Gamma-rays from globular clusters

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Abstract: Millisecond pulsars in globular clusters can accelerate leptons at the shock waves originated in collisions of the pulsar winds and/or inside the pulsar magnetospheres. Leptons diffuse gradually through the globular cluster comptonizing stellar and microwave background radiation. We calculate the GeV-TeV gamma-ray spectra for different models of injection of leptons and parameters of the globular clusters. The example calculations are shown for the globular cluster Omega Centauri (NGC 5139). A few other clusters, which might be potentially detected by the Cherenkov and satellite telescopes, are discussed in Bednarek & Sitarek (2007).

Introduction

Globular clusters (GC) seem to be likely sources of γ-rays due to the presence of possible sources of energetic leptons and very well localized, strong soft radiation field (they typically contain $\sim 10^5$-10^6 late type stars in a volume with the half-mass radius of the order of a few parsecs). Leptons are expected to be injected by millisecond pulsars (MSP). Typical globular cluster contains of the order of a hundred MSPs. In fact, more than 100 radio pulsars with spin periods in the range of a few to a few tens of milliseconds, have been detected in 24 globular clusters (e.g., Ter 5 - 23 MSP, 47 Tuc - 22 MSP). Only the upper limits on the γ-ray emission from the globular clusters are available, e.g. $(1-2)\times 10^{-7}$ ph. cm^{-2} s^{-1} above 100 MeV [9, 8] and 8×10^{-6} ph. cm^{-2} s^{-1} in energy range $0.75-30$ MeV [10]. The upper limits on the TeV γ-ray emission from the globular clusters, e.g. in the case of M 13 [3] and M 15 [6], do not constrain strongly the possible production of energetic particles in these type of objects.

In this paper we calculate the γ-ray emission in the GeV-TeV energy range from the whole population of MSP in the specific globular cluster. We assume that γ-ray emission is produced by leptons which scatter the stellar and microwave background radiation during their diffusion through the medium of the GC.

The model

The MS pulsars in GCs have the average period of the order of a few milliseconds and surface magnetic fields of the order of $\sim 10^9$ G (see e.g. Camilo & Rasio [2]). The characteristic energy loss rate due to the pulsar wind from an isolated pulsar can be estimated by applying the formula for the rotating magnetic dipole,

$$L_{\rm p} = 1.2\times 10^{35} B_9^2 P_4^{-4} \quad {\rm erg\ s^{-1}}, \tag{1}$$

where $B_{\rm p} = 10^9 B_9$ G is the surface magnetic field of the pulsar, and $P = 4P_4$ ms is the pulsar period.

Pulsars produce relativistic strongly magnetized winds which, when colliding with other winds, create relativistic shocks. If the pulsar winds collide between themselves, then typical distance from the pulsar to the shock can be estimated on

$$R_{\rm sh} \approx 0.5 R_{\rm c}/N_{\rm p}^{1/3}. \tag{2}$$

where $R_{\rm c}$ is the core radius of GC in pc and $N_{\rm p}$ is the number of MSP. We estimate the magnetic field strength at such shocks by simple re-scaling from the pulsar (assuming R^{-3} dependence in the inner pulsar magnetosphere and R^{-1} dependence in the pulsar wind),

$$B_{\rm sh} \approx 2.5\times 10^{-5}\sqrt{\sigma} B_9/P_4^2 \quad {\rm G}, \tag{3}$$

where σ is the magnetization parameter of the pulsar wind. We consider the case of leptons injected by the pulsars and additionally accelerated in such relativistic shocks with the mono-energetic and the power-law spectra. In the case of the shock acceleration mechanism, the acceleration rate is independent on the energy of lepton E provided that so called acceleration coefficient ξ is constant. It can be written as,

$$\left(\frac{dE}{dt}\right)_{\rm acc} = \xi c E/R_{\rm L} \approx 10^{13}\xi B_{\rm sh} \quad {\rm eV\ s^{-1}}, \quad (4)$$

and the corresponding acceleration time scale,

$$t_{\rm acc} = E/(dE/dt)_{\rm acc} \approx 10^5 E_{\rm TeV}/(\xi B_{-6}) \quad {\rm s}. \quad (5)$$

where $E = 1E_{\rm TeV}$ TeV is the energy of leptons, $B_{\rm sh} = 10^{-6}B_{-6}$ G is the magnetic field strength at the shock, and c is the velocity of light.

