Gamma-rays from accreting magnetars

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Abstract. **It is expected that strongly magnetized neutron stars (magnetars) can be also present inside massive binary systems. Then, a part of the wind of the massive star can be captured by the neutron star and interact with its inner magnetosphere. As a balance between the pressure of accreting matter and the rotating magnetosphere, a very turbulent, magnetized region is formed. We show that such conditions are good for acceleration of electrons to TeV energies. We calculate the gamma-ray spectra produced by these electrons in the comptonization process of thermal radiation from the massive star and the synchrotron spectra from electrons in the magnetic field of the inner magnetosphere. It is assumed that the accretion process occurs in the propeller stage. The spectra are shown for the example parameters of the binary system LSI +61 303 which has been recently discovered in the TeV gamma-rays by the MAGIC telescope.**

***Keywords*: Gamma-rays - stars:binaries - neutron stars**

I. Introduction

Neutron stars inside close binary systems can accrete matter from the companion star provided that their rotational period is relatively low. The accretion process can also occur in the case of strongly magnetized objects called magnetars. In fact, recently Dubus & Giebels [1] have claimed the detection of X-ray emission characteristic for magnetars from the massive binary LSI +61 303. This binary system belongs to the rare class of massive binaries emitting TeV γ-rays. The observed outburst of thermal X-ray emission might be due to the transient accretion of matter onto the surface of the neutron star. Moreover, quasi-periodic X-ray emission, with a frequency of 0.2 Hz, has been reported from the direction of this binary[2]. Whether this emission is in fact related to this massive binary, it is at present an open issue[3]. However, if it is true, then it makes sense to assume that the compact object inside LSI +61 303 is an accreting magnetar.

The aim of this paper is to investigate this hypothesis (see for more details [4]). We apply the general scenario of γ-ray production similar to the one recently proposed for accreting classical and millisecond neutron stars [5]. We calculate high energy radiation produced in the synchrotron and inverse Compton processes by primary electrons and secondary $e^{\pm}$ cascade pairs immersed in the magnetic fields of the magnetar and the massive star, and in the thermal radiation from the massive star surface.

II. Accreting magnetar model

We consider a compact binary system containing a strongly magnetized rotating neutron star (magnetar) and a massive companion star of the O,B type. It is assumed that mass from the stellar wind is effectively captured by the strong gravitational potential of the neutron star (NS). Depending on the period of NS and its surface magnetic field, the accretion process can occur in different phases. It can either occur in the accretor phase (for relatively slow rotators) or in the propeller phase. In this paper we concentrate on the propeller phase of the accretion process onto strongly magnetized neutron stars. In this case, the matter from the stellar wind can penetrate below the light cylinder radius of the rotating NS magnetosphere. This matter extracts rotational energy from the NS due to the interaction of the free falling matter with the rigidly rotating inner NS magnetosphere. As a result of this interaction, a very turbulent and magnetized transition region is formed. The distance at which the magnetic field starts to dominate the dynamics of the in-falling matter (the Alfven radius) can be estimated by requiring equilibrium between the magnetic field energy density and the kinetic energy density of the wind:

$$B_{\rm A}^2/8\pi = \rho v_{\rm f}^2/2, \tag{1}$$

where $B_{\rm A}$ is the magnetic field in the inner neutron star magnetosphere, $\rho = \dot{M}_{\rm acc}/(\pi R_{\rm A}^2 v_{\rm f})$ is the density of the accreting matter, $v_{\rm f} = (2GM_{\rm NS}/R_{\rm A})^{1/2}$ is the free fall velocity of the accreting matter, $R_{\rm A}$ is the Alfven radius, and G is the gravitational constant. The matter in this transition region is very turbulent and strongly magnetized providing good conditions for acceleration of particles to high energies. We will now estimate the location of this region from the surface of the neutron star. Using Eq. 1, and assuming that the neutron star has a dipole like magnetic field, i.e. $B_{\rm A} = B_{\rm NS}(R_{\rm NS}/R_{\rm A})^3$, we obtain

$$R_{\rm A} = 5.5\times 10^9 B_{14}^{4/7} M_{16}^{-2/7} \quad {\rm cm}, \tag{2}$$

where the magnetic field at the neutron star surface is $B_{\rm NS} = 10^{14}B_{14}$ G and the accretion rate is $M = 10^{16}M_{16}$ g s^{-1}. Then, we can estimate the magnetic field strength at the transition region,

