



Gamma-ray production in massive binary system Eta Carinae

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Abstract: We consider different scenarios for the acceleration of particles (both electrons and hadrons) and the production of the high energy radiation in the model of stellar wind collisions within the binary system Eta Carinae. The gamma-ray spectra calculated in terms of the specific radiation models are compared with the observations of Eta Carinae, and the neutrino spectra produced in hadronic collisions are confronted with the atmospheric neutrino background and the sensitivity of 1 km² neutrino telescope. We predict that the gamma-ray emission features at energies above ~100 GeV will show significant variability (or its lack) depending on the acceleration and interaction scenario of particles within the binary system.

Keywords: binary systems - gamma-rays: theory

1 Introduction

Eta Carinae is a binary system of two supermassive stars (for the summary of their basic parameters see Bednarek & Pabich 2011). The GeV γ -ray emission has been recently reported from the direction of Eta Carinae by the AGILE telescope (Tavani et al. 2009). The γ -ray flux was steady during the period of over one year corresponding to the pre-periastron passage except for a single flare lasting for about two days. The analysis of the whole Fermi-LAT data shows the γ -ray source to be consistent with the AGILE discovery (Abdo et al. 2010, Farnier, Leyder & Walter 2011). The γ -ray spectrum extends up to ~100 GeV, showing two distinct components. The first one is consistent with a power law spectrum (spectral index 1.6 ± 0.2) and a cut-off at 1.6 GeV. The second one is described by a power law with spectral index ~1.9 without evidence of a cut-off. The X-ray emission from Eta Carinae in the 22-100 keV energy range is very hard (differential spectral index equal to $\cong 1 \pm 0.4$, Leyder et al. 2008). More recent observations with INTEGRAL show that the hard X-ray component is well described by a power law spectrum (with photon index 1.8) without any strong variability at the periastron passage (Layder et al. 2010).

In general, non-thermal high-energy radiation from massive binary systems is interpreted as radiation from particles accelerated at the stellar wind shock. Both, leptons and hadrons can contribute to the γ -ray emission from the binary systems in the considered scenarios. In this paper we analyse different scenarios for the high-energy production in the general wind shock model with an application to the binary system Eta Carinae. In contrast to previous works,

we consider the acceleration of particles in two shocks with different properties appearing from the side of the Eta Carinae star and the companion star (Bednarek & Pabich 2011).

2 General scenario

We consider a scenario for the high-energy production in which the massive stars produce very strong winds colliding within the binary system and create a double shock structure. The location of the shock within the binary system, R_{sh} , can be estimated for the known value of the coefficient $\eta = \dot{M}_{comp} v_{comp} / (\dot{M}_{EC} v_{EC})$. The distance of the shock from the companion star can be obtained from $R_{sh}^{comp} = D\sqrt{\eta}/(1 + \sqrt{\eta})$ and from Eta Carinae $R_{sh}^{Eta} = D/(1 + \sqrt{\eta})$, where D is the separation of the stars and \dot{M} and v are the mass loss rates and the velocities of the winds of the companion stars.

It is believed that shocks produced in collisions of stellar winds are able to accelerate particles to relativistic energies. Note, however, that the conditions at the shocks from the sides of both stars can be quite different. Therefore, it is expected that spectra of leptons and hadrons accelerated at the shocks from the sides of both stars can have different properties because of the differences in the efficiency of the acceleration process, magnetic field strengths and energy losses of particles. Particles accelerated in different shocks can produce radiation at different energy ranges and at different dominant radiation processes. We also expect that depending on the shock (from the Eta Carinae or the companion star), particles can already lose energy close to the shock (i.e. within the binary system) or escape to the surrounding large-scale nebula. Therefore, high-energy ra-

diation with very different properties can be expected in this relatively simple scenario of the two stellar wind interactions.

