PROCEEDINGS OF SCIENCE

On the origin of the GeV and TeV emission in gamma-ray binaries*

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Gamma-ray binaries emit GeV and TeV gamma-ray radiation modulated with their orbital period. They may be formed of a young, non accreting pulsar orbiting a massive luminous star. The gamma-ray emission results from the Compton upscattering of stellar photons on relativistic electron-positron pairs efficiently accelerated, possibly where the stellar wind collides with the pulsar wind. Yet, the precise modeling of the spectral and temporal behavior of these binaries in gamma rays remains challenging. Here, we review our current understanding of the production of high-energy radiation in gamma-ray binaries. We also discuss the GeV gamma-ray emission detected in the microquasar Cygnus X-3 and its possible origin.

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1. Introduction

Two years ago, three high-mass X-ray binaries were known to radiate very high-energy radiation: PSR B1259−63 [1], LS I+61°303 [2], LS 5039 [3] and possibly joined by the unidentified TeV source HESS J0632+057 [4] (see also J. Skilton and E. Aliu contributions) and the microquasar Cygnus X-1 [5]. With the launch of the *Fermi* and *AGILE* gamma-ray space telescopes, the number of known binaries emitting gamma rays has increased. New binaries are also of different kind. In addition to LS I+61°303 and LS 5039 [6, 7], *Fermi* and *AGILE* discovered high-energy gamma-ray emission from the microquasar Cygnus X-3 [8, 9]. High-energy radiation was unexpectedly detected during a nova outburst in the symbiotic binary system V407 Cyg [10] (see the contribution by T. Cheung in these proceedings). Another surprise came out of the large number of millisecond pulsars seen in gamma rays [11]. Some amongst them are orbiting a low-mass companion star [12, 13]. The last example of binary system possibly emitting energetic photons is the colliding wind binary η Carinae [14] (see R. Walter contribution). In this proceeding, we review and discuss some of the possible mechanisms responsible for the high-energy emission in the gamma-ray binaries LS 5039, LS I+61°303, PSR B1259−63 (Section 2) and in the microquasar Cygnus X-3 (Section 3).

2. Gamma-ray binaries

2.1 Origin of the GeV-TeV orbital modulation

Gamma-ray binaries were first discovered by Cherenkov telescopes above 100 GeV as variable sources modulated with their orbital period. This variability is usually interpreted as the inverse Compton scattering of the UV photons from the massive star on relativistic electron-positron pairs efficiently accelerated in the system. In the pulsar wind nebula scenario [15, 16], energetic pairs are injected by a young non-accreting pulsar and (re)accelerated at the termination shock region between the stellar and the pulsar winds.

LS 5039 exhibits a stable orbital modulation at GeV [7] and TeV [17] energies where extrema coincide with conjunctions, suggesting that the orientation of the observer with respect to the position of both stars is crucial. GeV and TeV lightcurves are also anti-correlated. The GeV gamma-ray modulation can be explained in term of anisotropic inverse Compton scattering. The maximum/minimum of emission arises at superior/inferior conjunction where the pitch angle between electrons and stellar photons is maximum/minimum[1]. Above 30-50 GeV, gamma rays annihilate with the stellar radiation to produce new pairs. The process of pair production has a similar angular dependence (though not identical) as inverse Compton scattering. Gamma-ray absorption is maximum and minimum at the same orbital phases. The interplay between emission and absorption reproduces the features of the observed TeV lightcurve and provides also a robust explanation to the origin of the GeV-TeV anti-correlation (see *e.g.* [18, 19, 20, 21] and Fig. 1, *left* panel). The radiation from a cascade of pairs and gamma rays (initiated by pairs created by photon-photon annihilation) can reduce significantly the gamma-ray optical depth in LS 5039 and account for the

[1] The emission from relativistic pairs is highly beamed along their direction of motion, hence only those pointing at the observer should be considered.

gamma-ray flux observed close to superior conjunction, underestimated by pure absorption models [22].