$$B_{\rm A} = 610 M_{16}^{6/7} B_{14}^{-5/7} \quad {\rm G}. \tag{3}$$

According to the propeller scenario, the accretion can occur if the following conditions are fulfilled. At first, the radius of the transition region has to lay inside the light cylinder radius of the neutron star, i.e $R_A < R_{LC} = cP/2\pi$, where $P = 1P_1$ s is the rotational period of the neutron star, and c is the velocity of light. The above mentioned condition is fulfilled when,

$$P_1 > 1.2 B_{14}^{4/7} M_{16}^{-2/7}. \quad (4)$$

Secondly, the rotational velocity, $v_{\rm rot}$, of the magnetosphere at R_A has to be larger than the keplerian velocity, v_k, of the accreting matter. Accordingly, $v_{\rm rot} = 2\pi R_A/P \approx 3.5\times10^{10} B_{14}^{4/7} M_{16}^{-2/7}/P_1$ cm s^{-1}, must be larger than, $v_k = (GM_{\rm NS}/R_A)^{1/2} \approx 1.8 \times 10^8 B_{14}^{-2/7} M_{16}^{1/7}$ cm s^{-1}, for NS with rotation periods,

$$P_1 < 192 B_{14}^{6/7} M_{16}^{-3/7}. \quad (5)$$

This last condition on the NS period separates the propeller phase (lower periods) from the accretor phase (larger periods).

In the conditions expected for the transition region, particles should be accelerated efficiently. The acceleration rate of electrons with energy E (and the Lorentz factor γ) can be parametrized by,

$$\dot{P}_{\rm acc} = \xi cE/r_L \approx 970\xi_{-1} M_{16}^{6/7} B_{14}^{-5/7} \quad {\rm erg\ s^{-1}}, \quad (6)$$

where $\xi = 10^{-1}\xi_{-1}$ is the acceleration parameter, c the velocity of light, $r_L = E/eB_A$ the Larmor radius, and e the electron charge. During the acceleration process electrons suffer energy losses mainly due to the synchrotron process and the inverse Compton scattering on radiation from the massive star.

Electrons lose energy via the IC process in the Thomson (T) and the Klein-Nishina (KN) regimes. The photon energy densities from the massive star ($\rho_\star$) at the location of the NS can be approximated by, $\rho_\star = \frac{4\sigma T_\star^4}{c}\left(\frac{R_\star}{D}\right)^2 \approx 6.1 \times 10^3 T_4^4 \left(\frac{R_\star}{D}\right)^2$ erg cm^{-3}, where $T_\star = 3\times10^4 T_4$ K and σ is the Stefan-Boltzmann constant, D is the distance of the NS from the massive star.

We will now estimate the energy density of the magnetic field at the transition region (see Eq. 3), $\rho_B = B_A^2/8\pi \approx 1.4 \times 10^4 M_{16}^{12/7} B_{14}^{-10/7}$ erg cm^{-3}, The energy losses for each process (synchrotron and IC in the T regime) can be calculated from,

$$\dot{P}_1 = \frac{4}{3} c\sigma_T \rho\gamma^2 \approx 2.7 \times 10^{-14} \rho_{(\rm cap,B,\star)}\gamma^2 \quad \frac{\rm erg}{\rm s}, \quad (7)$$

where σ_T is the Thomson cross section.

The energy losses of electrons at large energies are dominated by the synchrotron process since the IC losses in the radiation field of the massive star decline due to the Klein-Nishina cross section. Therefore, the maximum energies of the accelerated electrons are determined by the balance between energy gains and energy losses due to synchrotron process. They can be expressed by,

$$\gamma_{\rm max} \approx 1.5 \times 10^6 \xi_{-1}^{1/2} B_{14}^{5/14} M_{16}^{-3/7}. \quad (8)$$

It is clear that realistic assumptions for this model allow electrons to reach TeV energies.

The maximum power that is available for the acceleration of the electrons is limited by the energy that can be extracted from the rotating neutron star by the in-falling matter. This matter from the stellar wind is accelerated to the velocity of the magnetic field lines at R_A. The power which has to be transfered from the rotating NS to the matter can be estimated from

$$L_{\rm acc} = \frac{\dot{M}_{\rm acc} v_{\rm rot}^2}{2} \approx 6 \times 10^{36} B_{14}^{8/7} M_{16}^{3/7} P_1^{-2} \quad \frac{\rm erg}{\rm s}. \quad (9)$$

By using Eq. 4, we can estimate the maximum power that can be extracted within the framework of this model in the propeller stage:

$$L_{\rm acc} \approx 4 \times 10^{36} M_{16} \quad {\rm erg\ s^{-1}}. \quad (10)$$

Only a part of this power, η, can be used to accelerate the electrons.

