Galactic Binary Systems

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The population of binary systems known to emit in the GeV and TeV bands consists of only a few firmly identified Galactic sources. These rare objects constitute extreme particle accelerators operating under varying, but regularly repeating, conditions. As such, they provide access to a unique laboratory in which to study particle acceleration, and the nature of gamma-ray production, emission and absorption processes near compact objects.

Here we review the current observational status of the field, and discuss some of the recent interpretations of the results.

1. Introduction

After many decades as an experimental technique at the fringes of mainstream astronomy, gamma-ray observations now constitute a well-established astronomical discipline. The Fermi-LAT catalogue is expected to increase the number of known high-energy (HE; 30 MeV – 30 GeV) sources into the many thousands, while the number of very-high-energy (VHE; 30 GeV – 30 TeV) sources is approaching 100. This allows for unbiased population studies of the major source classes (blazars, pulsars, pulsar wind nebulae, supernova remnants, etc.), which can probe the details of their evolution and the impact of their surrounding environments. Within this proliferation of objects, Galactic binary systems known to emit in the HE/VHE bands constitute just 6 sources, including one marginal detection and another which may not be a binary system at all. Their impact on high energy astrophysics is, however, disproportionately large.

The known gamma-ray binary systems comprise a compact object (black hole or neutron star) orbiting a massive (O or B type) main sequence companion. As such, they constitute an astrophysical particle accelerator operating under a varying, but regularly repeating, set of environmental conditions. Throughout the orbit, matter and photon field densities, as well as the system geometry and orientation with respect to the observer’s line of sight are continually changing. In addition, each system is unique; providing a range of stellar properties, compact object masses and orbital ephemerides. As a result, observations of gamma-ray binary systems can provide stringent and repeatable tests for models of particle acceleration and high energy emission in extreme astrophysical environments. Furthermore, the study of Galactic binary systems containing accretion powered jets may shed light upon the general mechanisms for astrophysical jet formation, with application to the much larger-scale structures produced in active galaxies.

In this report we review the known Galactic gamma-ray binary systems, with a focus on the current observational status in the GeV - TeV energy region.

2. History

To some extent, the whole field of VHE gamma-ray astronomy owes its existence to the study of binary systems. Observations close to a huge radio flare of Cygnus X-3 in 1972 led to claims of VHE gamma-ray emission\(^1\), which were repeated by numerous Cherenkov telescopes and cosmic ray particle detectors observing over a wide range of the gamma-ray spectrum during the 1970’s and 1980’s. Periodic emission from several other X-ray binary systems was also claimed (see e.g.\(^2\) for a review), which provided some of the impetus for the construction of new experiments in the 1990’s. These new instruments (notably Whipple, HEGRA and CAT) were equipped with imaging cameras which allowed to greatly reduce the background of cosmic ray showers, providing sensitivity at the level of \(\sim 5\%\) of the steady Crab Nebula flux. Despite this, they failed to confirm any of the earlier results.

At the lower energies probed by satellite-borne gamma-ray telescopes, among the 13 gamma-ray sources detected by COS-B was one, 2CG 135+01, whose error box contained a periodic radio and X-ray source, LS I +61\(^\circ\)303\(^3\). In each case, how¬ever, there was weak or no evidence for variability, no clear periodicity, and limited positional accuracy, which made the associations far from definitive.

The next breakthrough came from the ground, starting in 2004, when the current generation of atmospheric Cherenkov detectors (H.E.S.S., MAGIC and VERITAS) began to come online. These instruments provided an order of magnitude improvement in sensitivity over the previous generation, along with pointing accuracies of \(\sim 0.1\^\circ\). The detections of VHE emission from PSR B1259-63/SS 2883, LS I +61\(^\circ\)303 provided the first incontrovertible evidence for orbitally modulated gamma-ray emission from Galactic binary systems.

This year’s results from Fermi-LAT and AGILE reveal definitive HE detections of LS I +61\(^\circ\)303\(^4\).
LS 5039 [11] and Cyg X-3 [12, 13]. Long-term, sensitive monitoring of Galactic binary sources is providing key insight into their nature, while the critical importance of obtaining contemporaneous, time-resolved observations of the complete non-thermal spectra for these objects is becoming clear.

3. An overview of high energy binary systems

Fig. 1 shows the distribution, in Galactic coordinates, of the six known gamma-ray sources which have been linked with binary systems. In the following sections we will provide a brief description of the systems and review the status of gamma-ray observations.

