Binaries and GLAST
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Abstract. Radio and X-ray observations of the relativistic jets of microquasars show evidence for the acceleration of particles to very high energies. Signatures of non-thermal processes occurring closer in to the compact object can also be found. In addition, three binaries are now established emitters of high (>100 MeV) and/or very high (>100 GeV) energy gamma-rays. High-energy emission can originate from a microquasar jet (accretion-powered) or from a shocked pulsar wind (rotation-powered). I discuss the impact GLAST will have in the very near future on studies of such binaries. GLAST is expected to shed new light on the link between accretion and ejection in microquasars and to enable to probe pulsar winds on small scales in rotation-powered binaries.

Keywords: Gamma-ray; Pulsars; Black holes; X-ray binaries; Infall and accretion; Jets, outflows and bipolar flows

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INTRODUCTION

Binaries composed of a black hole or neutron star in orbit with a stellar companion are prominent sources of the X-ray sky. X-ray binaries are usually powered by accretion of matter from the companion. The gravitational energy released by accretion heats the plasma to temperatures in the range \(1 \text{ keV} < kT < 50 \text{ MeV}\) for a stellar-mass black hole, which is someway below the GLAST energy range. However, part of the power is also emitted non-thermally by particles of much greater energies. The radio emission from X-ray binaries, due to synchrotron radiation from electrons located in relativistic outflows, provides clear evidence for this.

These relativistic jets are the most striking demonstration of the analogy between accretion onto the stellar-mass compact objects in X-ray binaries and onto the supermassive black holes in Active Galactic Nuclei (AGN). X-ray binaries with relativistic jets have thus been denominated ‘microquasars’. Similarities also exist in timing and spectral characteristics. The conjecture, at least for black holes, is that the underlying scaling factor of the physical processes is the gravitational radius \(R_g = \frac{GM}{c^2}\) (and its associated timescale \(R_g/c\)).

The similarities have prompted speculation that some X-ray binaries may be analogs of blazars, AGNs dominated by non-thermal output because their relativistic jet is fortuitously aligned with the line-of-sight. Blazars emit a large fraction of their power in high energy (HE) gamma-rays (>100 MeV). Notwithstanding the possible issue that the microquasar population may be too small for a chance alignment to occur, finding genuine ‘microblazars’ could also prove exceedingly difficult if the scaling strictly holds, since the observed sub-hour TeV flaring in blazars translates to milliseconds for a microblazar. But even if the jet is misaligned, the high particle energies implied by the radio to X-ray observations make it likely, if not unavoidable, that HE gamma-ray emission should be present at some level in generic microquasars. Cataclysmic variables (AE Aqr) and colliding winds in Wolf-Rayet binaries have also been proposed to emit HE gamma-rays - but these systems will not be addressed here.

GLAST observations will soon open a new window into non-thermal processes in accreting binaries. Three compact binaries are presently known sources of HE gamma-rays. These three gamma-ray binaries (in that most of their radiative output is in gamma-rays, regardless of the underlying physics) are probably all rotation-powered by the spin-down of a young pulsar rather than accretion-powered. The current observational status and GLAST prospects for both types of sources are reviewed.

GLAST STUDIES OF ACCRETING BINARIES

X-ray jets

The best evidence for particle acceleration to high energies in accreting binaries comes from the observation of X-ray emission from localized regions in the relativistic jet of two microquasars, XTE J1550-563 and H1743-322...
The radio spectrum from these regions connects remarkably well with the X-ray spectrum across nine decades in energy. The overall spectral slope $\alpha \approx -0.6$ points to synchrotron emission from a canonical non-thermal distribution of electrons $dN \propto N^{-2.2}dE$ over nine orders-of-magnitude. The emission zone is resolved ($\approx 1''$). The equipartition magnetic field is $\approx 500 \mu G$ and the X-ray emitting electrons have energies $\approx 10$ TeV [1].