The total rotational energy of the magnetar is,

$$P_{\rm rot} = I\omega^2/2 \approx 4.4 \times 10^{46} P_1^{-2} \quad {\rm erg}. \quad (11)$$

where I is the angular momentum of inertia of the rotating NS calculated for its mass equal to $1.4 M_\odot$ and a radius of 10 km, $\omega = 2\pi/P$ is its angular velocity. This energy reservoir is sufficient to transfer the necessary power to the accreting matter for about one thousand years.

If parameters of the binary system are known, we can estimate the accretion rate onto the magnetar: $\dot{M}_{\rm acc} = R_c^2 \dot{M}_\star/(4D^2) \approx 5\times10^{15} M_{-7}/(v_8 D_{12})^2$ g s^{-1}, where $R_c = 2GM_{\rm NS}/v_w^2 \approx 3.7\times10^{10} v_8^{-2}$ cm, is the capturing radius, $D = 10^{12} D_{12}$ cm is the separation of the stars inside binary system, $\dot{M}_\star = 10^{-7}\dot{M}_{-7}$ M$_\odot$ yr^{-1} is the mass loss rate of the massive star, and $v_w = 10^8 v_8$ denotes the wind velocity and/or the NS velocity on its orbit around the massive star $v_8 \approx 0.37 D_{12}^{-1/2}$. For luminous stars, the wind velocity (of the order of $\sim 10^3$ km s^{-1}) is usually larger than the NS velocity. B type stars, present inside the known TeV γ-ray binaries, have a typical mass loss rate in the range of $10^{-(6-7)}$ M$_\odot$ yr^{-1} and stellar wind velocities of $\sim (1-3)\times10^3$ km s^{-1}. Accordingly, the typical accretion rates onto the NS are in the range of $\sim 10^{13-17}$ g s^{-1}, when the separation between the companion stars is smaller than 10 radii of the massive star.

III. Production of high energy radiation

In this model, radiation is produced by electrons via the synchrotron and IC process. We assume that primary electrons in the transition region reach a power law spectrum, $\propto E^{-s}$ up to $E_{\rm max} = m_e\gamma_{\rm max}$. At the highest energies (close to $E_{\rm max}$), the energy losses of electrons are dominated by the synchrotron process occurring in the magnetic field of the transition region. γ-ray production at these highest energies via IC scattering of thermal radiation from the massive star occurs typically at a lower rate than the synchrotron process. However, at lower energies the IC process can dominate. The energies of the IC γ-rays can be sufficient to initiate IC $e^{\pm}$ pair cascades in the radiation field of the massive star. Such cascades can develop if the optical depths for electrons in the anisotropic radiation field of the massive star are large enough.

We developed a Monte Carlo code which is able to calculate the synchrotron radiation from the primary electrons (in the magnetic field of the transition region), the secondary cascade $e^{\pm}$ pairs (in the magnetic field of the massive star), and the γ-ray spectra produced by IC $e^{\pm}$ pair cascade occurring in the anisotropic radiation field of the massive star. This code is based on an earlier version that has been used to binary systems [6]. In order to calculate the synchrotron spectrum produced by $e^{\pm}$ pairs inside the volume of the binary system, we have to define the distribution of the magnetic field around the massive star. The strength of the magnetic field as a function of distance from the center of the massive star can be described by the following equations [8],

$$B(r) \approx B_\star \times \begin{cases} (R_\star/r)^3, & R_\star \le r < R_{\star,\mathrm{A}}, \\ R_\star^3/(R_{\star,\mathrm{A}} r^2), & R_{\star,\mathrm{A}} < r, \end{cases} \quad (12)$$

where $B_\star$ is the surface magnetic field of the massive star, and $R_{\star,\mathrm{A}}$ is the Alfven radius within the massive stellar wind, which can be derived by solving the equation, $(1 - R_\star/r_{\star,\mathrm{A}}) = \xi(R_\star/r_{\star,\mathrm{A}})^4$, where $\xi = {B_\star}^2 R_\star/(\dot{M} v_\infty)$, $\dot{M}$ is the mass loss rate, and v_∞ is the stellar wind velocity.

