Highlights of Spanish Astrophysics VIII, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society held on September 8–12, 2014, in Teruel, Spain. A. J. Cenarro, F. Figueras, C. Hernández-Monteagudo, J. Trujillo Bueno, and L. Valdivielso (eds.)

Structure and nature of gamma-ray binaries by means of VLBI observations

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Abstract

Gamma-ray binaries are extreme systems that produce non-thermal emission from radio to very-high-energy (¿TeV) gamma rays, with the energy output in the spectral energy distribution (SED) dominated by the MeVGeV photons. Their broadband emission is usually modulated by the orbital cycle of the system, which suggests that the physical conditions are also periodic and reproducible. The diversity of systems, together with the reproducibility of the conditions within each system, makes gamma-ray binaries excellent physical laboratories. These systems produce outflows of relativistic particles emitting synchrotron radio emission that extend up to several astronomical units, which correspond to projected angular scales of a few milliarcseconds (mas) at typical distances of 2-3 kpc. Very Long Baseline Interferometry (VLBI) provide mas resolution and therefore can be used to directly see this radio outflow. Here we present VLBI observations of five of the six gamma-ray binaries known. We have revealed for the first time the radio structure of two gamma-ray binaries, and found periodic changes in the structure of other two. Based on these results we have established the basic properties and behaviour of the radio emission of gamma-ray binaries on AU scales, and we have contributed to find characteristics that are common to all of them.

1 Introduction

Some galactic binary systems have been detected in high-energy (HE; > 100 MeV) and/or very-high-energy (VHE; > 100 GeV) gamma rays (see [**?**] and references therein). Among these systems, gamma-ray binaries show a broadband non-thermal spectral energy distribution from radio to gamma-rays that is dominated by MeV–GeV photons. A review on the gamma-ray binary population and details on the particular properties of each source can be found in [**?**] and references therein. The spectral and brightness properties appear to be synchronised with the orbit of the binary system, which suggests that the physical conditions are also periodic and reproducible. Interestingly, they do not show evidence of the presence of an accretion disc. The wide range of different orbital periods and eccentricities of the known gamma-ray binaries ([?]) provides a diversity of different ambient conditions in which the physical processes take place. The diversity of systems, together with the reproducibility of the conditions within each system, makes gamma-ray binaries excellent physical laboratories in which acceleration, diffusion, absorption, and radiation mechanisms can be explored. Nevertheless, the number of known gamma-ray binaries is still very limited.

Five binary systems have been classified as gamma-ray binaries: PSR B1259−63, LS 5039, LS I +61 303, HESS J0632+057, and 1FGL J1018.6−5856 ([?]). The latter has not been clearly detected at TeV energies yet. In all of them the optical companion is a young massive star. The VHE gamma-ray emission can be interpreted as the result of inverse Compton upscattering of stellar UV photons by relativistic electrons, although hadronic models do exist as well. The acceleration of electrons can be explained by two excluding scenarios: acceleration in the jet of a microquasar powered by accretion ([?]), or shocks between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion [?, ?, ?]. In the last years, new observational results and fine modernisation have suggested that their powering source is a young non-accreting pulsar.

2 The systems

All gamma-ray binaries harbour massive O or Be star with masses about 10–30 $M_{\odot}$, a radius of ∼10 $R_{\odot}$, and a photosphere temperature of 20 000–40 000 K ([?]). The second component of the system is a degenerate companion, black hole or neutron star, whose nature is unknown in most of the cases. Orbital solutions are determined using measurements of the radial velocity of absorption lines from the the massive star photosphere. They are compact systems with orbital periods in the wide range from 4 days to 3.4 years. They have eccentric orbits from moderately eccentric to highly eccentric, up to $e \sim 0.9$ for the systems with long orbital periods. Some of the systems show hydrogen lines with double-peaked profile characteristic of circumstellar discs, typical of Be stars with well-developed discs fed by stable mass-loss. The equivalent width (EW) of the H_{α} line in Be/X-ray binaries provides a good estimate of the size of the circumstellar disc, which can be truncated by the interaction with the compact object through tidal torques. In general, the orbital parameters of the systems are very uncertain. An exception is PSR B1259−63, for which the detection of pulsations from the neutron star in the system has provided accurate orbital parameters thanks to pulsar timing. For the rest of the systems, the inclination of the orbit is barely restricted, which in turn makes very difficult to constrain the mass of the compact object.

