The effect of magnetic field of the massive star on the IC $e^{\pm}$ pair cascade in massive binary system

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***Abstract*. It is likely that TeV gamma-rays observed from a few massive binary systems are produced within the volume of the binary as a result of comptonization of stellar radiation by relativistic electrons. However what is the exact production site of this γ-ray photons and general scenario for the acceleration and injection of relativistic electrons is at present an open question. We analyze the effect of the magnetic field of the massive star on the TeV gamma-ray production in the Inverse Compton (IC) $e^{\pm}$ pair cascade process. We show how the gamma-ray spectra escaping from the binary system are influenced by the magnetic field of the massive star. Possible production sites of the TeV gamma-rays are investigated as a function of the strength of the surface magnetic field of the massive star.**

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

I. Introduction

The process of Inverse Compton γ-ray production in a cascade process initiated by relativistic electrons in the radiation of the massive star has been widely considered as responsible for the TeV γ-ray production in massive binary systems (such as LS 5039, LSI 303 +61, or Cyg X-1). However the role of the synchrotron energy losses from secondary $e^{\pm}$ pairs on the development of the IC $e^{\pm}$ pair cascade have not been studied in detail up to now. It can be easily shown, by comparing the energy losses on the synchrotron and the Inverse Compton processes that due to the Klein-Nishina effects the synchrotron energy losses should start to overcome the IC energy losses of $e^{\pm}$ pairs somewhere at energies above $E_{e^{\pm}} \approx m_e^2/\varepsilon$, where $\varepsilon \approx 3kT_\star$, where $T_\star$ the surface temperature of the massive star, and k is the Stefan-Boltzmann constant. Applying such procedure, Bednarek [1] has shown that synchrotron energy losses starts to dominate over IC energy losses of electrons with TeV energies for the magnetic field of the order of ~ 1 G.

The role of synchrotron emission from the first generation of secondary $e^{\pm}$ pairs has been recently considered by Bosch-Ramon et al. [2], [3]. It was concluded that the source of primary γ-rays has to be located at the borders of the binary system. This is in contrary to predictions of the cascade models postulating the origin of γ-rays inside the binary system. However, these works do not take into account possible production of γ-rays in the full cascade process. Note that the optical depths for the γ-rays injected at the distance of the compact objects from the massive stars in these TeV γ-ray binaries are typically larger than unity. Therefore, many generations of secondary $e^{\pm}$ pairs and γ-rays are expected.

In this paper, we study in detail the effects of the magnetic field of the massive star on the cascade process taking into account the synchrotron energy losses of all secondary $e^{\pm}$ pairs produced in the cascade. It is assumed that the cascade is initiated by the isotropic source of primary γ-rays inside the massive binary system close to the orbit of the compact object. As an example, the parameters of the TeV γ-ray binary system LS 5039 are considered.

II. The IC $e^{\pm}$ pair cascade with synchrotron losses

For the purpose of this work, we adopt the cascade code which follows the IC $e^{\pm}$ pair cascade in the anisotropic radiation of the massive star initiated by primary electrons or γ-rays (for the details of the code see e.g. Bednarek [4]). This code takes into account the effects of the massive star dimension, which are important in the close vicinity of the stellar surface. The code is able to calculate the γ-ray spectra escaping from the vicinity of the massive star at arbitrary directions. Note that the cascade can in principle develop also very close to the surface of the massive star where the magnetic field is expected to be quite strong. The code has been modified in the way that it includes the synchrotron energy losses of all generations of secondary $e^{\pm}$ pairs produced in the IC $e^{\pm}$ pair cascade. In order to perform specific calculations, the magnetic field structure around the massive star has to be defined. In general, 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 [5],

$$B(r) \approx B_\star \times \left\{ \begin{array}{ll} (R_\star/r)^3, & R_\star \leq r < R_{\star,\rm A}, \\ R_\star^3/(R_{\star,\rm A} r^2), & R_{\star,\rm A} < r, \end{array} \right. \quad (1)$$

where $R_\star$ and $B_\star$ are the radius and the surface magnetic field of the massive star, and $R_{\star,\rm A}$ is the Alfven radius within the massive stellar wind, which can be derived by solving the equation, $(1 - R_\star/r_{\star,\rm A}) = \xi(R_\star/r_{\star,\rm A})^4$. The solution can be approximated by:

$$R_{\star,\rm A} = R_\star \times \left\{ \begin{array}{ll} 1+\xi, & \xi \ll 1 \\ \xi^{1/4}, & \xi \gg 1, \end{array} \right. \quad (2)$$