IV. Application to LSI +61 303

As an example, we apply our model to the massive binary system LSI +61 303 which has been discovered as a TeV γ-ray source by the MAGIC Collaboration [9] and confirmed by the VERITAS Collaboration [10]. The TeV γ-ray emission from this binary system is observed only at a specific range of phases close to the apastron. No TeV γ-ray emission (above $\sim$ 200 GeV) has been observed (until today) close to the periastron passage. The multi-wavelength observations of LSI +61 303 show a hint of correlation between X-ray and TeV γ-ray emission [11]. LSI +61 303 belongs to a rare class of sources that are detected in the whole high energy range from X-rays up to TeV γ-rays [12], [13], [14].

The massive star in this binary system belongs to the class B0 V. It is characterized by a surface temperature of $T_\star = 29850$ K and a radius of $R_\star = 6.7 R_\odot$ (see e.g. [15]). The basic parameters of this binary system are not exactly known. Two sets of parameters have been proposed by Grundstrom et al. [17] and Casares et al. [16] . They are: the semi major axis: $a \sin i = 8.4$ and $8.2 R_\odot$, the eccentricity $e = 0.55$ and 0.72, the angle of the periastron passage $\omega_p = 0.3$ and 0.23, the phase of the observer $\omega_{\mathrm{obs}} = 33^{\mathrm{o}}$ and 70^{o}, the inclination angle $\alpha = 25^{\mathrm{o}}$ and 15^{o}, the distance at periastron and apastron $r_{\mathrm{p}} = 1.33$ and $1.32 R_\star$, and $r_{\mathrm{a}} = 4.60$ and $8.13 R_\star$, respectively.

We performed calculations of the synchrotron X-ray and the cascade IC γ-ray spectra for the location of the magnetar at periastron and apastron passages for both sets of parameters. The surface magnetic field of the massive star is investigated in the range of $B_\star = 10^{2-3}$ G and the surface magnetic field of the magnetar is fixed to $B_{\mathrm{NS}} = 3 \times 10^{14}$ G. Electrons that are accelerated in the transition region are described by a differential power law spectrum extending to the maximum energies given by Eq. 8. For the illustration we chose a spectral index equal to -2 and an acceleration parameter $\xi_{-1} = 1$. The power of the relativistic electrons is estimated from Eq. 9, by applying a specific energy conversion efficiency η. Note, that this power scales with the product of ηP_1^{-2} which is fixed in our calculations to be equal to 10^{-2}. We apply the inclination angles of the binary system that are consistent with the other basic parameters and assume a mass loss rate of the massive star equal to $3 \times 10^{-8} M_\odot$ yr^{-1} (for Grundstrom et al. [17]) and $10^{-8} M_\odot$ yr^{-1} (Casares et al. [16]). The results of the example calculations with the parameters mentioned above are shown in Fig. 1a,b,c,d. For all considered model parameters, the γ-ray spectra change drastically between the periastron and apastron passages. No emission above $\sim$1 TeV is found at the periastron due to inefficient acceleration. On the contrary, TeV γ-ray emission clearly extends to the TeV energy range at the apastron, in agreement with the MAGIC and VERITAS observations. Note that the γ-ray spectra also depend on the surface magnetic field of the massive star. For larger $B_\star$, secondary $e^{\pm}$ pairs from the IC cascade lose more energy due to the synchrotron process. This is the reason for increased synchrotron emission with increased $B_\star$.

The distances of the periastron passage, r_{p}, for both models are very similar, but the distances of the apastron passage, r_{a}, differ significantly. This can explain the stronger absorption features of the IC cascade spectrum at the apastron for the parameters proposed by Grundstrom et al. [17]. However the steeper IC cascade spectra obtained at the periastron passage for the Casares et al. [16] parameters have to be related to differences in the angle of the periastron passage with respect to the location of the observer.

The synchrotron spectra have a more complicated shape due two the components produced by primary electrons and secondary $e^{\pm}$ pairs. In general, for stronger $B_\star$, the synchrotron spectrum from secondary $e^{\pm}$ pairs is stronger (see dashed curves in Fig. 1), reaching saturation for $B_\star \sim 10^3$ G.

In this simple model, the energy conversion coefficient, η, is kept independent of the phase of the binary system. However, η may also depend on the accretion rate (i.e. the distance between the stars) in a way which is at present unknown. Therefore, any absolute normalization of the spectra is problematic since it may vary with the phase of the binary system (as observed in the hard X-rays [19]). Only detailed phase dependent

