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Gamma-rays from young open cluster Berk 87

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Abstract: Open clusters are concentrations of dense matter and young stars. It is expected that non-thermal processes play an important role in these objects due to the observations of non-thermal X-ray emission and directional coincidence with some EGRET sources. We calculate the gamma-ray spectra expected from the open cluster Berk 87 assuming that hadrons and leptons are accelerated.

Introduction

Open clusters, with the characteristic age of a few to several million years, contain many early type stars (OB and WR type) which produce strong radiation field and energetic winds. A fraction of the wind energy can be transfered to relativistic particles by diffuse shock acceleration process occurring at the shocked wind boundary and turbulent wind itself [1, 2]. Moreover, different type of objects related to the massive star evolution, supernova remnants, pulsar wind nebulae, massive binary systems, can also be responsible for acceleration of particles. Therefore, open clusters are expected to be likely sources of high energy neutral radiation (γ-rays, neutrinos, neutrons) produced in collisions of particles with the matter and soft radiation.

In fact, some open clusters have been found in the relatively large error boxes of the EGRET unidentified sources reported in the 3rd EGRET catalog [3], e.g. 3EG J2021+4716 and 3EG J2016+3657 - Berk 87, 3EG J2033+4118 - Cyg OB2, or 3EG J1027-5817 - Westerlund 2. TeV γ-ray sources have been reported inside the Cyg OB2 by the HEGRA group [4], Westerlund 2 by the HESS group [5], and Berk 87 by the Milagro group [6].

γ-ray production from open clusters have been considered [7, 8, 9, 5, 10]. We adopt a scenario for the acceleration of particles inside open clusters, originally proposed in [2], and study this general scenario in a more detail assuming that both, electrons and hadrons, are accelerated at the shocks formed as a result of the interaction of strong winds from the Wolf-Rayet (WR) type stars with the matter and radiation inside the open cluster and surrounding dense clouds.

Acceleration of particles

We assume that a part, $\eta_{\rm e}$, of the Wolf-Rayet (WR) star wind energy can go on acceleration of electrons and a part, $\eta_{\rm p}$, go on acceleration of hadrons. Since particles are accelerated in the considered scenario at the shock, it is assumed that they obtain a power law spectrum which spectral index is in the range $2 - 3$. The acceleration process of particles at the non-relativistic shock, formed in the wind of the massive star inside the open cluster, can be characterized by the energy gain rate and their energy losses on different radiation mechanisms (leptons - synchrotron, inverse Compton (IC), bremsstrahlung, hadrons - collisions with the matter) and escape from the acceleration region. The energy loss gains are described by the acceleration factor ξ. The effective density of the soft radiation field inside the open cluster is described by the factor μ which is the ratio of the effective density seen by leptons to the average density calculated for known dimension of the open cluster and by counting the contributions from all the massive stars inside the cluster. These processes are discussed in more detail in Bednarek [11]. The max-

