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Gamma-ray binaries

Abstract Recent observations have shown that some compact stellar binaries radiate the highest energy light in the universe. The challenge has been to determine the nature of the compact object and whether the very high energy gamma-rays are ultimately powered by pulsar winds or relativistic jets. Multiwavelength observations have shown that one of the three gamma-ray binaries known so far, PSR B1259−63, is a neutron star binary and that the very energetic gamma-rays from this source and from another gamma-ray binary, LS I +61 303, may be produced by the interaction of pulsar winds with the wind from the companion star. At this time it is an open question whether the third gamma-ray binary, LS 5039, is also powered by a pulsar wind or a microquasar jet, where relativistic particles in collimated jets would boost the energy of the wind from the stellar companion to TeV energies.

Keywords X-ray binaries · Microquasars · X-rays · Gamma-rays

A new window on the universe is presently being opened by ground-based telescopes that survey the sky by detecting very high energy (VHE) photons, which have energies greater than 100 gigaelectron volts (GeV). Because of their high sensitivity, and high angular and energy resolution, these telescopes are revealing and identifying a plethora of new extragalactic and galactic sources of VHE radiation. The Galactic Center, supernovae remnants, pulsar-wind nebulae, and a new class of binary stars called gamma-ray binaries have all been identified as VHE sources in the Milky Way. LS 5039 [1] is a new gamma-ray binary detected at VHE [2] (see Fig. 1). Recently, Albert et al. [3] confirmed the identification of LS I +61 303 as the third gamma-ray stellar binary, reporting a time variability in the signal that points to the mechanism for the VHE emission (see Fig. 2).

A microquasar-jet [5] model (see Fig. 3 left panel) has been proposed to account for the VHE emission from LS 5039. For LS I +61 303, Albert et al. [3] favored a mechanism, called inverse Compton scattering, by which relativistic particles collide with stellar and/or synchrotron photons and boost their energies to the VHE range [6]. In the context of the microquasar jet hypothesis, an alternative hadronic model has been proposed for the production of very energetic gamma-rays [8]. In this model the compact object accretes matter from the dense and slow equatorial wind of a Be primary star. Gamma-ray emission is originated from pp interactions between relativistic protons in the jet and cold protons from the stellar wind.

Microquasar jet models for the production of VHE photons were a natural hypothesis because VHE emission is also being detected from blazars, namely, active galactic nuclei (AGN) whose jets are closely aligned with our line of sight. Because the particle energy in microquasar jets is comparable to that of particles in AGN jets [5], it was expected that microquasars could also produce very high energy gamma-rays [9]. This idea had been strengthened by observations showing that the kinetic power of microquasar jets may be larger than $10^{39}$ erg s$^{-1}$, which is larger than the radiated power [10]. Furthermore, microquasar jets trigger shocks where electrons are accelerated up to TeV energies [11], providing the necessary conditions for VHE emission. However, it is believed that TeV photons from blazars are produced by relativistic Doppler boosting, which seems not to be the case in gamma-ray binaries.

Alternatively, relativistic particles can be injected in the surrounding medium by the wind from a young pulsar [12]. In this scenario the slowing rotation of a young pulsar provides stable energy to the non-thermal relativistic particles in the shocked pulsar wind material outflowing from the binary companion (see Fig. 3 right panel). As in one of the microquasar-jet models, the gamma-ray emission can be produced by inverse Compton scattering of the relativistic particles from the pulsar wind on stellar photons. In this context, LS I +61 303 would resemble the gamma-ray binary PSR B1259−63, a radio pulsar in an eccentric orbit around a star of spectral type Be [13]. In fact, recent ob-
servations at radio wavelengths have come in support of the idea that LS I +61 303 is a gamma-ray pulsar rather than a microquasar [14]. As expected from the pulsar wind model (see Fig. 3 right panel), VLBA images of the radio emission show a relativistic wind from the compact object that spins as a function of the orbital phase.

The compact objects in these three gamma-ray binaries (LS 5039, LS I +61 303 and PSR B1259−63) have eccentric orbits around stars with masses in the range of 10 to 23 solar masses, and these stars can provide the seed photons to be scattered by the inverse Compton effect to VHEs. PSR B1259−63 contains a pulsating neutron star, and for LS 5039 and LS I +61 303 the precise mass of the compact stars is not known. Certainly, they are no more than 5 solar masses, which is consistent with neutron stars and/or black holes of low mass. The question that remains open is whether the relativistic particles in LS 5039 come from accretion powered jets or from the rotational energy of a pulsar that is spinning down as in PSR B1259−63.

The pulsar wind model requires gamma-ray binaries with neutron stars young enough to provide large spin down energies. In fact, as in PSR B1259−63, LS 5039 contains a young compact object. Kinematic studies show that LS 5039 has been shot out from the plane of the Galaxy [15] some-time less than one million year ago by a supernova explosion produced when the compact object was formed. Furthermore, it had been proposed that LS I +61 303 is a pulsar wind source because the time variability and the radio and X-ray spectra resemble those of young pulsars [16]. Besides, LS I +61 303 contains a Be star like PSR B1259−63, and the high energy emission in both objects seems to be produced at specific phases of orbital motions of the compact objects around the Be stars. All Be/X-ray binaries known so far contain neutron stars and none is known to host a black hole.

However, the jets in LS 5039 seem to be steady and two sided, with bulk motions of 0.2 to 0.3 times the speed of light, as do the compact jets in black hole microquasars. Furthermore, in LS 5039 no major radio outbursts are observed similar to those in PSR B1259−63.

The detection of pulsations would be a definitive proof for the pulsar-wind mechanism in gamma-ray binaries. On the other hand, detection of VHE emission from a black hole binary (e.g. Cygnus X-1, V4641 Sgr, GX 339−4) would provide definitive observational ground to the microquasar-jet model. As done in [14] a direct way to distinguish between accretion and rotational powered gamma-ray binaries is to use radio images with high sensitivity and angular resolution that would establish clearly whether the high-energy particles that trigger the VHE emission emanate as pulsar winds or as highly collimated microquasar jets.

Gamma-ray binaries are becoming subjects of topical interest in high energy astrophysics, and their study has important implications. As microquasars, they would serve as valuable nearby laboratories to gain insight into the physics of AGN jets. As pulsar-wind gamma-ray binaries they are important because they are the likely precursors of a much larger population of high-mass X-ray binaries in the Milky Way. In particular, they may provide clues to understand the early evolution of the enshrouded hard X-ray binaries being discovered from space with satellite telescopes such as the European Space Agency’s International Gamma Ray Astrophysics Laboratory (INTEGRAL).
Fig. 2 Variable gamma-ray emission from the compact binary LS I +61 303 (from [3]). The crosses indicate the position of the compact binary.

Fig. 3 Alternative models for very energetic gamma-ray binaries. *Left*: Microquasars are powered by compact objects (neutron stars or stellar-mass black holes) via mass accretion from a companion star. The jets boost the energy of stellar winds to the range of very energetic gamma-rays. *Right*: Pulsar winds are powered by rotation of neutron stars; the wind flows away to large distances in a comet-shape tail, as has been shown in [14] to be the case for LS I +61 303. Interaction of this wind with the companion-star outflow may produce very energetic gamma-rays.
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