Gamma-ray binaries and microquasars

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Abstract. Identified Galactic gamma-ray sources include so far a small population of binaries that portrays a valuable set of features, making of them excellent targets for the study of ouflows in general as well as other physical ingredients that determine their broadband non-thermal spectral energy distributions, e.g. the particle acceleration, the gamma-ray attenuation, the complex hydrodynamical behaviour of accretion/ejection or colliding flows, etc. I briefly review here our knowledge about them, with particular focus on their high-energy emission.

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INTRODUCTION

Before proceeding with a discussion of the observed properties and theoretical models for gamma-ray binaries, it is necesary to provide an operational definition for this group. The definition of a class historically depends on choosing one or more "prototypes" and then discovering other sources that resemble the prototypes. In the case of gamma-ray loud binaries, we are yet discovering the population itself, so the studies are being comprehensively performed case-by-case. The preliminary efforts led to tentatives association of binaries in the large error boxes of the EGRET GeV gamma-ray sources (Hartman et al 1999). Weak or no variability, no periodicity, and/or limited positional accuracy attenuated that results.

It was only later that several identifications became definitive with the advent of the new generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) such as the Major Atmospheric Gamma Imaging Cherenkov (MAGIC), the High Energy Stereoscopic System (HESS) and the Very Energetic Radiation Imaging Telescope Array System (VERITAS). These instruments have revolutionized the field of gamma-ray astronomy (see e.g. Rico 2011, and Aharonian et al 2008 for details). They detected good positions and clear, orbitally modulated variability crucial to state that gamma-ray binaries are: massive stars with compact object companions that eventually emit most of their energy above 100 MeV, i.e. “rare” examples of high-mass X-ray binaries with MeV-TeV emission. Temporarily, this is a convenient choice so we include transients, but no massive binaries. In this way we exclude η-Carina, from whom there are hints of steady gamma-ray emission (see Tavani et al. 2009a; Abdo et al. 2010; Ohm et al. 2010), which could be generated in colliding wind regions, as explored by e.g Eichler & Usov (1993), Bengalia & Romero (2003), Bednarek & Pabich (2011), etc. Until now, no low mass X-ray binaries (LMXB) have been detected at gamma-rays, but they are also proposed as gamma-ray emitters e.g. Bosch-Ramon et al (2006); Romero & Vila (2008); Vila et al. (2011).

The Fermi-LAT/AGILE observational domain of high-energies (HE: $\sim 0.1 - 100$ GeV) includes at present four binary systems. As listed in the 2FGL catalog (Abdo et al. 2011), these are: Cygnus X-3, PSR B 1259-63, LS 5039 and LS I +61 303. The latter three are also firmly established TeV γ-ray binaries (Aharonian et al 2005a, 2005b; Albert et al. 2006; Acciari et al.2008). Cygnus X-1, the archetypal black hole binary system in our Galaxy, showed evidence of TeV emission (Albert et al 2007) once in a flaring state at very high energies (VHE: $\sim 0.1 - 100$ TeV), and once at HE during AGILE monitoring (Sabatini et al. 2010). Four gamma-ray flares were detected by AGILE from Cyg X-3 (Tavani et al. 2009b), but it was not detected at VHE. In adittion to these sources, a new one that recently arose with the aid of archive data analysis is the binary HESS J0632+057(see Aharonian et al. 2007 for the discovery, and Moldón, Ribó & Paredes, 2011 for further references). Finally, by the end of 2011 our list also includes a strong candidate, 1FGL J1018.6-5856 (Abdo et al.2010b), which shows the presence of a 16.6 periodic modulation between 100 MeV to 200 GeV (Corbet et al. 2011) but scarse data are by now available in X-rays that confirm this period (Li et al 2011).

All the six mentioned binaries are located in the galactic plane, well distributed in longitud (i.e. no centre bias) and within some ~ 3 kpc. The fact that all them contains a massive star may suggest that the primary star plays an important role in the production of gamma rays. Note that the massive star is in some of these binaries surrounded by a decretion disk, i.e. a dense equatorial mass ejection, with slow motion in comparison to the spherical component of the stellar (radiation driven) spherical wind. The properties of the known gamma-ray binaries and individual descriptions of them have been provided in more detail by Paredes (2008, 2011), to where we refer the reader. For an overview of the physical scenario, see e.g. Bosch-Ramon & Khangulyan (2009).

