Optical depths for gamma-rays in the radiation field of a star heated by external X-ray source

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***Abstract*. The surface of a low mass star inside a compact low mass X-ray binary system (LMXB) can be heated by the external X-ray source which may appear due to the accretion process onto a neutron star. As a result, the surface temperature of the star can become significantly larger than it is in the normal state resulting from thermonuclear burning. We wonder whether high energy electrons and gamma-rays, injected within the binary system, can efficiently interact with this enhanced radiation field. To decide this, we calculate the optical depths for the gamma-ray photons in the radiation field of irradiated star. Based on these calculations, we conclude that compact low mass X-ray binary systems may also become sources of high energy gamma-rays.**

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

I. INTRODUCTION

Recently TeV γ-rays have been observed from a few massive X-ray binaries (e.g. [1], [2]). However, up to now such γ-ray emission has not been reported from the low mass X-ray binaries [3] which are very luminous X-ray sources ($L_{\rm X} \sim 10^{36-39}$ erg s^{-1}, see the catalog of LMXB [4]). They likely contain a neutron star which accretes matter from the companion star. Sometimes X-ray emission shows also pulsations with the rotational period of the neutron star [5], [6]. Some LMXBs show also optical modulation with the period of the binary system which can be interpreted as a result of external heating of the stellar surface (e.g. Her X-1).

The mechanism for particle acceleration and γ-ray production in the massive TeV γ-ray binaries is not at present clear. It seems possible that acceleration of particles to TeV energies should also occur within the low mass X-ray binaries, although the mechanism of production of γ-rays may not operate there due to a relatively weak soft radiation field of the low mass star. However, in some LMXBs, the low mass star can be extensively heated by the X-ray source from the companion compact object. As a result, some parts of stellar surface can reach temperature comparable to those observed in the case of high mass stars. Relativistic particles accelerated inside such low mass binaries can find appropriate target for production of TeV γ-rays. In this paper we calculate the optical depths for γ-ray photons in the radiation field of irradiated low mass star in order to check whether γ-ray production in such systems can in principle occur.

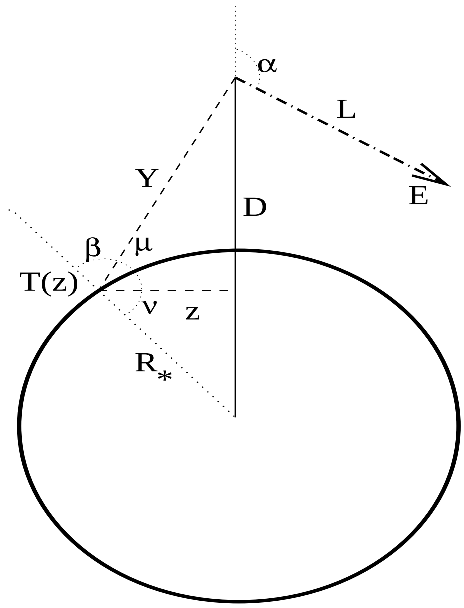

Fig. 1: Schematic picture of the geometrical situation considered in the paper. γ-ray photon with energy E propagates at the direction L and at the angle α. The star is irradiated by a point X-ray source at the distance D. X-ray photons arrive to specific places on the stellar surface at the angle β and heat the surface to temperature $T(z)$. z is the distance on the stellar surface measured from the direction D. The radius of the star is marked by $R_\star$. Y is the distance between the X-ray source and the specific place on the stellar surface.

II. SOFT RADIATION FROM IR-RADIATED STAR

The X-ray emission produced in the vicinity of the compact source in some close low mass X-ray binaries can reach the values of $\sim 10^{36-39}$ erg s^{-1}. A part of this X-ray emission can illuminate the surface of a companion star. As a result, the surface temperature rises significantly. We calculate the temperature profile onto the surface of such irradiated star by the point X-ray source located at the distance, D, from its surface. We assume that all X-ray emission absorbed by the stellar surface is irradiated as a black body emission with characteristic temperature $T(z)$, where z is defined in Fig. 1. Simple considerations turn to the temperature profile on the stellar surface of the type (see Fig. 1 for

