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## High energy emission from binaries with young pulsars

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**Abstract.** I review the formation of high energy radiation in the context of young pulsars orbiting massive stars such as PSR B1259-63. All detected gamma-ray binaries, systems where most of the radiative output occurs at energies above an MeV, could be powered by the dissipation of the pulsar rotational energy. The orbital-phase dependent radio morphology in LS 5039 and LS I +61°303 supports this interpretation. A magnetar-like burst has recently been observed that appears to be associated with LS I +61°303. The presence of a massive star brings strict geometrical and dynamical constraints on the physical processes at work. This can be used to probe pulsar winds on hitherto inaccessible scales.

### 1. Introduction

Several binaries have been detected at very high energies (VHE,  $>100$  GeV) in the past years (see contributions by J. Holder, S. Ohm and M. Ribó in these proceedings). Several high-energy (HE,  $>100$  MeV) gamma-ray sources observed by EGRET had been tentatively associated with binaries (eight can be found in the literature). The best-known is one of the brightest sources in the GeV sky, 2CG 135+01, detected more than 25 years ago. Searches for counterparts had identified the binary LS I +61°303 as the prime candidate because of its unusual radio emission (see below).

Imaging arrays of Cherenkov telescopes (HESS, MAGIC, VERITAS) removed all ambiguities based on their good spatial resolution and, most of all, their sensitivity that enabled the detection of orbital variability (?). The confirmed VHE-emitting binaries are PSR B1259-63, LS 5039 and LS I +61°303. They have been regularly detected and the orbital variability confirmed. In addition, a VHE flare at the detection threshold has been reported from the black hole candidate Cyg X-1 during a high X-ray flux state (?). If confirmed by another detection this would constitute a tremendous result and open a new window into the physics of microquasars. Finally, the VHE source HESS J0632+057 has also been tentatively associated with a binary (?).

#### 1.1. Gamma-ray binaries

PSR B1259-63, LS 5039, LS I +61°303 and HESS J0632+057 (in as much as it is indeed a binary) all share similar observational characteristics. Three have high-mass Be companions, one (LS 5039) has an O companion. This is low number statistics but that three have Be stars is perhaps a clue to their evolution. Cyg X-1 also has a massive companion. High stellar luminosities and/or strong stellar

winds may be an essential ingredient to generate a high VHE gamma-ray flux — by inverse Compton emission or pion production of high energy protons with the wind (see contribution by A. Araudo and G. Romero). All are X-ray sources and were known as high-mass X-ray binaries. However, their X-ray output reveal little as to their outstanding properties. A distinguishing trait is their hard spectra with no cutoff up to 100 keV, which would make them identifiable to hard X-ray telescopes like Simbol-X or NuSTAR (?). Another distinguishing trait is that all are radio-emitters. This is rare in high-mass X-ray binaries: only 10 out of 115 HMXBs in (?) are radio sources, including PSR B1259-63, LS 5039, LS I +61°303 (and Cyg X-1). HESS J0632+057 was also reported to be associated with a variable radio source at this meeting (see contribution by J. Skilton), adding credence to the binary interpretation.

The outstanding feature of PSR B1259-63, LS 5039, LS I +61°303 and HESS J0632+057 is that most of their radiative output is emitted in photons with energies greater than an MeV. Their spectral energy distribution show a rise in  $\nu F_\nu$  from radio to X-rays (ignoring the large contribution from the early-type companion in optical/UV), flattening or peaking between a few MeV and a few GeV, decreasing at TeV energies. Their VHE spectral luminosities are of the same order as their X-ray spectral luminosities. This is a major difference with X-ray binaries and the term gamma-ray binaries highlights this (?). For instance, it clearly separates Cyg X-1 from other VHE emitting binaries: in Cyg X-1, the X-ray luminosity is orders-of-magnitude greater than the transient VHE emission reported by MAGIC. The difference between X-ray binaries and gamma-ray binaries may not only be phenomenological but also have roots in the physical mechanisms at work in these systems.