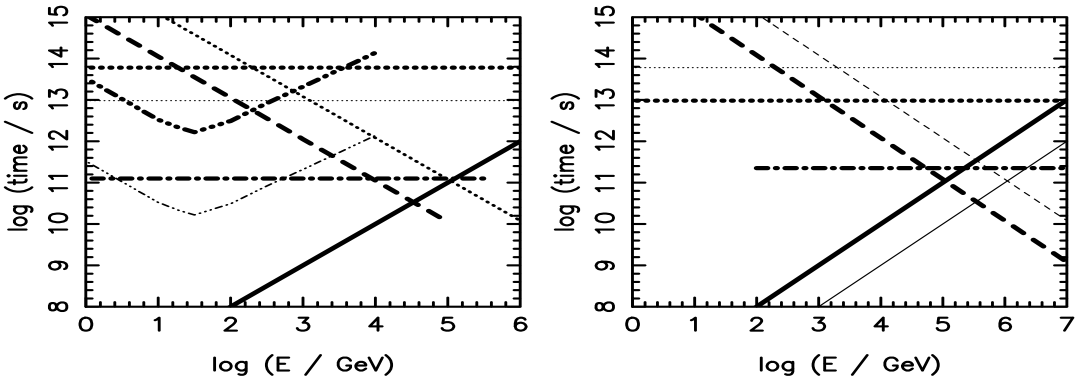

Figure 1: The characteristic time scales for electrons (left figure) on synchrotron (dashed line), bremsstrahlung (dot-dashed), ICS on stellar radiation (thick triple-dot-dashed), and for their energy gains (thick solid) are compared with the diffusion time scale of electrons from the open cluster, calculated for $R_{\rm oc} = 2$ pc (middle dotted), the age of the WR star in Berk 87, 3×10^5 yrs (thin dotted), and the age of the open cluster 2×10^6 yrs (thick dotted). The parameters which determine the energy losses and gains are the following: $B = 10^{-5}$ G, $N = 10^4$ cm^{-3}, $\xi = 10^{-5}$, and $\mu = 1$ (thick triple-dot dashed curve) and 100 (thin triple-dot dashed). The time scales for protons (right figure) losing energy on pion production in collisions with the matter (dot-dashed line), gaining energy from the acceleration mechanism if the magnetic field strength $B = 10^{-5}$ G (thick solid line) and $B = 10^{-4}$ G (thin solid line). The diffusion time of hadrons through the open cluster is shown by the dashed line, the age of the WR star, and the age of the open cluster are marked by the thick and thin dotted lines.

imum energies of accelerated particles are determined by balancing their energy gains and losses. These time scales and resulting maximum energies of electrons and hadrons are shown in Fig. 1. It is clear that electrons can be accelerated to energies above ~ 10 TeV. These ones with the highest energies cool by synchrotron process and those with lower energies mainly by IC and bremsstrahlung process. The maximum energies of hadrons are determined by their diffusion outside the open cluster. They lose energy on pion production in collisions with the matter.

Gamma-rays from Berk 87

The open cluster Berk 87 is at the distance of ~ 950 pc with the angular size equal to 8 arc min (~ 2 pc). The total mass of the young stellar association is estimated on $\sim 10^5$ $M_\odot$ and the density of matter inside the cores of compact regions is estimated on $\sim 10^5$ cm^{-3}. Berk 87 contains also rare type WR star, ST 3 (WR 142), which mass loss rate has been estimated on 1.7×10^{-5} $M_\odot$ yr^{-1} and the wind velocity on ~ 5200 km s^{-1} (the power of the wind is of the order of $\sim 10^{38}$ erg s^{-1}). The total stellar luminosity of Berk 87, $\sim 2 \times 10^{39}$ erg s^{-1} estimated by counting the contribution from the most luminous stars (the average energy density of stellar radiation ~ 260 eV cm^{-3}). Note, that the effective energy density of stellar photons, which are seen by accelerated electrons, is likely to be larger since at least a part of the electrons might diffuse against the massive star winds being exposed to much denser effective stellar radiation field [9]. We take this possibility into account by introducing the enhancement factor of the stellar radiation. This factor depends on the details of the diffusion and advection processes of electrons in the vicinity of specific stars of the open cluster.

The EGRET telescope discovered two point like sources, 3EG J2021+4716 and 3EG J2016+3657, in the direction of Berk 87 [3] and the GeV source J2020+3658 [12], which is likely related to 3EG J2021+3716. Also diffuse X-ray emission from this cluster has been observed by the EXOSAT ($\sim 5 \times 10^{32}$ erg s^{-1} [13] and by the ASCA satellites [14]. The region has been also observed by the Cherenkov telescopes at TeV energies: the upper limit on the level of 2×10^{-11} ph. $\mathrm{cm}^{-2}s^{-1}$ above 350 GeV (Whipple [15]) and at energies above 0.7 TeV on the level of 3×10^{-13} cm^{-2} s^{-1} (based on the 6.4 hr data) has been also reported (HEGRA [16]). Based on this last upper limit, the authors reject the pure hadronic model discussed in [7]. In fact, such an upper limit can only constrain the maximum energy of the accelerated protons, i.e. the model with rather flat injection spectrum of hadrons with the differential spectral index equal to 2. In a more recent paper, the HEGRA group puts the upper limit on the γ-ray flux from direction of Berk 87 on the level of 1.08×10^{-12} cm^{-2} s^{-1} above 0.9 TeV based on the 13.4 hr data [5]. Surprisingly, this second upper limit is much less restrictive that the earlier one. Very recently, the Milagro group reported positive detection of a quite extended source at energies > 12 TeV from the region containing Berk 87 with the flux estimated on 1.7×10^{-13} ph. cm^{-2} s^{-1} (MGRO J2019+37 [6]).