Two of the γ-ray binaries (Cyg X-1 and Cyg X-3) are confirmed high-mass microquasars (HMMQ), i.e. X-ray binaries that produce relativistic jets, while PSR B 1259-63is a confirmed high-mass binary hosting a non-accreting pulsar. Other MQs, like GRS 1915+105, SS433 and Sco X-1, that have been extensively searched for HE or VHE emission has eluded detection (Acero et al. 2009; Saito et al. 2009; Aleksić et al. 2011, Zanin et al. 2011), but are excellent targets for the upcomming Cherenkov Telescope Array (CTA[1]), the next generation of ground-based VHE gamma-ray instruments.

Between the gamma-ray binaries PSR B 1259-63has several distintic features. In particular it is the unique confirmed example of high-mass binaries harboring a young nonaccreting pulsar, in which the stellar and the pulsar winds collide. Only a rapidly rotating young pulsar would drive (through spin-down power) a wind that can stop

[1] www.cta-observatory.org

the accretion onto the pulsar. It is proposed that the massive star wind confines the relativistic pulsar wind in a collimated outflow, a comet-like structure accompanying the pulsar along its orbit. Particles accelerated at the termination shock then produce the non-thermal emission (Maraschi & Treves, 1981, Dubus 2006a). The nature of the compact object and the origin of the high-energy emission are unclear for some other binaries, in the one hand because of the uncertainties in their binary mass function where the usually unknown is the inclination, and on the other hand, because of the dificulties to detect pulsations in radio wavelengths. According to McSwain et al (2011) estimations, as long as the putative pulsar would not be eclipsed by the circumstellar disk or viewed through the densest wind regions, detecting pulsed emission migth be possible during part of the orbit of LS I +61 303. In adittion for LS I +61 303 and LS 5039, when an accreting microquasar model is assumed, there is no enough observed evidence of an accretion disk in either system. A comparison between the pulsar shocked wind and the accretion/ejection scenario have been debated for LS I +61 303 in Romero et al. (2007) with strong comments on the energetic budget.

MICROQUASARS

In HMMQs the compact object accretes matter from the stellar wind. Usually an accretion disk is formed around the compact object, though, it seems not to be a final requirement in order to hold the MQ case, (see Barkov & Khangulyan 2011 for numerical simulations). When an accretion disk is present there are two major characterictic states for its emission/configuration, which are reflected into the outcomming X-ray emission. Figure 1 illustrates the variety of X-ray spectra in Cyg X-3. The high-soft state is dominated by the thermal emission from a geometrically thin, optically thick standard disk (Shakura & Sunyaev 1973), and the low-hard state shows a power-law spectrum that is attributed the presence of a very hot plasma (corona) close to the central object where photons produced in the inner accretion disk are Comptonized (e.g. Narayan & Yi, 1995).

The presence of jets in MQs, i.e. whether they are in quiescent or in outburst, is intimately correlated to the X-ray state (e.g. Remillard & McClintock 2006) and it had been suggested in a unifying hypothesis that they follow a cycle in the X-ray spectral hardness vs. luminosity space (Fender, Belloni & Gallo, 2004). See a sketch in Figure 2. Besides of the complex details ruling such a cycle, it is important to stress that the jets have been detected only in binaries that are in the low-hard state (see e.g. Belloni 2010 and references therein).

The compact object in a MQ redirects part of the accretion power to launch collimated (mildly) relativistic outflows, sometimes in discrete ejections, and with observed boosting effects and superluminal motions. The jets of microquasars have bulk Lorentz factors of $\sim 1-10$. The basic assumption of the jet-disk symbiosis model (Falcke & Biermann 1995) that is customarily applied, assume that the accretion rate is coupled to the kinetic jet power through a factor that can be as large as to ~ 0.1 in order to sustain

