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Binary systems at gamma-rays

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Binary systems are today well established gamma-ray emitters, and the variety of the processes responsible for this emission is a hard act to follow among any other high-energy source class. After years of extensive theoretical modelling and complex MHD simulations predicting binary systems to be gamma-ray emitters, the last generation of GeV/TeV detectors have finally confirmed these perspectives, and have unveiled a rich phenomenology associated to these sources in the gamma-ray domain - including a number of observational facts which were not foreseen just a few years ago. Here we highlight some of the most relevant results on binary systems at gamma-rays obtained in the last years, from the bright and periodic emission in gamma-ray binaries hosting a non-accreting pulsar to the detection of gamma-rays produced in the jet/medium interaction regions in microquasars, and the discovery of gamma-ray emission following powerful explosions in novae systems.

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1. Introduction

The study of the sky in gamma-rays has been possible only in the last years, driven by highly optimised space-borne satellites at high-energies (HEs, 100 MeV$< E <$100 GeV) and the advent of ground-based Cherenkov telescope arrays that have demonstrated a tremendous discovery potential in the very-high-energy domain (VHEs, $E >$ 100 GeV). Amongst the Galactic population of newly discovered gamma-ray sources, binary systems have emerged as a particularly heterogeneous class, with a rich phenomenology that largely exceeds what was expected on theoretical grounds about 10–15 years ago. About 30 gamma-ray emitting binaries (GREBs from now on) have been identified as of mid-2022. GREBs that display the peak of their spectral energy distribution (SED) at $\gtrsim$ 1 MeV are dubbed *gamma-ray binaries*. Binaries powered by accretion onto a compact object, either a black hole or a neutron star, displaying relativistic jets are classified as *microquasars*. A massive fusion of hydrogen into helium at the surface of a white dwarf that is accreting gas from its companion star cause *novae explosions*, leading to particle acceleration and subsequent gamma-ray emission. Strong shocks developed at the interaction of powerful stellar outflows can give rise to variable gamma-ray fluxes in *colliding wind binaries*. HE gamma-rays have also been reported from recycled non-accreting *millisecond pulsars* in binary systems. In all cases, the variable but repetitive conditions within or around the system (matter and radiation fields) can be used to constrain the physics responsible for their observed properties.

In this proceedings we provide with an up-to-date census of known GREBs (see Table 1), highlighting some of the most remarkable results reported in the last years - since the 6th edition of the Gamma-Ray Symposium held in Heidelberg back in 2016. These include amongst others the discovery of several new gamma-ray binaries, the detection of powerful outburst in some of these systems displaying outstanding emission efficiencies, and the detection of pulsations in some of the most emblematic representatives (see Section 2); the discovery of large-scale emission from jet/medium interactions in microquasars (Section 3); and the detection of novae explosions at HEs and, for the first time, at VHEs in the cae of RS Ophiuchi (Section 4). These have been remarkable achievements in our understanding of binaries at gamma-ray energies, but there are still a number of questions that remain open, which will also be briefly discussed here. This review is not exhaustive, and the reader is referred to more extended works dedicated to these sources for an accurate description of the phenomenology of binary systems at gamma-ray energies, see e.g. [1–4].

γBs	PSR B1259–63 [5], LS 5039 [6], LS I +61 303 [7], HESS J0632+057 [8], 1FGL J1018.6–5856 [9], LMC–P3 [10], PSR J2032+4127 [11], HESS J1832–093 [12] 4FGL J1405.1-6119 [13], HESS J1828-099 [14]
μQs	Cyg X-3 [15], Cyg X-1 [16], SS433 [17] V404 Gyg [18], AGL J2241+4454 [19]
CWBs	Eta Carinae [20], γ^2 Velorum [21], HD 93129A [22]
Novae	V407 Cyg 2010 [23], V1324 Sco 2012 [24], V959 Mon 2012 [25], V339 Del 2013 [26], V1369 Cen 2013 [27], V5668 Sgr 2015 [28], V5855 Sgr [29], V5856 Sgr [30], V549 Vel [31], V357 Mus [32], V906 Car [33], V392 Per [34], V3890 Sgr [35], V1707 Sco [36], YZ Ret [37], V1674 Her [38], RS Oph [39]

Table 1: List of known GREBs grouped by category: gamma-ray binaries (γBs), microquasars (μQs), colliding wind binaries (CWBs) and novae, together with references to the corresponding observational studies conducted that revealed the binary nature of the sources. The list is an update from that previously reported in [4]. Note that the source AGL J2241+4454 has been claimed to be a microquasar, but its nature is still to be confirmed.