3.1. PSR B1259-63/SS 2883

PSR B1259-63/SS 2883 was the first gamma-ray binary system to be firmly detected at TeV energies, and the first known variable VHE source in our Galaxy. The system was discovered in the radio [14], and comprises a 48 ms pulsar orbiting a massive B2Ve companion. The orbit is highly eccentric \( (e = 0.87) \), with a period of 3.4 years. At apastron, the orbital separation is \( \sim 10 \) A.U. At periastron, the separation is only 0.7 A.U. and the pulsar passes close to, or possibly through, the circumstellar disk of the Be star, which is likely inclined with respect to the plane of the pulsar orbit. A remarkable feature of the initial H.E.S.S. detection was the discovery of a bright, spatially extended TeV source (HESS J1303-631) just 0.6° to the north of PSR B1259-63 (Figure 2), with no obvious counterpart at other wavelengths. There are now known to be many similar unidentified VHE sources along the plane of the Galaxy; the angular proximity of HESS J1303-631 and PSR B1259-63 is purely coincidental.

The combination of a long orbit, which is out of phase with our own orbit around the sun, complicates observations of this object. Figure 3 shows a top view sketch of the system, including a definition of the true anomaly, \( \theta \). Figure 4 shows the complete H.E.S.S.
dataset plotted with respect to this true anomaly. Note that, as yet, due to observing constraints, there are no observations of the system at periastron. The TeV emission exhibits two peaks, approximately 15 days before and after periastron. Within the limited sampling, it also appears that the lightcurve may be asymmetric with respect to periastron. The source spectrum at VHE energies shows no sign of variability, and is well-fit by a power-law with a photon index $\Gamma = 2.8$.

Various authors have attempted to explain the double bumped VHE lightcurve within a 'hadronic disk scenario', in which the circumstellar disk provides target material for accelerated hadrons, leading to $n^0$ production and subsequent TeV gamma-ray emission. The newly published 2007 H.E.S.S. observations disfavour this, since the onset of TeV emission occurs $\sim 50$ days prior to periastron, well before interactions with the disk could be expected to play a significant role. The next periastron will occur in December 2010, for the first time with Fermi-LAT coverage. Accompanying H.E.S.S. observations should also be possible, particularly during the post-periastron emission period.

3.2. LS 5039

LS 5039 consists of a compact object, either neutron star or black hole, orbiting a massive O6.5V (\(\sim 23 \, M_\odot\)) star in a 3.9 day orbit. The orbit is slightly eccentric ($e = 0.34$), inclined to the line of sight, and the orbital separation varies from $\sim 0.1$ A.U. at periastron to $\sim 0.2$ A.U. at apastron. Figure 5 sketches the orbit of the system.

Evidence for high energy emission associated with this source was first claimed by Paredes et al. [5], who noted the coincidence with an EGRET source, 3EG J1824-1514, and identified jet-like radio structures, leading to a microquasar interpretation. Variability in the EGRET source was never established, however, and high resolution VLBA radio observations by Ribo et al. [21] show morphological changes on short timescales which do not support the existence of a persistent jet.

Observations by H.E.S.S. in 2004 revealed that LS 5039 is a bright source of VHE gamma-rays [8]. Unlike PSR B1259-63 (and, to a lesser extent, LS I +61°303) LS 5039 is almost perfectly suited to TeV observations, with a short orbital period and a convenient declination angle, allowing sensitive observations at all phases over numerous orbits. Deep follow-up observations by H.E.S.S. provided a measurement of periodic variability in the TeV emission, modulated at the orbital period. The VHE emission is largely confined to half of the orbit, peaking around inferior conjunction, when the compact object is closest to us and co-aligned with our line-of-sight ($\phi = 0.67$ on Figure 5). The spectrum is also orbitally modulated, appearing significantly harder around inferior conjunction ($\Gamma = 1.85 \pm 0.06_{\text{stat}} \pm 0.1_{\text{syst}}$), but with an exponential cut-off at $E_\gamma = 8.7 \pm 2.0$ TeV. Recent X-ray observations with Suzaku, which continuously monitored one and a half full orbits [22], show a light curve remarkably similar to the TeV light curve, but with an amplitude of modulation $\sim 3$ times smaller. The hard X-ray spectrum and absence of X-ray emission lines favours a non-thermal origin for the emission.

