PROCEEDINGS OF SCIENCE

On the sub-TeV gamma-rays from Cyg X-3

Wlodek Bednarek
Department of Astrophysics, University of Lodz, Lodz, Poland
E-mail: bednar@astro.phys.uni.lodz.pl

The compact X-ray binary system Cyg X-3 has been recently discovered as a source of GeV γ-rays by the AGILE and the *Fermi* satellites. The question appears whether Cyg X-3 can be also detected in the TeV γ-rays by the Cherenkov telescopes. Here we discuss this problem in detail based on the anisotropic inverse Compton (IC) $e^{\pm}$ pair cascade model successfully applied to TeV γ-ray binaries. We calculate the γ-ray light curves and γ-ray spectra expected from the cascade process occurring inside the Cyg X-3 binary system. It is found that the γ-ray light curves at GeV energies can be consistent with the γ-ray light curve observed by the *Fermi* for reasonable parameters of the orbit of the injection source of relativistic electrons. Moreover, we show that in such a model the sub-TeV γ-ray emission (above 100 GeV) is expected to be below sensitivities of the present Cherenkov telescopes assuming that electrons are accelerated in Cyg X-3 to TeV energies. The next stage Cherenkov telescopes (MAGIC II, HESS II) should have the energy threshold in the range 20-30 GeV, in order to have a chance to detect the signal from Cyg X-3. Otherwise, the positive detection of γ-rays at energies above a few tens of GeV requires a telescope with the sensitivity of $\sim 0.1\%$ of Crab Units. We conclude that detection of sub-TeV γ-rays from Cyg X-3 by on-ground telescopes has to probably wait for the construction of the Cherenkov Telescope Array (CTA).

25th Texas Symposium on Relativistic Astrophysics - TEXAS 2010
December 06-10, 2010
Heidelberg, Germany

PoS(Texas 2010)169

1. Introduction

Recently, the AGILE and *Fermi* satellites reported positive transient detection of Cyg X-3 at GeV energies (Tavani et al. 2009, Abdo et al. 2009). The γ-ray emission from Cyg X-3 has been discovered before the major radio flares (Tavani et al. 2009). It shows a modulation with the period of the binary system (Abdo et al. 2009). The emission above 100 MeV is well described by a single power law with differential spectral index $-2.7 \pm 0.05(stat) \pm 0.20(syst)$ and the peak flux $\sim 2 \times 10^{-6}$ ph cm^{-2} s^{-1}. Interestingly, the γ-ray light curve at GeV energies from Cyg X-3 shows general features that are quite similar to those observed recently from other TeV γ-ray binaries MAGIC telescope has observed Cyg X-3 for ~ 70 hours in different emission states. No positive signal has been reported up to now (Saito et al. 2009). The upper limits are on the level of 1% of the Crab Unit (C.U.) above ~ 250 GeV.

The observed modulation of GeV γ-ray emission from Cyg X-3 strongly suggests that photons has to originate in the radiation process which occurs inside the binary system. The most likely scenario is the interaction of electrons with the anisotropic radiation of the WR type companion star and development of the IC e$^{\pm}$ pair cascade (Bednarek 1997 and Sierpowska & Bednarek 2005). We perform detailed calculations of the γ-ray spectra escaping towards the observer located at different directions in respect to the orbital plane of the Cyg X-3 binary system for different locations of the source of energetic leptons within the binary.

2. Scenario for gamma-ray production

Let us consider the conditions in the jet in Cyg X-3 which allow acceleration of electrons to a few TeV. The maximum energies of particles are determined by the balance between the energy gain from the acceleration mechanism and energy losses on the synchrotron radiation. The limit on the maximum energies of electrons accelerated at the shock, $E_{\rm max}^{\rm syn} \approx 60(\xi/B)^{1/2}$ TeV, where ξ is the acceleration parameter and B is the magnetic field strength in the acceleration region. TeV electrons produce first generation of γ-rays in the IC process by scattering anisotropic radiation from a companion star. These γ-rays are absorbed in the interaction with this same radiation field. As a result, γ-ray spectrum is formed in the IC $e^{\pm}$ pair cascade process occurring in the whole volume of the binary system. The efficiency of the cascade process (the final γ-ray spectra escaping towards the observer) strongly depends on the location of the observer in respect to the source of primary electrons and the companion star.

We apply this general cascade scenario to the binary system Cyg X-3, in order to investigate its likely behaviour at sub-TeV γ-ray energies. We assume that somewhere inside the binary system a point like isotropic source of relativistic electrons appears. The source accelerates electrons with the power law spectrum extending up to TeV energies. In our calculations, we apply the single power law differential spectrum for electrons, $dN/dE \propto E^{-3.4}$, with the cut-off at 3 TeV. The spectral index has been chosen in order to be consistent with the differential spectral index of the GeV γ-ray emission observed by the *Fermi* satellite (Abdo et al. 2009). We calculate the γ-ray light curves at energies above 1 GeV, 100 GeV, and 330 GeV. We show the γ-ray spectra at specific phases of the injection source. The results are discussed for the circular and eccentric orbits of the source of relativistic electrons.

