Study of gamma-ray binaries in the Fermi era

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Abstract

There are a small but growing number of high mass X-ray binaries that also exhibit MeV–TeV emission. Currently, this category of "*gamma*-ray loud binaries" includes only four systems: PSR B1259–63, LSI +61° 303, LS 5039, and HESS J0632+057. Here we discuss the temporal and spectral properties of the systems basing on the latest X-ray and gamma-ray (Fermi) observations.

1. Introduction

γ-ray-loud binary systems are a newly identified class of X-ray binaries in which either accretion onto the compact object (a neutron star, or a black hole), or interaction of an outflow from the compact object with the wind and radiation emitted by the massive companion star leads to the production of very-high energy (VHE) γ-ray emission. Four such systems PSR B1259–63, LS 5039, LSI +61° 303 and HESS J0632+057, have been firmly detected as persistent or regularly variable TeV γ-ray emitters [4, 5, 7, 6]. The nature of the compact source is known only for the PSR B1259–63. In this system a 48 ms radio pulsar is in a highly eccentric 3.4 year orbit with a Be star SS 2883. The nature of the compact source in other systems has been a subject of an ongoing debates. In the case of the black hole, the origin of the high-energy activity has to be accretion, see e.g. [10]. In the case of neutron star, it might be accretion as well. However, the source activity may also be due to interactions of a young rotation-powered pulsar with the wind from the companion star, see e.g. [14]. However, in both cases the origin of the observed high-energy emission is a result of the interaction of the relativistic outflow with the companion wind. Two of γ-ray-loud binaries, LSI +61° 303 and LS 5039, turned out to be bright in GeV energy domain and are included into the first Fermi LAT Bright Source List [1]. In both binaries a spectral cut-off at several GeV has been detected. Below we explore the possible explanations of such a cut-off in the LSI +61° 303 case.

2. Possible interpretations of the LSI +61° 303 GeV spectral cut-off

At low energies LAT spectrum of LSI +61° 303 is described by a simple power law $E^{-\Gamma}$ with a photon index $\Gamma = -2.4$, [2]. This slope is consistent extrapolation of the MAGIC and Veritas results ([7, 3]) to the lower energies, see Fig.1. However, the energy spectrum appears to turn at energies ~6 GeV,[2]. One of the processes affecting the source spectrum at high energies is an absorption of photons due to ther interaction with soft photons of the companion star and the following pair production. For the case of LSI +61° 303 this effect was studied in e.g. [13]. On Fig.1 we show the attenuation of LSI +61° 303 spectrum due to the $\gamma\gamma$ pair production at different orbital phases under the assumption that the TeV flux comes directly from the compact object. The case of the high energy emission coming from the jet was considered by [8], and the similar conclusion was reached of the importance of the process only at energies higher than few tens of Gev. Thus simple account of the $\gamma\gamma$ pair production fails to explain the observed defficiency of GeV photons.

More soffisticated studies were done in [9], where the detailed calculations of the γ-ray production in the cascade model were studied. However even in this case the predicted turn over of the spectrum took place at energies higher than it is observed by Fermi.