Observationally, LS 5039 represents a rather challenging target for Fermi-LAT, since it is located in a region with a large diffuse background flux and with significant source confusion (notably from PSR J1826-1256). Results are first being shown at this conference [23], and reveal that the source is detected at all orbital phases, with the emission peaking close to superior conjunction, in apparent anti-phase with the VHE results. Spectral variability is also seen in the LAT data, with $\Gamma = 2.25 \pm 0.11$ at inferior conjunction and $\Gamma = 1.91 \pm 0.16$ at superior conjunction. Most strikingly, a sharp spectral cut-off at $E_\gamma = 1.9 \pm 0.5$ GeV is observed in the hard state, indicating that the VHE spectra cannot be simply a smooth extrapolation of the lower energy emission.

3.3. LS I +61°303

Similar to LS 5039, LS I +61°303 consists of a compact object, either neutron star or black hole, in this case orbiting a BOVe star with a circumstellar disk ($\sim 12.5 \, M_\odot$) in a 26.5 day orbit. The orbital eccentricity, $e$, is 0.537, and the orbital separation varies from $\sim 0.1$ A.U. at periastron ($\phi = 0.275$) to $\sim 0.7$ A.U. at
Figure 4: Integrated VHE flux above 1 TeV from all combined HESS observations of PSR B1259-63 as a function of the true anomaly, with the corresponding orbital phases shown on the upper axis (from [15]).

Figure 5: A top view of the orbit of LS 5039, showing the relative orbits (r/a) of the optical star and its compact companion of unknown mass. The relative orbit of the compact object is shown as a solid line, while the optical star’s relative orbit depends greatly on the mass of the companion. The dashed line indicates the optical star’s orbit assuming a 3.7 M_☉ black hole, while the dotted line assumes a 1.4 M_☉ neutron star. Figure from Aragona et al. [19].

apastron. Figure 8 sketches the orbit of the system.

The original identification of a bright high energy source with COS-B [24], coincident with a periodic radio source [25], ensured that LS I +61°303 would be a prime target for EGRET. An EGRET source was duly detected [26], showing some evidence for variability, but no measurable periodicity, or correlation with emission at other wavelengths. This fact, along with the large positional uncertainty, prevented a definitive association of the HE source with the binary system. As with LS 5039, evidence for radio jet structures has been found in LS I +61°303 [26]. More recent observations question this microquasar interpretation [27], since the radio structure can be seen to vary around the orbit (although see [28] for a counter-argument).

The detection of a variable VHE source at the location of LS I +61°303 with MAGIC [29], later confirmed by VERITAS [29], completed the identification this source as a gamma-ray binary. The object is now one of the most heavily observed locations in the VHE sky, with deep exposures by the two observatories spread over half a decade. Despite this, the VHE source is much less well-characterized than LS 5039, owing to its relatively weak VHE flux, and an inconvenient orbital period which closely matches the lunar cycle, making observations over all orbital phases almost impossible within a single observing season.
VHE emission is only clearly detected close to apastron (Figure 9) between phases $\phi = 0.5 - 0.8$, with a peak flux $\sim 10\%$ of the steady Crab nebula flux and a power-law spectrum with index $\Gamma \sim 2.6$. Observations with MAGIC have established modulation at the binary period [30], as well as a correlation between VHE and XMM X-ray fluxes during 60\% of one orbit [31]. The only published VHE observations since the launch of Fermi show no clear detection of the source, although exposure close to the apastron phases was limited [32].

X-ray modulation at the orbital period has been measured with the Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor [33, 34], although regular observations taken every 2 days over a period covering 6 orbital cycles in 2007-2008 with the RXTE Proportional Counter Array (PCA) show no evidence for phase-dependent flux modulation [35]. These same measurements, as well as later measurements by Ray & Hartman [36] reveal bright X-ray flaring episodes lasting longer than 10 minutes, with substructure on the timescale of a few seconds. A much shorter timescale flare, lasting 0.23 seconds, has also been detected with the Swift Burst Alert Telescope (BAT) [37]. In both cases, the X-ray variability may be related to other sources in the same field-of-view (e.g. [38]). As with LS 5039, a hard X-ray spectrum and absence of X-ray emission lines favours a non-thermal origin for the emission.