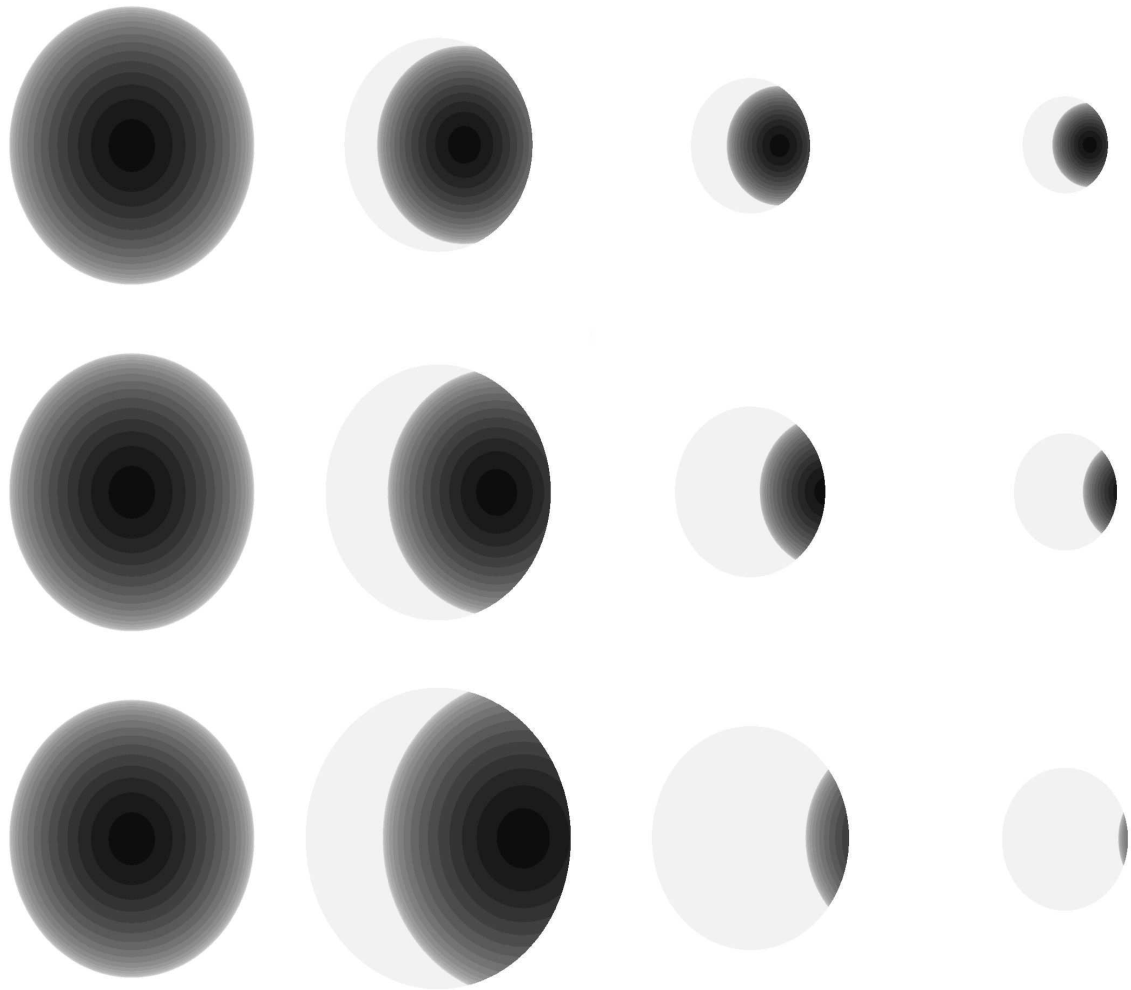

Fig. 2: The radiation field seen by γ-ray photon at different locations along the direction of propagation L. γ-rays are injected at the distance $H = 2R_\star$ at the angle $\alpha = 45^\circ$ (upper panel), 90° (middle panel, and 120° (bottom panel) in respect to the line defined by the injection point and the center of the star. The propagation distance is equal to $L = 0$ (left), $R_\star$ (left-middle), $3R_\star$ (right-middle), and $5R_\star$ (right). The star has the radius $R_\star = R_\odot$ and surface temperature $T_\star = 6000$ K. The grey scale denotes the range of temperature starting from 7×10^4 K (dark grey) to 6×10^3 K (white).