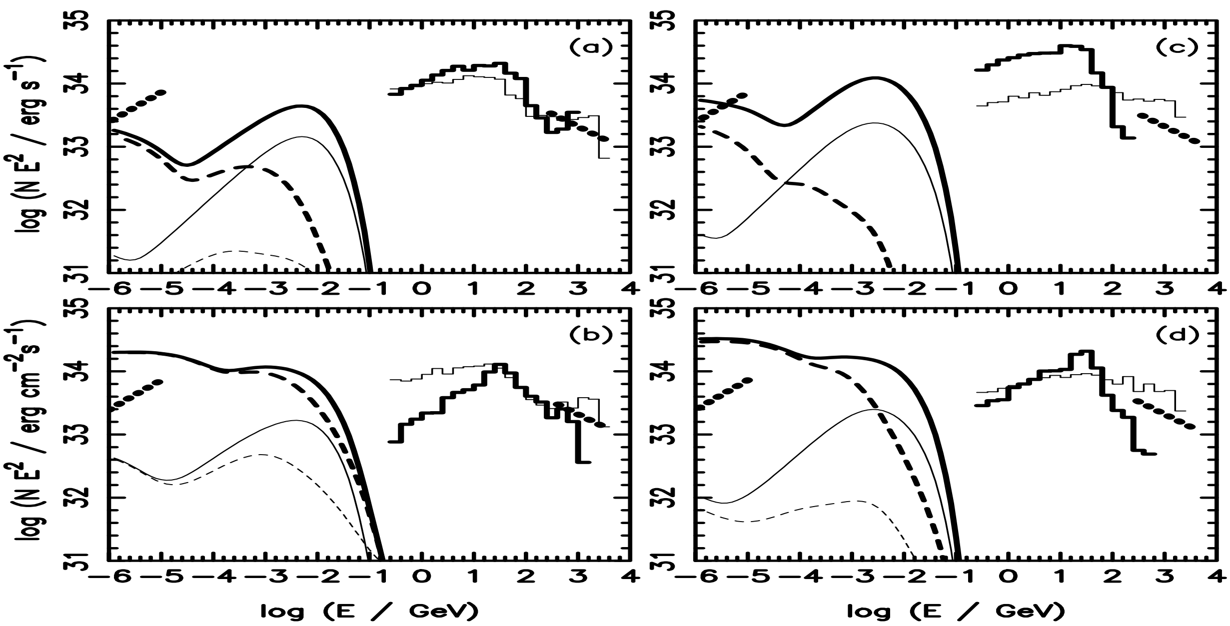

Fig. 1: The X-ray spectra (curves) and TeV γ-ray spectra (histograms) calculated for the periastron (thick) and apastron (thin) passages of the magnetar inside the binary system LSI +61 303 for two different sets of the basic parameters: figures (a) and (b) represent model by Grundstrom et al. [17] and (c) and (d) model by Casares et al. [16]. The surface magnetic field of the massive star is $B_\star = 10^2$ G (a) and (d); $B_\star = 10^3$ G (b) and (e). The calculations have been done for $\eta p_1^{-2} = 10^{-2}$ and $\xi_{-1} = 1$. For comparison we show the level of the X-ray and TeV γ-ray emission reported by RXTE [18], MAGIC [9] and VERITAS [10] as dotted lines.

multi-wavelength observations can put constraints on the injection details of the electrons at different phases of the binary system.

V. Conclusion

We have show that strongly magnetized, accreting neutron stars (magnetars) close to massive stars inside binary systems can be responsible for the acceleration of electrons up to TeV energies. These electrons interact with the magnetic field of the inner magnetosphere of the magnetar and with the soft radiation field of the massive companion producing X-rays (synchrotron process) and γ-rays (inverse Compton process). A part of the injected γ-rays can be absorbed in the radiation of the massive star developing IC $e^\pm$ pair cascade. Secondary $e^\pm$ pairs lose a significant part of their energy due to synchrotron emission. The γ-ray spectra produced in this scenario can extend up to TeV energies and the synchrotron spectra can extend up to MeV energies. The processes discussed above concern a specific stage in the evolution of the binary system, when the accretion rate onto the neutron star is in the range that can be described by the propeller phase. When the accretion rate is different, the magnetar can move to the ejector or the accretor phase during which different scenarios should be considered. We expect (based on the comparison of Eq. 10 and 11) that the propeller phase of accretion onto the neutron star, in which γ-ray fluxes can be detected, is relatively short lived. This may explain the small number of massive binaries discovered up to now in TeV γ-rays. Applying the parameters of the binary system LSI +61 303, we have shown that such a model can explain the TeV γ-ray emission observed close to the apastron passage of the neutron star. The lack of observable TeV γ-ray emission from the parts of the orbit close to the periastron is due to inefficient electron acceleration and the suppression of TeV γ-rays in the IC $e^\pm$ cascade process in which also the synchrotron energy losses play an important role.

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