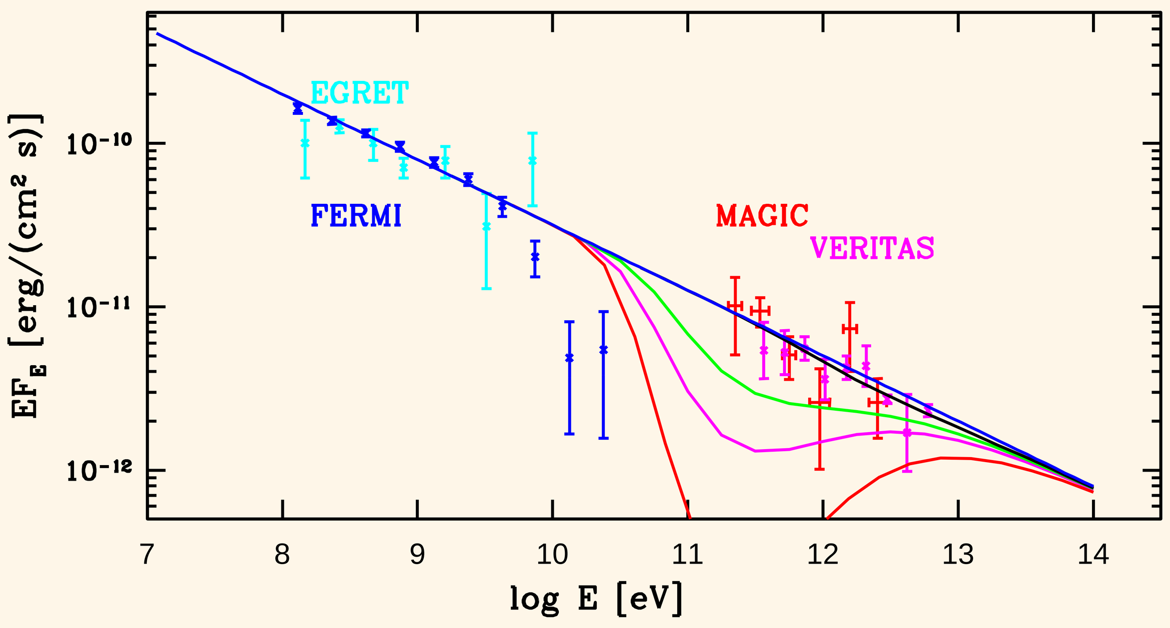

Figure 1: Attenuation of LSI +61° 303 spectrum due to the $\gamma\gamma$ pair production at different orbital phases. Blue line is an extrapolation of a GeV spectrum before the cut-off. Black, and red lines shows the effect of γ-ray absorption at superior and inferior conjunctions, while green and magenta lines correspond to intermediate (φ= 0.6 and 0.8) phases.

Another possibility for the origin of the observed cut-off at GeV energies is a different origin of the GeV (synchrotron), and TeV (IC) photons, see [17, 10]. In [17] the shape of the injected spectrum was assumed to be very hard, $\Gamma_e = 1$, so that the most power is injected close to cut-off energy 100 TeV. Such hard electron spectrum could be produced if electrons are direcly injected from cold relativistic pulsar wind with large bulk Lorentz factor $\Gamma_{\rm bulk} \sim E_{\rm cut}/m_e c^2$. Otherwise, hard electron injection spectrum could be formed if the synchrotron emitting electrons are produced in interactions of high-energy protons. As it is seen from the Fig.2 the overall shape of the keV-TeV band spectrum is readily reproduced in the synchrotron-dominated model.

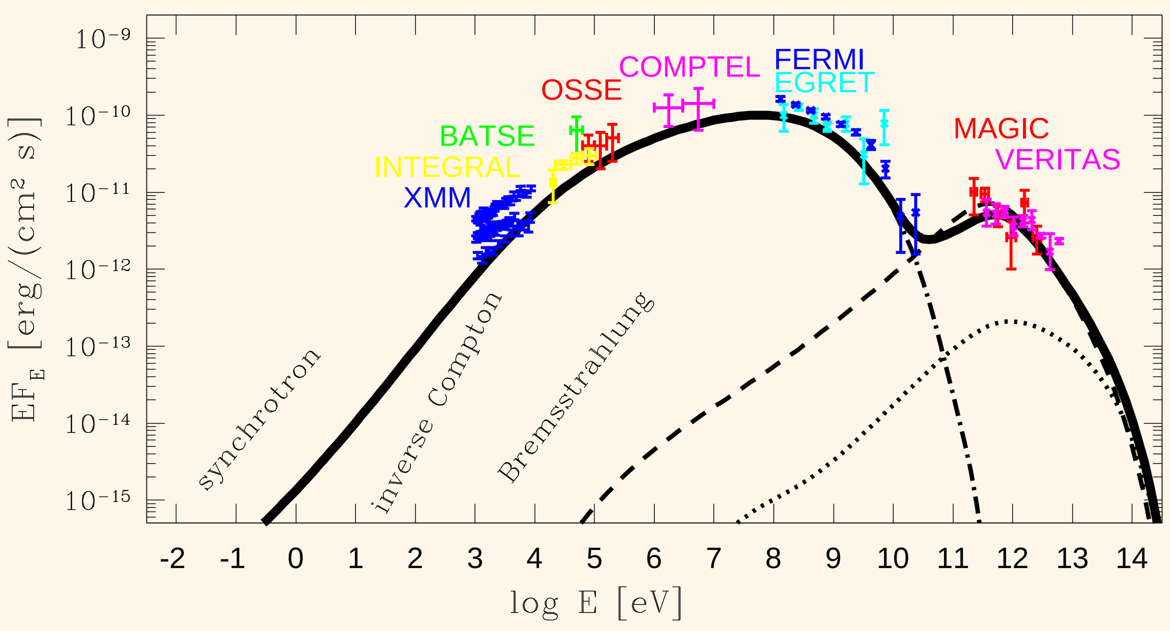

Figure 2: Model spectra compared to the data, which are the same as those in [11] except for the added data from the VERITAS [3] and *Fermi* [2] telescopes. The dot-dashed, dotted and dashed curves show the spectral components from the synchrotron, bremsstrahlung and IC processes, respectively.

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3. Origin of the PSR B1259–63 emission.