The maximum energies, which leptons ($e^{\pm}$) can reach in such pulsar wind shocks, are limited by different processes such as the Larmor radius of leptons, the radiation processes and advection along the shock surface and after that their diffusion outside the GC. They are discussed in detail in Bednarek & Sitarek [1]. The synchrotron energy loss rate is,

$$\left(\frac{dE}{dt}\right)_{\rm syn} = \frac{4}{3}c\sigma_{\rm T}U_{\rm B}\gamma_{\rm e}^2 \approx 8.3\times 10^{-4}B_{\rm sh}^2\gamma_{\rm e}^2 \quad {\rm eV\ s^{-1}}, (6)$$

where $U_{\rm B}$ is the energy density of magnetic field, $\sigma_{\rm T}$ is the Thomson cross section, and $\gamma_{\rm e}$ is the Lorentz factor of leptons.

Based on the observed luminosity of specific globular cluster and on the density profile for the distribution of the stars inside the cluster, we calculate the energy density of stellar photons inside the cluster core which allow us to estimate the efficiency of γ-ray production by leptons with specific energies. This average density of stellar photons in the core of GC is $U_{\rm rad} \approx 300$ eV cm^{-3}. This allows us to estimate the energy loss rate on ICS in the Thomson (T) regime,

$$\left(\frac{dE}{dt}\right)_{\rm IC}^{\rm T} = \frac{4}{3}c\sigma_{\rm T}U_{\rm rad}\gamma_{\rm e}^2 \approx 7.6\times 10^{-12}\gamma_{\rm e}^2 \quad {\rm eV\ s^{-1}}. \quad (7)$$

However, the limit on the maximum energies of accelerated leptons can be also given by the advection time scale of leptons along the surface of the shock. The velocity of the plasma flow downstream of the relativistic shock can be estimated at $v_{\rm adv} \sim c/3$. Then, the advection time scale is,

$$t_{\rm adv} = R_{\rm sh}/v_{\rm adv} = 0.5R_{\rm c}/(N_{\rm p}^{1/3}v_{\rm adv}). \quad (8)$$

where $R_{\rm sh}$ is defined by Eq. 2.

We conclude that the maximum energies of leptons accelerated at the shocks are usually limited by advection process of leptons along the shock and not by the dimension of the shock in the pulsar wind or the energy losses on the synchrotron or IC scattering processes. Leptons injected with different energies in the central core of the globular cluster diffuse gradually in the outward direction. In order to answer the question whether leptons can lose significant part of their energy during the diffusion through the thermal radiation field inside the GC, we estimate the collision rate on IC process in the Thomson regime for supposed parameters inside the GC. It is found to be close to ~ 100 [1]. Therefore, leptons with energies up to ~ 1 TeV should interact frequently with stellar photons producing γ-rays with comparable energies. However, leptons with energies above ~ 1 TeV have chance to escape from the radiation field of the GC without interaction with stellar photons. These high energy leptons interact frequently with the MBR producing γ-rays in the energy range from tens MeV up to hundreds GeV.

Let us assume that a part, η, of the wind energy of pulsars inside the GC is converted into relativistic leptons (so called energy conversion efficiency). Then, the power injected in relativistic leptons is

$$L_{\rm e} = \eta N_{\rm p}L_{\rm p} = 1.2\times 10^{35}\eta N_{\rm p}B_9^2P_4^{-4} \quad {\rm erg\ s^{-1}}. \quad (9)$$

The spectrum of leptons accelerated at the shocks can be approximated by a single power-law with the spectral index α between $E_{\rm min}$ and $E_{\rm max}$.

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We calculate the γ-ray spectra produced by leptons which IC up-scatter the stellar photons and the MBR. For considered energies of leptons the scattering process of stellar radiation can occur in the T or the KN regimes. We neglect the synchrotron energy losses of leptons for the considered range of their energies and expected values of the magnetic field inside the GCs. It is assumed that leptons are injected homogeneously inside the core of GC. Since diffusion of leptons from the core occurs in the variable thermal radiation field, the importance of the scattering process in both considered radiation fields (thermal photons and MBR) can differ significantly. In order to calculate the γ-ray spectra produced by leptons diffusing outward the center of GC we apply the Monte Carlo method.