## 2. Pulsars in gamma-ray binaries

PSR B1259-63 was discovered in a radio search for pulsars (?). The pulsations identify the compact object as a neutron star. PSR B1259-63 has a 3.5 year orbit when LS I +61°303 has a 26 day orbit and LS 5039 has a 4 day orbit. The orbital motion of LS 5039 and LS I +61°303 can be followed in the radial velocity of optical lines from the companion (?). The solutions accommodate a neutron star if the systems are seen at inclinations  $\approx 60^\circ$  or black holes of a few solar masses for very low inclinations. The similarities in spectrum and variability between the three systems argue in favour of pulsars *à la* PSR B1259-63 over black holes. Gamma-ray binaries would thus all have young pulsars interacting with their companion (?).

The lack of pulsations in LS 5039 or LS I +61°303 should not surprise. The stellar wind from the companion is expected to absorb any radio pulsation from a spinning neutron star, as is observed in PSR B1259-63 for a few months when the neutron star nears periastron passage. The binary separation in LS I +61°303 is actually never greater than the binary separation at periastron in PSR B1259-63, so the amount of stellar wind material probed is always very important. The absorption is even stronger in LS 5039. No limits on radio pulsations on LS 5039 or LS I +61°303 could be found in the literature. There are limits on pulsations in the X-ray band:  $< 25\%$  in the 0.01-1000 Hz range for LS 5039 (?) and  $< 1\%$  in the 0.01-500 Hz range for LS I +61°303 (?). X-ray

pulsations are not necessarily expected, especially if the pulsar is non-accreting and its pulsed X-ray emission faint: in PSR B1259-63 there is a <2% upper limit on the amplitude of an X-ray pulsation at the 47.7 ms radio pulse period (?).

### 2.1. PSR B1259-63

The measured decrease in frequency of the radio pulses from PSR B1259-63 indicate a spindown power  $\dot{E} \approx 8 \cdot 10^{35} \text{ erg s}^{-1}$ , a magnetic field of  $3 \cdot 10^{11} \text{ G}$  and a spindown timescale of 300,000 years (?). Pulsar models have the rotation energy carried away in a highly relativistic wind (?). Observations of pulsar wind nebulae (PWN) show the pulsar wind emits little radiation before it interacts with the surrounding medium (as expected if the wind particles have no momentum transverse to the magnetic field lines). In PWN this is usually material in the supernova remnant or the ISM. Here, the pulsar wind interacts with the stellar wind of its companion. Be stars are  $\approx 10 M_{\odot}$  massive stars rotating rapidly and characterised by a dense circumstellar envelope in the form of a keplerian equatorial disk (?). Be stars also have a fast, tenuous, “polar” wind. The interaction between the pulsar wind and the stellar wind (equatorial or polar) leads to a shock where the ram pressure of the winds balance. Particles are isotropised and accelerated to very high energies at the shock. The subsequent synchrotron and inverse Compton emission results in radio to TeV radiation (??). HESS observations of PWN show the fraction of the spindown power that is emitted in the VHE band is about 0.1% (?). This also applies to PSR B1259-63 although the interaction occurs much closer to the pulsar. The same process could work in LS 5039 and LS I +61°303 (??). The power in the pulsar wind decreases as it spins down. At some point the power is insufficient to hold stellar material at bay and accretion occurs. The outcome is an X-ray pulsar in a Be HMXB. The lifetime of a gamma-ray binary is short, shorter than the HMXB phase. Population synthesis indicate there may be about a hundred such systems in our Galaxy. The planned Cherenkov Telescope Array would be able to detect about half of them (?).

