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PAIR CASCADING IN GAMMA-RAY BINARIES

Cerutti, B.[1], Dubus, G.[1] and Henri, G.[1]

Abstract. In some gamma-ray binaries, pair production is strong and shapes the very high energy (VHE > 100 GeV) radiation output. In LS 5039, a one-zone leptonic model reproduces the VHE gamma-ray modulation observed by HESS, but fails at orbital phases where gamma-gamma absorption is predominant. The development of pair cascading was proposed as an explanation for this discrepancy. We report on the formation of pair cascading radiation in a binary environment. One-dimensional and three-dimensional cascade radiation calculations are presented. The effect of the ambient magnetic field in the development of cascades is crucial and discussed.

1 Introduction

Gamma-ray binaries are well-established gamma-ray sources in the Galaxy. These systems are composed of a massive companion B*e*/O type star and a compact object. The three binaries discovered so far: LS 5039, LSI +61°303 and PSR B1259−63, present the same spectral and temporal characteristics throughout the electromagnetic domain from radio to TeV energies (see *e.g.* Dubus 2006b, and references therein). In the standard pulsar wind nebula scenario (Maraschi & Treves 1981; Dubus 2006b), the non-thermal radiation is emitted by a population of ultra-relativistic electron-positron pairs produced and accelerated at the vicinity of a young pulsar.

LS 5039 is composed of a O6.5V type star and an unknown compact object in a 3.9 day orbit. The orbital modulation of the VHE gamma-ray flux was observed by HESS (Aharonian et al. 2006). These observations enable to put strong contrains on models such as the particle distribution and the magnetic field (Dubus et al. 2008). LSI +61°303 and PSR B1259−63 contain a B*e* type star. The absence of a B*e* equatorial wind component in LS 5039 reduces the number of unknowns and makes this system an ideal object for modeling. In this tight binary, $\gamma\gamma$-absorption is strong and shapes the light-curve at VHE (Dubus 2006a). The combination of anisotropic inverse Compton scattering and pair production explains the observed modulation except close to superior conjunction where the flux is underestimated (Dubus et al. 2008). This mismatch occurs precisely at orbital phases where absorption is predominant. The produced pairs can reprocess a significant fraction of the absorbed radiation and initiate a cascade. The radiation emitted in the cascade decreases the global $\gamma\gamma$-opacity in the system, providing a viable explanation for this discrepancy. In this proceeding, we report on the formation of one-dimensional and three-dimensional pair cascading radiation in LS 5039.

2 The physics at work and the effect of the magnetic field on pair cascading

The absorption of the primary gamma-rays provides a large density of secondary pairs in the binary system. New generations of particles are produced as long as the photons radiated in the cascade stay close to the massive star and have enough energy for pair production. The escaping gamma-ray radiation is the result of a competition between emission and absorption. In addition to pair production, triplet pair production ($\gamma + e^{\pm} \rightarrow e^{\pm} + e^{+} + e^{-}$) provides also new pairs (Mastichiadis 1991), but these electrons may not contribute much to the cascade (see details in Cerutti et al. 2009a). The annihilation of pairs is ignored as well here since it occurs for pairs that are almost thermalized.

[1] Laboratoire d'Astrophysique de Grenoble, UMR 5571 CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble, France

The ambient magnetic field has a dramatic influence on the development of the cascade. If the magnetic deviations of pairs trajectories are small ($B < 10^{-8}$ G in LS 5039), all the particles involved in the cascade are boosted in the direction of the primary gamma-ray because of relativistic effects. In this case, the cascade is one-dimensional and develops along the line of sight. From a distant observer, the system appears as a point-like and anisotropic gamma-ray source (see §3). For stronger magnetic field, pairs undergo sizeable deflections and radiate in other directions, the cascade becomes three-dimensional. If the Larmor radius of the electrons is smaller than the Compton interaction length $R_L < \lambda_{ic}$, pairs are confined and isotropized locally by the magnetic field. In the following, three-dimensional 'isotropic' cascade refers to this particular case. For LS 5039, the cascade can be considered as isotropic for $B > 10^{-2}$ G. The cascade radiation then originates from a spatially extended region and depends on the viewing angle (see §4). If the magnetic field strength exceeds a few Gauss, pairs cool down *via* synchrotron radiation rather than by inverse Compton scattering and the cascade is quenched (Bednarek 1997, Khangulyan et al. 2008).

