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Gamma-rays, neutrinos and cosmic rays from dense regions in open clusters

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Abstract

We analyse the high energy processes, occurring within open clusters containing massive binary systems, which turn to the production of high energy γ-rays and neutrinos. Nuclei, accelerated within the binary systems, inject protons and neutrons as a result of their fragmentation in collisions with stellar radiation and matter of the winds. We calculate the radiation produced by these protons and neutrons during their interaction with the matter of the stellar wind and the open cluster. The detectability of γ-ray emission and neutrino emission by the present and future Cherenkov telescopes and the neutrino telescopes is discussed.

Keywords: stars: binaries: close — open clusters — radiation mechanisms: non-thermal — gamma-rays: theory — neutrinos

1. Introduction

Up to now, TeV γ-ray emission has been detected from the direction of 3 open clusters (i.e. Cyg OB 2 [1], Westerlund 2[2], and Westerlund 1[3]). Also the supermassive binary system Eta Carina, within the Carina Nebula complex, has been detected up to ~100 GeV[4,5,6,7,8] but not in the TeV energy range[9]. This emission can originate in collisions of strong winds produced by massive stars in open clusters (e.g.[10,11,12,13,14]), at the shocks formed within massive binary systems (e.g.[15,16,17,18,19,20]), in the interaction of SNRs shock waves with dense clouds[21], within PWNe, or as a result of the interaction of PWNe with dense matter of the open cluster[22,23,24,25,26]. It is likely that in specific open cluster a few processes can be important since different types of objects (massive star winds, SNRs, PWNe) might inject relativistic particles with comparable power, i.e. of the order of 10^{50} erg.

In the present paper we investigate in detail the high energy radiation expected in hadronic processes within and around the massive binary systems surrounded by the large concentration of matter. It is assumed that nuclei are accelerated in the region of colliding winds within the binary stars (e.g. see[27]). These nuclei can severely disintegrate, in the interaction with the radiation field of massive stars and with the matter of the stellar winds, injecting neutrons and protons. Charged protons diffuse through the open cluster producing γ-rays and neutrinos in collisions with the matter of the stellar wind cavity and dense environment of the open cluster. On the other hand, neutrons move balistically through the wind cavity and decay on protons at some distance from the binary system which can be still within the wind cavity or already within the open cluster. Protons, from their decay, can also contribute to the high energy γ-ray and neutrino spectrum. As an example, we perform calculations of the γ-ray and neutrino fluxes produced in the clusters surrounding the Eta Carina supermassive binary system and WR 20a binary system in the open cluster Westerlund 2. The details of this scenario are discussed in Bednarek et al.[28].

2. Binary systems within the open cluster

We consider a massive binary system in which one or both companion stars belongs to the class of the Wolf-Rayet (WR) stars. WR type star produces fast and dense wind, due to the huge mass loss rate, which

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can be of the order of $\dot{M}_{\rm WR} = 10^{-5}\dot{M}_5$ M$_\odot$ yr^{-1}. The winds propagate with the characteristic velocities of the order of $v_{\rm w} = 10^3 v_3$ km s^{-1}. The density of the wind drops with the distance from the star according to, $n_{\rm w}(r) \approx 3.2\times10^{11}\dot{M}_{-5}/v_3R_{12}^2r^2$ cm^{-3}, where $R_{\rm WR} = 10^{12}R_{12}$ cm is the radius of the star, and $r = R/R_{\rm WR}$ is the distance from the star in units of the stellar radius. The massive binary systems are usually immersed itself within a relatively dense open clusters (OCs). Typical densities of the OCs are of the order of $n_{\rm oc} = 10n_{10}$ cm^{-3} and temperatures of the gas of the order of $T_{\rm oc} = 10^4T_4$ K. At certain distance from the binary system, the pressure of the stellar wind is balanced by the pressure of thermal gas within the OC. We estimate the dimension of such stellar wind cavity on, $R_{\rm cav} \approx 1.1\times10^{19}[\dot{M}_{-5}v_3/(n_{10}T_4)]^{1/2}$ cm. The radii of the wind cavities around WR type binary systems within the open clusters are typically of the order of a few parsecs for the density of surrounding matter of the order of ~ 10 cm^{-3} and its temperature $T_{\rm oc}\sim10^4$K.