### 2.2. Collimated outflows

The overall geometry of the interaction region in the hydrodynamical approximation is set by the ratio of the momentum fluxes  $(\dot{M}_w v_w)/(E/c)$ . The interaction has a cometary shape with an opening angle decreasing with increasing strength of one of the winds. This situation is strictly identical to what happens in the colliding wind binaries (see the many contributions on this subject in this volume). A difference is that the study of an interacting pulsar - stellar wind system requires relativistic MHD simulations and these can show deviations from the hydro expectations. Steps have been taken towards this aim with application to the case of PSR B1259-63 (?). Very high bulk Lorentz factors are found in the post-shock wind in this simulation, possibly because the external medium acts as a nozzle and there is no magnetic field to which to channel part of the energy of the flow. This can be contrasted with the classic PWN model of ? where the post-shock flow speed is  $c/3$  decreasing to  $\sigma c$  (where  $\sigma$  is the magnetisation of the initial pulsar wind). Very high bulk Lorentz factors seem unlikely because they would cause a huge (de)boost of the emission when the flow is (un)aligned

with the line-of-sight, giving a hugely phase-dependent lightcurve compared to what is observed in PSR B1259-63 in X-rays or VHE gamma-rays.

The particles gradually lose energy by radiative or adiabatic losses as they are carried away in the post-shock flow. Synchrotron emission initially in the tens of MeV domain shifts down to X-rays, optical and radio far away from the compact object, in regions that are optically thin to free-free absorption. In LS 5039 and LS I +61°303, VLBI observations have resolved the radio emission on milliarcsecond scales (??). Unfortunately, this has not yet been achieved for PSR B1259-63 for instrumental reasons. A natural interpretation of the maps was that the radio emission arises from compact jets akin to those seen in the low/hard X-ray state of microquasars. However, the radio maps of LS 5039 and LSI +61 303 show that the position angle of the elongated emission changes with orbital phase in a reproducible way from orbit to orbit. This is does not fit with a relativistic jet whose orientation does not change as the compact object moves along its orbit. On the other hand, this fits nicely with a cometary tail directed away from the companion star that is turning as the pulsar moves along its orbit. This is a good reason to support the pulsar hypothesis.

One issue is whether such collimation can be expected at all. In LS 5039 the momentum flux of the stellar wind is about 100 times greater than that from a  $10^{36}$  erg s<sup>-1</sup> pulsar wind because the orbital separation is so small (a tenth of an a.u.) and the densities so great. In LS I +61°303 the momentum flux of the polar wind is comparable to that of the pulsar wind. In this case no collimation is expected. It is unclear what happens if the pulsar wind interacts with the equatorial envelope. A sign that this may be happening is that LS I +61°303 has radio outbursts that are very similar to those seen in PSR B1259-63 where they are attributed to the pulsar crossing the Be disk. Alternatively, the pulsar wind may cause the stellar wind to become confined and it is radio emission from the stellar wind that we are observing. Investigations have only started and there are good prospects that future work will resolve the issue through the comparison of observations with numerical modelling.

### 2.3. A magnetar burst in LS I +61°303 ?

An intriguing piece of evidence with regards to the nature of the compact object was revealed on September 10, 2008. At 12:52 UT the *Swift* BAT triggered on a burst in the direction of LS I +61°303. Subsequent analysis revealed that the very spiky burst lasted only 230 ms and had a spectrum best fitted by a 7.5 keV blackbody. Assuming a distance of 2 kpc (LS I +61°303), the total energy involved is  $10^{37}$  erg s<sup>-1</sup> and the radius of the blackbody is 100 meters (?). The lightcurve, duration, fluence and spectrum have all the right characteristics of a magnetar burst (?). The association of the BAT burst with LS I +61 303 would provide further evidence for a neutron star.

