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GAMMA-RAY EMISSION FROM BINARIES WITH GLAST

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Abstract. The upcoming launch of GLAST will bring unprecedented sensitivity and coverage to the high-energy gamma-ray domain (0.1-10 GeV). Studies of compact binaries, composed of a normal star and a compact object, will greatly benefit from these new observations. Gamma-ray emission will shed new light on the non-thermal processes that are known to occur in these sources and how they are powered (accretion, pulsar spindown etc). In light of the history of gamma-ray emission from binaries, I will discuss the foreseen detections and their impact on our knowledge of pulsar winds and the link between accretion and ejection.

1 Introduction

Gamma-ray emission from binaries has suffered from a checkered history. In 1962, the first cosmic source of X-rays beyond our solar system, Sco X-1, was discovered and rapidly associated with a compact binary (Giacconi et al. 1962). By the 1970s, papers on X-ray binaries were regularly making it into *Nature* since the fast pace at which X-ray observations were evolving led to discovery after discovery into the fascinating physics of these objects. At the same time, early efforts were made to extend the observations to higher energies. ESA's Cos B unveiled a couple dozen sources of high energy gamma-rays in our Galaxy, one of them (2 CG 135+01) tentatively related with a binary system composed of a Be star and a mysterious compact object (Gregory et al. 1979). Many such systems were already known in X-rays: what made this one highly unusual was that it was also a radio emitter, bursting at periodic intervals. Yet, a firm association could not be made, even using the data collected by EGRET in the 1990s, because of the poor angular resolution and the limited sensitivity which did not allow detailed timing studies. At even higher energies, the 1970s saw pioneering efforts to detect the flash of Cherenkov light emitted as a gamma-ray impinges on the upper atmosphere. In the 1980s, various devices looking at very high energies started collecting an amazing collection of results, notably reporting constant, flaring, pulsing or episodic emission from binaries – including a muon signal from Cyg X-3 that was a big thorn in the foot of theorists (see Chardin & Gerbier 1989 for a critical assessment). Unfortunately, confirmation was hard to get and by the end of the 1980s, as the third generation of TeV gamma-ray detectors were about to come on-line, the situation had become extremely confused if not controversial.

In 1992, Trevor Weekes wrote a review paper on "Galactic Sources of VHE Gamma-rays" which still makes for enlightening reading (in spite of the dramatic improvements the field has seen recently). He separates VHE sources into three categories: (1) the established sources, whose emission was predicted by and confirmed by several groups – there was only one source at the time, the Crab Nebula; (2) the predicted sources of VHE emission that are not detected yet such as supernova remnants; (3) the serendipitous sources. "In this category are included all sources that do not have any firm a priori basis for their selection as candidate VHE sources: *i.e.* there are no observations at other wavelengths that make a compelling case for the presence of non thermal processes, nor are there detailed models that necessitate VHE emission" (Weekes 1992). VHE gamma-ray emission from binaries obviously fell into this category. At the time, X-ray observations had more or less established that X-ray binaries seemed to (roughly) show two types of spectra: a soft, thermal spectrum peaking in soft X-rays and a hard power-law spectrum cutting off around 100 keV. Although radio emission was observed, there were few outstanding reasons to expect TeV non-thermal emission.

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This story takes a first interesting twist since 1992 was also the year during which Mirabel and Rodriguez published their discovery of the first "microquasar", appearing on the cover of *Nature* (Mirabel & Rodriguez 1992). In 1994, they followed-up with the observation of superluminal motion in the radio emission of GRS 1915+105 (Mirabel et al. 1994). These, and many other observations, showed that binaries power highly relativistic jets hosting non-thermal distributions of high-energy particles, and that these jets may be the major depositaries of the energy provided by accretion. All of a sudden the scale-free character of physical processes between stellar-mass black holes and super-massive black holes, encapsulated in the term microquasar, became much more deeply rooted in reality. The second twist was that 1992 was also the year during which T. Weekes and his team reported the discovery of TeV emission from an active galactic nucleus (Punch et al. 1992). The TeV emission arise from a relativistic jet whose orientation happens to coincide with our line-of-sight, relativistic effects causing an enormous boost to the observed high energy flux. Thus, by the end of 1992, "a compelling case for the presence of non thermal processes" and high energy gamma-ray emission in binaries was starting to emerge. The 1990s saw Cherenkov imagers putting TeV astronomy on a sure footing and EGRET expand the catalog of GeV sources to the hundreds. Unfortunately, none could confim gamma-ray emission from binaries and the unfolding of the story had to wait the mid-2000s.