Electrons of such energies necessarily emit in the GLAST energy range. However, the prospects for detecting this emission are not favorable. Synchrotron losses limit the maximum possible electron energy to a few PeV, in which case the spectrum could extend to a 100 MeV at a level $\approx 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$, too faint for GLAST observations in the Galactic Plane. Moreover, the short radiative timescale ($\approx 5$ days) of PeV electrons would lead to a break or cutoff in the spectrum below 100 MeV. (The timescale also shows the particle acceleration has to occur in situ, although why and how it occurs is not understood but could involve internal shocks, magnetic energy dissipation or a shock with the ISM.) Self-Compton or inverse Compton on CMB photons are also unlikely to lead to detectable levels of emission for GLAST. In both cases an inverse Compton luminosity greater or equal to the synchrotron luminosity requires a magnetic field $< 3 \mu G$, a hundred times below equipartition. Therefore, although these observations undoubtedly show the presence of particles of high-energies in microquasar jets, the gamma-rays emitted in those conditions are not likely to be detected by GLAST.

### Large scale jet-ISM interaction

The dissipation of the jet power in the ISM is a possible source of gamma-ray emission for GLAST. The energy involved can be substantial. For example, radio observations show the a.u.-scale compact jet of Cyg X-1 is prolonged into a parsec-scale structure associated with the termination shock. The inferred power inconspicuously transported to the large scales is comparable to the bolometric luminosity of the binary [2]. Jets can therefore quietly inject large amounts of high energy particles into the ISM, which might be traced by their gamma-ray emission. Heinz & Sunyaev [3] estimate their contribution could reach 10% of the Galactic cosmic ray luminosity. If there is indeed a significant component of high energy nucleons, a jet interacting with a nearby molecular cloud (effectively modeled as an accelerator + beam dump in [4]) would create pions. The subsequent decay, bremsstrahlung and inverse Compton emission can be detected by GLAST, depending upon the jet power and composition, but also upon the duty cycle of the ejection process, the distance of the cloud to the source etc. As an example, the emission predicted in Fig. 12 of [4] is detectable within a year for a microquasar at a distance of 1 kpc (e.g. A0620-00, XTE J1118+480, the latter having the advantage of a large Galactic latitude $b=+62.3^\circ$). Such observations would give new clues as to the content and power of relativistic jets in binaries.

### Gamma-ray spectral states and major ejections

Gamma-ray emission originating closer in to the compact object can also be expected. There is reasonable evidence from CGRO observations for soft power-law tails (spectral slope $\alpha \approx -1.5$) extending beyond 100 keV, up to several MeV in some X-ray binaries [5]. These soft tails are a defining property of the very high state (or steep power law state) together with significant thermal emission (around a keV) and fast variability (QPOs) [6]. This is most clearly seen in the high state of Cyg X-1 where the power-law extends to 10 MeV. Extrapolating shows the 100 MeV emission was beyond the reach of EGRET but should be detectable by GLAST within days. Cyg X-1 spends 90% of its time in the hard state where there is a hint for a similar, but fainter, power-law component that could be detected in a year by GLAST. These power-laws can be produced in plasmas where a fraction of the accretion energy goes into non-thermal channels [7]. Models predict a cutoff in the GLAST energy range either because there is a maximum electron energy or because pair production sets in when the plasma compacity is high.

Changes in X-ray spectral states can therefore be surmised to be associated with changes in HE gamma-ray luminosity, the very high X-ray state (resp. hard X-ray state) involving high (resp. low) levels of gamma-ray emission. Interestingly, spectral state changes from hard to very high X-ray states have been conjectured to be associated with major relativistic ejections [8] and one should note, perhaps naively, that if jets are composed of $e^+e^-$ pairs then there has to be some gamma-ray emission linked to the pair production, if only at a few MeV. Radio/IR observations of discrete ejections in GRS 1915+105 show non-thermal emission cooling with expansion. Extrapolating back to early times, the fluence expected in a day by Attoyan & Aharonian [9] in HE gamma-rays is detectable by GLAST. Gamma-
ray monitoring of outbursting binaries or sources such as GRS 1915+105, a task that is well-suited to GLAST, can therefore shed light on how spectral state changes relate to ejection events.

THE OBSERVATIONAL STATUS: GAMMA-RAY BINARIES

The view from space

Although the above (should) demonstrate that there are reasonable grounds to expect HE gamma-rays from compact binaries, observational confirmation has proved elusive and when found, arguably disconcerting. Several tentative associations of binaries with EGRET sources were made based on positional coincidence and/or the detection of variability, with the source 2CG 135+01 figuring prominently as the first and most secure: follow-up observations carried out after the initial COS B discovery had revealed a high-mass X-ray binary, LS I+61 303, in a 26 day elliptical orbit showing periodic radio outbursts [10]. The latter feature being rare, this highlighted the system as a plausible counterpart. Yet, although variability was reported in the EGRET data, neither this nor the position were enough to formally identify the two (the HE variation not being tied to variability at other wavelengths and the stellar counterpart being localized only in between the 95% and 99% confidence contours of the HE source). The limited angular resolution combined with the strong underlying Galactic diffuse HE emission resulted in error boxes of a several tens of arcmins, too large to pick up the needle in the haystack of possible Galactic Plane counterparts.