We consider consequences of acceleration of nuclei within the binary system located in the open cluster. Nuclei (from the stellar winds) can be accelerated within the collision region of the winds (e.g.[14]). The reconnection of the magnetic field and the diffusive shock acceleration process can play an important role in this place. We show that nuclei can efficiently disintegrate in the dense radiation and matter of the winds from massive stars. As a result, neutrons are injected. They decay at the distance from the binary system which is determined by their Lorentz factors. Protons, extracted from nuclei, lose energy on interaction with the dense wind close to the binary system. They also suffer adiabatic energy losses in the expanding wind within the wind cavity. We consider high energy processes in which γ-rays and neutrinos are produced in hadronic collisions in the above described scenario.

Massive stars produce fast and dense winds with the mass loss rates of the order of a few $10^{-6}-10^{-4}$ M$_\odot$ yr^{-1} (characteristic for the Wolf-Rayet (WR) and O type stars). During the main sequence stage, the outer parts of stars are completely lost and only inner parts, composed of heavy nuclei, are left. Therefore, the winds of early type stars are expected to be mainly composed from nuclei heavier than hydrogen such as helium to oxygen. Massive stars are frequently found within the massive binary systems in which strong winds collide providing conditions for acceleration of nuclei to large energies. The propagation and interaction of relativistic nuclei with the stellar radiation field results in their photo-disintegration to neutrons, protons and secondary nuclei. We perform numerical simulations of propagation of nuclei in the radiation field of the massive stars in order to determine the rate of injection of different nuclei. Note that density of stellar photons in the vicinity of massive star, $n_{\rm ph}\approx 2\times10^{16}T_5^3$ ph. cm^{-3} (where $T = 10^5T_5$ K is the surface temperature of the massive star), is a few orders of magnitude larger than density of matter in the stellar wind. Therefore, it is expected that nuclei with sufficiently large energies interact at first in collisions with stellar photons rather than with the matter of the stellar wind. After that, nuclei can suffer significant fragmentation in collisions with the matter of the stellar wind. This second process is independent on energy of nuclei. Therefore, lower energy nuclei can also suffer strong disintegration process in collisions with dense matter of the stellar winds in the case of stars with exceptionally strong winds such as considered in this paper. Neutrons released from nuclei in collisions with the matter have the spectrum similar to the spectrum of primary nuclei. Therefore, neutrons with low energies can decay relatively close to the binary system where the density of matter is still high. On the other hand, high energy neutrons can even reach dense regions outside the wind cavity of the massive binary system. In this paper we calculate γ-ray and neutrino spectra produced by protons extracted from nuclei and also from protons from neutrons decaying at some distance from the binary system. These neutrons decay within the wind cavity and also within the dense open cluster in which binary system is immersed.

We estimate the maximum energies of hadrons accelerated in the shock region of colliding winds following the conditions considered e.g. in[20,27]. The maximum energies of hadrons are determined by comparing their acceleration time scale and their escape time scale from the acceleration region or collision time scale with the matter of the stellar wind. The acceleration time scale is given by, $\tau_{\rm acc} = E_{\rm h}/\dot{P}_{\rm acc}\approx 0.02\gamma_{\rm h}/(\chi_{-5}B_3)$ s, where $E_{\rm h}$ and $\gamma_{\rm h}$ are the energy and the Lorentz factor of particles, $\dot{P}_{\rm acc} = \chi c E_{\rm h}/R_{\rm L}$ is the acceleration rate, $\chi = 10^{-5}\chi_{-5}$ is the acceleration coefficient, $R_{\rm L} = Ac\gamma_{\rm h}/ZeB_{\rm sh}$ is the Larmor radius of hadron in the magnetic field at the shock $B_{\rm sh}$, c is the velocity of light, e is the elemental charge, and A and Z are the mass and charge numbers of nuclei. We apply $A/Z = 2$. $B_{\rm sh}$, is related to the surface magnetic field of the massive star by assuming its dipolar structure close to the surface up to $\sim 1.2R_\star$ and radial structure at larger distances[29]. For the distance of the collision region from the star equal to $R_{\rm sh} = 2R_\star$, $B_{\rm sh}$ drops to $\sim 0.25B_\star$. The advection time scale of hadrons from the collision region is estimated from, $\tau_{\rm adv}\approx R_{\rm sh}/v_{\rm w}\approx 10^4R_{12}/v_3$ s, where $R_{\rm sh} = 10^{12}R_{12}r_{\rm sh}$ cm is the distance of the col-