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Spectral energy distribution of gamma-ray binaries:

sources and processes

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Abstract. Gamma-ray binaries are suitable sources to study high-energy processes in jets and outflows in general. In the last years, there has been a lot of activity in the field of gamma-ray binaries to identify the different factors that shape their non-thermal spectra, which ranges from radio to very high energies, as well as their lightcurves. In this work, I discuss the main aspects of the non-thermal emission in this class of objects, which presently includes high-mass microquasars, high-mass binaries hosting a non-accreting pulsar and, probably, massive star binaries; few potential candidates to be gamma-ray binaries are also presented. Finally, the importance of gamma-ray absorption is discussed, and the main physical ingredients, which are likely involved in the non-thermal radiation in gamma-ray binaries, are briefly considered.

Key words. X-ray: binaries – Gamma-rays: theory – Radiation mechanism: non-thermal

1. Introduction

Gamma-ray binaries are binary systems formed by two objects, generally one non-degenerated star and a compact object or another non-degenerated star, which emit gamma-rays.

Three gamma-ray binaries have been detected so far in high- (HE: $\sim 0.1-100$ GeV) and very high-energy (VHE: $\sim 0.1-100$ TeV) gamma-rays: LS 5039, LS I +61 303 and Cygnus X-1 (at $\sim 4\,\sigma$) (Kniffen et al. 1997; Paredes et al. 2000; Aharonian et al. 2005a, 2006a; Albert et al. 2006, 2007; Acciari et al. 2008; Abdo et al. 2009a,b; Sabatini et al. 2010). In addition to these three sources, there are a gamma-ray binary and a candidate for it, PSR B1259−63 and HESS J0632+057, respectively, detected above 100 GeV, but not below (Aharonian et al. 2005b, 2007). Finally, Cygnus X-3 has been detected in the HE but not in the VHE band (Tavani et al. 2009a; Abdo et al. 2009c; Saito et al. 2009), as well as probably η-Carina, which could have been detected only in the HE range (Tavani et al. 2009b). Among all these sources, there are two confirmed high-mass microquasars (HMMQ) (Cygnus X-1 and Cygnus X-3), one confirmed high-mass binary hosting a non-accreting pulsar (PSR B1259−63), possibly a massive star binary (η-Carina), two high-mass binaries harboring a compact object of unknown nature (LS 5039 and LS I +61 303;

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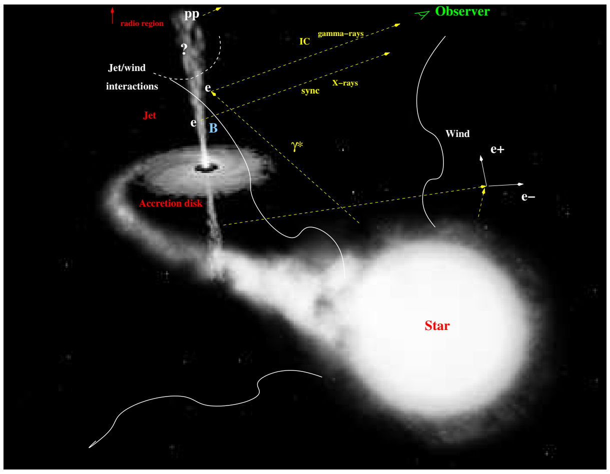

Fig. 1. Illustrative picture of the microquasar scenario, in which the main elements and processes relevant to this work are shown (background image adapted from ESA, NASA, and Félix Mirabel).

see, e.g., Dubus 2006a; Chernyakova et al. 2006; Romero et al. 2007; Bosch-Ramon & Khangulyan 2009), and a high-mass binary candidate (HESS J0632+057).

In the following, we briefly introduce the different types of source that have been detected in gamma-rays (Sect. 2), as well as others that may be detectable in the nearby future (Sect. 3). The importance of gamma-ray absorption in gamma-ray binaries is also discussed (Sect. 4), and a short inventory is made, together with some remarks, of all the different physical ingredients that are probably to be considered in these sources (Sect. 5). For a very recent observational overview of gamma-ray binaries, we address the reader to Paredes (2010).