general picture),

$$T(z) = \left(T_\star^4 + \frac{L_{\rm X} \cos\beta / 4\pi\sigma_{\rm SB} R_\star^2}{z^2 + (D^2 - \sqrt{R_\star^2 - z^2})^2} \right)^{1/4}$$

$$\approx \left(1.3 \times 10^{15} + \frac{1.4 \times 10^{41} (L_{38} \cos\beta / R_\odot^2)}{z^2 + (D - \sqrt{R_\star^2 - z^2})^2} \right)^{1/4} \text{K}, \quad (1)$$

where distances are defined in Fig. 1, $L_{\rm X} = 10^{38} L_{38}$ erg s^{-1} is the luminosity of the X-ray source, $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant, $\beta = \pi - \mu - \nu$, $\cos\mu = z/R_\star$ and $\tan\nu = (D - \sqrt{R_\star^2 - z^2})/z$. The distances D, $R_\star$, and z are expressed in units of the Solar radius $R_\odot$. The value of z can change in the range from 0 to $z_{\rm max} = R_\star \sqrt{D^2 - R_\star^2}/D$.

The distribution of temperature on the surface of such irradiated star seen from different locations outside the star is shown in Fig. 2. Note, that for reasonable parameters of the low mass X-ray binary system (e.g. $L_{\rm X} = 10^{38}$ erg s^{-1}, and $D = 2R_\star$), the surface temperature can increase up to a few 10^4 K. It is comparable to the surface temperature of the massive stars within the high mass X-ray binaries. Therefore, we expect that the optical depths for TeV γ-rays also in the soft radiation of such irradiated low mass stars can exceed unity.

The γ-ray photon injected at a specific place sees the hot part of the star at different angles. Therefore, the soft radiation field seen by the γ-ray photon changes significantly during its propagation in the vicinity of the star (due to the change of the viewing angle and the distance from the stellar surface). In Fig. 2 we show the example radiation field from the stellar surface as seen by the γ-ray photon at different propagation distances L. Note that, for the propagation angles $\alpha > 90^{\circ}$, the solid angle subtracted by the limb of the star at first increases. Thus, γ-ray photon finds itself in a significantly stronger radiation field, i.e. closer to the hot region on the stellar surface.

III. The optical depths for gamma-rays

The optical depths for γ-ray photons injected at an arbitrary distance from the surface of the star in the case of fixed surface temperature were calculated for the first time in the general case by Bednarek [7], [8]. These calculations took into account dimensions of the star. Therefore, they can be used in the general case, i.e. for arbitrary location of the γ-ray photon (including also the stellar surface) and arbitrary directions of propagation (also the outward direction from the stellar surface). The optical depths for γ-rays close to the surface of the stars with other parameters (surface temperature and radius) can be easily re-scaled from those early calculations. For example, γ-ray photons with energies, $E_\gamma^{\rm o}$, propagating at specific distances D and in directions (defined by the angle α) close to the star with specific parameters ($T_{\rm o}$ and $R_{\rm o}$) are related to the optical depths around arbitrary stars with $T_\star$ and $R_\star$ in the following way,

$$\tau(\frac{E_\gamma^{\rm o}}{S_{\rm T}}, T_\star, R_\star, D, \alpha) = S_{\rm T}^3 S_{\rm R} \tau(E_\gamma^{\rm o}, T_{\rm o}, R_{\rm o}, D, \alpha) \quad (2)$$

where $S_{\rm T} = T_\star/T_{\rm o}$, $S_{\rm R} = R_\star/R_{\rm o}$, and the distance D from the stellar center of a specific star is measured in stellar radii. The optical depths for γ-rays have been frequently discussed in the context of the massive stars inside the high mass X-ray binaries.