In Table 1 we list the main optical and orbital properties of the known gamma-ray binaries. AGL J2241+4454 is included in the table because it was initially considered a potential gamma-ray binary. However, some properties are fundamentally different from the rest of the members. In particular the gamma-ray emission appears to be produced in flares instead of being periodic emission correlated with the orbital cycle. Furthermore, the discovery of an accretion disk around the now identified black hole in the system ([?])

Table 1: Orbital properties of the known and candidate gamma-ray binaries (ordered by increasing orbital period). The table is adapted from [?].

Name	Spectral type	$M_{\rm opt}$ [$M_\odot$]	i [°]	$P_{\rm orb}$ [day]	e	d [kpc]	Reference
LS 5039[a]	O6.5 V((f))	21–50	> 12	3.91	0.35	2.9	[?], [?]
1FGL J1018.6−5856	O6 V ((f))	$\sim$37	–	16.58	–	$\sim$5.4	[?], [?]
LS I +61 303[b]	B0 Ve	10–15	> 10	26.50	0.54	1.9	[?],[?], [?], [?]
AGL J2241+4454[c]	B3 IVne+sh	6–10	67–80	60.37	0.40	$\sim$2.6	[?] , [?]
HESS J0632+057[d]	B0 Vpe	13–19	47–80	315	0.83	$\sim$1.4	[?], [?], [?], [?]
PSR B1259−63[e]	O9.5 Ve	31	19–31	1236.79	0.87	2.3	[?], [?], [?]

[a]Other names: HESS J1826−148, 1RXS J182615.1−145034
[b]Other names: 2CG 135+01, HIP 12469
[c]Other names: HD 215227, MWC 656
[d]Other names: HD 259440, MWC 148
[e]Other names: LS 2883

suggests that this source is an X-ray binary with gamma-ray emission, different from the other gamma-ray binaries whose spectral energy distribution is dominated by gamma-ray photons.

3 Observations

Gamma-ray binaries are powerful sources of non-thermal emission. All of them are efficient particle accelerators and can be detected and studied through the whole electromagnetic spectrum, from low-frequency radio emission at MHz frequencies to very- high-energy gamma-ray emission at teraelectronvolt (TeV) energies, which makes them excellent natural physical laboratories. Here we will briefly describe the general properties of the multiwavelength emission of gamma-ray binaries. Particular details on the emission of each source can be found in [?].

Gamma-ray binaries are detected by ground-based Imaging Atmospheric Cherenkov Telescopes above 100 GeV. They are variable but recurrent TeV sources, and have been detected periodically at particular orbital phases showing a significantly regular behaviour. They appear as point-like sources, with a typical limit on extended emission $< 0.1°$, whereas nearly all other TeV sources in the Galactic Plane are extended. The *Fermi*/LAT and *AGILE* satellites have characterised the high energy (HE) emission of these sources. The typical HE spectrum of a gamma-ray binary is a power-law with an exponential cutoff around a GeV. HESS J0632+057 remains undetected at Gev energies. For the rest of sources, a clear orbital modulation has been detected. Interestingly, apart from the relatively faint HE emission of PSR B1259−63 during periastron, the source displayed an unexpected GeV flare with a luminosity close to the spindown power of the pulsar that lasted seven weeks ([?]). 1FGL J1018.6-5856 was discovered thanks to its 16.558 day modulation in *Fermi*/LAT data

([?]).