The view from the ground

Breakthrough observations were obtained by the ground-based Cherenkov telescopes operated by the HESS and MAGIC collaborations. These observe at a higher threshold ($\geq 100$ GeV) but benefit from a larger collecting area and a better angular resolution. Three binaries were detected: PSR B1259-63, LS 5039 and LS I+61 303 [11, 12, 13]. The latter two had tentative EGRET associations but not PSR B1259-63, possibly because the HE gamma-ray emission is highly variable along the 3.5 year orbit and confined to a short period around periastron passage. The next passage occurs this year, too early for GLAST so searches may have to wait 2010 (unfortunately, periastron passage cannot be observed by HESS before 2014). The localizations are much more precise: for instance, LS 5039 is coincident with HESS J1826-148 within the positional uncertainty of 30”, excluding a nearby SNR and a pulsar that were within the error box of the EGRET source 3EG 1824-1514. More importantly, all three binaries display variability. In LS 5039, it was demonstrated that the $\geq 100$ GeV flux is strongly modulated on the orbital period [14] and there is little doubt that the fluxes measured in PSR B1259-63 and LS I+61 303 also depend on orbital phase.

Gamma-ray binaries

All three binaries have high mass O or Be type companions with compact objects in eccentric orbits. The X-ray output from these binaries is about $10^{34}$ erg/s, rather low in itself compared to typical X-ray binaries, and smaller or comparable to the emission above 100 MeV. These systems are therefore gamma-ray loud, a first surprise. All of them display radio emission, resolved in LS 5039 and LS I+61 303 as collimated outflows on milliarcsecond scales, immediately suggesting a microquasar nature [15]. X-ray and radio variability, when (and if) present is of limited amplitude (odd in accreting binaries) and occurs on the orbital timescale. The overall spectral energy distributions are similar for all three systems, showing (in $vF_v$) a rising spectrum from radio to X-rays flattening around an MeV and reaching energies of several TeV. However, PSR B1259-63 is not a microquasar but a young 48 ms pulsar with a spin-down power $\approx 10^{36}$ erg s$^{-1}$. The relativistic pulsar wind is sufficient to quench any wind accretion and the emission is thought to arise from particles accelerated where the pulsar and stellar wind interact [16]. This paints a rather different picture than accretion-powered scenarios.
Gamma-ray binaries as compact pulsar wind nebulae

Why the observational properties of the three gamma-ray binaries should bear any resemblance is disconcerting unless all are actually rotation-powered by a young pulsar [17]. This can explain the low, steady level of emission, conceivably modulated as the pulsar moves around its orbit. Pulsed emission would be absorbed in the stellar wind because of the smaller orbital separations in LS 5039 and LS I+61 303 (as observed near periastron in PSR B1259-63). The pulsar wind is confined by the stellar wind to a cometary nebula pointing away from the massive companion, producing the collimated radio outflow. Radio VLBI observations of LS I+61 303 recently reported by [18] are consistent with this picture, showing a periodic sweep of the radio tail with orbital phase which appears irreconcilable with an accretion-powered jet: LS I+61 303 is almost certainly powered by a pulsar. The small-scale radio morphology of LS 5039 has been successfully modeled as a pulsar wind nebula [17] but this does not provide the same level of certainty in the absence of observations at other orbital phases. Other models have proposed the emission arises in a relativistic jet powered by accretion [19, 20], but that hypothesis seems rather uneconomical to this author. At this stage, it seems more probable that HE gamma-ray emission from accretion-powered binaries has yet to be detected and that, when this will be achieved, their observational properties will be clearly different from those of the rotation-powered binaries.