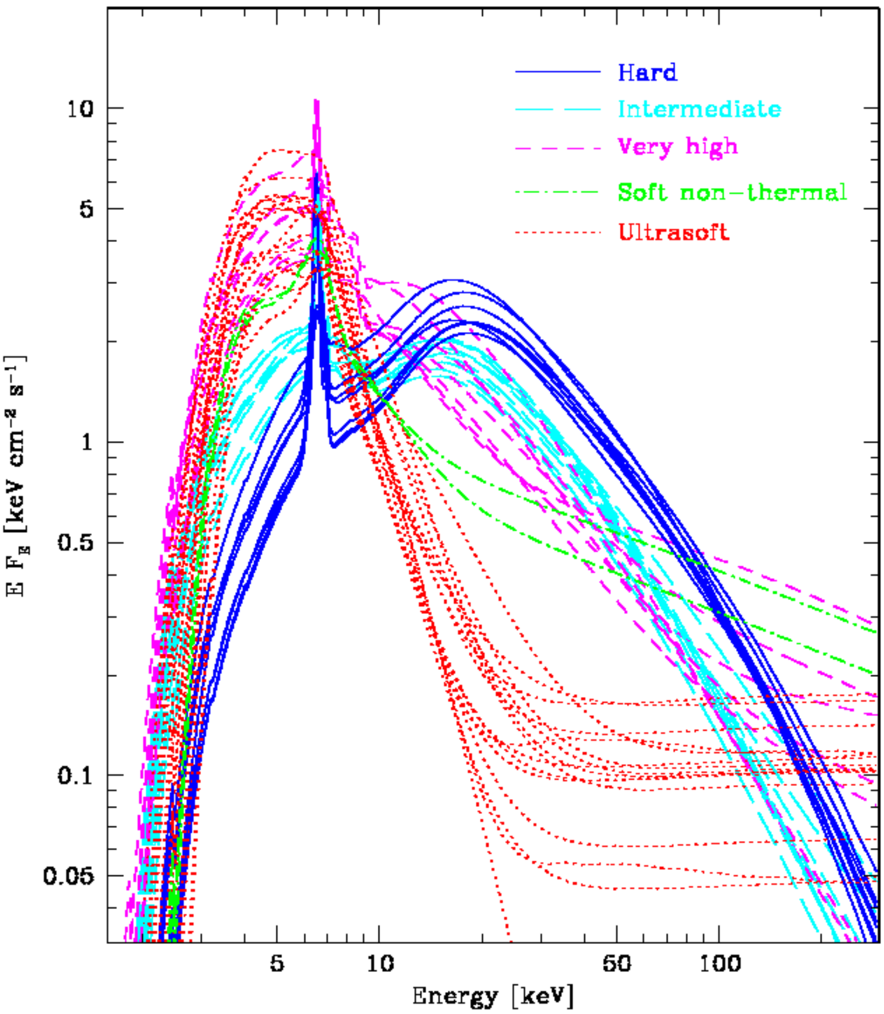

FIGURE 1. Cygnus X-3 exhibits complex temporal and spectral patterns in X-rays. These are the unabsorbed spectral shapes in all states from Hjalmarsdotter et al. (2009).

the observed emission of the large-scale (about 5 pc in diameter) ring-like structure that appears to be inflated by the inner radio jet of Cyg X-1 (Gallo et al.2005). The matter content of the jets is unknown: a relativistic electron population is responsible for the synchrotron radio emission along the jets (Mirabel & Rodriguez 1999). In the case of SS 433 the iron X-ray line observations have proved the presence of ions in the jets (Kotani et al. 1994). The best available models for the SEDs of gamma-ray emitting MQs assume a lepto-hadronic combination in the jet. The definitive confirmation of the importance of hadronic radiation processes should come from the observations of the neutrino signals from the *gamma*-ray binaries (e.g. as calculated by Levison & Waxman 2001, Reynoso & Romero, 2009). See Komissarov (2011) and references therein for