LS I +61°303 was one of the few non-pulsar objects firmly identified in the Fermi-LAT Bright Source List, on the basis of the orbital modulation of the gamma-ray flux [39], and was the only Galactic source on the first year LAT monitored source list. Figure 10 shows the light-curve phase-averaged over multiple orbits. The HE emission peaks close to periastron, in apparent anti-phase with the non-contemporaneous VHE results. The LAT spectrum is constant, within a power law index of $\Gamma = 2.21 \pm 0.10_{\text{stat}} \pm 0.06_{\text{syst}}$ and, as with LS 5039, displays sharp cut-off, at $E_{\gamma} = 6.3 \pm 1.1$ GeV (Figure 11).
3.4. Cygnus X-1

As will be discussed in more detail later, PSR B1259-63/SS 2883, LS 5039 and LS I +61°303 can all plausibly be explained as binary systems containing a non-accreting neutron star. The compact object in the Cygnus X-1 system, however, is the best known candidate for a stellar mass black hole. The system is believed to comprise a 21 ± 8 M_⊙ black hole in a circular orbit around an O9.7 Iab companion of 40 ± 10 M_⊙, with a period of 5.6 days [40, 41]. Cygnus X-1 is one of the brightest known X-ray sources, and displays the well-known high/soft and low/hard spectral states [42], which are believed to relate to the accretion rate onto the compact object. The soft component is observed when thermal emission from the accretion disk dominates, while the high energy hard component is believed to be produced by inverse Compton boosting, either by thermal electrons in a corona, or at the base of a relativistic jet.

Gamma-ray emission from Cygnus X-1 has not been detected by any satellite observatories. In the VHE regime, a deep, 40 hour exposure by MAGIC in 2006 also showed no evidence for steady emission; however, a search for variability on shorter timescales revealed an excess signal with a statistical significance of 4.1σ during a single 79 minute period [43]. As illustrated in Figure 12, the VHE excess occurred during the rising edge of a hard X-ray flare; observations on the following night during the falling edge of a second X-ray peak showed no such excess. The result is intriguing, being the first evidence for VHE emission from an accreting binary system, but clearly requires follow-up observations for confirmation and characterization of the gamma-ray light curve structure before any strong conclusions can be drawn.

3.5. Cygnus X-3

Cygnus X-3 is another presumably accretion-powered system, comprised of a 10-20 M_⊙ compact object and a Wolf-rayet star companion, with a short orbital period of 4.8 hours [44]. As discussed in the introduction, Cygnus X-3 holds an important place in the history of the field of gamma-ray astronomy, particularly for the ground-based instruments. At present, there is no strong evidence for VHE emission from the source. Compelling evidence for HE emission was also lacking until very recently, with the appearance of new results from AGILE [45] and Fermi-LAT [13]. The results are discussed in greater detail elsewhere in these proceedings [46]. Briefly, both the LAT and AGILE observe HE emission only intermittently, during soft X-ray states in which radio flares are also observed. These radio flares are believed to be associated with relativistic plasma ejection events, and the peak gamma-ray emission appears to precede major radio flares by a few days. Figure 13 shows the LAT lightcurve for Cygnus X-3. The emission seen by the LAT during the active phases is also observed to be modulated at the 4.8 hour orbital period, providing the definitive association of the gamma-ray source with Cygnus X-3.

3.6. An Enigma: HESS J0632+057

The sources discussed above are all well-known objects at radio through X-ray wavelengths and their binary nature is certain. The reported gamma-ray
observations clearly show that binary systems can be among the brightest objects in the GeV-TeV sky, and so the possibility of identifying new binaries through their high energy emission alone is not unreasonable. Hinton et al. [47] have proposed that one of the unidentified TeV sources discovered by H.E.S.S., HESS J0632+057 [18], might be an example of such a gamma-ray binary system. This source was originally detected during two observations of the Monoceros Loop SNR region, separated by 1 year, with integral fluxes above 1 TeV of ∼3% of the Crab Nebula flux. At TeV energies, binary systems are indistinguishable from point-like objects; of the ∼40 unidentified TeV sources, only HESS J0632+057 and the Galactic centre source HESS J1745-290 are point-like. Follow-up observations with XMM-Newton have revealed an X-ray source, XMUM J063259.3+054801 coincident with the TeV source, and with a massive star MWC 148, spectral type B0pe. The X-ray source presents a hard power-law spectrum (\( \Gamma = 1.26 \pm 0.04 \)) and is variable on hour timescales - consistent with the X-ray properties of established gamma-ray binary systems.