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. This approximation

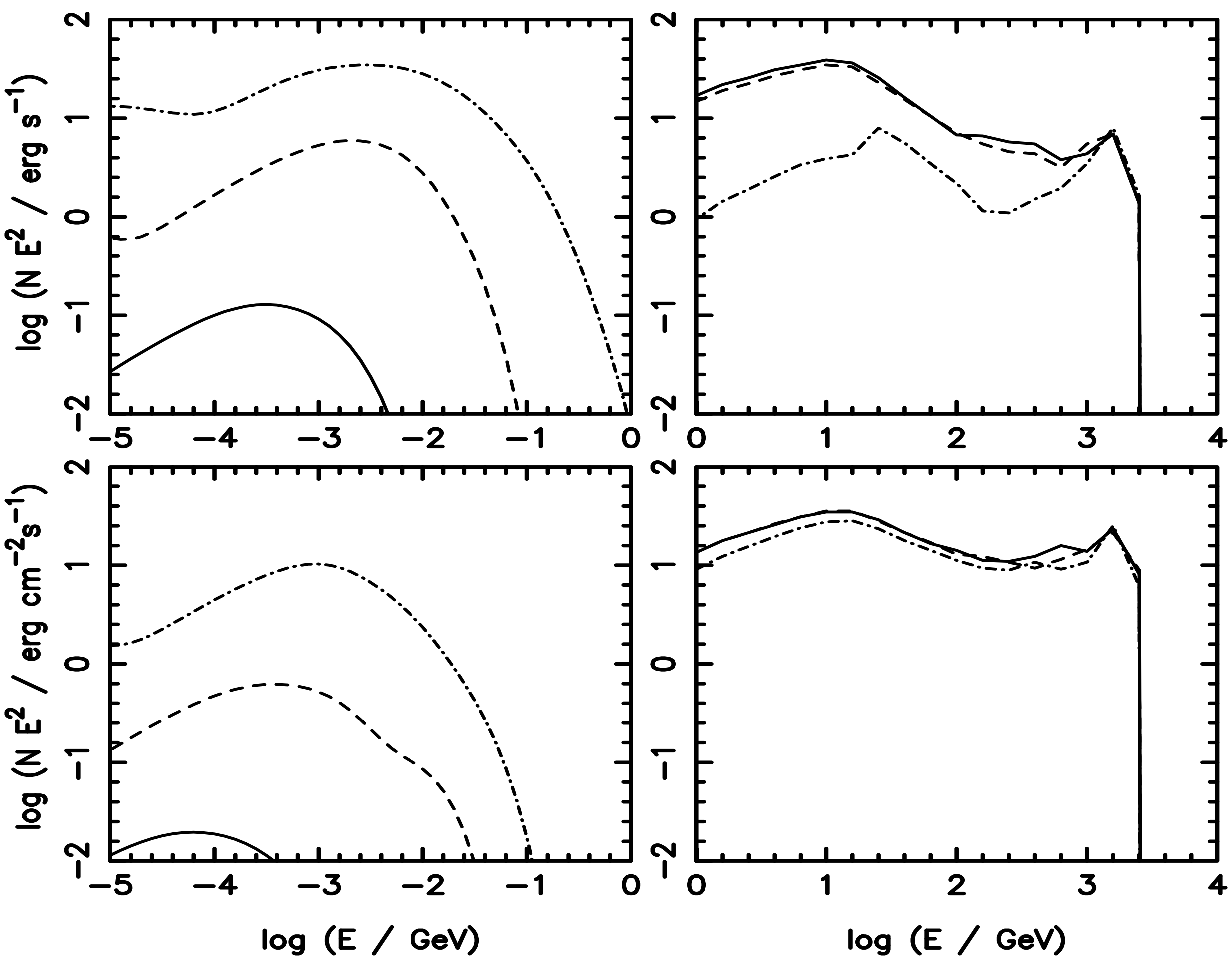

Fig. 1: The synchrotron and γ-ray spectra produced in the IC $e^{\pm}$ pair cascade initiated the primary γ-rays from the point source at the distance $R = 2R_{\star}$ (upper panels) and $5R_{\star}$ (bottom panels). The spectrum of primary γ-rays is of the power law type with the differential spectral index -2 up to 3 TeV. The synchrotron spectra, produced by secondary cascade $e^{\pm}$ pairs, are shown on the left figures and the cascade γ-ray spectra (averaged over all sphere) are shown on the right figures. The massive star has the parameters of the star in the binary system LS 5039. Its surface magnetic field is $B_{\star} = 30$ G (solid curves), 300 G (dashed curves), and 3000 G (dot-dashed curves).

of the magnetic field structure is valid inside the most important part of the binary system (i.e. within $\sim 10R_{\star}$), for stars which have a typical rotation velocity lower than $\sim\ 10\%$ of their wind velocity. Note, that the distance of the compact object inside the binary system LS 5039 changes in the range $\sim 2.2 - 4.4R_{\star}$.

The cascade calculations are performed for the surface magnetic fields characteristic for the massive stars of the O,B type and WR type. They are expected in the range $3 \times 10^{(1-3)}$ G (see e.g. [6]).

III. Cascade γ-ray and synchrotron spectra

As an example we perform the Monte Carlo simulations of the IC $e^{\pm}$ pair cascade for the massive star inside the binary system LS 5039 discovered as a TeV γ-ray source by the HESS Collaboration [7]. The surface temperature of this star is equal to 3.9×10^4 K and its radius to $9.3R_{\odot}$, where $R_{\odot}$ is the radius of the Sun. The compact object in this system moves around an elliptic orbit with the periastron at the distance of $R = 2.2R_{\star}$ and the apastron at the distance of $R = 4.4R_{\star}$ [8]. For these two locations of the compact object, the optical depths for the γ-rays are clearly above unity for most of the directions on the sky [9]. Therefore, the IC $e^{\pm}$ pair cascade effects are important as shown e.g. in [10], [11].

As we already mentioned, the previous cascade code used by us has been substantially developed by including the synchrotron energy losses of the secondary $e^{\pm}$ pairs of all cascade generations (which resulted in substantial increase of the simulation time of the IC cascade). We assume that the point source injects isotropically primary γ-rays from the distance of $2R_{\star}$ and $5R_{\star}$ from the center of the massive star. The γ-rays are injected with the power law spectrum. The differential spectral index has