PoS(Texas 2010)169

2.1 The case of Cyg X-3

The shape of the GeV γ-ray light curve measured by the *Fermi* satellite shows a modulation with the period of the binary system but also clear asymmetry. The increasing part of the γ-ray light curve takes clearly longer than the decreasing part. Also the asymmetry in respect to the phase 0.5 is visible (the phase zero is counted in the *Fermi* plot from the location of the compact object behind the companion star, Abdo et al. 2009). Such asymmetry in the GeV γ-ray light curve may be expected in the case of an eccentric orbit of the compact object (injection source of relativistic particles) along the companion star.

As an example, we perform calculations of the γ-ray light curves for different inclination angles of the binary system and specific parameters of the eccentric orbit of the electron injection source located at or close to the compact object: the angle of the periastron is equal to $\omega = 60^o$ (measured in respect to phase zero), the eccentricity $e = 0.3$ and the semimajor axis $a = 2.25R_\star$. In our modelling, we assumed that: (1) electrons are injected inside a point like, isotropic source and interact only with the anisotropic radiation of the companion star; (2) the injection rate of electrons does not depend on the distance between the injection source and the companion star. The expected γ-ray light curves above three different energies are shown in Fig. 1. Interestingly, for the above parameters, we obtain the GeV γ-ray light curves which general shapes strongly resamble the γ-ray light curve measured by the *Fermi*. Note, that the level of the modulation of the γ-ray flux with the orbital period increases with the inclination angle, changing by a factor of $\sim$5 for the inclination $i = 30^o$ and up to a factor of $\sim$100 for the inclination angle $i = 60^o$. At present, it is difficult to decide which inclination angle describes the observations better due to the lack of knowledge on the precise location of the baseline emission in the *Fermi* light curve.

We also show the expected γ-ray light curves at sub-TeV energies for three inclination angles of the binary system. A clear unticorrelation of the GeV and sub-TeV emission is also expected in the case of Cyg X-3 with the maximum emission at phases $\sim$0.3-0.4. The largest sub-TeV γ-ray fluxes are expected for large inclination angles. We also show in Fig. 1 the γ-ray spectra for specific phases of the binary system and compare them with the sensitivities of the present Cherenkov telescopes (around $\sim$ 1% Crab Unit). The spectra have been normalized to the GeV peak emission reported by the *Fermi*. A clear break in the γ-ray spectra is observed between 10-100 GeV in most of these spectra. Its precise location depends on the phase of the binary system. However, these spectra are not able to reach the level of the 1% C.U. So then, they are undetectable by the present Cherenkov telescopes.

Note that these calculations have been performed under the assumption that the injection source is in the plane of the binary system (identified with the compact object inside the binary). However, the source of relativistic electrons can not be located far away from the plane of the binary system since in such a case the modulation of the GeV γ-ray signal drops significantly being in contradiction with the measurements by the *Fermi*-LAT telescope.

3. Discussion and Conclusion

We have applied the anisotropic IC $e^\pm$ pair cascade model, developed for the γ-ray production in the TeV γ-ray binaries, to the X-ray binary system Cyg X-3, recently discovered as a source of