2. Gamma-ray binaries

Gamma-ray binaries (γBs) are characterised by displaying their SED peak in the gamma-ray band. These systems are composed of a compact object, either a neutron star or a stellar-mass black hole, and a non-degenerate companion star. Whereas the nature of the compact object is yet unconfirmed in most cases, the detection of pulsations has been reported for PSR B1259–63, PSR J2032+4127 and, very recently, also from LS I +61 303 (40). As for the companion star, γBs are high-mass binary systems: none of the identified cases have been reported to harbour a low-mass companion. These high-mass stars can feature a dense circumstellar disk in some instances. γBs featuring an O-type companion typically display a single-peak profile in their γ-ray light-curve, with the peak location along the orbit depending on the geometrical properties of the system. γBs featuring an O*e* or B*e* star display instead several peaks in their light-curves, the location of which tend to be correlated with the times in which the compact object crosses the companion's circumstellar disk.

As of today, ten systems have been claimed to be γBs based on observations at HEs and/or

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VHEs (see Table 1), with the most recent candidates being 4FGL J1405.1-6119 [13] and HESS J1828-099 [14]. This may constitute just a small fraction of the whole Galactic population of these systems, a situation likely to improve noticeably with the advent of CTA [41].

On the theoretical side, the emission from γBs harbouring a non-accreting pulsar can be produced at the interface of the pulsar wind with that of the companion star, where particle acceleration can be highly efficient. Gamma-rays are then generated through inverse Compton (IC) scattering of relativistic electrons/positrons off seed photons provided by the companion star or photons produced in the circumstellar disk, when present. Additionally, strong gamma-ray flares have been detected close to the periastron passage in the pulsar-powered system PSR B1259–63. The nature of these excepcional outburst is still unknown. Several models have been proposed, amongst which a scenario where "cold" electrons from the un-shocked pulsar wind can up-scatter photons from the companion star, leading to gamma-rays that can be detected only in restricted orbital-phase intervals in which this emission is "uncovered" towards the observer [42, 43]. The alternative to the leptonic scenario for the production of gamma-rays contemplates instead γBs hosting a black hole, in which case HE/VHE emission would then be powered by accretion, and produced from a (yet undetected) jet-like structure in analogy to microquasars (see below). In this regard, a strong debate concerning the nature of the powering engine in one of the first γBs discovered, LS I +61 303 (see for example [44, 45] and [46]) has been recently solved out thanks to the detection of pulsations from the system [40]. The phenomenological similitudes of this source with other γBs like HESS J0632+057 or HESS J1832–093 strongly favours also a pulsar-powered scenario in these systems

Apart from the powering engine, several questions remain open on the phenomenology observed in γBs. On spectral grounds, two separate components have been observed in the spectra of a number of γBs at energies above a few tens of GeV [47]. A clear interpretation for such double-component is still pending, despite several scenarios having being proposed (see e.g. [48] and references therein). In addition, the light-curves in several γBs display distinct features that are still unexplained, including the asymmetric flux profiles in the light-curve of PSR B1259–63 close to periastron, the detection of non-negligible fluxes at orbital phases where the absorption of gamma-rays should be severe in LS 5039 , the origin of the sharp dips in the light-curve of HESS J0632+057 right after its periodic maximum at orbital phases $\sim 0.3 - 0.4$, or the erratic localisation of the main VHE peak in LS I +61 303, displaying remarkable cycle-to-cycle variability. A unified picture applicable to the whole γB class should account for these observational features and defers further investigation.