The known gamma-ray binary systems have already undergone many years of intensive multiwavelength study, which has allowed to construct full spectral energy distributions, and to characterize the periodic and non-periodic variability timescales. Such studies are now just beginning for HESS J0632+057. A faint, unresolved radio source has been detected at the position of MWC 148. The VLA observations [20] consist of three exposures separated by ∼1 month and show significant variability at 5 GHz. Ongoing observations with XRT onboard the Swift satellite reveal X-ray variability on timescales from days to months, with no clear evidence for periodicity as yet (Figure 14). Follow-up VHE observations by VERITAS resulted in upper limits below the reported H.E.S.S. flux (Figure 15), indicating that the source is also variable at TeV energies [51]. At present, there is no known HE counterpart to HESS J0632+057; the closest source is 0FGL J0633.5+0634 (LAT PSR J0633+06), at an angular separation of 0.8°.

As things stand, the nature of HESS J0632+057 remains a mystery. As a variable, point-like TeV source, co-located with a massive Be star, it is certainly a promising binary candidate, and the overall spectral energy distribution is compatible with this scenario. Contemporaneous measurements over all wavelengths will help to shed light on the situation, and the detection of a periodic emission component at any wavelength would provide definitive evidence.

4. Discussion

Interpretation of the emission from Galactic gamma-ray binary systems drives an extremely active field, a full review of which is beyond the scope of this article. An overview of some of the important issues, and a selection of the different models can be found in these articles and references therein:[52, 53, 54, 55, 56, 57, 58].

One of the key questions to answer is the ultimate nature of the power source: whether accretion onto a compact object, or the spin-down power of a neutron star. In the case where pulsar emission is observed, such as with PSR B1259-63/SS 2883, the answer is clear. For the other sources, the question remains, although the evidence at present (in the opinion of this reviewer) favours LS 5039 and LS I +61°303 as non-accreting, pulsar-wind driven systems (e.g. [54]), and Cygnus X-3 and Cygnus X-1 as accreting systems driving relativistic jets. Too little is known about HESS J0632+057 to make even an educated guess.

Beyond this basic paradigm, the details of the interpretation can vary widely. The particle acceleration mechanism may be through colliding shocks in a
jet, magnetic reconnection events, or shock acceleration at the pulsar wind - stellar wind interaction. The energetic particle population may be hadron or lepton dominated, leading to different production mechanisms for the high energy emission: $\pi^0$-decay through hadronic interactions with surrounding matter, or inverse Compton boosting of local photon fields by energetic leptons. The gamma-ray emission can originate in very different locations: close to a jet or in the circumstellar environment, in the wind interaction region or the pulsar wind zone or, in the case of curvature radiation, within the pulsar magnetosphere itself. Once produced, the observed gamma-ray flux is modulated by a number of factors: both the geometry of the system with respect to the line of sight, and varying photon field intensities and matter density around the orbit lead to varying energy-dependent gamma-ray production and absorption efficiencies. Additionally, a number of other effects, such as stellar wind clumping, the impact of geometrical uncertainties and particle cascading could play a significant role.

Despite this wide range of factors to address, significant progress has been made in the efforts to model these systems, and concrete predictions exist which are now being put to the test by the Fermi-LAT observations and the TeV instruments. To give just one example, Figure 16 shows predicted light curves over the HE and VHE energy bands for LS 5039, in the
context of a leptonic particle population powered by a non-accreting pulsar wind [59].

In the near future, we can expect a number of observational questions to be addressed. The existence of the Fermi-LAT GeV cut-offs in LS 5039 and LS I +61°303 is particularly intriguing, since it implies that the HE and VHE emission may have different origins (for example, the HE emission could be magnetospheric, or associated with a hadronic particle population). The identification of a pulsed component to the gamma-ray emission would clarify this. It seems likely that the LAT will also add to the catalog of gamma-ray binaries, and this information can be used to guide new VHE observations: Cygnus X-3 is already highlighted as an obvious candidate for targeted VHE follow-up. The strongest observational constraints to the emission models are always provided by long-term, strictly contemporaneous multi-wavelength campaigns, several of which are presently underway or planned for the near future. The next periastron pass for PSR B1259-63/SS 2883 at the end of 2010 will be the first chance to observe both the HE and VHE emission from this object while, at the time of writing, the Be-pulsar binary 1A 0535+262 has entered a giant outburst state. This occurs only once every five - ten years, and so represents the first opportunity for sensitive HE/VHE observations of this object.

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Figure 16: Predicted theoretical light curves for the energy intervals 100 GeV-1 TeV, 10-100 GeV, and 1-10 GeV. Both inclination angles and interacting lepton spectra considered are shown (dot-dashed curves, $i = 30$; solid curves, $i = 60$; black curves, variable spectrum of primary leptons; green curves, constant spectrum along the orbit). Figure from [59]

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