3 One-dimensional cascade

In the one-dimensional case, the cascade dynamics can be explicitly and exactly described with a semi-analytical method. In LS 5039, the cascade radiation contribution is strong and highly variable along the orbit (see Fig. 1). The orbital parameters are taken from Casares et al. (2005) with an inclination of $i = 60^{\circ}$. The cascade does add more flux at superior conjunction as expected but overestimates HESS observations and the modulation cannot be accurately reproduced anymore. One-dimensional pair cascading can be ruled out but three-dimensional cascade cannot be excluded by this study. If magnetic deviations on pairs trajectories are large, the cascade radiation is redistributed at other orbital phases. This redistribution depletes the density of pairs at phases where many pairs are produced to the benefit of phases where only a few are created. Hence, one-dimensional pair cascading provides a theoretical upper-limit on the contribution of pair cascading radiation at superior conjunction (for more details see Cerutti et al. 2009a, submitted). In LSI $+61^{\circ}303$ and PSR B1259$-$63, the cascade does not play any major role in the formation of the VHE γ-ray radiation, pair production remains small in these systems (Dubus 2006a). Note that such cascade is appropriate in an unshocked pulsar wind where the magnetic field is frozen into the plasma of pairs (Sierpowska-Bartosik & Torres 2008).

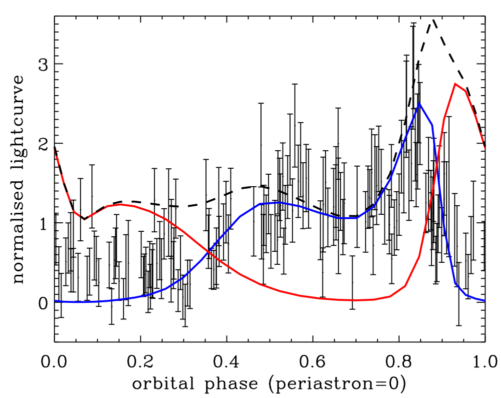

Fig. 1. Phase-resolved VHE light-curves in LS 5039. The one-dimensional cascade contribution (red line) is compared to the primary source (blue line) and to HESS measurements (black data-points, taken from Aharonian et al. 2006). The black dashed-line represents the sum of both components.

4 Three-dimensional isotropic cascade

The computation of three-dimensional pair cascading is not straightforward since no equations can be explicitly formulated in this case. Nevertheless, a semi-analytical approach is possible if the cascade is decomposed into discrete generations of pairs and gamma-rays. In the three-dimensional isotropic cascade model, pairs are locally isotropized and confined at their creation site by a disordered magnetic field. The binary system environment is surrounded by a plasma of secondary pairs radiating *via* inverse Compton scattering and synchrotron radiation. Figure 2 gives the spatial distribution of the first generation of VHE gamma-rays as observed by a distant observer at superior (*top*) and inferior (*bottom*) conjunctions in LS 5039. The first generation is extended and depends on the relative position of the observer compared with both stars. The anisotropic effects arise from the angular dependence in pair production and inverse Compton scattering. Synchrotron radiation is computed for a population of pairs with an isotropic distribution of pitch angles to the magnetic field. Even though the massive star is assumed point-like for spectral calculations, eclipses are taken into account (Fig. 2).

Figure 3 shows the VHE integrated γ-ray flux radiated by the first generation of pairs along the orbit in LS 5039. In this case, the cascade contribution is perfectly correlated with the primary source modulation. Phase-averaged spectra and modulation remain nearly unchanged. Interestingly, the cascade flux does not dominate except close to superior conjunction between phases $0.0 < \phi < 0.15$. At superior conjunction ($\phi \approx 0.06$), the flux is increased by a factor six thanks to the first generation of pairs, but more generations have to be considered to explain HESS observations (Cerutti et al., in preparation).