GLAST STUDIES OF ROTATION-POWERED BINARIES

Gamma-ray orbital modulation

That all three gamma-ray binaries have high-mass stellar companions may be instrumental to generate the HE emission, as these will provide copious amounts of seed photons for inverse Compton scattering. On the other hand, the large photon densities at UV energies also imply pair production with TeV photons can be important. The starlight both provides a source and a sink for gamma-rays. Gamma-ray absorption has a strong orbital dependence as the cross-section for pair production depends on the angle between the two photons. The effect can be dramatic on gamma-rays emitted towards the observer and crossing head-on the path of stellar photons. In LS 5039, the tight 4-day orbit brings the compact object to within a stellar radius from the O6V star. Gamma-rays of >30 GeV emitted close to the compact object are modulated with peak attenuation at superior conjunction (when the compact object is behind the star as seen by the observer) [21]. Such an orbital modulation has been observed in LS 5039 by HESS with a peak and trough at the predicted orbital phases [14].

However, the flux at superior conjunction is not completely absorbed. Furthermore, the >100 GeV spectrum varies from a soft power law at superior conjunction (low flux) to a hard power law at inferior conjunction (high flux), whereas pure absorption predicts a dip in the spectrum around a TeV. Other effects must play a role. One is that a pair cascade is initiated when the newly created \( e^+ e^- \) up-scatter star photons back into the absorption range. The magnetic field has to be low enough (\( \leq 10 \) G) to prevent synchrotron losses from dominating. The radiated energy is redistributed below the pair production threshold (\(< 30 \) GeV) i.e. in the GLAST range. Calculations show an anti-correlation of the HESS and GLAST light-curves [22], detectable within a year [23], that would prove the existence of a cascade.

A second effect is that inverse Compton scattering is also anisotropic. For example, this will decrease the gamma-ray flux around inferior conjunction, when the (incoming) star photons and (outgoing) gamma-ray photons both go towards the observer: in this configuration the energy of the outgoing photon and the cross-section for IC are small. There actually is a hint of a dip in the HESS light-curve at this phase.

Probing pulsar winds

Besides these geometrical effects, the efficiency with which gamma-rays are emitted may also change along the orbit. The variations in the >100 GeV flux observed by HESS and MAGIC in LS I+61 303 and PSR B1259-63 do not match the expected light-curve for pure absorption (whose effect is marginal due to the wider orbits) and so must be intrinsic to the emission process [24]. LS I+61 303 may prove a Rosetta stone for this problem as its orbit is both wide enough (0.2-0.7 a.u.) to avoid most cascading and absorption, but short enough (26 days) to allow for detailed studies over many orbits. MAGIC reports a minimum in flux close to periastron (which is close to inferior conjunction, where absorption is minimal) and a maximum towards apastron. The explanation is straightforward with a compact pulsar
wind nebula. The pulsar wind is contained by the stellar wind of the Be companion. At periastron, the ram pressure of the dense equatorial wind crushes the PWN nebula to a small distance from the pulsar. The magnetic field at the shock location is strong and particles lose energy rapidly to synchrotron emission without radiating much inverse Compton above $>10$ GeV. At apastron, the stellar wind is polar and diffuse, implying a large shock distance and weaker magnetic field, allowing for higher particle energies emitting more HE inverse Compton gamma-rays. Hence, phase-resolved spectral energy distributions from X-rays to VHE gamma-rays can yield information on the magnetic field at different locations, forming a probe of the relativistic wind as a function of distance to the pulsar.

**Population studies of gamma-ray binaries**

The pulsar spin-down timescale is short ($\sim 10^5$ years for PSR B1259-63) and can only power the binary emission for a brief period of time. Accretion from the stellar wind is then no longer quenched by a pulsar wind and an X-ray pulsar turns on. Hence, gamma-ray binaries are the progenitors of the longer-lived, accretion-powered high-mass X-ray binaries (HMXBs). Because most of their output is in gamma-rays, GLAST all-sky observations provide a unique way of identifying these progenitors and studying them as a population, constraining the birth rate and evolution of HMXBs. Population synthesis calculations find there should be around 30 active gamma-ray binaries in order to match the present-day population of HMXBs, assuming the rotation-powered phase lasts only $10^4$ years [25]. They should be visible throughout the Galaxy if their luminosity in the GLAST band is comparable to that of the three known systems ($\sim 10^{35}$ erg s$^{-1}$). This estimate does not take into account the reduction in sensitivity to be expected in the Galactic Plane due to the diffuse emission. In this respect, the Magellanic Clouds, which harbor a comparatively very large population of HMXBs, might also make for good dedicated studies despite being more distant.

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