All of the systems are detected in X-rays and show a modulation on the orbital period. The spectra are hard power laws with photon index $\Gamma \sim$1.5–2 and with no measured cutoff in X-rays. Emission extending up to 4″ from PSR B1259−63 has been detected in *Chandra* observations of PSR B1259−63 ([?]). Thermal emission from the massive star dominates the near-infrared, optical, and ultraviolet emission in gamma-ray binaries. Optical observations provide information on the star properties, the distance to the system, the orbital parameters, and the proper motion of the systems. Variability on the optical magnitude and properties of the emission lines are observed with the same periodicity of the orbit (see for example [?]).

Also, all gamma-ray binaries are radio sources, something unusual amongst the wider population of high-mass X-ray binaries. Their variable radio spectra is consistent with synchrotron emission. The radio emission is variable, in most cases the variability is correlated with the orbital phase, although secular differences can be seen from orbital cycle to cycle. Pulsed radio emission has only been detected in PSR B1259−63, whereas only upper limits have been obtained in targeted searches for some of the other sources. In case they contained a pulsar, the lack of pulsations can be explained by the intense stellar wind that produces an extremely high absorption in the smaller orbits.

Interestingly, extended and variable radio emission at AU scales has been reported for gamma-ray binaries (see for example [?]). The sources are resolved on milliarsecond scales by VLBI observations at cm wavelengths. In the next section we discuss the properties of the radio outflow detected in most of the known gamma-ray binaries.

4 Extended radio emission in gamma-ray binaries

Four gamma-ray binaries have been detected with VLBI. We describe the main properties of the systems and the results from recent and new VLBI observations.

PSR B1259−63 The binary system PSR B1259−63/LS 2883 is formed by a young 48 ms radio pulsar in an eccentric orbit of 3.4 years around a massive main-sequence star [?]. The spectral type of the massive star, O9.5 Ve, and some of the binary parameters have been recently updated by [?], who obtained a distance to the system of 2.3±0.4 kpc. PSR B1259−63 is the only gamma-ray binary in which radio pulsations have been detected up to now.

We observed PSR B1259−63 with the Australian Long Baseline Array (LBA) at 2.3 GHz in 2007 during three epochs corresponding to 1.3, 21.2, and 315.5 days after the periastron passage [?]. In the first two epochs the radio source showed extended emission up to projected distances of $\sim$ 50 mas, or $\sim$ 120 AU. The third epoch, obtained closer to the apastron passage, showed a faint point-like source, which was interpreted as emission from the pulsar that indicates the position of the binary system. The position of the binary system within the nebula for the first two epochs was estimated using the size of the orbit and the proper motion of the system. The results showed that the peak of the radio emission is displaced from the binary system. Preliminary VLBI images of the 2010 periastron passage of PSR B1259−63 suggest that its VLBI structure varies periodically (Moldón et al., in preparation).

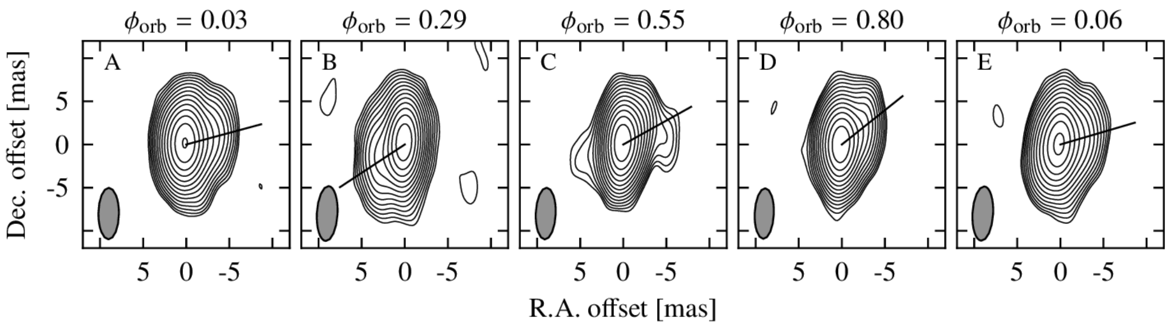

Figure 1: VLBA images of LS 5039 at 5 GHz from project BR127, obtained during five consecutive days in July 2007 [?]. Each column, labelled with the run name and orbital phase, corresponds to one epoch. The self-calibrated images were produced using a natural weighting scheme. The restoring beams are plotted in the bottom-left corner of each panel. Dashed contours are plotted at −3 times the rms noise of each image and solid contours start at 3 times the rms and scale with $2^{1/2}$.