3 Acceleration of particles

In general, the acceleration rate of particles at the shock can be parametrised by $\dot{P}_{\text{acc}} = \xi cE/R_L \approx 0.1\xi_{-5}B \text{ GeV s}^{-1}$, where $\xi = 10^{-5}\xi_{-5}$ is the acceleration parameter, E is the energy of particle (in GeV), R_L is the Larmor radius of particles in the magnetic field B (in Gauss), and c is the velocity of light. This acceleration process can be limited either by the advection of particles along the shock surfaces with the stellar winds or by their energy losses through different radiation processes. The characteristic time scale for the advection process along the shock is, $\tau_{\text{adv}} = 3R_{\text{sh}}/v_w \approx 3 \times 10^5 R_{13}/v_3 \text{ s}$, where $R_{\text{sh}} = 10^{13} R_{13} \text{ cm}$ is the distance of the shock from the centre of the star and $v_w = 10^8 v_3 \text{ cm s}^{-1}$ is the stellar wind velocity. The cooling time scale of electrons on the synchrotron and IC (in the Thomson regime) processes can be estimated from, $\tau_{\text{syn/IC}} = E_e/\dot{P}_{\text{syn/IC}}$, where E_e is the electron energy and $\dot{P}_{\text{syn/IC}}$ are the energy loss rates of electrons on both processes. These time scales are estimated as, $\tau_{\text{syn}} = E_e m_e^2 / (4/3 c \sigma_T U_B E_e^2) \approx 3.7 \times 10^5 / B^2 E_e \text{ s}$, and $\tau_{\text{IC/T}} \approx (170/E_e) [(T_4^4/R_{\text{sh}}^2)_{\text{comp}} + (T_4^4/R_{\text{sh}}^2)_{\text{EC}}]^{-1} \text{ s}$, where σ_T is the Thomson (T) cross section, U_B and U_{rad} is the energy density of the magnetic and radiation fields, m_e is the electron mass, R_{sh} is the distance of the shock from a specific star expressed in units of the stellar radius of the specific star, and $T = 10^4 T_4 \text{ K}$ is the surface temperature of the specific star. The cooling time scale in the Klein-Nishina (KN) regime can be roughly estimated by introducing the energy of electrons into the above formula for the IC losses, corresponding to the transition between the Thomson and the Klein-Nishina regimes, $E_e^{\text{T/KN}} = m_e^2 / (3k_B T) \approx 97/T_4 \text{ GeV}$. Then, the cooling time scale of electrons in the KN regime in the radiation field of both stars is approximately given by $\tau_{\text{IC}}^{\text{KN}} \approx 0.27 E_e [(T_4^4/R_{\text{sh}}^2)_{\text{comp}} + (T_4^4/R_{\text{sh}}^2)_{\text{EC}}]^{-1} \text{ s}$. The maximum energies of accelerated electrons should be determined by balancing the energy gains from the acceleration process with the energy losses on the synchrotron and IC processes (the advection time scale of electrons along the shock and their bremsstrahlung energy loss time scale are clearly longer). The efficiency of these two processes depends on the energy density of the magnetic and radiation fields in the acceleration region. The synchrotron losses dominate over the IC losses in the T regime for the magnetic field $B_{\text{sh}} > 40 [(T_4^4/R_{\text{sh}}^2)_{\text{comp}} + (T_4^4/R_{\text{sh}}^2)_{\text{EC}}]^{1/2} \text{ G}$.

By balancing the synchrotron energy losses with the acceleration energy gains, we obtain the limit of the maximum energies of accelerated electrons at the shock, $E_e^{\text{max}} \approx 190(\xi_{-5}/B)^{1/2} \text{ GeV}$. On the other hand, by balancing the acceleration time scale with the IC energy loss time scale (in the T regime), we estimate the maximum energies

of electrons as $E_e^{\text{max}} \approx 4(\xi_{-5} B_{\text{sh}})^{1/2} [(T_4^4/R_{\text{sh}}^2)_{\text{comp}} + (T_4^4/R_{\text{sh}}^2)_{\text{EC}}]^{-1/2} \text{ GeV}$. To consider the high-energy processes in the Eta Carinae binary system, we have to fix the basic parameter that describes the considered scenario, which is the strength of the surface magnetic field of both stars. As an example, we use the value of $2 \times 10^3 \text{ G}$ for the surface magnetic field of the companion star and 200 G for the Eta Carinae star. Then, the magnetic field at the shock from the companion star is estimated to be $B_{\text{sh}}^{\text{comp}} \sim 60 \text{ G}$ and at the shock from the Eta Carinae star as $B_{\text{sh}}^{\text{comp}} \sim 100 \text{ G}$. We also fixed the values of the acceleration parameter ξ for both shocks by estimating them from $\xi \sim (v_w/c)^2$. Because the velocity of the winds from both stars differs significantly, we obtain, $\xi_{\text{EC}} \sim 5 \times 10^{-6}$ and $\xi_{\text{comp}} \sim 10^{-4}$.