2 Seeing the gamma-ray light in binaries

Combining fine stereoscopic imaging of the Cherenkov shower, multi-telescope trigger and a large collecting area, HESS was the first instrument to firmly detect gamma-ray emission from a binary, PSR B1259-63 (Aharonian et al. 2005b). This was soon followed by the detection of LS 5039 (Aharonian et al. 2005a) and LS I +61 303 (by MAGIC, Albert et al. 2006). What makes those detections and associations firm is (1) the quality of the localizations (sub-arcmin) which ruled out other possible counteparts; (2) the ability to consistently re-observe the sources; (3) the presence of periodic variability tied to orbit, most prominently in LS 5039 where the period measured in gamma-rays precisely matches the orbital period from the radial velocity seen in the optical spectral lines of companion star (Aharonian et al. 2006).

What is the distinct factor that makes those three binaries gamma-ray emitters compared to the hundreds of compact binaries known? All have high-mass O or Be companions. The large luminosity and high temperature of the stellar radiation compared to that in low-mass X-ray binaries / microquasars may play an important role in seeding inverse Compton scattering to VHE energies. The presence of a strong stellar wind – unlike the late-type donor stars of LMXBs – may also play a major role. The periods are 4 days (LS 5039), 26 days (LS I +61 303) and 3.5 years (PSR B 1259-63). The orbits are eccentric and the compact object always passes within an astronomical unit of its companion star: this may be important. Most tellingly, all of these systems are radio emitters. This is unusual in high-mass X-ray binaries: of the 114 sources in the HMXB catalog of Liu et al. (2006), only 9 are radio-emitters. In LS 5039 and LS I+61 303, radio very long baseline interferometry resolved the emission down to milliarcsecond scales.

The nature of the compact object in LS 5039 and LS I +61 303 is unknown but optical studies constrain the mass function. For both systems, a black hole would imply the systems are seen with a low inclination (about 20-30 degrees) whereas a neutron star would imply larger inclinations (about 50-70 degrees). In PSR B1259-63, the compact object is 48 millisecond young pulsar. Based on their similar observational properties, I have argued that all three systems are composed of a young neutron star (Dubus et al. 2006b, 2006c). The young pulsar generates a strong relativistic wind which interacts with the stellar wind of the massive star. Particles are accelerated to very high energies at the shock between the two winds, making those objects *compact plerions* (Tavani & Arons 1997). Because their X-ray luminosities (about 10^{33}-10^{34} erg/s) are lower than their gamma-ray luminosities (about 10^{34}-10^{35} erg/s above 100 MeV), because of the unity in mechanism, and to distinguish them from the usual X-ray binaries powered by accretion, I have suggested to call these outstanding sources *gamma-ray binaries* (Dubus et al. 2006b).

3 Pulsar wind physics with gamma-ray binaries

Strong evidence towards explaining gamma-ray pulsars by a pulsar wind - stellar wind interaction has come about from the weakest photons. The stellar wind collimates the shocked material into a comet-like shape. This is seen on a bigger scale in fast-moving pulsars zipping through the ISM (e.g. the Mouse nebula). The scale is set by the pulsar – shock distance which is much smaller in gamma-ray binaries because the stellar wind is much denser than the ISM. Furthermore, the axis of the comet nebula changes with time as the pulsar revolves around its companion star. This creates complex radio morphologies that should exhibit orbital-phase related changes. Such an observation was reported late last year by Dhawan and collaborators (Dhawan et al. 2006). VLBI radio maps show a periodic sweep of a radio tail with orbital phase in LS I +61 303. This appears irreconcilable with an accretion-powered jet to this author: LS I+61 303 is almost certainly powered by a pulsar.

The gamma-ray emission and cometary morphology of the shocked material provide new ways to investigate pulsar wind physics. It has been known since the 1960s that high magnetic fields and fast rotation in pulsars lead to the formation of a strongly relativistic wind. The spin-down energy close to the pulsar is in the magnetic field. Yet, observations of pulsar wind nebulae such as the Crab show that this energy is transfered into particle kinetic energy on scales of 0.1 pc. This conclusion is reached by modelling the emission at the shock of the pulsar wind with its surrounding medium (Kennel & Coroniti 1984). The pre-shock pulsar wind itself is not observable because the magnetic field is frozen in the particle outflow so that there is no synchrotron emission. This process by which a strongly magnetized structure leads to a highly relativistic particle outflow is still poorly understood. It is of broad interest to astrophysicists as similar processes may occur in the vicinity of rotating black holes. Indeed, models of "Poynting-flux dominated" jets for gamma-ray bursts and AGNs have raised much interest in the past years.