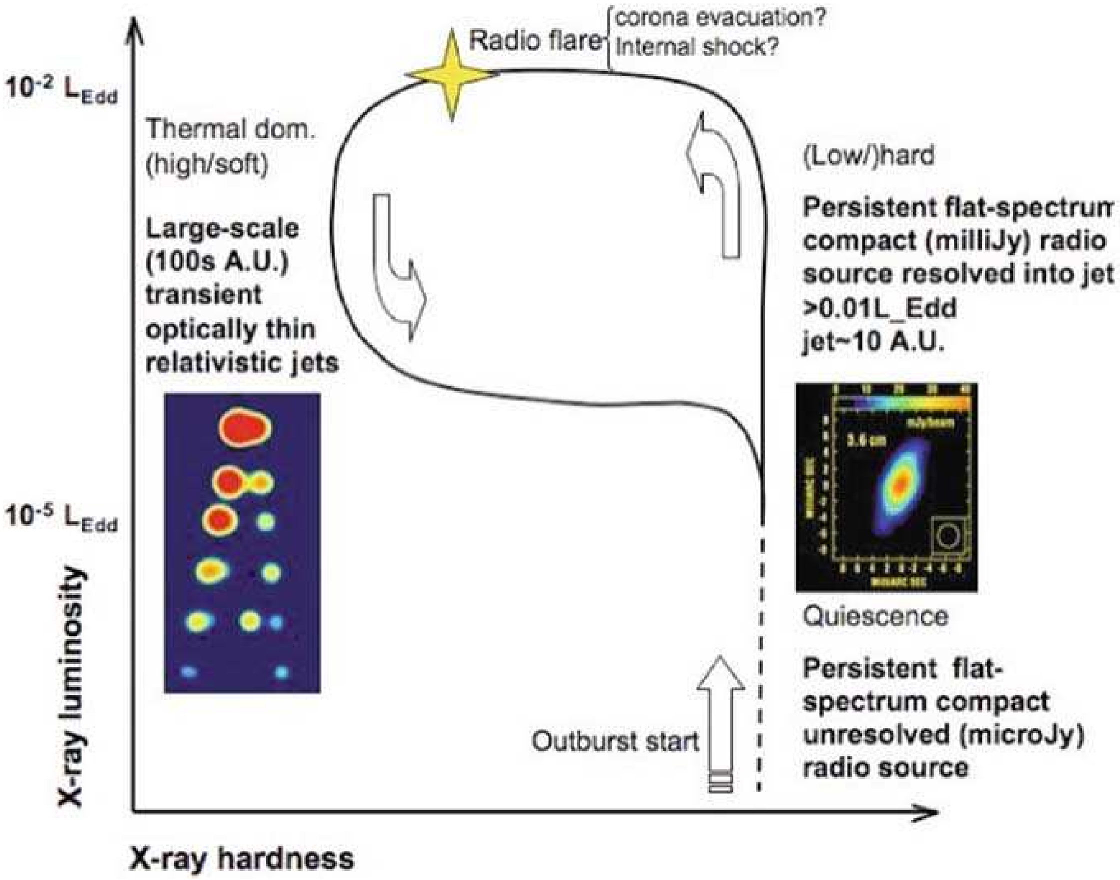

FIGURE 2. Observational properties of the evolution of accretion/ejection components in galactic black-hole binaries. Adopted from Gallo (2009), and see also `http://www.issibern.ch/teams/proaccretion/Documents.html`

details on the collimation and launch of the jets.

Relativistic populations of particles may arise as the result of particle diffusive acceleration at shocks inside the jet itself, recollimating shocks or medium shocks, i.e, with different sizescales. Other particle acceleration processes, related to magnetic reconnection for instance, can be effective as well (Bosch-Ramon & Rieger, 2011). If a fraction of the particles in the corona are relativistic, the corona might also radiate gamma-rays; see Romero et al. (2010a). Considerable observational evidence supports the idea that the wind structure is clumpy, and the interaction of the jets and the wind inhomogeneities might help explain the flaring activity in gamma-ray as considered by Araudo et al (2009), Figure 4. These many proposals are consistent with our actual knowledge, and the final dominant acceleration site and mechanism need not be one and the same in all sources. Further theoretical developments are needed to clarify this issue.

Typically the injection of the accelerated particles follows a power-law distribution in

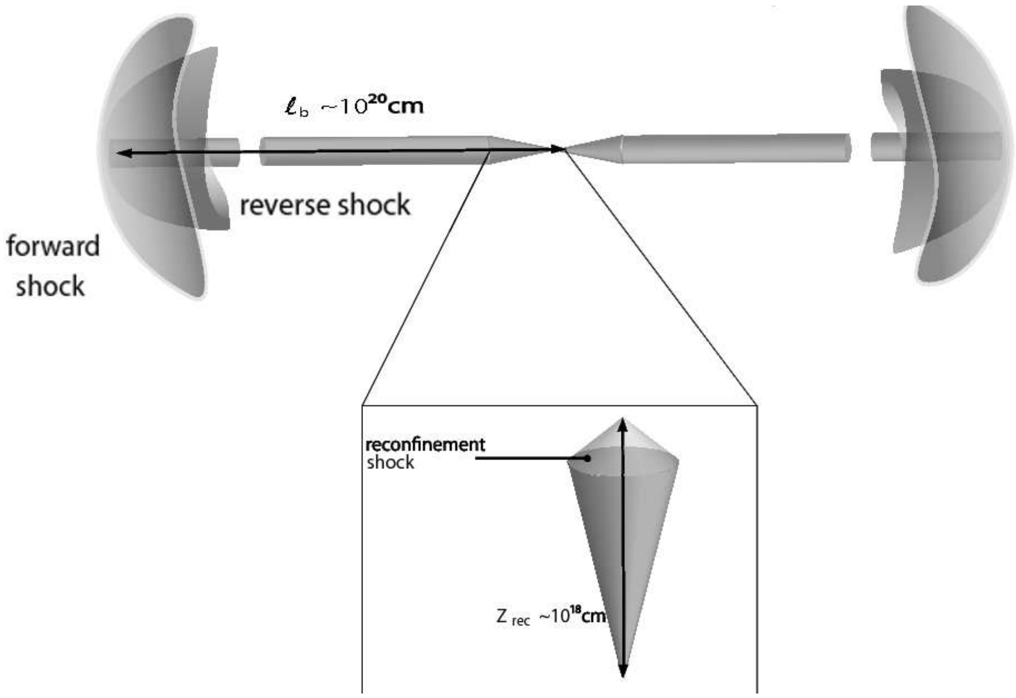

FIGURE 3. Particle acceleration regions: Some proposals include the jet/medium interactions: i.e. particle acceleration at the termination or recollimation shocks leads to the HE and VHE emission. Adopted from Bordas et al. (2010).