Was the burst associated with LS I +61°303 ? Current evidence suggests it was. The BAT localisation places the burst within 88 arcseconds of the binary, with an uncertainty radius of 2.2 arcmin. LS I +61°303 is by far the strongest radio and X-ray source in the BAT error circle. ? point out there are several other X-ray sources in the error box. These are faint X-ray sources detected in a 50 ks Chandra exposure, with fluxes  $\gtrsim 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>. A density of about 0.3 sources per arcmin<sup>2</sup> are expected at or above this flux limit using

the Galactic Plane log N - log S relationship from ?. This is compatible with the handful sources that are seen in the 15 arcmin<sup>2</sup> circle so there is nothing unusual: there are plenty of faint X-ray sources everywhere in the Galactic Plane. However, LS I +61°303 is about 1000 times brighter in X-rays than those faint sources. The density for sources at least as bright is about  $3 \cdot 10^{-5}$  per arcmin<sup>2</sup>. The probability of a chance coincidence is  $< 4 \cdot 10^{-4}$ . This carries no a priori. Consider now that there are only  $\sim 20$  known candidate SGR/AXP in our Galaxy. The source density is very small. If it were bigger then we should see many more SGR bursts and flares. There's only one major SGR flare per year or so and there is no observational bias going against seeing those. Hence, it seems unlikely the space density of magnetars is very large and that the association with LS I+61°303 a pure coincidence. Additional observations reported at this conference (see the contribution of A. Muñoz-Arjonilla) did not reveal any other promising counterpart besides LS I+61°303.

It is curious that no other burst has been seen in the 30 years this source has been scrutinized (there are no GRB in the databases that are good candidates for a previously overlooked burst). The BAT sensitivity around 10 keV may have been the key instrumental breakthrough. The burst suggests a magnetar strength field of order  $10^{15}$  G. Prohibiting accretion then requires a pulsar spindown power greater than  $5 \cdot 10^{36} B_{15}^{-2/7} \dot{M}_{18}^{8/7}$  erg/s or, equivalently, a spin  $P < 1.5 B_{15}^{4/7} \dot{M}_{18}^{-2/7}$  seconds. AXPs/SGRs cluster at periods of 7s. Trying to place LS I +61°303 in the pulsar ( $P, \dot{P}$ ) diagram, it is tempting to locate it midway between AXPs/SGRs and the high energy emitting pulsars (now discovered aplenty by *Fermi* as we learned at this conference – see contribution by I. Grenier). This would require a lower magnetic field, about  $10^{14}$  G. The neutron star might be at the tail end of magnetar activity, perhaps explaining why burst activity is rare and why the quiescent X-rays do not show the characteristic pulsed, thermal spectrum of magnetars. Finally, an intriguing speculation is that the roughly circular, fragmented radio emission seen surrounding LS I +61°303 with a 5 arcmin radius is the remnant of the supernova that gave birth to the neutron star. ? favour an HII region, in part because the SNR would be so very faint for its size (at the distance of LS I +61°303). There are only single frequency radio observations and the radio spectrum needs to be checked for thermal or non-thermal emission.

### 3. Modelling the high energy emission

Modelling the high energy emission poses some interesting challenges. Take LS 5039. The compact object is between 1 and 3 stellar radii away from the surface of the  $10 R_{\odot}$ , 40 000 K companion. The companion fills in almost half of the sky seen from the pulsar. Ram pressure balance assuming a typical O star wind and a PSR B1259-63 type pulsar puts the interaction site about  $10^{11}$  cm away from the pulsar. A 50 ms pulsar has a light cylinder radius  $R_L = cP/2\pi$  of  $2 \cdot 10^8$  cm, so the shock is between  $10^3$  and  $10^4 R_L$ . As a comparison, the Crab pulsar termination shock is 0.1 pc away or about  $10^9 R_L$ . Gamma-ray binaries probe pulsar winds much much closer in.

The stellar luminosity is about  $10^{39}$  erg s $^{-1}$  so there is a huge number of photons with an average energy of a few eV on which the high energy particles can interact. The observer will probe different line-of-sights to the interaction region as the system revolves. The interaction region itself may change in shape since the orbits are eccentric and the winds are inhomogeneous. The difficulties can be taken a step at a time. The good thing is that, unlike AGNs for instance, here the source of seed photons is identified and the geometry is quite constrained. Stochastic fluctuations will happen but the orbital motion will also produce a regular modulation more readily accessible to modelling.