2. Physical scenario of established gamma-ray sources

2.1. High-mass microquasars

Microquasars are X-ray binaries with radio jets (see, e.g., Mirabel & Rodríguez 1999; Ribó 2005), and when hosting a massive star, they are called HMMQ. The power supply in these objects can be either accretion or an accreting rotating black-hole, and emission would be directly powered by a jet launched in the inner regions of the accretion disk. The jet can produce non-thermal populations of relativistic particles via diffusive shock acceleration or other mechanisms at different spatial scales (for a recent review, see Bosch-Ramon 2010a; see also, e.g., Levinson & Blandford 1996; Romero et al. 2003; Paredes et al. 2006; Rieger et al. 2007). In the context of HMMQ, the most efficient gamma-ray mechanism would be inverse Compton (IC) scattering of the stellar photons (e.g. Paredes et al. 2000; Dermer et al. 2006; Bosch-Ramon et al. 2006a). A sketch of the microquasar scenario is shown in Fig. 1.

Beside the jet itself, stellar wind-jet dynamical interactions at the binary spatial scales could also lead to non-thermal emission in HMMQs (Perucho et al. 2008), and that the likely clumpy nature of the wind (Owocki & Cohen 2006) could lead to HE and VHE flares (see, e.g., Araudo et al. 2009).

An example of the importance of the wind-jet interaction is shown in Fig. 2, in which it is shown a 2-dimensional map of the density of a jet of power 10^{35} erg s^{-1} that is launched and interacts with the stellar wind, which is coming from the top. Note that the jet is suffering significant bending and strong disruption not far beyond an asymmetric recollimation shock. Jets significantly more powerful, of up to 10^{37} erg s^{-1}, may be still affected by jet

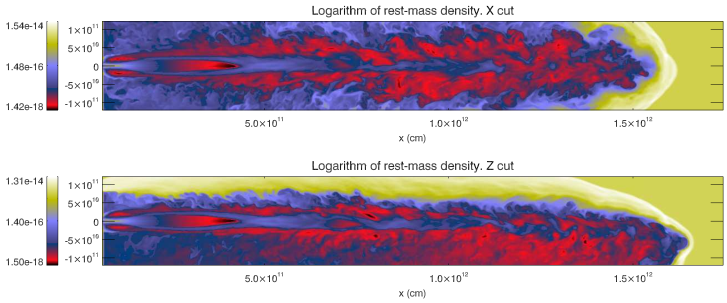

Fig. 2. Two-dimensional map of the density of a jet interacting with the stellar wind, which is coming from the top.

disruption due to the growth of non-linear instabilities triggered in the recollimation shock (see Perucho et al. 2010).

2.2. High-mass binaries with a non-accreting pulsar

In young pulsar binary systems, the non-thermal emission is expected to be generated in the region of collision between the massive star (non-relativistic) and the pulsar (relativistic) winds (e.g. Maraschi & Treves 1981; Tavani & Arons 1997; Kirk et al. 1999; Dubus 2006a; Khangulyan et al. 2007; Neronov & Chernyakova 2007), although the shocked pulsar wind, advected away and accelerated by strong pressure gradients (Bogovalov et al. 2008), could also be a source of Doppler boosted emission (Khangulyan et al. 2008a). The unshocked pulsar wind may be also a source of gamma-rays (e.g. Khangulyan et al. 2007), which may suffer reprocessing in the stellar field due to pair creation (see, e.g., Sierpowska-Bartosik & Torres 2007). This reaccelerated flow may release kinetic energy far from the shock region, increasing the complexity of the phenomenology of the standard scenario, since this could affect the non-thermal emission in the whole spectrum. A picture representing the scenario discussed in this section is shown in Fig. 3.

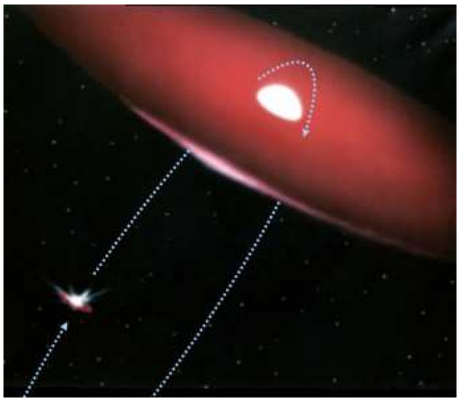

Fig. 3. Illustration of a binary system consisting of a pulsar and a Be star. The pulsar orbits a massive Be star with a disk-like outflow of stellar material (from Hubble archive). Around periastron, the pulsar outflow interaction with the stellar wind is the strongest, leading to particle acceleration and non-thermal emission. More regular and circular systems may yield stable emission all along the orbit.