energies, extending up to values many order of magnitude above the rest mass energy. The high-energy cutoff depends on the competing processes which in turn depend on the ambient conditions, therefore diffusion and/or advection should be considered along with the radiative processes. The SED can be computed once the (time-dependent) distribution of particles ($N(E)$) is known, and such distribution is to be inferred from the injected one by solving the transport equation under appropriate assumptions (see e.g. Aharonian 2004, Bosch-Ramon et al. 2006 and references). Several processes contribute to the final SED, since particles can interact with the magnetic, radiation and matter fields of the jet. The different contributions are indicated in Figure 5 where exampling SEDs are shown. The details on the calculation are properly discussed in Bosch-Ramon, Romero & Paredes (2006).

When the system contains a Be star, the presence of a dense equatorial outflow in addition to the tenuous stellar wind can strongly influence either the matter accretion rate if the binary is a HMMQ or the location of the contact discontinuity in the pulsar wind collision scenario. It is thus important to adequately take into account the circumstellar environment of the Be star, in order to construct a satisfactory model for TeV binaries (see Okazaki et al 2011, for a recent study of PSR B 1259-63, and Lamberts et al 2011, for the effects of instabilities in the colliding winds). In Figure 6 we show an example of the results from numerical Smoothed Particle Hydrodynamics (SPH) simulations that illustrates how mass transfer proceeds through the overflow from Be disk, and further, the peak in the accretion is set by the inward propagation of a density wave (Figure 7), determining the lightcurve at HE and VHE (Romero et al. 2007, Okazaki et al 2008). The jet propagation and integrity can be also dynamically affected by the stellar wind. Perucho et al. (2008, 2010) have determined limiting conditions under which the jet can be disrupted by the growth of instabilities or suffer significant bending at the binary spatial scales.

An important ingredient provided by the massive star beside the matter supply is its dense soft radiation field. Relativistic electrons upscatter the stellar photons to VHE through Inverse Compton (IC) interactions. The IC contribution may dominate the gamma-ray emission, but the stellar radiation field can also absorb gamma-rays by pair creation within the binary system. The importance of gamma-ray absorption in gamma-ray binaries have been studied by several authors (e.g. Protheroe 1986; Bednarek 1997, 2011). The optical depth is strongly dependent on the location of the γ-ray emission region if it is close to the compact object, and on the orientation of the system as seen by the observer. The attenuation has been found to be relevant for photon energies $\sim$10 GeV to 10 TeV, well within the observational range. Its study may help to set constraints on the location of the emission region (e.g. Dubus 2006b), as done for Cygnus X-1, which was detected in a configuration with the black hole behind the companion star, when the absorption of gamma-ray photons is expected to be highest (Zdiarski et al. 2009; Romero et al 2010b).

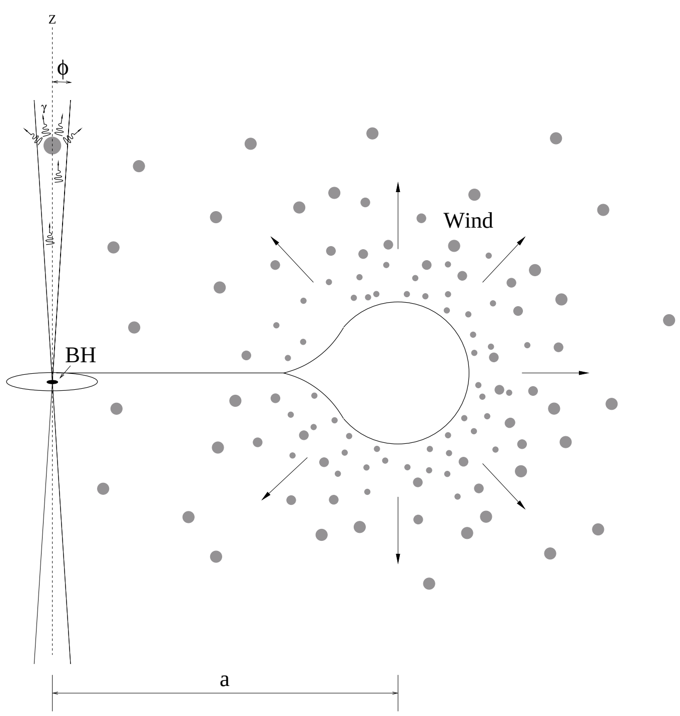

FIGURE 4. Sketch for the interaction between the jets and clumps from the stellar wind, from Araudo et al (2009).