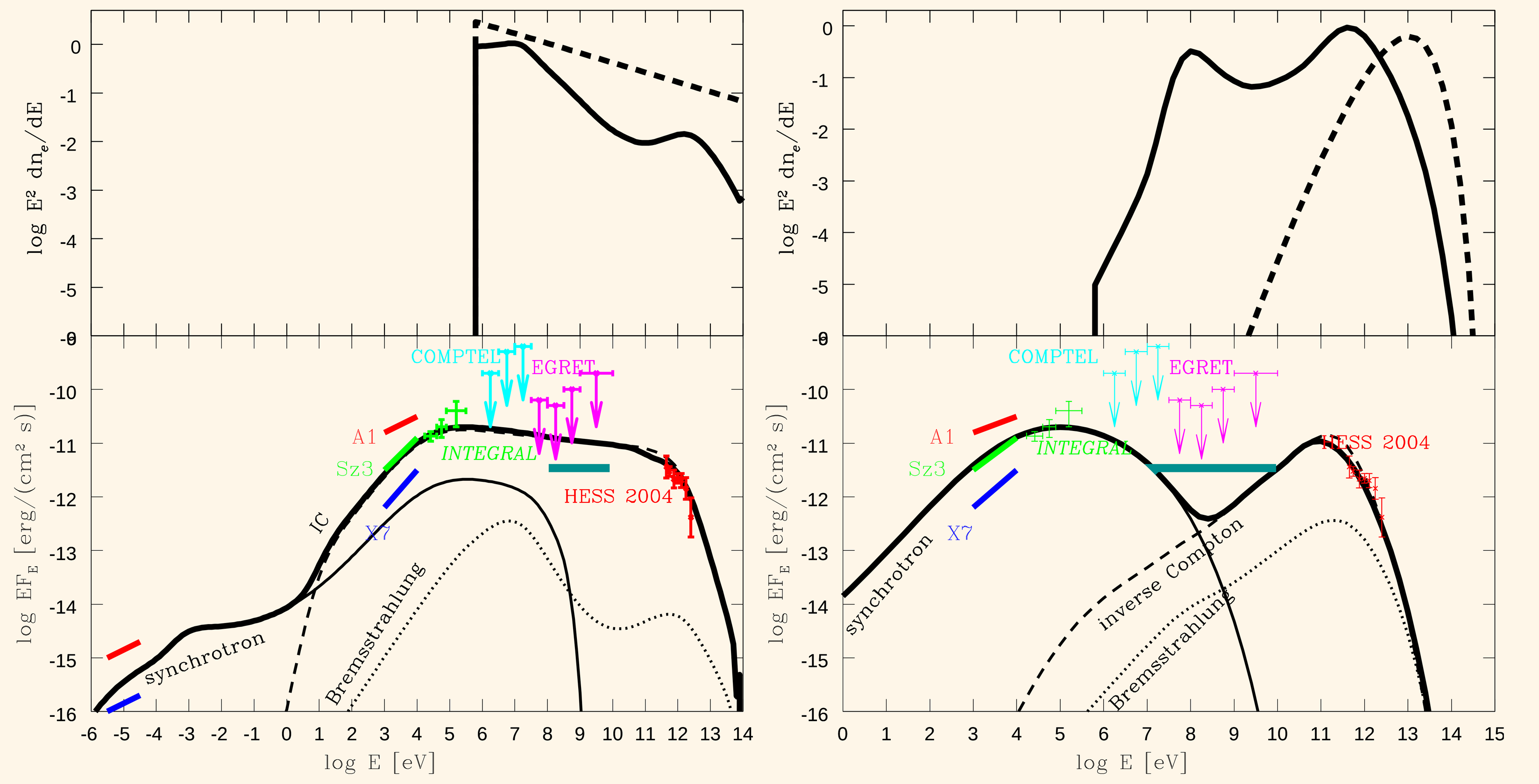

Figure 3: Spectral energy distribution of PSR B1259–63 in the IC (left) and synchrotron (right) models. Top panels show the initial electron injection spectrum (dashed line) and the resulted spectrum of the cooled electrons (solid line). Picture is taken from [12] Thick cyan line shows estimated 1 month Fermi sensitivity for this region

PSR B1259–63 is the only γ-ray loud binary system for which we are sure in the nature of the compact source. During the orbital motion pulsar wind interacts either with polarwind or an equatorial disk of the companion The disk of the Be star in the PSR B1259–63 system is believed to be tilted with respect to the orbital plane. While the inclination of the disk is not constrained, the line of intersection of the disk plane and the orbital plane is known to be oriented at about 90° with respect to the major axis of the binary orbit and the pulsar passes through the disk twice per orbit. While radio and X-ray emission in this system is detected along the whole orbit, the TeV emission was detected only near the periastron [4]. It is not clear yet whether the observed X-ray emission from PSR B1259–63 is due to the inverse Compton (IC) [11], or synchrotron [18, 15, 19] emission.