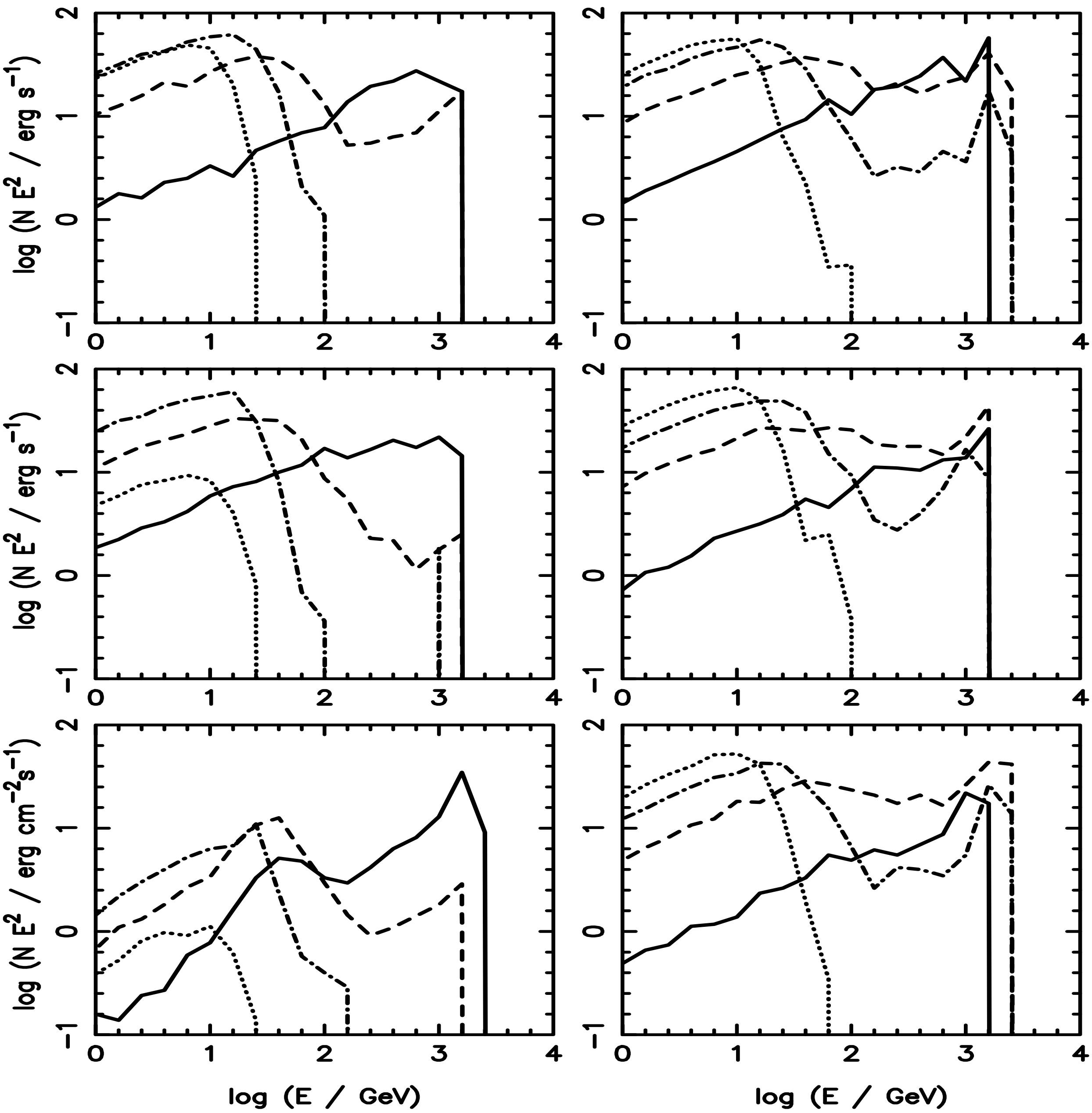

Fig. 2: The cascade γ-ray spectra are shown for different range of the cosine of the observation angle measured in respect to the direction defined by the center of the massive star and injection place of the γ-rays: $\cos\theta = 0.9 \div 1$ (solid curve), $0.3 \div 0.4$, (dashed), $-0.3 \div -0.2$ (dot-dashed), $-0.9 \div -0.8$ (dotted). The source of primary γ-rays is at the distance of $R = 2R_\star$ (left figures) and $5R_\star$ (right figures). The surface magnetic field of the massive star is fixed on: $B_\star = 30$ G (upper panel)), 300 G (middle panel), and 3000 G (bottom panel).

been fixed on -2 and the spectrum extends up to 3 TeV. Note that these primary γ-rays initiate the cascade in the anisotropic radiation field of the massive star (in relation to the injection place of primary γ-rays). Therefore, the cascade γ-ray spectra escaping at different angles in respect to the direction defined by the injection place and the center of the massive (the angle $\theta = 0^\circ$ defines direction outward the massive star) should differ significantly (see e.g. [10]).