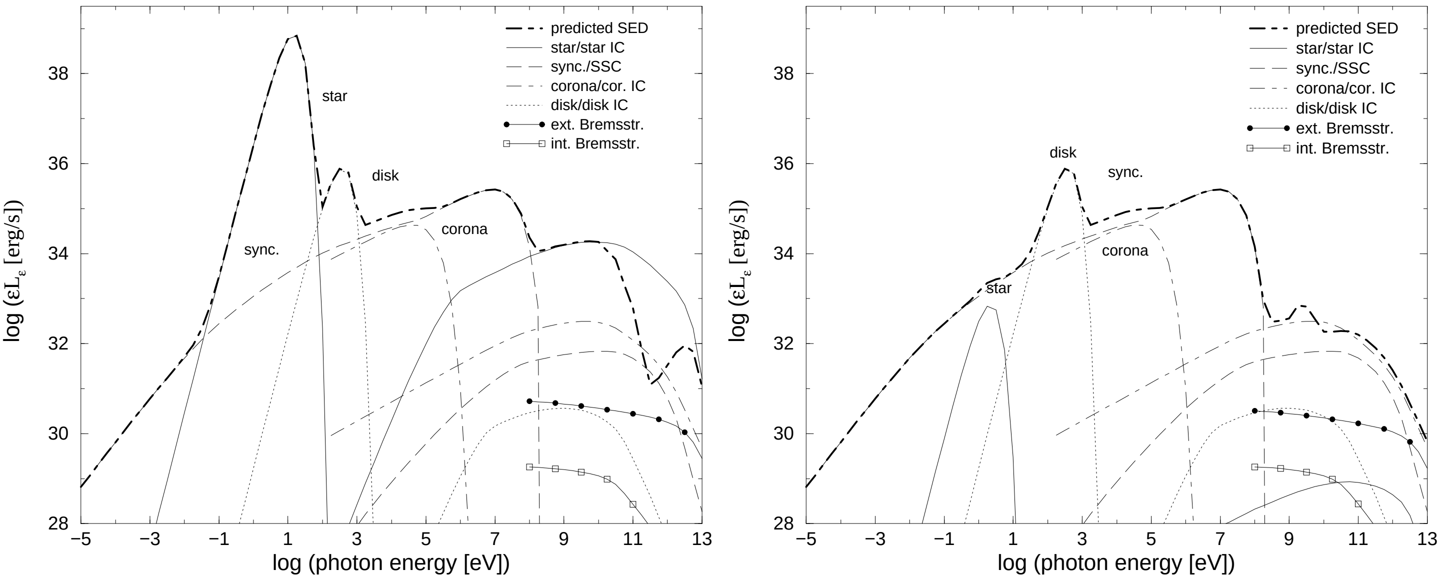

FIGURE 5. Spectral energy distribution computed for a HMMQ (from Bosch-Ramon et al. 2006). The predicted total SED, summing up all the contributions is affected by absorption in the photon field of the star. At the right: for a low mass MQ. See also Vila & Romero (2010) for predicted HE features in the SED of the LMMQ GX 339-4.