Here we are interested in the case of the low mass binary systems in which the companion star produces relatively weak soft radiation field due to its low surface temperature. However, in the presence of a nearby strong X-ray source, the surface temperature of the star can increase significantly due to the irradiation process (see section 2). Therefore, relativistic electrons injected not far from the surface of the low mass star in compact X-ray binary can also suffer strong energy losses on the inverse Compton scattering (ICS). Primary γ-rays and secondary cascade γ-rays can be efficiently absorbed in this soft radiation field. In order to check whether such processes may become important, we calculate the optical depths for γ-rays following the standard prescription,

$$\tau = \int_\ell dl \int d\epsilon d\Omega n(l, \epsilon, \Omega) \sigma_{\gamma\gamma}(\epsilon, \theta)(1 - \cos\theta), \quad (3)$$

where $n(l, \epsilon, \Omega)$ is the differential density of soft photons with energy ϵ which arrive from the low mass star inside the solid angle Ω to instantaneous location of the γ-ray photon at the propagation distance l, $\sigma_{\gamma\gamma}$ is the pair production cross section, and θ is the angle between the momentum vectors of the gamma-ray and soft photon. ℓ denotes the path along propagation direction of the gamma-ray photon in the soft radiation field.

We investigate the optical depths for γ-rays as a function of their energies and other free parameters describing the geometry of the picture (injection distance D and the angle α). The stars with different radii and surface temperature are considered. The X-ray luminosity of the compact object (a neutron star) is fixed on $L_{\rm X} = 10^{38}$ erg s^{-1}. The optical depths as a function of γ-ray photon energy for selected injection angles and distances from the companion star are shown in Fig. 3. The calculations show that the optical depths are significant. For specific range of energies of γ-ray photon, they increase unity provided that γ-rays are injected within $D \sim 2R_\star$ from the center of the star at the part of the hemisphere containing the star. Note that the optical depths increase also for stars with lower radius. This is due to the fact that irradiating X-ray source is closer to the stellar surface, thus heating it to higher temperature.

IV. Discussion and Conclusion

We showed that the optical depths for TeV γ-rays, injected inside the LMXB close to the surface of the companion star irradiated by the X-ray source, can become larger than unity. Due to similar cross section for the $\gamma - \gamma \to e^\pm$ absorption process and the cross section for the Inverse Compton Scattering (ICS) of soft photons by relativistic electrons, also the optical depths for electrons on the ICS of stellar radiation should have similar values. Therefore, it is expected that in the LMXBs, in which companion star is effectively heated by the close X-ray source, the production and cascading of γ-rays can be efficient, provided that electrons are injected with TeV energies close to the stellar surface. However in general, the optical depths (see Fig. 3) are lower than the optical depths expected in the HMXBs detected in the TeV γ-rays (such as LS 5039 or LSI 303 +61 [9]). So then, the cascading effects in LMXBs should not be so efficient. As a result, it is expected that the GeV emission produced in the cascade process within LMXBs is weaker than in the case of HMXBs (both mentioned above HMXBs have been detected by the EGRET and the *Fermi* Observatories). We expect that the TeV γ-ray emission, which is not so efficiently absorbed within compact LMXBs with strongly irradiated companion star, can be produced on the level not very much lower than observed in LS 5039 and LSI 303 +61.

Someone can wonder whether absorption of γ-rays should not also occur efficiently in the radiation field of the X-ray source. Note however, that absorption peak in such radiation field should appear at energies of 2-3 orders of magnitude lower than in the case of absorption in the stellar radiation, i.e. in the GeV energy range. Moreover, γ-rays moves in the outward direction in respect to the X-ray source. Thus, the geometrical effects can additionally significantly decrease the optical depths.

