PHOTON-PHOTON ABSORPTION OF VERY HIGH ENERGY GAMMA RAYS FROM MICROQUASARS: APPLICATION TO LS 5039

Markus Böttcher¹ and Charles D. Dermer²

Received 2005 August 16; accepted 2005 October 6; published 2005 November 1

ABSTRACT

Very high energy (VHE) γ-rays have recently been detected from the Galactic black hole candidate and microquasar LS 5039. A plausible site for the production of these VHE γ-rays is the region close to the base of the mildly relativistic outflow. However, at distances comparable to the binary separation, the intense photon field of the stellar companion leads to substantial γγ absorption of VHE γ-rays. If the system is viewed at a substantial inclination (i ≠ 0), this absorption feature will be modulated on the orbital period of the binary as a result of a phase-dependent stellar-radiation intensity and pair-production threshold. We apply our results to LS 5039 and find that (1) γγ absorption effects will be substantial if the photon production site is located at a distance from the central compact object of the order of the binary separation (≈ 2.5 × 10⁻³ cm) or less; (2) the γγ absorption depth will be largest at a few hundred GeV, leading to a characteristic absorption trough; (3) the γγ absorption feature will be strongly modulated on the orbital period, characterized by a spectral hardening accompanying periodic dips of the VHE γ-ray flux; and (4) γ-rays can escape virtually unabsorbed, even from within ≈10⁻³ cm, when the star is located behind the production site as seen by the observer.

Subject headings: gamma rays: theory — radiation mechanisms: nonthermal — stars: winds, outflows — X-rays: binaries

1. INTRODUCTION

Recent observations (Aharonian et al. 2005) of ≈250 GeV γ-rays from the X-ray binary jet source LS 5039 with the High Energy Stereoscopic System (HESS) establish that microquasars are a new class of γ-ray-emitting sources. These results confirm the earlier tentative identification of LS 5039 with the EGRET source 3EG J1824-1514 (Paredes et al. 2000). In addition to LS 5039, the high-mass X-ray binary LS I +61 303 (V615 Cas) also has a possible γ-ray counterpart in the MeV–GeV energy range (Gregory & Taylor 1978; Taylor et al. 1992; Kniffen et al. 1997).

Microquasars now join blazar active galactic nuclei (AGNs) as a firmly established class of very high energy (VHE; with energies of a few hundred GeV to TeV) γ-ray sources. The nonthermal continuum emission of blazars is believed to be produced in a relativistic plasma jet oriented at a small angle with respect to our line of sight. Their radio through UV/X-ray emission is most likely due to synchrotron emission by relativistic electrons in the jet, while the high-energy emission can be produced by Compton upscattering of lower energy photons off relativistic electrons (for a recent review, see, e.g., Böttcher 2002) or through hadronic processes (Mannheim & Biermann 1992; Atoyan & Dermer 2001; Mücke et al. 2003).

Because of their apparent similarity to their supermassive AGN cousins, it has been suggested that Galactic microquasars may be promising sites of VHE γ-ray production (e.g., Bosch-Ramon et al. 2005b). While earlier work on γ-ray emission from X-ray binaries focused on neutron star magnetospheres as γ-ray production sites (e.g., Moskalenko et al. 1993; Moskalenko & Karakula 1994; Bednarek 1997, 2000), the VHE γ-ray detection of LS 5039 suggests that the γ-ray production is more likely to be associated with the jets. High-energy γ-rays of microquasars can be produced via hadronic (e.g., Romero et al. 2003) or leptonic processes. In the latter case, the most plausible site would be close to the base of the mildly relativistic jets, where ultrarelativistic electrons can Compton upscatter soft photons. Possible sources of soft photons are the synchrotron radiation produced in the jet by the same ultrarelativistic electron population (synchrotron self-Compton [SSC]; Atoyan & Aharonian 1999), or external photon fields (Bosch-Ramon & Paredes 2004; Bosch-Ramon et al. 2005b). Both LS 5039 and V615 Cas are high-mass X-ray binaries that are rather faint in X-rays, with characteristic 1–10 keV luminosities of ~10⁴⁶ ergs s⁻¹. This is much lower than the characteristic bolometric luminosity of the high-mass companions of these objects, at L₂ ≳ 10⁴⁸ ergs s⁻¹. Consequently, the dominant source of external photons in LS 5039 and V615 Cas is the companion’s optical/UV photon field.

