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Binaries with the eyes of CTA

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ABSTRACT

The binary systems that have been detected in gamma rays have proven very useful to study high-energy processes, in particular particle acceleration, emission and radiation reprocessing, and the dynamics of the underlying magnetized flows. Binary systems, either detected or potential gamma-ray emitters, can be grouped in different subclasses depending on the nature of the binary components or the origin of the particle acceleration: the interaction of the winds of either a pulsar and a massive star or two massive stars; accretion onto a compact object and jet formation; and interaction of a relativistic outflow with the external medium. We evaluate the potentialities of an instrument like the Cherenkov telescope array (CTA) to study the non-thermal physics of gamma-ray binaries, which requires the observation of high-energy phenomena at different time and spatial scales. We analyze the capability of CTA, under different configurations, to probe the spectral, temporal and spatial behavior of gamma-ray binaries in the context of the known or expected physics of these sources. CTA will be able to probe with high spectral, temporal and spatial resolution the physical processes behind the gamma-ray emission in binaries, significantly increasing as well the number of known sources. This will allow the derivation of information on the particle acceleration and emission sites qualitatively better than what is currently available.

1. Introduction

The many spectacular discoveries made in recent years by both satellite-borne (*AGILE, Fermi*) and ground-based gamma-ray telescopes (H.E.S.S., MAGIC and VERITAS) have revealed a variety of new sources of high-energy particles in the Galaxy. Among these sources we can mention star-forming regions, accreting black holes and microquasars, early-type stars with very strong stellar winds, young isolated pulsars and their nebulae and pulsars in binary systems. The physics of particle acceleration and interaction in the complex environment of such astrophysical systems is extremely rich. The detection of very high energy (VHE) gamma rays ($E > 100$ GeV) by the current imaging atmospheric Cherenkov

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telescopes (IACT) from the systems PSR B1259-63 [1,2], LS 5039 [3], LS I +61 303 [4,5] and HESS J0632+057 [6], as well as the hint of a VHE flare in the black hole binary Cygnus X-1 [7], provides a clear evidence of very efficient particle acceleration in binary systems containing compact objects (see e.g. [8]). In addition, one of the brightest *Fermi*/LAT sources, 1FGL J1018.6-5856, has been proposed to be a new gamma-ray binary [9] that could be associated with a H.E.S.S. source [10]. Furthermore, there are other binary systems from which VHE emission is expected from a theoretical point of view [11]. Although they have not yet been detected with the current generation of Cherenkov telescopes, their emission at HE gamma-rays (E >100 MeV) has already been reported in some cases (e.g. Cygnus X-3, V 407 Cyg and Eta Carinae). It is expected that CTA will find new gamma-ray binaries, allowing population studies that will have an impact on evolutionary models of high-mass binary systems. With a few exceptions, most of the gamma-ray binaries detected, either accreting or non-accreting sources, are all within 3 kpc of the Sun, in a volume equal to about $\sim$ 10% of the volume of our Galaxy. Assuming a uniform distribution, although they should follow population I stars with more objects in the spiral arms, this is consistent with >50 or so gamma-ray binaries in our Galaxy. This number is also dependent on the duty cycle of gamma-ray emission: VHE emission in HESS J0632 +057, LS I +61 303, PSR B1259-63 is strongly dependent on orbital phase and in some sources the orbital periods can be (very) long. With a ten times improvement in sensitivity, CTA should be able to probe for gamma-ray binaries of comparable luminosities up to the Galactic center. CTA can thus be reasonably expected to detect a couple of dozen gamma-ray binaries. The VHE counterparts of LS 5039, HESS J0632+057 and (possibly) 1FGL 1018.6-5856 were discovered in the H.E.S.S. Galactic Plane survey. The ten times more sensitive Galactic Plane survey planned for CTA should thus enable many discoveries of such systems, which are otherwise very difficult to uncover by X-ray, optical or radio surveys. A survey of the central portion of the galactic plane is planned for the beginning of CTA operation (see [12]), which will pinpoint new gamma-ray binaries candidates.

The study of known and/or new compact binary systems at VHE is of primary importance because their complexity allows us to probe several physical processes that are still poorly understood. Some of these systems are extremely efficient accelerators that could shed new light, and eventually force a revision of, particle acceleration theory (see e.g. [13]). The particle injection and radiation emission mechanisms in binary systems vary periodically due to an eccentric orbit and/or interaction geometry changes. This may provide information on the location of the high energy particles, on the energy mechanism(s) powering relativistic outflows, on the nature of the accelerated particles, and on the physical conditions of the surrounding environment. The presence of strong photon fields allows the study of photon-photon absorption and electromagnetic cascades. All these processes occur on timescales $\lesssim$ 1000 s, a proper study of which would require at least a 5σ (standard deviations) detection for $\sim$ one hour exposure times.