LS 5039 This system, located at 2.9 ± 0.8 kpc, is composed by an ON6.5 V((f)) massive star and a compact object of unknown mass in a 3.9 d orbit [?]. The radio emission appears extended when observed with VLBI on mas scales. At 5 GHz, the source shows a main core and extended bipolar emission that has been detected at projected angular distances between 1 and 180 mas (3–500 AU) from the core [?, ?, ?].

We observed LS 5039 with the VLBA at 5 GHz during five consecutive days, covering a whole orbital cycle [?]. The resulting self-calibrated images are shown in Fig. ??. The radio morphology on mas scales is variable, with changes in less than 24 hours. Images at similar orbital phases show a similar morphology. We found that this behaviour is stable on time scales of years. Therefore, the gamma-ray binary LS 5039 shows periodic orbital morphological variability. We computed a model of the evolution of an outflow of relativistic electrons accelerated as a consequence of the interaction of the massive star and the wind of a young non-accreting pulsar. The model accounts for the main morphological features of LS 5039 [?].

LS I +61 303 This gamma-ray binary contains a rapidly rotating B0e main sequence star with a stable equatorial shell, and a compact object orbiting it every 26.5 d in an eccentric orbit with $e = 0.72$ [?]. It displays quasi-periodic radio outbursts at radio, X-rays and gamma-rays modulated by a long-term periodicity of ~ 4.6 yr [?]. [?] conducted several VLBI observations showing an orbital variability that these authors interpreted as the signature of a cometary tail produced in the colliding winds scenario. Another interpretation of the data suggests that the changes are compatible with a precessing microblazar [?].

We observed LS I +61 303 with the VLBA in 2007 at 8.4 and 2.3 GHz during five epochs separated by two days and covering an X-ray/TeV outburst. We found extended and variable emission on scales of 5–10 AU. The observed morphology is compatible with the one found in observations conducted one year before at similar orbital phases, which suggests that the periodic orbital modulation is stable on time scales of years. We obtained accurate astrometry at two radio frequencies and found the relative offsets between them. The behaviour found is similar to the one expected from an outflow whose axis passes close to the line of sight of the observer (Moldón et al., in preparation).

HESS J0632+057 The proposed optical counterpart of HESS J0632+057 is the massive B0pe star MWC 148 [?]. A periodicity of 321 ± 5 d was revealed by long-term X-ray observations conducted with *Swift*/XRT [?] and was refined to 315^{+6}_{-4} d by [?]. MWC 148 was confirmed to be a binary system by means of radial velocity observations [?]. The radio counterpart is variable, although no detailed radio light curve is available.

We observed HESS J0632+057 with the European VLBI Network (EVN) at 1.6 GHz in ToO mode in two epochs: February 15 and March 17, 2011, following the report of an X-ray outburst. The first observation (e-EVN) was conducted 9 days after the peak of the X-ray outburst, whereas the second observation (full EVN) was conducted 30 days later. The source is point-like during run A and displays extended emission up to projected distances of 75 AU in run B [?]. The peak of the emission is displaced 21 AU between runs. The radio counterpart of HESS J0632+057 is unambiguously identified with MWC 148.

AGL J2241+4454 We conducted a VLBI campaign to search for the radio counterpart of the gamma-ray binary candidate AGL J2241+4454 based on its possible association with a binary system containing a Be star (MWC 656). However no compact radio emission was found coincident with the position of the star. Given the low upper limits obtained in three VLBI observations we conclude that the source may display transient radio emission lasting less than ∼20–30 days, or that the source displays a fast expanding outflow resolved by VLBI observations. A well sampled monitoring at different orbital phases will be needed to constrain the radio emission of this source.