The intense radiation field of the high-mass companion, however, will also lead to γγ absorption of VHE γ-rays in the ~100 GeV–TeV photon energy range if VHE photons are produced close to the base of the jet. For the case of LS 5039, Aharonian et al. (2005) have estimated that VHE emission produced within ~10⁻³ cm of the central engine of this microquasar would be heavily attenuated (τγγ ~ 20 for Eγ ~ 100 GeV), and the observed spectrum of VHE photons would be hardened compared to its intrinsic shape. For comparison, the γγ opacity due to stellar radiation backscattered by the stellar wind in the vicinity of the binary system (for which the angle of incidence between the line of sight and the target soft photon field would be more favorable for γγ absorption) can be estimated as τγγ (ν) ~ (L₂ν/Me)²Λν / (2.7 × 48π²r²m_pσ_T e²_e), where L₂ is the stellar luminosity, M is the mass outflow rate, Λν is the terminal velocity of the stellar wind, and eₚ is the dimensionless mean photon energy of the stellar radiation field. For LS 5039, L₂ ~ 7 × 10⁴⁶ ergs s⁻¹, m_p e_e ~ 3.5 eV, M ≈ 10⁻⁶ M_S☉ yr⁻¹, and Λν ~ 2500 km s⁻¹ (McSwain & Gies 2002), which yields τγγ (ν) ~ 0.1/λ_p, where λ_p ~ 10⁻¹⁰ cm. Consequently, the γγ opacity will be strongly dominated by the direct stellar photon field. In the same spirit, one can also estimate the effect of γ-ray absorption in the field of atomic nuclei in the stellar wind. Using a total absorption cross section per unit mass of

¹ Astrophysical Institute, Department of Physics and Astronomy, Ohio University, Athens, OH 45701.
² E. O. Hulbert Center for Space Research, Code 7653, Naval Research Laboratory, Washington, DC 20375-5352.
\(\sigma_H \sim 0.012 \text{ cm}^2 \text{ g}^{-1}\) for GeV–TeV \(\gamma\)-rays, we find \(\tau_{\gamma, z} \approx \sigma_H M/(4\pi \nu L_{\nu}) \approx 1.3 \times 10^{-7}/r_{12}\) for LS 5093, which is also always much smaller than the \(\gamma\gamma\) absorption depth.

In this Letter, we provide a more detailed analysis of the expected \(\gamma\gamma\) absorption trough caused by direct companion star light, including its temporal modulation due to the orbital motion. The model description and the derivation of the general expression for the \(\gamma\gamma\) opacity as a function of \(\gamma\)-ray photon energy and orbital phase is given in \$2$. Numerical results for LS 5039 are presented in \$3$. Section 4 contains a brief summary and discussion of our results.

2. Model Description and Analysis

We choose a generic model setup as illustrated in Figure 1 (for a comparable model setup in the AGN case, see Böttcher & Dermer 1995). The orbital plane of the binary system defines the \((x, y, z)\)-plane. The jet, assumed to be perpendicular to this plane, defines the \(x\)-axis. The system is inclined with respect to our line of sight by an inclination angle \(i\). An azimuthal (phase) angle \(\phi\) is defined such that \(\phi = 0\) in the direction of the \(x\)-axis. The line of sight lies in the \((x, z)\)-plane. The \(\gamma\)-ray production site is located at a height \(z_0\) along the jet. The phase angle of the companion star at the time of production of a \(\gamma\)-ray photon at \(z_0\) is denoted \(\phi_0\). The distance the photon travels along the line of sight is denoted by \(l\), whereas a starlight photon travels a distance \(x\) before interacting with the \(\gamma\)-ray photon. The angle of incidence between the two photons is \(\theta\), and \(\mu \equiv \cos \theta\). The star was located at azimuthal angle \(\phi_1\) at the time when a photon, leaving the star at that time, interacts with a \(\gamma\)-ray photon that has travelled a distance \(l\) from \(z_0\). This yields \(\phi_1 = \phi_0 + (2\pi/P)(l - x)/c\), where \(P\) is the orbital period.

With the definitions as shown in Figure 1, the distance \(x\) can be calculated as \(x = |x| = |r - s|\), where \(s\) is the orbital separation of the binary system. We find

\[
x^2 = s^2 + l^2 + z_0^2 + 2l(z_0 \cos i - s \sin i \cos \phi_1).
\]

From Figure 1, \(\mu = l \cdot x/(l \cdot x)\), which yields

\[
\mu = \frac{l + z_0 \cos i - s \sin i \cos \phi_1}{x}.
\]

