60^\circ$ for the case of a neutron star). The level of variability of the TeV emission for the place of injection of primary particles at the base of the jet is clearly larger for the inclination angle $\theta = 60^\circ$ than for $\theta = 25^\circ$. However, these differences seem to be too low in order to put constraints on the inclination angle of binary system LS 5039 based only on the observations made with the Cherenkov telescopes at their present sensitivity.

If the identification of the binary system LSI +61° 303 with the EGRET source 3EG J0241+6103 is correct (see Introduction), then the average $\gamma$-ray luminosity ($>100$ MeV), $\sim 8 \times 10^{46}$ erg s$^{-1}$, is only about a factor of 3 lower than in the case of LS 5039. This suggests that $\gamma$-ray properties of these two sources should be quite similar. Our simulations of the propagation of primary $\gamma$-rays show that absorption of $\gamma$-rays is similar in both binaries at the periastron passage of the compact object (if primary particles are injected at the base of the jet) but is less important at the apastron passage of LSI +61° 303. The TeV fluxes from LSI +61° 303 predicted by the propagation effects should be relatively larger with respect to its GeV fluxes than observed in the binary system LS 5039. This feature might help in the detection of LSI +61° 303 at TeV energies. The maximum in the TeV $\gamma$-ray light curve predicted by the propagation effects in LSI +61° 303 should occur at the phase $\sim$0.2–0.4, measured from the periastron. The TeV $\gamma$-ray signal is expected to be modulated by an order of magnitude with the maximum for the case of injection of primary electrons injected farther along the jet (at a distance of a few stellar radii; see the case of $z = 3r_\star$ in Fig. 12). Also, strong variability of the GeV flux is possible (even by an order of magnitude) for the case of injection of primary electrons farther from the base of the jet (see e.g. the case of $z = 3r_\star$ in Fig. 12b). Injection of electrons at the base of the jet predicts modulation by a factor of $\sim$2 with the minimum when the compact object is in front of the massive star. Reanalysis of the EGRET data indicates probable modulation of the GeV signal from the source towards LSI +61° 303 (Tavani et al. 1998; Wallace et al. 2000) with the maximum emission near periastron (Massi 2004). This is inconsistent with the predictions of propagation effects for the case of injection of primary electrons studied here, which show a deficit of GeV emission close to periastron. Therefore, if this modulation is real, then the mechanism responsible for such a modulation of GeV emission should be even more efficient since propagation effects considered here work in the opposite direction. For the case of isotropic injection of primary $\gamma$-rays, the GeV signal is only weakly modulated with the period of the binary system due to the domination of primary $\gamma$-rays at such low energies.

In this paper we have only analysed the effects of propagation of $\gamma$-rays inside these two binary systems assuming that the efficiency of particle acceleration and spectra of injected particles do not depend on the location of the place of injection of primary particles along the jet, i.e. they are uniformly distributed along the jet, i.e. from $z = 0r_\star$ to $5r_\star$ (LS 5039) or $3r_\star$ (LSI +61° 303). Proper analysis of $\gamma$-ray emission from these sources requires, except if considering the IC $e^\pm$ pair cascade effects, a detailed model for the efficiency of the accretion process, the conversion of accretion energy into particles, the acceleration of particles (their spectra) and the production of $\gamma$-rays. Such models, which unfortunately do not take into account the cascade effects analysed in this paper but discuss only the production of $\gamma$-rays in the Inverse Compton process far away from the base of the jet, have been recently discussed by Bosch-Ramon, Romero & Paredes (2006) and Dermer & Böttcher (2005).

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