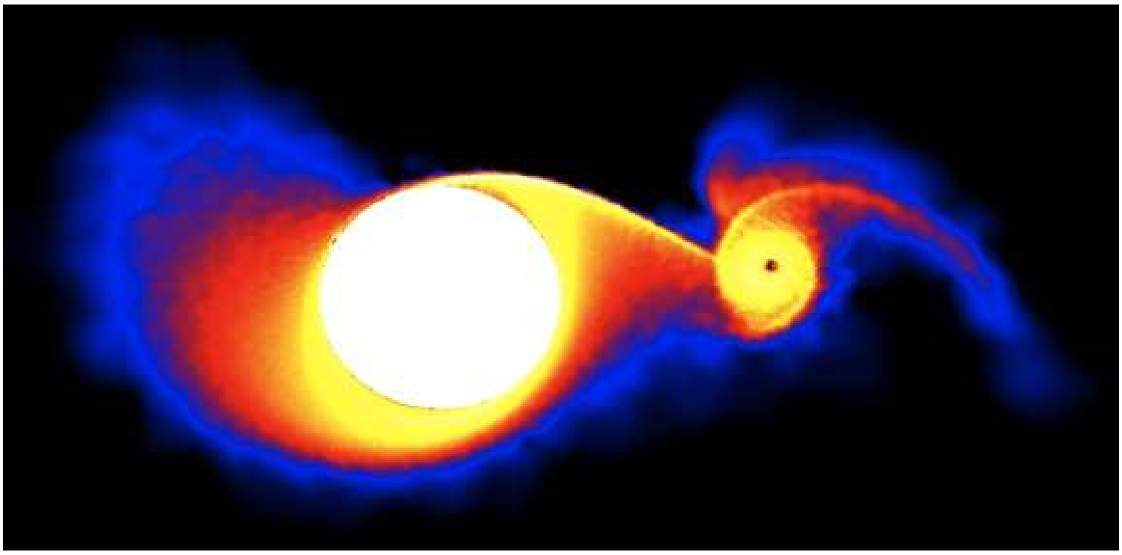

FIGURE 6. Snapshots from a Be disc simulation and the corresponding accretion disc over a compact object. The parameters of the simulation were set as to reproduce the puzzling gamma-ray binary LS I +61 30 The color scale corresponds to surface density in cgs units on a logarithmic scale. See Romero et al (2007).

The pairs created in the photon-photon annihilation (secondary leptons) may produce more gamma-rays that may be also absorbed, triggering an electromagnetic cascade. In this way, the effective optical depth to gamma-rays can be significantly reduced. If the

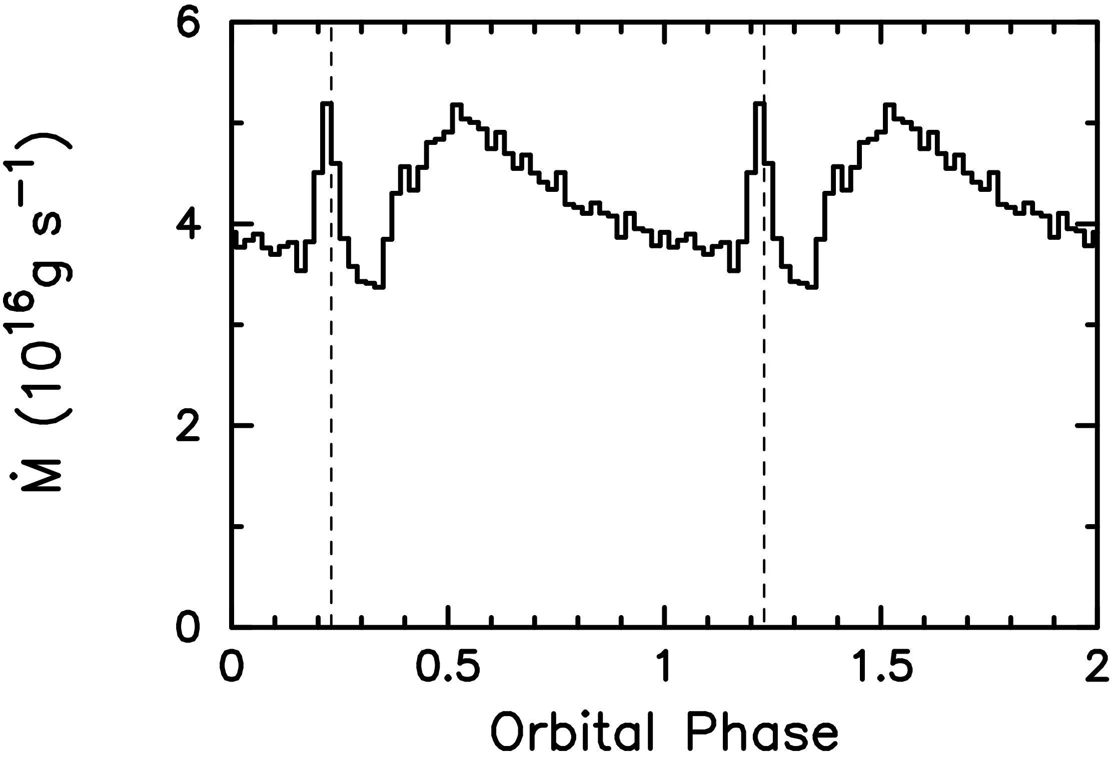

FIGURE 7. Phase dependence of the accretion rate onto the compact object as derived from the same simulations of Fig 6. The vertical dashed lines denote periastron passage at phase 0.23 with the orbital solution by Casares et al. (2005).

magnetic field is low enough, electromagnetic cascades develop through a combination of pair creation and IC scattering and considerably changing the outcomming spectrum (e.g. Orellana et al 2007 for a HMMQ). Under a stronger ambient magnetic field in the region of gamma-ray absorption the energy of the pairs is channeled by the synchrotron radiation, and the cascade is suppressed (Khangulyan et al. 2008). As the pairs diffuse over the whole system, an extended broadband non-thermal emitter can arise (Bosch-Ramon, Khangulyan, & Aharonian 2008). Finally, a tunned magnetic field of intermediate strength can lead to a spatially extended cascade (e.g. Cerutti et al. 2010) which needs of a careful treatment, i.e through 3D numerical simulations (e.g. Pellizza et al. 2010).