### 3.1. Radiative processes

The main ingredients are common to nearly all models. First, one needs efficient acceleration of electrons (positrons). VHE observations show gamma-rays up to several TeV, requiring electrons of at least comparable energy. Acceleration of electrons to such energies may be prevented by radiative losses or by the size of the accelerator region. To fix ideas, take a 10 TeV electron and the orbital separation as the characteristic size. This is about 0.1 au at closest. The minimum field required to be able to confine such an electron is 0.02 G. Radiative losses are a more pressing problem. Two processes compete: inverse Compton scattering on star photons and synchrotron emission. The star photons have mean energies of a few eV so inverse Compton becomes inefficient when the energy of the electron exceeds a few tens of GeV (30 GeV in LS 5039). The cross-section drops in the Klein-Nishina regime for higher energy electrons and inverse Compton does not limit the maximum energy. At some point the dominant radiative process becomes synchrotron radiation since the timescale continues to decrease with energy. The acceleration timescale of the electron is at least the timescale for one Larmor gyration. The synchrotron timescale must be larger than that. Taking a 10 TeV electron this means the magnetic field must be  $<35$  G. Plausible values of the magnetic field are thus  $O(1)$  if leptonic models apply and VHE emission is detected. Larger values will cause a cutoff in the electron distribution and kill the VHE emission. This may be what is happening at periastron in LS I +61 $^{\circ}$ 303. MAGIC and VERITAS consistently detect VHE emission only at phases slightly before apastron, but never at periastron although this is where there is maximum seed photon density.

The switch between inverse Compton dominated losses and synchrotron dominated losses occurs at an electron energy which depends on the magnetic field. Synchrotron losses being more efficient than IC in the Klein-Nishina regime, this causes a break in the electron spectrum, reflected as a break in the VHE emission and in the synchrotron emission at lower energy. The corresponding energies are (assuming a  $10 R_{\odot}$ , 40 000 K star at  $d=0.1$  au and  $B=1$  G):

$$\epsilon_{\text{sync}} = 750 d_{0.1}^{-2} B_1^{-1} \text{ keV}$$

$$\epsilon_{\text{IC}} = 4 d_{0.1}^{-1} B_1^{-1} \text{ TeV.}$$

Spectral changes are expected if the orbital separation  $d$  changes (orbital eccentricity  $\neq 0$ ) and/or if the magnetic field changes (because the interaction region fluctuates with variability in the wind).

### 3.2. Orbital modulations

Several effects can combine to give orbital modulations in addition to, or regardless of, the intrinsic variations discussed above. Inverse Compton scattering occurs on an anisotropic source of photons. The outgoing radiation will also have an angular dependence. Simply said, the outgoing emission will be faint when the source of seed photons is behind the electrons as seen by the observer (i.e. at inferior conjunction) and will be maximum when the source is in front of the electrons (at superior conjunction). The spectrum will also change from hard to soft (respectively) because of the angular dependence of the switch from Thomson to Klein-Nishina regime at  $\gamma h\nu_*(1 - \beta \cos \psi) \approx m_e c^2$  ( $\gamma$  is the Lorentz factor of the electron,  $\psi$  the angle between electron and photon).

The outgoing photons will have energies up to several TeV. This is enough to create  $e^+e^-$  pairs with photons from the star. Again, the threshold and opacity depend on the angle of the VHE photon with the stellar photon. The opacity will be highest at superior conjunction and lowest at inferior conjunction. Again this can cause a modulation of the VHE flux even in the absence of any intrinsic change in the source emission. HESS observations of LS 5039 show a maximum at inferior conjunction and a minimum at superior conjunction, as expected if  $\gamma\gamma$  absorption plays a role (it definitely should if the VHE source is close to the compact object).