The magnetic field strength in the winds of stars has a complicated dependence on the distance from the star. In a small region close to the stellar surface the magnetic field has a dipole structure, i.e., $B(R) \propto R^{-3}$. However, in most cases this region is very small and it can be neglected. At larger distances the magnetic field has a radial structure. Then, its strength drops as $B(R) \propto R^{-2}$. This dependence dominates for distances characteristic for the periastron and apastron passages of the stars in the Eta Carinae binary system. The above dependence of the magnetic field strength on the distance from the star has interesting consequences. The maximum energies of electrons, determined by the balance between their acceleration efficiency and the synchrotron energy losses, should increase proportionally with the distance of the shock from the stellar surface provided that the acceleration efficiency is independent of the magnetic field strength. Note however that at certain distance from the stars the adiabatic losses can dominate over the synchrotron energy losses. On the other hand, the maximum energies of electrons, determined by the IC energy losses in the T regime, should stay independent of the distance from the star.

Hadrons lose energy mainly on collisions with the matter of the stellar winds. The time scale for the energy losses on pion production in proton-proton collisions can be estimated from $\tau_{\text{pp}} = (\sigma_{\text{pp}} k c \rho_w)^{-1} \approx 6.3 \times 10^4 R_{13}^2 v_3 / \dot{M}_{-4} \text{ s}$, where $\sigma_{\text{pp}} \approx 3 \times 10^{-26} \text{ cm}^2$ is the cross section for $p-p \rightarrow \pi$ production, $k = 0.5$ is the in-elasticity coefficient in this collision, and ρ_w is the density of the stellar wind at the shock region. This energy loss time scale for the shock from the side of the Eta Carinae star is estimated to be $\sim 4 \times 10^4 \text{ s}$ and from the side of the companion star as $\sim 3.4 \times 10^5 \text{ s}$ at the closest region of the shock to the stars and at their periastron passage. The time scales for energy losses by hadrons and their escape (advection) from the acceleration site do not depend on their energy. We expect that hadrons accelerated at the shock from the side of the Eta Carinae star interact efficiently within the binary system but those accelerated from the side of the companion star escape from the binary system to the surrounding nebula and interact there with the matter of expanding winds and the matter expelled during the past outbursts in the binary system.

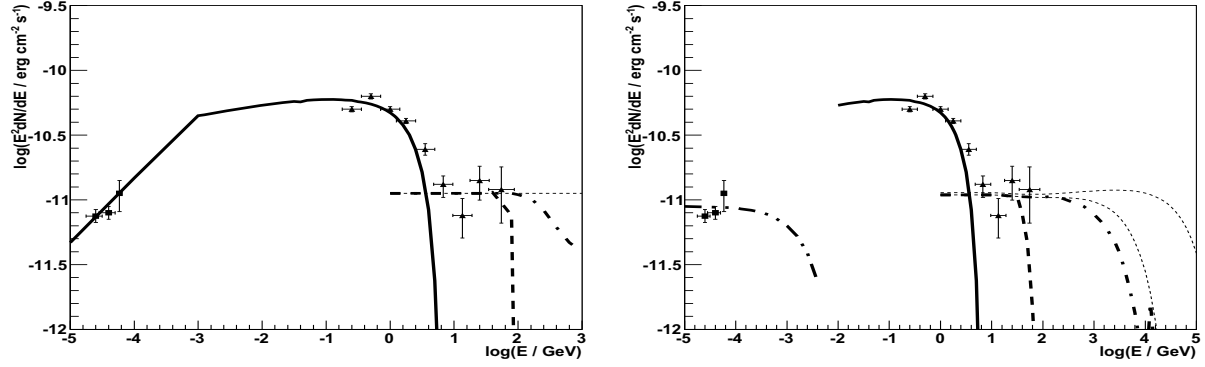


Figure 1: X-ray and γ -ray spectra expected for the model A (left) and model B (right) at the periastron passage of the stars in the binary system Eta Carinae. The results of the calculations are shown for the model A: without any absorption (thin dashed), with absorption for the γ -ray propagating at the angle equal to 50° (towards the star) at distance from the star $D = 1.4R_{\text{EC}}$ (dashed), and at the same angle but for the parts of the shock at the distance from the star $D = 10R_{\text{EC}}$ (dot-dashed). For Model B (right panel): γ -rays from electrons, accelerated at the shock from the side of the Eta Carinae star, scattering stellar radiation in the T regime (solid), γ -rays from decay of neutral pions produced by hadrons accelerated at the shock from the side of the Eta Carinae star: unabsorbed spectrum (thin dashed curve extending to lower energies), spectra absorbed in the stellar radiation for distances from the star: $D = 1.4R_{\text{EC}}$ (thick dashed) and $D = 10R_{\text{EC}}$ (dot-dashed). Secondary leptons from decay of charged pions (produced in hadronic collisions) lose energy on the synchrotron radiation (dot-dot-dashed curve). The γ -ray spectrum produced by hadrons, which are accelerated at the shock from the side of the companion star and produce pions in the interactions within the Eta Carinae nebula, are shown by the thin dashed curve extending to higher energies.