In **IC** model:

- The observed hard spectrum ($\Gamma \simeq 1.2$) at the disk entrance, along with the successive softening and sharp flux rise, was attributed by [11] to the injection of high energy electrons at the disk entrance (e.g. due to the proton-proton collisions), or to a sharp decrease of the high energy electron's escape velocity accompanied with the modification of their spectrum by Coulomb losses.
- Hard spectrum ($\Gamma \simeq 1.3$) observed in 2007 coincides with a local "dip" in the X-ray light curve during the broad flare associated to the disk passage. It can be explained by Coulomb losses of the $\sim$ 10 MeV electrons, in this case the break at the $\sim$ 5 keV energy, observed by Suzaku, has to be ascribed to the so-called "Coulomb" break in the electron spectrum.
- the break in the X-ray spectrum can be also related to the existence of a low-energy cut-off in the electron spectrum. Indeed, the IC cooling time of the X-ray emitting electrons of the energy E is comparable to the escape time:

$$t_{IC(T)} = \frac{3\pi m_e^2 c^4 D^2}{\sigma_T L_\star E} \simeq 6\times10^5 \left[\frac{10^{38}\text{erg s}^{-1}}{L_\star}\right]\left[\frac{D}{10^{13}\text{cm}}\right]^2\left[\frac{10\text{MeV}}{E_e}\right]\text{s} \quad (1)$$

$$\sim t_{\rm esc} \simeq D/V \simeq 10^6\left[D/10^{13}\text{ cm}\right]\left[V/10^7\text{ cm/s}\right]\text{ s} \quad (2)$$

If the IC emitting electrons are initially injected at energies much larger than 10 MeV (e.g. as a result of the proton-proton interactions, [16]), they would not be able to cool to energies below $\sim$ 10 MeV, which can explain the deficiency of the IC emission at the energies below the $\sim$ 5 keV break energy.

In **Synchrotron** model:

- Hardening of the spectrum to photon indexes $\Gamma_{\rm ph} < 1.5$ on a day time scale can be achieved if the electron energy loss is dominated by IC scattering losses in the Klein-Nishina regime. The Klein-Nishina regime of IC scattering becomes important at energies above $E_e \geq m_e^2c^4/(2.7kT_*) \sim 30$ GeV. Electrons with a power law energy distribution $N_e \propto E_e^{-\Gamma}$ cooled in the Klein-Nishina regime form a spectrum $N_e(E_e) \propto E_e^{-\Gamma+1}\times\left[\ln\frac{4EkT}{m^2c^4} - \frac{2\Gamma}{\Gamma^2-1} - 0.6472\right]^{-1}$, much harder than $N_e(E_e) \propto E_e^{-(\Gamma+1)}$ in Thompson limit. Thus the resulting synchrotron spectrum is proportional to $\epsilon^{-\Gamma/2}$ and can be harder than 1.5.
- A sharp break in the spectrum at TeV energies is related to the fact that the cooling rate of the multi-TeV electrons is determined by the synchrotron, rather than IC energy losses. The break energy $E_{\rm br}$ can be determined by equating the synchrotron loss time to the IC loss time in the Klein-Nishina regime. The synchrotron emission produced by electrons with the energy $E_{\rm br}$ is emitted at the energy $\epsilon_S = \frac{e\hbar B E_e^2}{m_e^3c^5} \simeq 10\left[\frac{B}{1\text{ G}}\right]\left[\frac{E_e}{0.5\text{ TeV}}\right]^2$ keV, which is close to the observed break energy $\epsilon \simeq 5$ keV in the *Suzaku* spectrum.

Thus X-ray data alone do not allow us to distinguish between the synchrotron and IC origin of the X-ray emission from the source. All observed peculiarities of the X-ray spectral evolution could be explained within the frame of each model [12]. **However, the origin of the observed spectral hardening can be readily clarified with the help of the simultaneous X-ray and GeV-TeV band observations.** In this respect, the data of 2010 periastron passage will be highly valuable because of availability of detailed monitoring of the source in 100 MeV-10 GeV band by Fermi. If the observed X rays have an IC origin, then the observed hardening during the drop of the flux is primarly connected to the hardening of electron spectrum below ~10 MeV, so that no tight correlation between the X-ray spectral evolution and the GeV-TeV energy band emission is expected. On the other hand, in the case of synchrotron origin of the observed X-rays, the spectral hardening can be produced if the electron cooling is dominated by the IC energy loss in the Klein-Nishina regime. This implies that the IC flux from the system in the very-high-energy band at the moment of the spectral hardening should dominate over the X-ray flux, so that a correlation of the hardness of the X-ray spectrum with the GeV-TeV flux level is expected. Besides all that Fig.3 shows that the mere detection or undetection of the GeV emission by Fermi would alow to choose between the models, see the estimated 1 month Fermi sensitivity.