2.3. Massive star binaries

Massive star binaries are systems in which a strong shock takes place between the winds of the stars. These shocks have speeds of up to few 1000 km s^{-1} and are collisionless and strongly supersonic, and particle acceleration and non-thermal emission up to gamma-ray energies, mainly through IC, could be efficient in there (Eichler & Usov 1993; Benaglia & Romero 2003; Bednarek 2005; Reimer et al. 2006; De Becker 2007; Pittard 2010). In Fig. 4

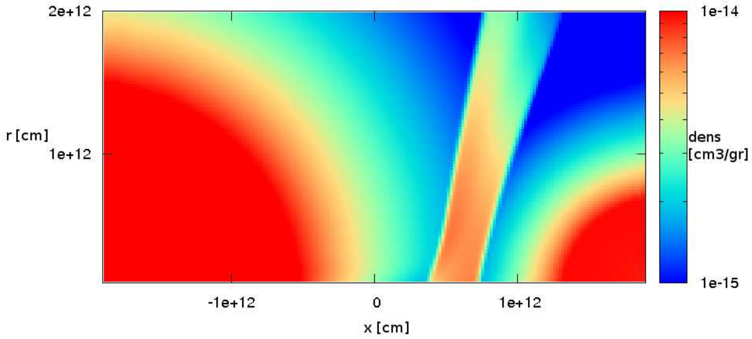

Fig. 4. Two dimensional map of the density distribution in a system of two O stars with colliding winds. The wind of the star to the left is 10 times denser than that of the star to the right.

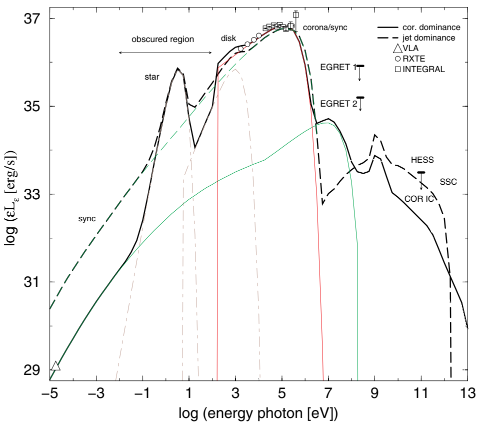

Fig. 5. Computed spectral energy distribution of the non-thermal emission from 1E 1740.7−2942 for two situations. In one case, the hard X-rays come from a corona (long dashed line), whereas in the other, they are of synchrotron origin and come from the jet. Absorption in the accretion disk and corona photon fields has been taken into account (see the two dips below and above ~ GeV energies). For details, see Bosch-Ramon et al. (2006b).

we show the result of a 2-dimensional simulation of the hydrodynamical interaction between the winds of two O stars. The strong shock between the two stellar winds is clearly visible in the density jump.

3. Other potential gamma-ray binaries

Beside HMMQ, non-accreting pulsar high-mass binaries and massive star binary systems, all of them already detected in gamma-rays, other binaries are potential candidates to be also found in this energy range.

Low-mass microquasars have been also proposed to be HE and VHE emitters. In these objects, the most efficient gamma-ray mechanisms could be external IC with accretion photons, synchrotron self-Compton or hadronic interactions in the inner-most regions of the jet base (e.g. Atoyan & Aharonian 1999; Bosch-Ramon et al. 2006a; Romero & Vila 2009). In microquasars in general, the corona (or the base of the jet) could be also a non-thermal emitting region (e.g. Gierlinski et al. 1999; see also Romero et al. 2010), as well as the termination region of the jet in the ISM (Bordas et al. 2009). In Fig. 5, we show the computed spectral energy distribution for a powerful jet of a low-mass microquasar. The dominant IC component is either IC scattering off corona photons or synchrotron self-Compton; note the soft spectrum above GeV energies due to the Klein Nishina effect. Gamma-ray absorption in the accretion disk and corona fields can be significant in this context (for details, see Bosch-Ramon et al. 2006b).