The maximum energies of accelerated hadrons can be estimated by comparing the energy gains from the shock with energy losses on hadronic interactions or the advection from the acceleration site. The comparison of τ_{acc} with τ_{pp} allows us to estimate the maximum energies of hadrons $E_p \approx 6.3\xi_{-5}BR_{13}^2v_3/\dot{M}_{-4}$ TeV. If the above condition is not fulfilled, then the maximum energies of hadrons are determined by the escape along the shock. Then, the maximum energies are estimated as $E_p \approx 30\xi_{-5}BR_{13}/v_3$ TeV. We calculate the expected radiation output only from the hadrons at limiting distances from the star.

4 Comparison with observations

In model A we assumed that the GeV γ -ray emission is produced by electrons accelerated at the shock from the side of the Eta Carinae star and the multi-GeV hard γ -ray emission is produced by electrons accelerated at the shock from the side of the companion star. We assume that electrons are accelerated with the power law spectrum defined by the spectral index $\alpha_{\text{inj}} = 2$. For electrons accelerated at the shock from the side of the Eta Carinae star, the main energy loss mechanism is the IC scattering in the T regime. We compare the hard X-ray to γ -ray IC spectrum expected from the electrons accelerated at the shock from the side of the Eta Carinae star with the observations of this binary system in Fig. 1. Electrons accelerated at the shock from the side of the companion star can reach energies of the order of ~ 100 GeV. Electrons also lose energy in the IC scattering process, which in this case occurs in

the T and in the KN regimes (the synchrotron energy losses are neglected). We show that this IC emission can be responsible for the the hard multi-GeV γ -ray spectrum observed from the direction of the Eta Carinae binary system. For the injection spectrum of electrons with the spectral index $\alpha_{\text{inj}} = 2$, the IC γ -ray spectrum is also produced with the spectral index $\alpha_\gamma = 2$, both in the T and KN regimes. However, as we showed above, γ -rays produced at the part of the shock relatively close to the companion stars are efficiently absorbed in the stellar radiation field. We take these absorption effects into account by applying the optical depths for the γ -rays in the radiation fields of the Eta Carinae and companion stars and using simple absorption law, $\propto \exp[-\tau(E_\gamma)]$. The unabsorbed γ -ray spectrum (produced at distances $> 10R_{\text{EC}}$ from the Eta Carinae star) are shown by the dotted curves. We conclude that model A predicts a clear modulation of the γ -ray signal at energies above ~ 100 GeV with the period of the binary system. The γ -ray spectrum produced at the periastron passage by electrons accelerated at the part of the shock that are the closest to the Eta Carinae star should cut-off just below ~ 100 GeV.

In model B the GeV γ -ray peak is also produced by electrons accelerated at the shock from the side of the Eta Carinae star but the multi-GeV hard γ -ray emission is produced by hadrons that are also accelerated at the shock from the side of the Eta Carinae star. At the periastron passage the hadrons accelerated at this shock can reach energies ~ 250 TeV for the magnetic field strength at the shock from the side of the Eta Carinae star. These maximum energies are independent of the distance from the s-

tars in the case of the radial structure of the magnetic field. The number of collisions of relativistic hadrons with the matter of the Eta Carinae wind, already close to the acceleration site within the binary system, can be estimated as, $N_{\text{bin}}^{\text{col}} \approx \tau_{\text{adv}}/\tau_{\text{pp}} \approx 4.8\dot{M}_{-4}/(v_3^2 R_{13})$. For the parts of the shock close to the Eta Carinae star at the periastron passage, the collision rate is estimated to be ~ 15 , and at the distance of $10R_{\text{EC}}$ it is still ~ 1.5 . Therefore, we conclude that these hadrons are efficiently cooled already close to the shock within the binary system through the large range of the binary phases. We calculate the spectra of γ -rays and secondary leptons from the decay of the pions produced in hadronic collisions assuming the power law spectrum of hadrons with the spectral index $\alpha_p = 2$. In Fig. 1, γ -ray spectra from decay of π^0 are compared with the γ -ray observations of the Eta Carinae binary system. As in the model A, the TeV γ -rays produced within ~ 10 stellar radii should be efficiently absorbed in the thermal radiation of the Eta Carinae star. We take this absorption effect into account by showing in Fig. 1 the unabsorbed γ -ray spectra (thin dashed curves) and absorbed spectra for the parameters of the binary system as for model A. We conclude that the Cherenkov telescopes should detect a clear modulation of the γ -ray signal at energies above ~ 100 GeV with the orbital period of the binary system.