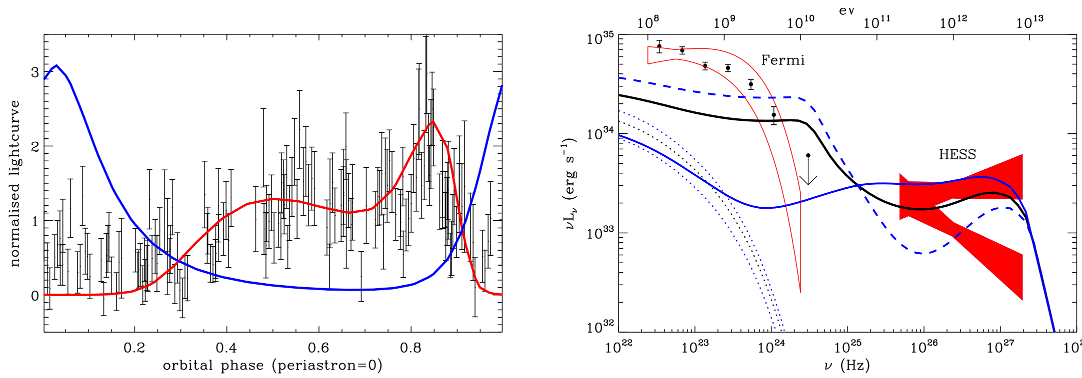

Figure 1: Left panel: Modeled gamma-ray modulation in the *Fermi* energy range ($>$ 1 GeV, blue line) and in the HESS band ($>$ 100 GeV, red line) taken from [19]. HESS datapoints from [17] are overplotted. **Right panel:** Simulated gamma-ray spectra (solid and dashed lines) with *Fermi* and HESS measurements (bowties). See [19] for more details.

In LS I+61$^{\rm o}$303, the origin of the gamma-ray modulation is unclear. The GeV and TeV modulations are inconsistent with anisotropic Compton emission (assuming a constant injection of fresh particles along the orbit). *Fermi* reported an orbital modulation with a peak right after periastron and a minimum just after apastron. The TeV modulation is almost in anti-phase with the *Fermi* lightcurve with a maximum close to apastron, but contrary to LS 5039 this anti-correlation cannot be attributed to gamma-ray absorption. Pair production is too small in this system. The TeV modulation could be due to relativistic Doppler boosted emission in the shocked pulsar wind [23] or dominant adiabatic losses [24], but the origin of the orbital variability remains to a large extent misunderstood. The situation has become even more puzzling since we know that LS I+61$^{\rm o}$303 shows an important inter-orbital variability at GeV (see D. Hadasch's proceeding) and at TeV[2]. The overall gamma-ray variability could be related to the complex interaction between the B*e* star wind (in particular its equatorial component) and the pulsar wind.

PSR B1259 – 63 produces TeV gamma rays close to periastron [1] where the stellar photon density is maximum. However, the modulation presents complex features that cannot be interpreted with anisotropic Compton emission only. Other processes might be at work and dominate in this elongated system. The gamma-ray emission could also be related to the passage of the pulsar through the B*e* disk of the companion. A few weeks after the end of this conference, *Fermi* has detected PSR B1259 – 63 during the periastron passage.

2.2 Origin of the GeV emission

Fermi observations of the gamma-ray binaries LS 5039 and LS I +61$^{\rm o}$303 have also revealed unexpected spectral properties. The high-energy spectra are both composed of a power-law and an exponential cut-off at a few GeV (2.1 and 6.3 GeV). This energy cut-off is too low to be consistent

[2] After two years of non-detection [25], VERITAS has detected TeV emission from LS I+61$^{\rm o}$303 close to periastron [26].

with pair production with stellar photons (minimum threshold at 30-50 GeV). The TeV emission is not a simple extrapolation of the high-energy emission (Fig. 1, *right* panel). Electrons radiating at GeV and TeV may be two distinct populations. Because gamma-ray pulsars have similar spectral properties, the high-energy component could be the magnetospheric emission from the pulsar. If it is so, the origin of the orbital modulation is unclear in the framework of classical models of pulsar emission (*e.g.* polar caps, outer gaps) and should be revisited in the context of a strong external source of radiation (from the companion star, see M. Kapala's proceeding). Alternatively, the high-energy spectrum could be emitted by the upscattering of stellar light onto pairs in the unshocked pulsar wind assuming a broad energy distribution for the electrons with a high energy cut-off around 10-20 GeV, but this model fails in reproducing the modulation in LS I $+61^{o}303$ [27].