Accreting pulsar X-ray binaries might be also sources of gamma-rays, as it has been suggested by, e.g., Romero et al. (2001) and

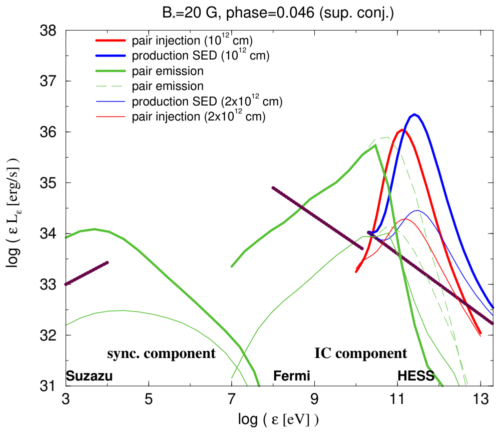

Fig. 6. Computed spectral energy distribution of the radiation produced by secondary pairs in LS 5039 (green lines) at the orbital phase associated to the superior conjunction of the compact object (the binary system properties can be found in Aragona et al. 2009). Two different configurations have been taken, one in which the emitter is at a height of 10^{12} cm (production gamma-ray spectrum: thick solid blue line; corresponding pair injection: thick solid red line), and at 2×10^{12} cm (production gamma-ray spectrum: thin solid blue line; corresponding pair injection: thin solid red line) above the compact object. The production spectral energy distribution (thin long-dashed) of the secondary IC emission is also shown.

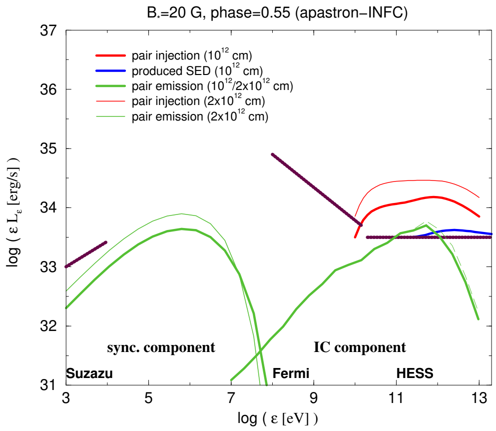

Fig. 7. The same as in Fig. 6 but for the inferior conjunction of the compact object.

Sguera et al. (2009), each of these works pointing to different powering mechanisms: proton beams moving along the pulsar magnetospheric magnetic lines and colliding with the accretion disk, or sudden ejections of matter through the formation of a magnetic tower preceded by high-rate accretion events. This high-rate accretion events would lead to overcome the magnetic pressure of the pulsar magnetosphere allowing for jet formation (see, e.g., Massi & Kaufman Bernadó 2008, and references therein).

4. Impact of gamma-ray absorption

Other non-thermal emitting regions different from those already discussed could exist in any type of compact high-mass binary. If gamma-ray absorption takes place under the photon field of the star (Ford 1984; Protheore & Stanev 1987; Moskalenko & Karakula 1994; Boettcher & Dermer 2005; Dubus 2006b; Khangulyan et al. 2008b; Reynoso et al. 2008), the whole binary system could be an efficient broadband non-thermal emitter. In such a case, the created pairs can radiate through synchrotron and IC emission in the whole spectral band, interacting with the ambient magnetic field and stellar photons, respectively (Bosch-Ramon et al. 2008a).

In case the energy density of the magnetic field is much smaller than that of the stellar photon field, IC becomes the dominant cooling channel of these pairs. Then these pairs can produce more gamma-rays that to their turn may be also absorbed, triggering what is called an electromagnetic cascade. In this way, the effective optical depth to gamma-rays can be significantly reduced. The deflection of the created pairs in the ambient magnetic field determines whether the cascade is linear or three dimensional (e.g. Bednarek 1997; Aharonian et al. 2006b; Orellana et al. 2007; Sierpowska-Bartosik & Torres 2007; Zdziarski et al. 2009; Cerutti et al. 2010).