In the present calculations, it is assumed that electrons and hadrons are injected uniformly during the lifetime of the Wolf-Rayet star (which is of the order of $\sim 3 \times 10^5$ yrs). We consider two hypothesis, either γ-rays from the EGRET energy range up to the highest energies observed are due to only hadrons (model A), or they are due to the contribution from electrons and hadrons (model B). Following parameters describing the content of Berk 87 have been applied: the magnetic field inside the volume of the cluster 10^{-5} G, density of matter 10 cm^{-3}, the average density of stellar photons is obtained by counting the contribution of the most luminous stars (estimated on $\sim 2 \times 10^{39}$ erg s^{-1}).

Since the spectra of EGRET sources are flat, we assume in model A that hadrons has to have also the spectral index close to 2. The γ-ray spectra produced by hadrons are on the level of the EGRET flux for the energy conversion efficiency from the WR star wind (WR 142) to particles $\eta_{\mathrm{p}} = 3 \times 10^{-3}$ (see Fig. 2). Note that the spectrum obtained for weaker magnetic field is not able to explain the extended emission reported by the Milagro experiment. On the other hand, the γ-ray spectrum calculated for stronger magnetic field is clearly above the upper limits reported by the Whipple and HEGRA experiments at TeV energies, although it is consistent with the Milagro flux provided that $\sim 10\%$ of hadrons, which escaped from the open cluster, interact with the matter of the molecular clouds. We also show (bottom Fig. 2) the γ-ray spectra produced by hadrons which are injected with the steeper spectrum (spectral index 2.4) and the maximum energies determined by 10^{-4} G. γ-ray emission produced in dense clouds is quite extended, and that's why difficult to be observed with the Cherenkov telescopes of the Whipple and HEGRA telescopes. Therefore, we claim that these γ-ray spectra are generally consistent with the observations by different telescopes at the TeV energies. However, the spectrum of hadrons has to become significantly flatter below ~ 100 GeV in order to be consistent with the flat spectrum characteristic for the EGRET sources. Such a break is difficult to explain in the simple shock acceleration scenario. Based on these calculations, we conclude that the pure simple hadronic model is unlikely.

Let us consider the production of γ-rays in open clusters in the hybrid model (model B) in which hadrons and electrons are accelerated inside the open cluster. Electrons are assumed to be injected with the power law spectrum and spectral index 2.4 extending up to the maximum energies $\sim 10^5$ GeV (for the magnetic field 10^{-5} G). The spectrum of electrons is normalized to the power of the Wolf-Rayet star WR 142 with the coefficient $\eta_{\mathrm{e}} \approx 5 \times 10^{-3}$ (in the EGRET energy range). The photon spectra produced by electrons in the synchrotron, bremsstrahlung and IC processes are shown in Fig. 2. The EGRET spectrum is described in such a model by the combination of bremsstrahlung spectrum at lower energies and IC spectrum at higher energies. Due to the Klein-Nishina effects and efficient colling of electrons with the largest energies on the synchrotron process, the γ-ray spectra from bremsstrahlung and IC processes have to steepen. These spectra do not overcome the upper limits introduced by the Whipple and HEGRA telescopes. However, they are not able to explain the extended emission at the highest energies reported by Milagro group. In order to explain all these results simultaneously, we postulate additional production of γ-rays by hadrons which have escaped from the open cluster and interact inside surrounding dense clouds. Hadrons are accelerated inside the open cluster with the spectral index as postulated for electrons and with the cut-