3. Cygnus X-3

3.1 Gamma-ray emission and modulation

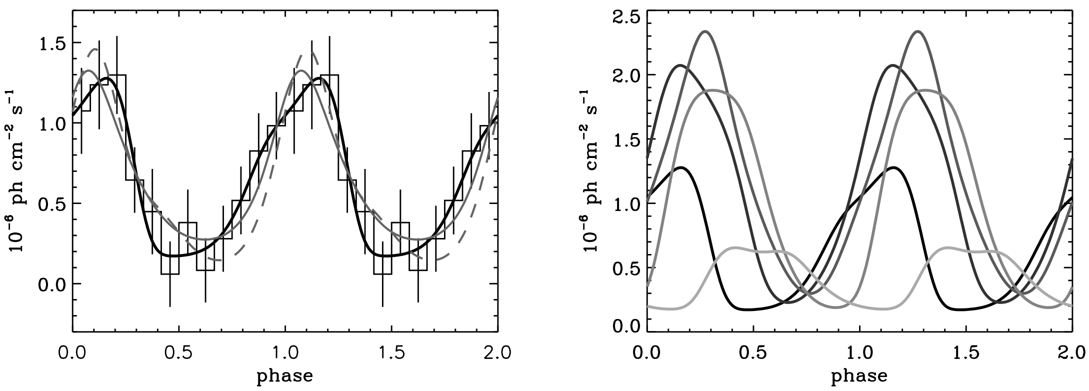

Figure 2: Left panel: Modeled gamma-ray lightcurve in Cygnus X-3 above 100 MeV and comparison with the *Fermi* folded lightcurve. The black solid line is the best-fit solution to the data. **Right panel:** Effect of the precession of the jet on the gamma-ray modulation. See reference [28] for more details.

The accreting high-mass X-ray binary Cygnus X-3 is composed of a Wolf-Rayet star and an unknown compact object, possibly a black hole. In 2009, *AGILE* [9] and *Fermi* [8] detected high-energy gamma rays correlated with major radio flares, *i.e.* with the presence of a relativistic jet in the system. In addition, the gamma-ray emission is modulated with the 4.8 h orbital period suggesting that geometrical effects play an important role. Assuming that gamma rays are emitted by pairs injected in the jet and upscattering the stellar radiation, it is possible to reproduce the correct modulation (Fig. 2, *left* panel). A complete exploration of the parameter space shows that the shape of the theoretical lightcurve matches well observations if pairs are injected away from the compact object, at distances $\sim$ 1-10 times the orbital separation [28] ($10^{11} \lesssim H \lesssim 10^{12}$ cm). The jet should be inclined, oriented close to the line of sight and mildly relativistic ($v_{\rm jet}/c \lesssim 0.9$). This scenario favors a black hole in Cygnus X-3 because a smaller fraction of the Eddington lumionosity is needed to power the gamma-ray flux. Another important consequence of this model concerns the long term variability of the gamma-ray modulation. If the jet precesses, the shape and amplitude of the gamma-ray modulation is changed dramatically (Fig. 2, *right* panel). This could explain the non-detection of Cygnus X-3 by EGRET and *COS-B*.