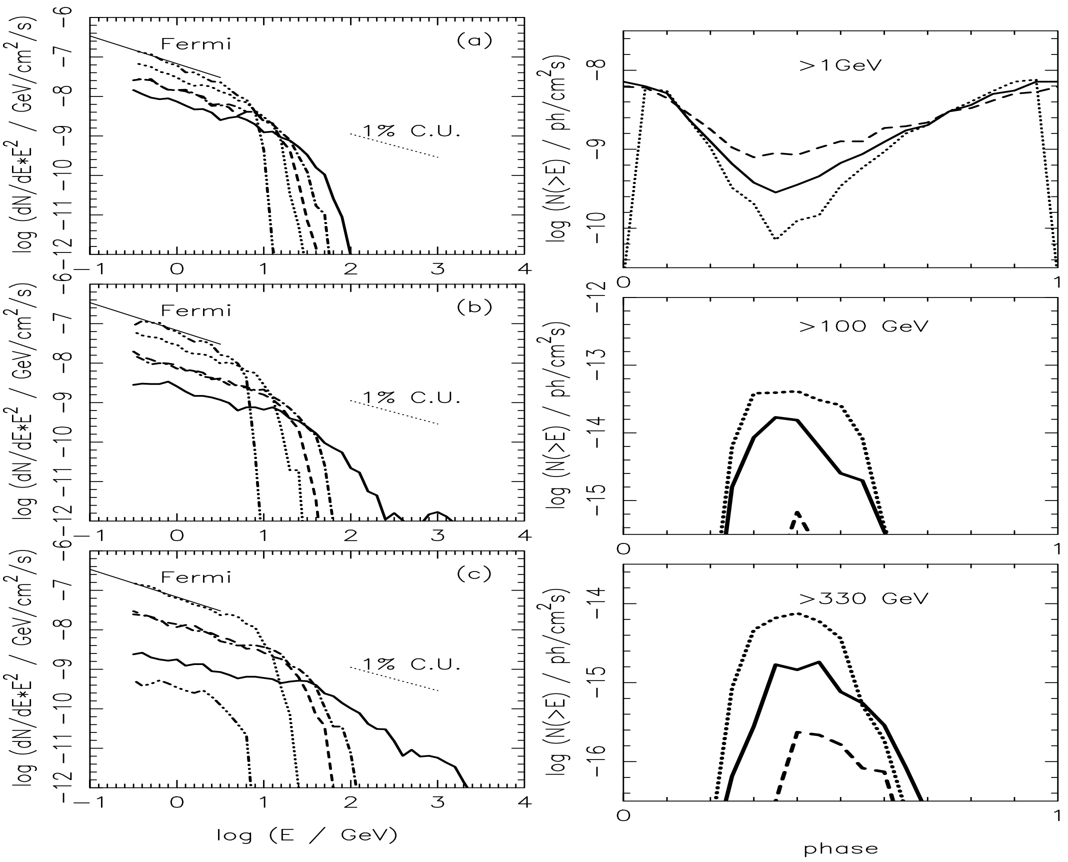

Figure 1: Right figures: The example γ-ray light curves for the eccentric orbit of the injection source of electrons with the angle of the periastron passage $\omega = 60^o$, the eccentricity $e = 0.3$, and the semimajor axis $a = 2.25R_\star$. At phase zero, the injection source (a compact object) is behind the companion star. γ-rays are produced in the IC $e^\pm$ pair cascade process initiated by primary electrons (with the differential power law spectrum $\propto E^{-3.4}$ extending up to 3 TeV) injected from a point like source. The light curves are shown for γ-rays with energies above 1 GeV (top panel), 100 GeV (middle), and 330 GeV (bottom). The inclination angle of the binary system is equal to: $i = 30^o$ (dashed curve), 45^o (solid), 60^o (dotted). Left figures: The γ-ray spectra produced at different phases of the injection source of relativistic electrons in the binary system Cyg X-3. The parameters of the orbit and the spectrum of primary electrons are as in right figures. The inclination angle of the binary system is fixed on: $i = 30^o$ (a), 45^o (b), 60^o (c). The spectra for phases $\varphi = 0.$ (triple-dot-dashed curve), 0.2 (dashed), 0.4 (solid), 0.6 (dot-dashed), 0.8 (dotted).

variable and modulated GeV γ-ray emission. The γ-ray light curves and spectra are calculated for the case of injection of γ-rays mainly within (or close to) the plane of the binary system as expected in the accreting neutron star model (Bednarek 2009). For reasonable parameters of the Cyg X-3 binary system, we obtained the GeV γ-ray light curves which have general features consistent with the observations of this source by the *Fermi*-LAT telescope. Moreover, it is found that the sub-TeV γ-ray emission is not expected to be produced on the level allowing its detectability by the present Cherenkov telescopes. The lack of detectable sub-TeV γ-ray emission from Cyg X-3 is a consequence of huge optical depths for γ-ray photons propagating within the binary system. Such large optical depths are the consequence of a small compactness of the binary system and high surface temperature of the companion star ($\sim 10^5$ K). Detection of the γ-ray signal from sources similar to Cyg X-3 with on-ground telescopes will be only possible with the next generation of Cherenkov telescopes which are expected to have sensitivity on the level of ~ 0.1% of Crab Units or by the telescopes which will be able to perform observations with the sensitivity of ~ 1% C.U. in the 20-30 GeV energy range. Such sensitivities are planned for the future Cherenkov Telescope Array (CTA). Note however, that in the case of Cyg X-3 another complication is introduced by the transient nature of the GeV γ-ray emission (a few day outbursts, Tavani 2009). This will additionally lower the chances for detection of Cyg X-3 in the TeV energies even with the CTA telescopes. The chances for detection can significantly rise if the γ-ray spectrum in the GeV energies is flatter during some outbursts than reported recently (differential spectral index -2.7). Therefore, investigation of a larger number of GeV γ-ray outbursts from Cyg X-3 by the AGILE and the *Fermi* telescopes will be of great importance for planning future sub-TeV γ-ray observations with the Cherenkov telescopes.

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PoS(Texas 2010)169