1FGL J1018.6−5856 For completeness, a short comment on this new gamma-ray binary candidate. 1FGL J1018.6−5856 was discovered by searching for periodicities of *Fermi* sources, and shows intensity and spectral modulation at GeV energies with a 16.6-day period [?]. The proposed optical counterpart is an O6V((f)) star. The source has a variable flux density of 2–5 mJy as measured with Australia Telescope Compact Array (ATCA), although no extended emission has been reported so far.

As a summary, in Table **??** we show the list of known gamma-ray binaries with the orbital period of the system, and the properties of the VLBI structure of each source. Periodic morphological changes have been seen in LS 5039, LS I +61 303, and PSR B1259−63, whereas for the recently discovered sources HESS J0632+057 and 1FGL J1018.6−5856, more data is needed in order to obtain evidence of periodicity.

Source	$P_{\rm orb}$ [d]	Observed	VLBI structure	Variability
LS 5039	3.9	Yes	Yes	Periodic changes
1FGL J1018.6−5856	16.6	No	?	–
LS I +61 303	26.5	Yes	Yes	Periodic changes
AGL J2241+4454	60.4	Yes	?	Non-detected
HESS J0632+057	315	Yes	Yes	Variable
PSR B1259−63	1236.8	Yes	Yes	Periodic changes

Table 2: Summary of the VLBI observations of the known gamma-ray binaries.

5 Conclusions and open questions

Gamma-ray binaries can now be considered a class of binary systems, showing similar properties through the whole electromagnetic spectrum, albeit with a rich diversity of phenomenologies and peculiarities. VLBI observations combined with multifrequency analysis have already proven useful to study the nature of gamma-ray binaries ([**?**]). There is still a wide margin to study and understand these sources at all wavelengths, and there are open questions that will be addressed in the following years.

First, do all gamma-ray binaries contain pulsars? The models that describe the non-thermal emission as produced by the shock between the wind of a young non-accreting pulsar and the stellar wind give a simpler explanation for the non-thermal peculiarities of gamma-ray binaries than accreting models. Therefore, it is expected that the compact object in these systems is a pulsar, although it has only been found in PSR B1259−63 ([**?**, **?**]). Another important question is what is the relevance of the Be phenomenon in the gamma-ray emission. What happens to the decretion disk in eccentric systems, and what is the relation between the observational parameters of the disk and the gamma-ray emission. These can be explored by detailed multiwavelength monitoring of the optical properties along the orbit ([**?**]). One fundamental question is where and how is the GeV emission produced? In the shocked or in the un-shocked pulsar wind? Also, it is important to know if the GeV emission is pulsed, as suggested by the spectral properties and supported by some models. Any search of GeV pulsations in, for instance, *Fermi* data requires a much better determination of the orbital parameters.

To answer these questions we require to conduct detailed multiwavelength campaigns targeted at very specific orbital phases of the binary system, and we need to better constrain the orbital parameters to understand the relation between the emission and the configuration of the star-outflow-compact object geometry. On the other hand, new instrumentation will be fundamental for future studies, not only for the possibility of conducting deeper observations of the known systems, but also because they will discover new and diverse systems. For that, planned instruments like the Cherenkov Telescope Array (CTA) at GeV-TeV energies, and the Square Kilometer Array (SKA) at radio wavelengths will provide a new age on the study of gamma-ray binaries.

Acknowledgments

The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The European VLBI Network (http://www.evlbi.org/) is a joint facility of European, Chinese, South African, and other radio astronomy institutes funded by their national research councils. The Australian Long Baseline Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility by CSIRO. This research has made use of the NASA's Astrophysics Data System Abstract Service, and of the SIMBAD database, operated at CDS, Strasbourg, France.

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