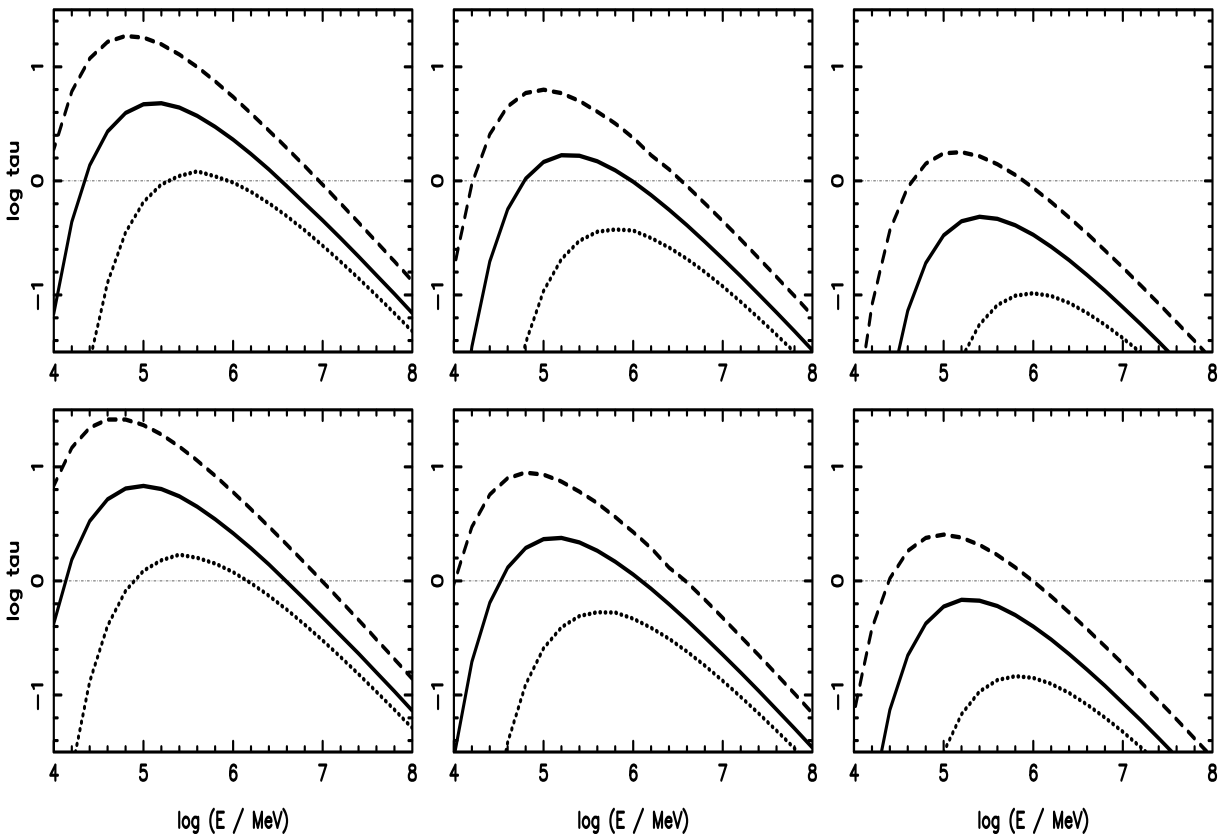

Fig. 3: The optical depths as a function of energy of γ-ray photon for the injection distance from the star $H = 1.5R_\star$ (left figures), $2R_\star$ (middle), and $3R_\star$ (right). γ-ray photon moves at the angle $\alpha = 45^o$ (dotted curve), 90^o (solid), and 135^o (dashed) from the direction defined by the injection place (close to the X-ray source) and the center of the star. The parameters of the star in the binary system are: $T_\star = 6000$ K, $R_\star = R_\odot = 7 \times 10^{10}$ cm (upper panel), and $T_\star = 5000$ K, $R_\star = 0.5R_\odot$ (bottom panel).

Assuming the characteristic dimension of the X-ray source equals to $\sim 10^6$ cm (the order of a neutron star radius or the inner disk radius) and the luminosity of the X-ray source 10^{38} erg s^{-1}, we estimate the temperature of the X-ray source on $T_{\rm X} \approx 2 \times 10^7 L_{38}^{1/4} R_6^{1/2}$ K. Based on this, we estimate the conditions under which the optical depths in the radiation of such X-ray source become lower than the optical depths in the radiation from the companion star. Taking into account the ratio of the corresponding photon densities and the dependence of the optical depths on γ-ray energy (after the peak at the absorption curve, see e.g. Bednarek [7]), we conclude that absorption of γ-ray photons on stellar radiation should dominate over the absorption on the X-ray radiation provided that the injection distance is larger than $\sim 10^9$ cm from the X-ray source (i.e. still inside the binary system). Therefore, we can safely neglect absorption of TeV γ-rays in the radiation of the X-ray source for γ-rays produced at such distances from the X-ray source.

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