3. Microquasars

Microquasars (μQs) are defined as X-ray binary systems displaying relativistic jets, with their naming being adopted from their similitudes with Active Galactic Nuclei (AGN) [49]. The detection of gamma-ray emission from AGNs prompted μQs to be obvious HE and VHE emitter candidates. Contrary to AGNs, however, μQs tend to display different X-ray spectral states resulting from distinct regimes of accretion onto the compact object. The emission of hard X-rays could be produced by persistent jets in the so-called $low/hard$ spectral state [50]. This component may eventually reach higher, γ-ray energies. In fact, the non-thermal (synchrotron) emission resolved in the radio/IR band in the jet-like structures of several systems imply the presence of highly energetic electrons outflowing in these jets. In accounting for the environmental photon field, e.g. from the companion star, these high-energy electrons may also emit γ-rays through IC processes (51, 52).

On theoretical grounds, the production of γ-ray emission from the inner regions of μQs jets could be produced either through IC emission at the jet base where the photon field of the companion star is the strongest, or through hadronic interactions and subsequent π^0-decay to gamma-rays, considering relativistic protons being present in the jets (see [53–56]). In this hadronic case, μQs could also be be contributors to the Galactic cosmic-ray sea [57]. Indeed, the jets of two μQs have been reported to contain baryons following the detection of lines of highly ionised elements (in SS433 [58], and in 4U 1630–47 [59]). On the larger scales, γ-rays could also be produced at the jet/medium interaction regions [60, 61].

The capability of microquasars to produce gamma-rays in the inner regions of the system has been demonstrated with the detection of the microquasars Cyg X-3 and Cyg X-1 (see [15] and [62] for the former; see [63, 64] and [65] for the latter). In addition, the analysis of six years of $Fermi$-LAT observations resulted in the first detection of a γ-ray signal towards the μQ SS433 [17]. Several follow-up studies at HEs confirmed and expanded upon these results [66–68]. Intriguingly, variable emission was found from Fermi J1913+0515, a source located tens of parsecs away from the central engine, with a periodicity consistent with the precession of the system [68]. Meanwhile, the HAWC collaboration reported on the detection of the large-scale jets of SS433/W50 [69]. This detection has been confirmed recently by H.E.S.S., as reported for the first time in this Symposium (see L. Olivera-Nieto et al. in these proceedings). In parallel, HAWC announced that another microquasar, V4641 Sgr, seems to produce extended TeV emission. This could also be the result of large-scale jet/medium interactions, but further observations with higher resolution instruments like H.E.S.S. may be needed to probe this hypothesis.

4. Novae explosions

Binary systems that are composed of a white dwarf which accretes from a low-mass companion that has filled its Roche Lobe give rise to classical novae. They display bright flares in the optical band produced by thermonuclear explosions on the surface of the white dwarf. γ-ray emission from novae was (rather unexpectedly) detected from several CNe (see [70] and references therein). The first of such detections occurred in the symbiotic system V407 Cyg, hosting a Mira giant secondary star with a dense stellar wind. γ-rays from CNe could be produced through IC emission by electrons accelerated at the shock between the no va ejecta and the companion's wind (see e.g. [71]). On the contrary, the detection of further CNe at HEs (see Table 1), but this time from systems hosting main-sequence companion stars with a much lower density circumstellar material, seems to require different scenarios for the observed gamma-ray fluxes.

In the VHE domain, the MAGIC and H.E.S.S. collaborations have recently reported on the first detection of a nova at this energy range in the case of RS Ophiuchi [72, 73]. This detection has been further confirmed by the first prototype of the CTA-N array, the LST-1 (see A. Aguasca-Cabot et al. in these proceedings). An hadronic scenario is favoured over a leptonic model, with proton maximum energies increasing with time during the first days of the outburst. These uncooled accelerated protons could contribute and localy dominate the CR density. Furthermore, if a similar acceleration efficiency would be operating in phenomenologically similar SNe, these could sustain the galactic CR flux at PeV energies [73].

5. Concluding remarks

The study of GREBs offers the opportunity to constrain particle acceleration and high-energy emission/absorption processes in extreme environments. However, different mechanisms seem to be operating among sub-classes of binaries. From bright, periodic gamma-ray emission in gamma-ray binaries to extended emission from jet/medium interactions in microquasars or thermonuclear explosions in novae. Further studies of these systems are needed to solve a number of open questions, which should make use of the improved capabilities of new facilities being developed in the gamma-ray band, up to the ultra-high energy regime, together with information provided by the monitoring of GREBs at lower energy bands.

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