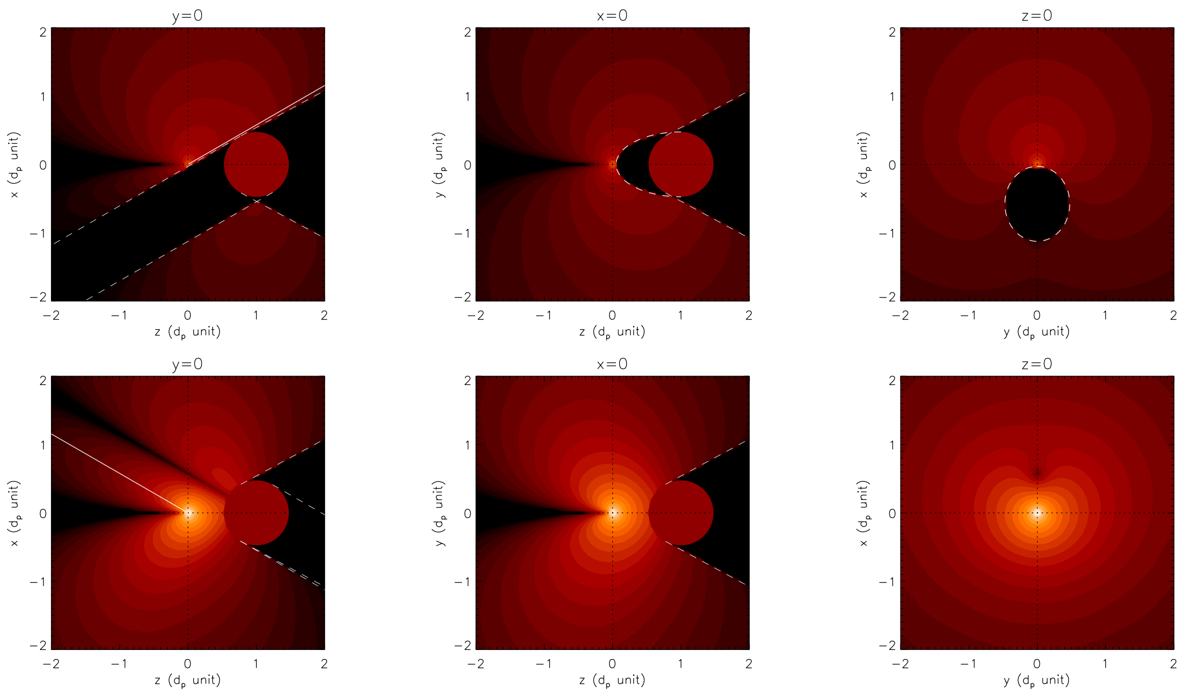

Fig. 2. These maps depict the spatial distribution and intensity of the VHE radiation produced by the first generation of pairs of the cascade in LS 5039 as observed by a distant observer (white solid line, left panels). Distances are normalized to the orbital separation d. The system is viewed at superior (*top*) and inferior conjunctions (*bottom*) in the three orthogonal planes: front view (*left*), top view (*middle*) and right view (*right*). The primary source lies at the origin. The eclipsed regions by the massive star (red disk) are delimited by white dashed lines.

5 Summary and conclusion

Pair production in gamma-ray binaries induces an addition complication in the modeling of the high energy gamma-ray emission. In some tight binaries such as LS 5039, pair production is strong and shapes the VHE gamma-ray output. Depending on the ambient magnetic field, a cascade of pairs can be initiated in the system. One-dimensional cascade arises if the magnetic field is unrealistically small ($B < 10^{-8}$ G) but provides a theoretical upper-limit to the cascade contribution at superior conjunction. HESS observations can rule out this kind of cascade. More realistic types of cascades such as three-dimensional isotropic cascade provide a viable explanation to understand HESS observations particularly at superior conjunction where the cascade radiation dominates over the primary source. Yet, the effect of the next generations of particles has to be

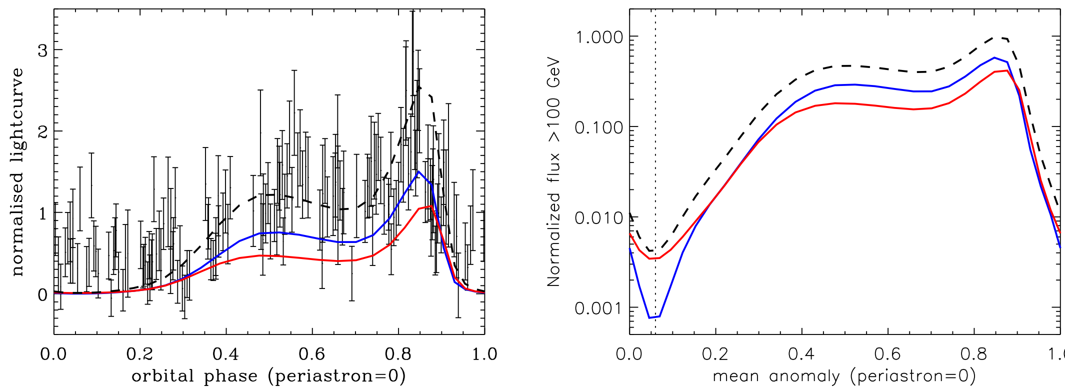

Fig. 3. *Left:* The same as in Fig. 1 for a three-dimensional cascade (first generation). *Right:* The same light-curves are shown in a semi-logarithmic scale. Superior conjunction is indicated by the black dotted line ($\phi \approx 0.06$).

studied. Complementary investigations using a Monte Carlo code are necessary to corroborate and confirm the implication of cascades in the formation of VHE radiation in gamma-ray binaries.

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