The secondary leptons, from decay of charged pions, produce synchrotron radiation with the spectral index $\alpha_{\text{syn}}^{e^\pm} = 2$ which is not far from the observed value. The spectrum of secondary leptons extends up to $E_{e^\pm}^{\text{max}} \approx E_p^{\text{max}}/(8\mu) \sim 1$ TeV, where μ is the multiplicity of pion production by protons. Electrons with these energies ($E_e = m_e\gamma_e$) are able to produce synchrotron radiation at the shock from the side of the Eta Carinae star with energies up to $\varepsilon_{\text{syn}} \approx m_e(B/B_{\text{cr}})\gamma_e^2 \sim 5$ MeV. The level of this emission should also be comparable to the level of the hard γ -ray component from Eta Carinae, which is indeed the case (see Abdo et al. 2010 and Farnier et. al. 2011).

In principle, the hard γ -ray component could be also produced by hadrons accelerated at the shock from the side of the companion star. However, these hadrons escape to the Eta Carinae nebula from the binary system without significant energy losses close to the acceleration site. We conclude that hadrons injected into the nebula surrounding the Eta Carinae binary system should interact efficiently, producing γ -rays and neutrinos. The maximum energies of hadrons escaping from the binary system can be as high as ~ 5 PeV. These maximum energies drop with the distance of the shock from the companion star if the radial dependence of its magnetic field reaches values of ~ 250 TeV for the distance of $20R_{\text{EC}}$. We calculate the γ -ray spectrum expected from hadrons within the nebula with the power law spectrum, applying the spectral index equal to 2 and the maximum energies of hadrons equal to 5 PeV (Fig. 1). If hadrons are accelerated efficiently at the shock from the side of the companion star, a γ -ray emission extending up to multi-TeV energies is expected. This emission component should be steady, i.e., independent of the phase of the

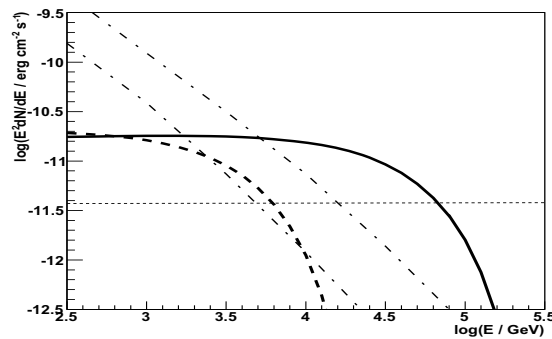


Figure 2: Muon neutrino spectra produced by hadrons which are accelerated at the shocks from the side of the companion star up to energies of 5 PeV (solid curve) and the side of the Eta Carinae star up to energies of 250 TeV (dashed). The power law spectrum of hadrons is applied with the spectral index equal to 2. The range of the atmospheric neutrino background (vertical and horizontal) within 1° degree of the source is marked by dot-dashed curves (Lipari 1993). The 1 yr sensitivity of the km^2 neutrino detector (expected for the IceCube detector) is marked by the thin dotted line.

binary system because the absorption effects in the stellar radiation fields within the Eta Carinae nebula are not important.

5 Neutrinos from Eta Carinae

Hadrons accelerated at both shocks should also produce neutrinos in collisions with dense matter of the Eta Carinae wind and the matter entrained within the Eta Carinae nebula during past outbursts. The maximum energies of accelerated hadrons are estimated to be ~ 250 TeV and 5 PeV, depending on the model. We calculate the muon neutrino spectra produced by these hadrons. It is assumed that hadrons have a power law spectrum with the spectral index equal to 2. There is a chance that neutrinos would be detected by the 1 km^2 detector because the predicted spectrum is above the atmospheric neutrino background and above the sensitivity of the 1 km^2 neutrino detector at energies between a few TeV and a few tens of TeV.

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