If the magnetic field is high enough, electromagnetic cascades are suppressed (Khangulyan et al. 2008b) and the X-ray (synchrotron) and GeV (single-scattering IC) emission from secondary pairs can dominate the secondary energy output (Bosch-Ramon

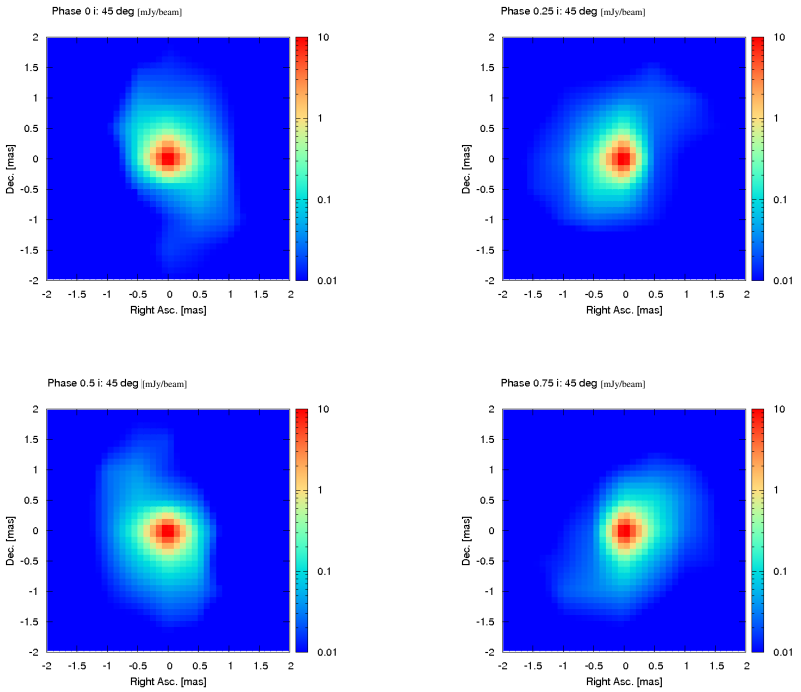

Fig. 8. Computed image of the 5 GHz radio emission, in the direction to the observer, for different orbital phases. Units are given in mJy per beam, being the beam size ∼ 1 milliarcsecond.

et al. 2008a). As two examples of this, we show in Figs. 6 and 7 the spectral energy distribution of the secondary radiation for a gamma-ray binary with system properties similar to those of LS 5039. The magnetic field in the stellar surface has been fixed to 20 G. For stronger enough magnetic fields, the secondary radio emission may be also significant (Bosch-Ramon 2009, 2010b). In Fig. 8, we show 5 GHz radio images for a similar case but adopting a star magnetic field of 200 G. The images for four different orbital phases are presented: 0.0 (superior conjunction of the compact object), 0.25, 0.5 (inferior conjunction), and 0.75.

5. Main elements to understand the gamma-ray emission

The phenomenology at high energies of gamma-ray binaries can be (at least) semi-quantitatively explained accounting for a set of ingredients or physical processes and effects: the angular dependence of gamma-ray absorption and IC scattering and the (moderate) role of absorption (Khangulyan et al. 2008b), in some cases locating the emitter at some height above the orbital plane (for acceleration and modeling arguments, see Khangulyan et al. 2008b; for absorption arguments, see Bosch-Ramon et al. 2008b), likely accounting for adiabatic losses (e.g. Khangulyan et al. 2007; Takahashi et al. 2009; Zabalza et al. 2010). The role of the magnetic field, e.g. through the impact of synchrotron cooling, is crucial for the VHE spectrum and luminosity. In HMMQs, one should not neglect the impact of the stellar wind on the non-thermal processes (Perucho et al. 2010).

All the mentioned physical effects and processes are present to different extents in all the known types of gamma-ray binaries. This makes in some cases the identification of the specific nature of the object a difficult task, as it is shown by the debate on the nature of LS 5039 and LS I +61 303, i.e. HMMQs versus non-accreting pulsar high-mass binaries, if not a really new class of object. Therefore, it is of primary importance to apply comprehensive approaches to study theoretically these objects, including semi-analytical modeling, numerical calculations (secondary emission) and (magneto)hydrodynamical simulations, as well as carry out simultaneous multiwavelength observations with high angular, spectral and time resolution. Nowadays, the field of gamma-ray binaries seems to be the best example for the need of such a complex multidisciplinary approach, if one wants to understand the details of the physical processes taking place in these objects, as well as to distinguish between different scenarios and models.

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