Gamma-ray binaries present new prospects for studying this on hitherto unreachable scales. The pulsar wind terminates very close to the pulsar because of the dense stellar wind of the early-type companion, down to 0.01 AU in LS 5039. In addition, the distance of the shock to the pulsar varies along the orbit as the compact object samples varying density conditions. The wind parameters determine the physical conditions at the shock, which in turn influence the emission properties. The proposed methodology is to combine well-sampled multi-wavelength observations over many orbits in several objects with careful modelling in order to derive a measure of the magnetization (the relative importance of magnetic and kinetic energies) as a function of distance to the pulsar and constrain particle acceleration at the termination shock. In these proceedings, Ceruti et al. report on a study of the gamma-ray modulation of LS 5039 as seen by HESS, paving the way towards this objective. They show that the combination of anisotropic inverse Compton scattering and gamma-ray absorption by pair production on stellar photons suffices to explain the spectral changes with the orbit. The magnetic field at periastron is constrained to 0.8 ± 0.2G and the power-law distribution of the injected accelerated electrons has an index of -2 ± 0.3. The model predicts a very strong modulation in the GLAST energy range, almost anti-correlated with HESS (Dubus et al. 2007). Extending such models to the other gamma-ray binaries using HE and VHE data from Cherenkov telescopes and GLAST promises a new window to understand pulsar winds. GLAST should also enable the detection of several more systems from their bright gamma-ray emission (compared to X-rays): there should be a few dozen in our Galaxy.

4 Ficta voluptatis causa sint proxima veris

With gamma-ray binaries powered by pulsars, whether the accretion-powered microquasars (*X-ray* binaires) emit gamma-rays like AGNs remains an open question, but one likely to be settled in the coming years. Very recent observations by the MAGIC collaboration, made public in June 2007, indicate fleeting gamma-ray emission from the binary Cyg X-1 (Albert et al. 2007). Again, the companion is an early-type star and radio images show a compact jet. However, the gamma-ray emission is definitely not powered by a pulsar. This is a canonical accreting source and, indeed, the first source where dynamical evidence for a black hole was found. The MAGIC detection occurs during one night and is of low significance: 3.2σ post-trial. The emission appears to last only a few hours and, crucially, is related to simultaneous strong flaring in the X-ray band adding credence to the detection.

This author wants to believe but cannot resist the temptation to quote T. Weekes once again: "One of the chief concerns in VHE gamma-ray astronomy must be the credibility of the episodic source detections [...] It is no embarrassment to theoretical astrophysics if no VHE emission at all is seen from any of these objects". There is definite evidence for non-thermal particles in Cyg X-1 and other microquasars, but one has to concede that the lack of VHE emission (at currently detectable levels) would be no embarrassment. Observations of radio to X-ray emission on parsec scales due to synchrotron radiation from electrons located in relativistic outflows (Corbel et al. 2002) provide limits on the inverse Compton that can be expected: these are well below detectable levels with GLAST or ground-based VHE telescopes. CGRO observations have detected a non-thermal power-law tail in both the low and hard states of Cyg X-1. It is steep (photon index ≈ 3, Grove et al. 1998). Extrapolating it to the GeV range shows it may be detectable there by GLAST. Extrapolating it to the TeV domain shows that what MAGIC detected was well above, most likely another component. This is good news, as it improves the prospects of future detections with GLAST, and bad news as it increases the burden of proof for observers: this emission was not exactly expected.

At the risk of re-stating the obvious, further observations will be needed to confirm episodic gamma-ray emission from Cyg X-1. Strong X-ray flaring episodes with order-of-magnitude changes in luminosity, akin to the one associated with the MAGIC detection, have been observed several times before (Golenetskii et al. 2003). There appears to be no evident link to the X-ray spectral state, which is slightly disappointing as changes in X-ray spectral states (on longer timescales) have been conjectured to be linked to major ejection episodes (Fender et al. 2004). The statistics are uncertain but there may be several such strong, rapid flares every year so a dedicated, patient VHE monitoring program has the capacity to pick a few more. The Cyg X-1 flares have been related to the Supergiant Fast X-ray Transients, high-mass X-ray binaries that show strong flaring decaying rapidly (Negueruela et al. 2007). MAGIC may have uncovered just the tip of the iceberg of a whole new phenomenology of fast transient gamma-ray emitters. Detecting transient emission is ideally suited to the abilities of GLAST. The coming years will see gamma-ray observations bear on non-thermal processes around compact objects and their relationship to the formation of relativistic jets.

5 Conclusion

Emission from compact binaries above a few MeV was speculative and on uncertain observational grounds until the results presented above were obtained. The current Cherenkov telescopes together with GLAST are opening up a new window into the physics at work close to black holes and rapidly-rotating neutron stars with great breakthrough potential. Studies of microquasars link up with active galactic nuclei or gamma-ray bursts studies, and studies of gamma-ray binaries link up with studies of pulsar wind nebulae or isolated neutron stars.

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