The interaction of binary systems with the Interstellar medium (ISM) could also be powering a new class of TeV sources, which could be resolved/detected with enough resolution/sensitivity. For a deep study of the processes taking place in compact binary systems we need to go beyond the present IACT's capabilities. Below, we report on examples of numerical simulations performed to show how the forthcoming CTA observatory [14] could fulfill these objectives.

The structure of the paper is as follows: in Section 2 we outline the stellar gamma-ray source classes that are idoneous targets for CTA. In Section 3 we introduce key questions in high-energy astrophysics that CTA can address and the requirements to achieve them. In Section 4 we present the results of some performance tests of the capability of CTA to achieve the aims. Finally we present a summary in Section 5.

2. Binary systems with gamma-ray emission

2.1. Binary systems with young non-accreting pulsars

PSR B1259-63 was the first variable galactic source of VHE gamma-rays discovered [1]. It has also been detected at HE by *AGILE*[15] and *Fermi*/LAT [16,17]. The system contains a O9.5 Ve main sequence donor (LS 2883) and a 47.7 ms radio pulsar orbiting its companion every 3.4 years in a very eccentric orbit (see [18] and references therein). Particles are accelerated in the shock between the relativistic wind of the young non-accreting pulsar and the stellar wind of the massive companion star [19–21]. These particles, by inverse Compton (IC) up-scattering of stellar UV photons should produce VHE gamma rays. The strong wind-wind interactions may also produce extended synchrotron radio emission, as recently reported by [18].

The other binary systems that have been unambiguously detected at TeV energies, showing gamma-ray flux modulations coincident with their orbital periods, are LS 5039 with $P_{\rm orb} \approx 3.9$ d [22] and LS I +61 303 with $P_{\rm orb} \approx 26.5$d [23]. *Fermi* has also detected emission modulated with the orbital period in both systems [24,25]. Although the nature (black hole or neutron star) of the compact object in LS I +61 303 and LS 5039 has not yet been determined [26,27], both systems present some similarities with PSR B1259-63. They show variable milli-arcsecond scale radio structure [28–30], similar to that found in PSR B1259-63. VLBA images of LS I +61 303 obtained during a full orbital cycle show a rotating elongated morphology [30], which may be consistent with a model based on the interaction between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion [20]. A similar behavior has been observed in LS 5039. This system was observed with the VLBA during five consecutive days showing an orbital morphological variability, displaying one sided and bipolar structures, but recovering the same morphology when observing at the same orbital phase [31]. The broadband emission from radio to VHE gamma-rays of the three sources is variable and periodic, peaking at MeV–GeV energies.

For LS I +61 303 and LS 5039, the GeV and TeV emission are well anticorrelated. In particular, in LS 5039, the GeV emission peaking around the compact object superior conjunction/periastron, and the TeV radiation around inferior conjunction/apastron. The GeV and TeV spectra are also roughly anticorrelated, with the GeV emission getting harder for lower fluxes, and the TeV emission for higher ones (e.g., [22,32]). In both sources, the behavior is more or less compatible with radiation produced by IC and moderate gamma-ray absorption, processes through which the changing geometry along the orbit induces a modulation in both flux at TeV and GeV, and spectrum at TeV (and GeV if cascades were important). Additional effects like varying radiative and adiabatic losses could also affect spectra and fluxes [33]. We note that also IC $e^{\pm}$ pair moderate cascading can be important [34–36]. However, the relatively low flux around 10 GeV in both LS 5039 and LS I +61 303, below the extrapolation of data and model predictions, strongly indicates that the emitter, although of likely leptonic+IC nature, should be quite complex (and probably located in the periphery of the binary system for LS 5039).

The most recent addition to the selected group of gamma-ray binaries emitting up to very high energies is HESS J0632+057 [37]. The source was initially detected by the H.E.S.S. experiment [6], but the subsequent non detection by VERITAS excluded it as a steady gamma-ray emitter [38]. The gamma-ray variability was confirmed recently by VERITAS and MAGIC which reported an increase of gamma-ray flux during 2011 February 7–9 (see Refs. [39,40], respectively). The increase in TeV flux coincides with the time of a large X-ray peak, that could imply that the same population of electrons is producing the X-ray and TeV emission [41],