With these quantities, we can evaluate the \(\gamma\gamma\) opacity of a \(\gamma\)-ray photon with dimensionless energy \(\epsilon_0 = E_\gamma/(m_\gamma c^2)\) as

\[
\tau_{\gamma\gamma}(\epsilon_0, z_0, \phi_0) = \int_0^\infty \int_{2\sin(i - \mu)}^{2\sin(i + \mu)} d\sigma_{\gamma\gamma}(\epsilon_0, \epsilon, \mu)n_{ph}^*(\epsilon, x),
\]

where \(\sigma_{\gamma\gamma}\) is the pair-production cross section and

\[
n_{ph}^*(\epsilon, x) = \frac{15}{4\pi^2 m_\gamma c^2} \frac{L_\gamma \epsilon^2}{\Theta_x^2 x^2 (e^{\epsilon_{ph}} - 1)}.
\]

The stellar spectrum is approximated by a blackbody with dimensionless temperature \(\Theta_x = kT_x/m_\gamma c^2\), and the star is approximated as a point source.

3. Results for LS 5039

Casares et al. (2005) have analyzed optical intermediate-dispersion spectroscopic observations of LS 5039, which provided an estimate of the mass of the compact object of \(M_\star = 3^{+13}_{-0.10} M_\odot\), indicating that it is likely to be a black hole. Other relevant parameters of the binary system are \(P = 3.91\) days, the luminosity of the O6.5 V type stellar companion, \(L_* = 10^{3.3} L_\odot\), with an effective surface temperature of \(T_{eff} = 39,000\) K, a viewing angle of \(i = 25^\circ\), and an orbital separation of \(a \approx 2.5 \times 10^{12}\) cm (Casares et al. 2005). Note that the center of mass is rather close to the massive \((M \approx 23 M_\odot)\) stellar companion. However, because the light-travel and jet propagation times on the length scales investigated here \((\approx 10^{14}\) cm) are much shorter than the orbital period, the detailed dynamics of the orbital motion are irrelevant for our purposes; at any given phase \(\phi_0\), the geometry is basically stationary. An additional complication could be introduced by the substantial eccentricity of the orbit, \(e = 0.35\), with periastron at a phase angle of \(\phi \sim 0.6\pi\) (Casares et al. 2005). However, in view of the still rather poor quality of the data currently available and expected in the near future, this can be regarded as a higher order effect that may be introduced at a later stage.

The inset to Figure 2 illustrates the shape of the absorption trough caused by \(\gamma\gamma\) absorption and its dependence on the orbital phase. Here we assume that the intrinsic \(\gamma\)-ray spectrum is a power law with photon index \(\alpha_{ph} = 2.5\) and \(z_0 = 10^{12}\) cm. The various curves illustrate the orbital modulation of the absorption trough, with the lowest (most heavily absorbed) curve corresponding to \(\phi_0 = 0\) and the highest (least absorbed) curve corresponding to \(\phi_0 = \pi\). The modulation is a combined consequence of two effects: for phase angles closer to \(\pi\), (1) the...
average distance of the star to any point on the line of sight is longer and (2) the angle of incidence \( \theta \) is smaller. In addition to effect 1 causing the overall photon number density of the stellar photon field to decrease, effect 2 causes the threshold for \( \gamma \gamma \) pair production to increase as \( \epsilon_{\gamma\mu} = 2/ [\epsilon_a (1 - \mu)] \). This leads to a decreasing overall depth of the absorption trough, and a shift of the minimum of the absorption trough toward higher photon energies.

Figure 2 shows the dependence of the absorption feature on the location \( z_0 \) of the VHE \( \gamma \)–ray production site. The \( \gamma \gamma \) opacity is plotted for two photon energies, \( E = 250 \) GeV and \( E = 1 \) TeV at \( \phi_0 = 0 \). GeV–TeV photons produced within \( z_0 \sim s \) from the compact object will be heavily attenuated for this phase angle. For photons produced at \( z_0 \gg s \), \( \gamma \gamma \) attenuation becomes negligible. The two curves cross over at \( z_0 \approx s \) in Figure 2, which illustrates the shift of the minimum of the absorption trough to higher photon energies with increasing distance from the central engine. This is a consequence of the decreasing incidence angle, as discussed above.

Figure 3 quantifies the orbital modulation of the \( \gamma \gamma \) absorption trough for the same parameters as used in the inset to Figure 2. The dotted and dot-dashed curves show the orbital modulation of the optical depth, illustrating that (1) it is maximized for \( \phi_0 \approx 0, 2\pi \), and (2) the minimum of the absorption trough shifts toward higher photon energies for phases closer to \( \pi \). The most feasible way to detect an orbital modulation would be to measure a periodicity of the observed photon flux. The solid and short-dashed curves in Figure 3 show the integrated photon number flux above energies \( E_0 = 250 \) GeV and \( E_0 = 1 \) TeV, respectively. This illustrates that the relative modulation is most pronounced at several hundred GeV, noting that the \( \gamma \gamma \) absorption is largest at photon energies \( E_i \approx 2 \times 10^3 \) cm. The different curves represent the escaping photon spectrum at various orbital phases, from \( \phi_0 = 0 \) (bottom curve) to \( \phi_0 = \pi \) (top curve) in steps of \( \pi/10 \).