REMARKS

Gamma-ray binaries constitute an extraordinary valuable (still small) population of HE and VHE sources. Uptodate each of the 5 confirmed (plus one candidate) systems is unique and the population, as well as the data quality, are increasing in such a way that the field have become extremely active. Gamma-ray binaries may provide the keys to an understanding of astrophysical jets, and many related issues, some of which share a

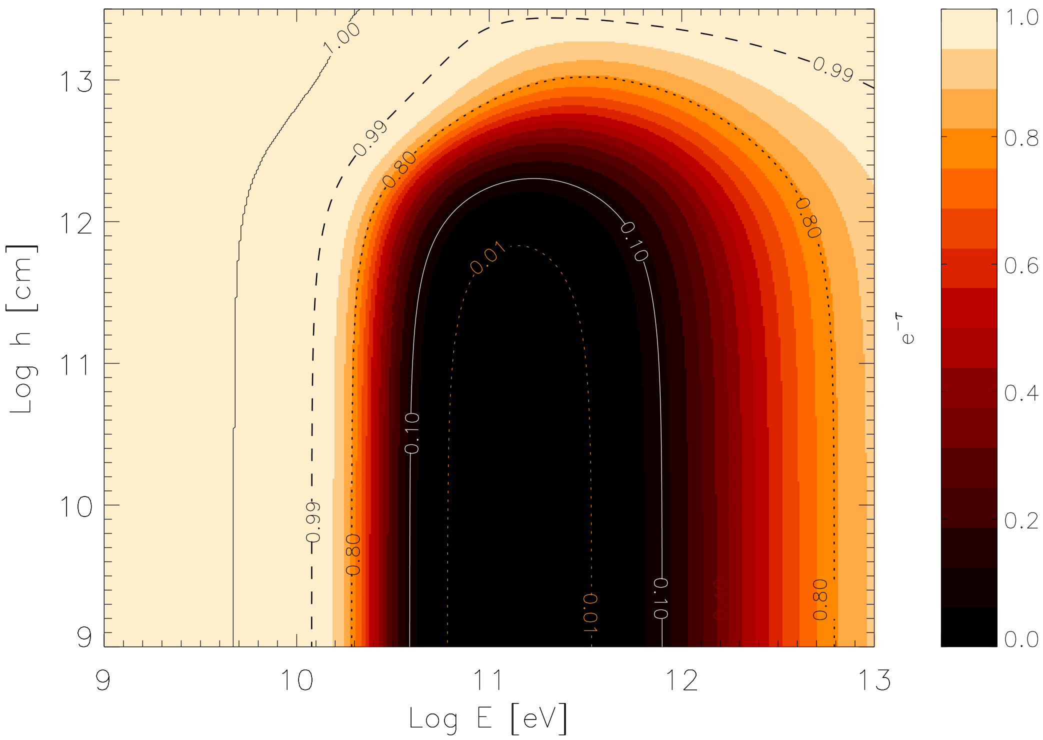

FIGURE 8. Attenuation map ($\exp(-\tau_{\gamma\gamma})$) for Cygnus X-1 at the orbital phase of the TeV flare. It can be seen that the absorption drops strongly with the height above the compact object from where the photon propagates (Romero et al. 2010b).

common problematic with accreting objects at different scales.

They are natural particle accelerators operating under varying, but regularly repeating, environmental conditions, so they provide a constraining laboratory for models of particle acceleration, and gamma-ray production, emission and absorption processes, etc. By now the relatively large number of parameters involved in the models due to the many physical processes and effects, make uneasy to estimate the properties of a source in unique way. This also anticipate that a variety of gamma-ray emission features from massive binaries would be found.

The new instrumentation in gamma-rays, and the planned next generation (in particular CTA) that will improve the actual angular resolution and better suppress cosmic-ray background events, will be crucial to carry out refined studies in order to discover more sources, allowing to speak of a real population in statistical terms. Multiwavelength studies have already proven to be essential complementary tools in this area. Refined models/simulations including variability, acceleration prescriptions, absorption and secondary emission may help constrain the acceleration and radiation mechanisms, and disentangle the location and contributions from different emitting regions.

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