However, the opacity at superior conjunction is so large ( $\tau_{\gamma\gamma} \approx 40$ ) that no VHE flux should make it through to the observer. This is contradicted by observations that show a weak, but significant, flux at this orbital phase. There are two possible solutions to this puzzle. One is that the VHE source is actually not at the location of the compact object but further away in a region where the  $\gamma\gamma$  opacity is lower. If far enough then the absorption becomes negligible. This is not desirable because the minimum in VHE flux at superior conjunctions then becomes difficult to explain. Nevertheless, a compromise can certainly be found (?). Another solution is that the pairs that are created also participate in the VHE emission, generating a cascade. This is actually unavoidable. If the magnetic field is too strong then the pairs cool by synchrotron rather than inverse Compton. No further VHE photons are created and the cascade is quenched. This occurs if  $B > 3 E_{\text{TeV}}^{-1} d_{0.1}^{-1}$  G where  $E = 1$  TeV is the energy of the electron/positron. For  $\approx 100$  GeV electrons (where absorption of the IC photons will be maximum),  $B$  must be greater than 30 G for the cascade to be quenched, close to the upper limit derived from acceleration. The cascade will be quenched, but so will the acceleration of the initial electrons to very high energies. All in all, given the plausible values for the magnetic field intensity, it seems unavoidable that some emission from pairs contributes. The question is how much. The problem is difficult and orbital-phase dependent (see the contribution by B. Cerutti in these proceedings for more details).

Several groups have come up with reasonable fits to the data using these ingredients (????). All predict a peak close to periastron in the *Fermi* HE gamma-ray lightcurve of LS 5039, due to the angular dependence of inverse Compton scattering. See also the contributions by V. Bosch-Ramon and D. Khangulyan in these proceedings.

### 3.3. Direct views of the pulsar wind

Pulsar winds are not expected to generate synchrotron emission before their termination shock. The general view is that the pulsar wind is mostly composed of mono-energetic electrons and positrons with little momentum transverse to the magnetic field. This rules out synchrotron but does not forbid inverse Compton emission if there is a source of seed photons. There isn't much to go around in PWN: the interstellar radiation fields or thermal emission from the neutron star surface. In gamma-ray binaries there is the large radiation field from the companion star. So large that the inverse Compton emission produces an intense emission line, dragging the pulsar wind down before it reaches the shock (??). This is incompatible with observations (?). The VHE spectra are power laws, not lines. One possibility is that the particle distribution in the pulsar wind is more complicated than a simple mono-energetic law. Pulsar wind theory is not at a stage where this can be ruled out. This is the approach taken by (?). The predictions are quite indistinguishable from models where emission is thought to arise from an isotropic distribution of electrons beyond the termination shock.

An intriguing alternative is that the pulsar wind energy is actually mostly carried by the magnetic field rather than the particles. Observations of the Crab nebula suggest the magnetization  $\sigma = B^2/(4\pi\Gamma n_e m_e c^2)$  is  $\ll 1$  at the termination shock. However, this is at  $10^9 R_L$  whereas the shock occurs much closer in in gamma-ray binaries. Pulsar winds must start with high values of  $\sigma$  and how they reach low values far from the neutron star is not understood yet. As the object rotates, the misaligned magnetic field dipole generates a wave-like equatorial current sheet. This pattern will dissipate, giving energy to the wind particles in the process, given enough time (?). The scale of the pattern is given by the size of the light cylinder and dissipation cannot occur faster than the time light takes to cross this scale. Plugging in the relevant relativistic transforms, this means the bulk Lorentz factor of the wind must be less than some value for dissipation to occur:  $\Gamma \lesssim (R_s/R_L)^{1/2}$ . This is only 100 for gamma-ray binaries, much less than values thought to be reasonable in pulsar winds. Hence, the pulsar wind could stay highly magnetized all the way up to the termination shock. The energy is not in the particles so these do not radiate much inverse Compton emission. The line disappears. Dissipation and acceleration could still occur at the termination shock, tying in with previous results (?). This is a nice illustration of how gamma-ray binaries can be used to get novel constraints on pulsar wind physics.

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