4. SUMMARY AND DISCUSSION

We have presented a detailed analysis of the effect of \( \gamma \gamma \) absorption of VHE \( \gamma \)-rays near the base of the jet of a microquasar by the intense photon field of a high-mass stellar companion. We include the time-dependent periodic modulation of this effect due to the binary’s orbital motion. We applied our results to the specific case of LS 5039, which has recently been

![Image](Image 46x522 to 290x727)

![Image](Image 320x512 to 566x727)
identified as the counterpart of the VHE $\gamma$-ray source HESS J1826−148. Our results can be summarized as follows:

1. VHE $\gamma$-rays produced closer to the central engine than $z_0 \sim 10^{12}$ cm, which is of the order of the binary separation $s$, would be subject to very strong $\gamma\gamma$ absorption due to the stellar radiation field at orbital phases close to $\phi_0 = 0$.

2. For VHE photon production sites at $z_0 \leq s$, the $\gamma\gamma$ opacity, and thus the VHE $\gamma$-ray flux, would be strongly modulated on the orbital period of the binary system ($P = 3.91$ days in the case of LS 5039). At orbital phases close to $\phi_0 = \pi$, the intrinsic VHE $\gamma$-ray flux would still be virtually unabsorbed even for $z_0 \sim 10^{12}$ cm.

3. The orbital modulation of the VHE $\gamma$-ray flux would be characterized by a spectral hardening in the $\sim 300$ GeV–1 TeV range during flux dips. At lower energies, the spectrum softens with decreasing flux.

The HESS collaboration has reported no evidence for either flaring or periodic variability from LS 5039 (Aharonian et al. 2005), although Casares et al. (2005) suggest that there is weak evidence for variability of the HESS emission with the orbital period. Periodic variability may also be indicated by X-ray observations (Bosch-Ramon et al. 2005a) of LS 5039.

Besides $\gamma\gamma$ opacity effects, there are a few alternative scenarios that might cause a periodic modulation of the $\gamma$-ray flux:

1. As a consequence of the substantial eccentricity of the orbit, the rate of mass transfer from the stellar companion to the compact object, which is believed to be dominated by wind accretion, is likely to be periodically modulated. This modulation would also be expected to appear at radio and X-ray energies.

2. Analogous to the phase-dependent modulation of the incidence angle for $\gamma\gamma$ absorption, this geometrical effect would also yield a more favorable angle for Compton scattering of starlight photons into the $\gamma$-ray regime at phases $\phi_0 \sim 0$.

3. The orientation of the jet may also be misaligned with respect to the normal of the orbital plane (Maccarone 2002; Butt et al. 2003) and possibly precessing about the normal (Laarwood 1998; Torres et al. 2005), leading to additional modulations, including a changing Doppler boosting factor.

Effect 1 would be expected to lead to an overall hardening of the $\gamma$-ray spectrum at all energies with increasing $\gamma$-ray flux, while effect 2 would lead to an overall softening throughout the GeV–TeV photon-energy range because of the Klein-Nishina cutoff becoming noticeable at lower observed photon energies with increasing flux. Both effects are in contrast to the $\gamma\gamma$ absorption trough investigated in this Letter. A stationary misalignment of the jet could lead to a slight enhancement of the orbital modulation (if the jet makes a smaller angle with the line of sight than the orbital-motion axis) or reduce it (in the opposite case), but would not change our results qualitatively. A $\gamma$-ray flux modulation due to jet precession can easily be disentangled from the orbital modulation, since the precession period is generally different from the orbital period, so that its effect would average out when folding observational data with the orbital period. Consequently, a measurement of a nonthermal absorption trough at VHE $\gamma$-ray energies modulated with the orbital period would firmly establish the importance of $\gamma\gamma$ absorption effects and thus place a robust limit on the distance $z_0$ of the VHE $\gamma$-ray production site in LS 5039.

We thank Guillaume Dubus, Mathieu de Naurois, and Valenti Bosch-Ramon for helpful correspondence, and the referee for a helpful and constructive report. This work was partially supported by NASA through XMM-Newton GO grant NNG 04GI50G, NASA INTEGRAL Theory grant NNG 05GK59G, and GLAST Science Investigation DPR-S-1563-Y. The work of C. D. D. is supported by the Office of Naval Research.

REFERENCES