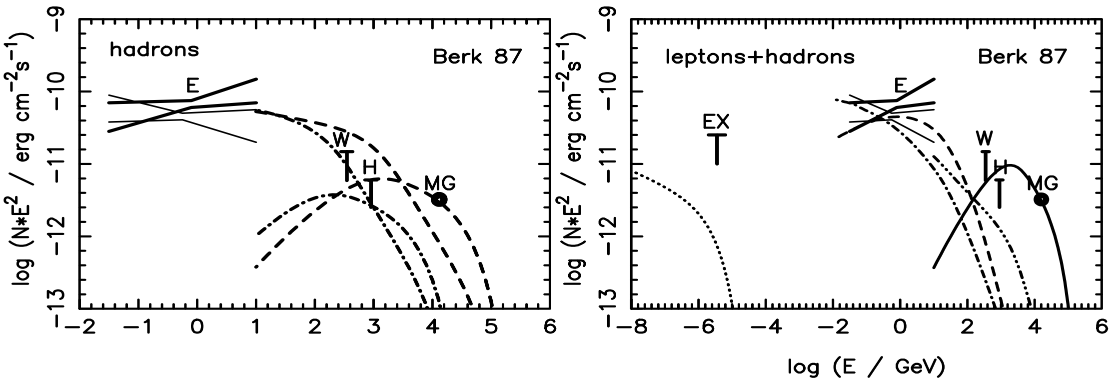

Figure 2: The multiwavelength spectrum observed from the region toward the open cluster Berk 87: the EXOSAT satellite (marked by EX, Warwick et al. 1988), the unidentified EGRET sources from the 3rd Catalog 3EG 2016+3657 (thin solid) and 3EG J2021+3716 (thick solid) (E, [3]), the Whipple upper limit (W, [15]), the HEGRA upper limit (H, [4]), and the Milagro detection of the extended source MGRO J2019+37 (MG, filled circle [6]). γ-ray spectra produced by hadrons interacting with the matter inside the open cluster with density 10 cm^{-3} and with the matter of the surrounding molecular clouds with density 10^4 cm^{-3} (left figure). Hadrons are injected with the power law spectrum with the spectral index 2.1 and the high energy cut-off obtained for the magnetic field 10^{-4} G (dashed curves) and 10^{-5} G (dot-dashed curves). The energy conversion efficiency into relativistic particles is $\eta_{\rm p} = 3 \times 10^{-3}$. The capturing factor of hadrons by the surrounding massive clouds is $\xi = 10\%$ (dashed spectra) and 4% (dot-dashed spectra). The comparison with the photon spectra produced by electrons in the synchrotron (dotted curve), IC (dashed) and bremsstrahlung (dot-dashed) processes and the γ-ray spectra from decay of $\pi^{\rm o}$ produced by hadrons in collisions with the matter with density 10 cm^{-3} inside the open cluster (triple dot-dashed curve) and hadrons which escaped from the open cluster into the surrounding molecular clouds with density 10^4 cm^{-3} (solid curve) (right figure). Both, electrons and hadrons, have the power law spectrum (spectral index 2.4) and the high energy cut-offs determined by the magnetic field 10^{-5} G. It is assumed that electrons and hadrons take a part $\eta_{\rm e} = 5 \times 10^{-3}$ and $\eta_{\rm p} = 10^{-3}$ of the power of the WR star wind. All hadrons escaping from the open cluster are captured by molecular clouds. The density of radiation is described by $\mu = 1$.

off at energies expected for this above mentioned value of the magnetic field. In order to meet the Milagro flux, a part, $\eta_{\rm p} = 10^{-3}$, of the power of the WR star wind should be transfered to relativistic hadrons.

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