In Fig. 1, we show the spectra of γ-rays produced in such IC $e^\pm$ pair cascade, with additional synchrotron energy losses, averaged over all escaping directions, i.e. for the whole solid angle. The surface magnetic field of the massive star has been chosen from the range $30 - 3000$ G. It is clear that the effects of the magnetic field of the star are negligible for the injection distance of $5R_\star$, at which most of the observed TeV γ-ray emission is produced [7]. However, γ-ray spectra calculated for the distance of $2R_\star$ and the largest value of the applied surface magnetic field of the massive star (i.e. 3000

G) show clear decrease at energies below ~ 1 TeV in respect to the γ-ray spectra for weaker magnetic fields. This decrease is due to the synchrotron energy losses of secondary $e^{\pm}$ pairs produced in the IC cascade as a result of absorption of primary γ-rays. We show also the synchrotron spectra produced by the secondary cascade $e^{\pm}$ pairs. These spectra are flat in the hard X-rays, peak at MeV energies and cut-off at hundred MeV for the strong surface magnetic field. As expected, the power in these spectra is clearly unti-correlated with the power in the γ-ray spectra. The lower level of γ-ray emission corresponds to the higher level of synchrotron emission. Therefore, the synchrotron emission of secondary $e^{\pm}$ pairs at apastron should be lower than at periastron provided that the injection rate of primary particles does not depend on the phase of the binary system.

In Fig. 2, we show how the cascade γ-ray spectra depend on the observation angle, θ, measured in respect to the direction defined by the injection place of primary particles and the center of the massive star. It is clear that synchrotron energy losses of secondary $e^{\pm}$ pairs does not have strong influence on the directional emission of γ-rays produced in the cascade process. However as expected, the γ-ray spectra, produced in the cascade in the case of the surface magnetic field equal to 3000 G, are on a much lower level. This reduction of γ-ray emission is the strongest for large angles θ, i.e. corresponding to directions passing close to the massive star surface. Clearly this effect is due to the extraction of energy from the cascade $e^{\pm}$ pairs by the synchrotron process in a relatively strong magnetic field close to the stellar surface.

Note, that the synchrotron emission from secondary cascade $e^{\pm}$ pairs can not be responsible for the X-ray emission features recently observed by the SUZAKU observatory from LS 5039. The X-ray emission is clearly correlated with the TeV γ-ray emission during the orbital period [12], [13], with the maximum of X-ray flux occurring close to the apastron. This is in contrary to the expectations from the simple cascade model provided that the acceleration efficiency of particles does not depend on the phase of the binary system. Either the nature of the X-ray emission is different (e.g. it is related to other processes around the compact object such as the accretion disk or the shock wave in the pulsar wind), the acceleration process of particles is linked to the phase of the binary system, or the observed synchrotron emission is due to accelerated primary electrons.

IV. Conclusion

We have performed detailed calculations of the γ-ray and synchrotron spectra produced in the IC $e^{\pm}$ pair cascade for the binary system LS 5039. The cascade is initiated by primary γ-rays from a point source at some distance from the massive star. In the present calculations we have also taken into account the synchrotron energy losses of secondary cascade $e^{\pm}$ pairs.

It is found that the synchrotron energy losses of secondary $e^{\pm}$ pairs can significantly change the γ-ray spectra escaping from the binary system for the surface magnetic field of the massive star of the order of a few 10^3 G, provided that the source of primary γ-rays is close to the massive star, i.e. at the periastron of its orbit. When the source is at the apastron, the effects of synchrotron losses of secondary $e^{\pm}$ pairs are negligible even for the strongest surface magnetic fields expected within the binary system. Note, that most of the TeV γ-ray emission observed from the TeV γ-ray binary systems is produced close to the apastron. Therefore, we conclude that synchrotron process does not have strong effect on the observed TeV γ-ray emission even if it is produced within the binary system. However, synchrotron energy losses are essential at the distance of the periastron passage of the compact object (supposed source of primary γ-rays). Therefore, synchrotron energy losses may be, at least partially, responsible for the low level of TeV γ-ray emission at the periastron passage of the compact object on its orbit around the massive star.

Note that in the IC $e^{\pm}$ pair cascade process we assume local complete isotropisation of secondary $e^{\pm}$ pairs from absorption of γ-rays (similar assumption is also done in [2], [3]). In a more realistic case, the secondary $e^{\pm}$ pairs should follow the local structure of the stellar magnetic field which may introduce additional unexpected features, such as re-distribution of the cascade energy between different directions on the sky (see e.g. [14]). Such more complete cascade calculations which also include the effects of diffusion with the stellar wind should be the aim of the future work.

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