3.2 Gamma-ray absorption and coronal emission

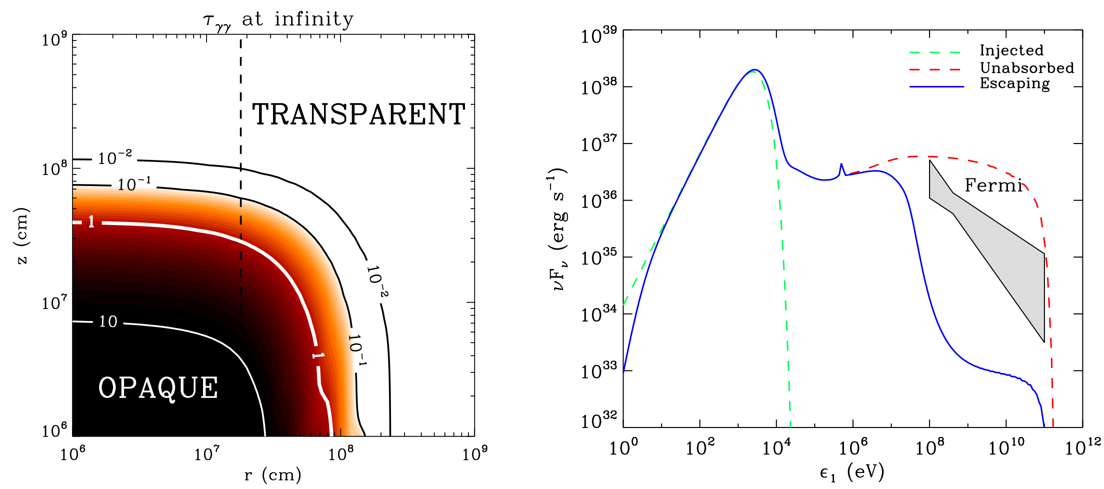

Figure 3: Left panel: Spatial dependence of the gamma-ray optical depth $\tau_{\gamma\gamma}$ integrated along the line of sight above the accretion disk for 1 GeV photons (contours corresponds to $\tau_{\gamma\gamma}=10^{-2}$, 0.1, 1 and 10). The disk is inclined at an angle 30° with respect to the observer, has a bolometric luminosity $L_{\rm disk}=10^{38}$ erg s^{-1} and an inner radius $R_{\rm in}\approx 2\times 10^{7}$ cm. **Right panel:** Simulated emission from the corona with `BELM` for a radius $R_{\rm c}=10^{8}$ cm. The thermal emission from the accretion disk (green dashed line) is comptonized by thermal and non-thermal electrons in the corona. The *Fermi* power-law is shown by the gray bowtie.

GeV gamma rays annihilate with ~ 1 keV X-ray photons. In Cygnus X-3, the X-ray spectrum is complex and variable. During the reported gamma-ray flares the source was in the soft X-ray state, *i.e* dominated by a bright thermal component most probably from the accretion disk around the compact object. A precise calculation of the gamma-ray optical depth above an optically thick, geometrically thin disk indicates that GeV gamma rays would escape the system if they are injected at least 10^{8} cm away from the center of the disk [29] (Fig. 3, *left* panel). In addition to the thermal radiation from the accretion disk, archive *RXTE* data shows that the soft state spectrum is dominated by a non-thermal tail above 10 keV up to 100 keV without any sign of high-energy cut-off [30]. This high-energy emission could be attributed to the radiation from the disk, comptonized by a population of thermal and non-thermal electrons injected in a hot corona around the compact object. It is quite tempting to extend this non-thermal power-law in the high-energy domain. The modeling of the emission from an isotropic, homogeneous and spherical corona (of radius $R_{\rm c}$) with the code `BELM` [31] shows that gamma rays are highly absorbed by the non-comptonized radiation from the disk, unless the corona is unrealistically extended $R_{\rm c}\gtrsim 10^{10}$ cm [29] (Fig. 3, *right* panel).

4. Summary and conclusions

Our understanding of the gamma-ray modulation in gamma-ray binaries is contrasted. In

LS 5039, the GeV and TeV modulation can be explained in term of anisotropic inverse Compton emission and pair production only. In LS I $+61^{o}303$ and PSR B1259 $-$ 63, the gamma-ray variability is not completely understood possibly because of our poor knowledge of the interaction between the relativistic pulsar wind and the complex B*e* stellar wind. Some progress may be expected from relativistic MHD simulations of these systems. The high-energy spectral component in LS 5039 and LS I $+61^{o}303$ reminds the typical spectrum of gamma-ray pulars. If this emission is from the pulsar magnetosphere, the origin of the orbital modulation is not clear. In Cygnus X-3, anisotropic Doppler boosted Compton scattering reproduces well the observed gamma-ray modulation if pairs are injected in a mildly relativistic and inclined jet. In addition, gamma rays are absorbed by soft X-rays from the accretion disk if injected at a distance $\lesssim 10^{8}$ cm. For this reason, dominant gamma-ray emission from the corona is very unlikely.

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