The example γ-ray spectra obtained for the mono energetic and the power law spectra of leptons are discussed in Bednarek & Sitarek [1]. The characteristic two bump structures appear in these γ-ray spectra when considering the mono energetic leptons due to the comptonization of optical and MBR photons. In the case of the power law spectra, we consider a range of the spectral indexes between α=2-3, expected for relativistic shocks. On the other hand, we also fix the low energy cut-off in these power-law spectra on $E_{\rm min} = 1$ GeV or 100 GeV. This low energy cut-off might correspond to energies of leptons injected into the pulsar wind from the inner magnetospheres of the millisecond pulsars. The power-law spectrum of leptons is normalized to the part of power of the millisecond pulsar winds present inside the core of GC, L_e (see Eq. 9), assuming the average pulsar parameters, $B_9 = 1$ and $P_4 = 1$. Depending on the low energy cut-off, the γ-ray spectra peak in the hundred MeV or hundred GeV energy ranges. We also investigated the spectral shape and intensity as a function of the distance from the core of the GC for different values of the magnetic field strength which define diffusion process of leptons. It is found that for reasonable magnetic fields ($10^{-6} - 10^{-5}$ G), the γ-ray source produced by these leptons should be well concentrated around the center of GC.

Omega Centauri (NGC 5139)

We performed calculations of the γ-ray spectra and fluxes expected on the Earth from four clusters in which a large number of millisecond pulsars is expected: 47 Tuc (22 MSP detected and ~ 260 MSP expected), Ter 5 (23, and ~ 230 MSP), M15 (8 and $\sim$ 117 MSP), and M13 (5 and $\sim$ 102 MSP), assuming the energy conversion efficiency from the pulsar to relativistic leptons equal to $\eta = 0.01$ and the presence of 100 MSP (see [1]). It is concluded that these GCs should be detected by the present Cherenkov telescopes and/or the satellite telescopes (AGILE, GLAST) provided that these parameters are reasonable. Here, we calculate the spectra for one more massive and close globular cluster on the southern hemisphere, i.e. Omega Centauri (NGC 5139). It is at the distance of 5.3 kpc, is one of the largest GC, $L = 2.5 \times 10^6 L_\odot$, has the core radius ~ 1.4 pc and the half mass radius ~ 4.2 pc [5]. The estimated number of MSPs in Omega Centauri is ~ 340 [11].

Table 1: The upper limits on the parameter $N_{\rm p} \cdot \eta$ based on the sensitivities of different telescopes (G - GLAST;H - HESS).

Model $E_{\rm min}$, α	NGC 5139 (G)	NGC 5139 (H)
100 GeV, 2.1	0.5	0.015
100 GeV, 3.0	0.25	0.06
1 GeV, 2.1	0.15	0.03
1 GeV, 3.0	0.15	2
mono: 1 TeV	1	0.03
mono: 10 TeV	5	0.03

The results of calculations are shown for leptons with the power law spectrum extending up to 30 TeV (Fig. 1a) and 3 TeV (Fig. 1b), and for the mono energetic leptons with energies 1 TeV and 10 TeV (Fig. 1c). They are compared with sensitivities of different telescopes. It is clear that for the assumed energy conversion efficiency $\eta = 0.01$ and 100 MSP present inside NGC 5139, the γ-ray telescopes should easily detect γ-rays from this source. The detection by the GLAST instrument will be possible even for the value of $N_{\rm p} \cdot \eta = 1$, in the case of steep spectrum of leptons extending up to 1 GeV or a flat spectrum extending above 100 GeV. In other cases, the value of $N_{\rm p} \cdot \eta$ should be significantly larger (see Tab. 1). However, the Cherenkov telescopes of the HESS type should easiely detect the Omega Centauri in all considered power law injection spectra of leptons (accept the case of a steep spectrum extending up to 1 GeV). Such Cherenkov TeV observations have the power to constrain the parameter $N_{\rm p} \cdot \eta$ on the level of

< 0.1, i.e. significantly below the present theoretical estimates.

Conclusion

Our calculations allow us to put strong constraints on the product of the power conversion efficiency times number of MSPs in specific GC ($N_{\rm p} \cdot \eta$). If the acceleration of leptons occurs above ~ 1 TeV, then the most restrictive limits obtained by the HESS and VERITAS type Cherenkov telescope arrays on the power conversion efficiency of leptons are of the order of $\eta \sim 10^{-(3\div4)}$, provided that $N_{\rm p} \sim 100$ MSPs are present in specific GC as expected in some estimations [11]. The GLAST and MAGIC telescopes can provide also an order of magnitude more restrictive limits on η, than e.g. estimated from the observations of the Crab Nebula ($\eta \sim 10\%$) or expected in the case of isolated MSPs i.e. $\sim 3\%$ [4], provided that leptons are accelerated by $N_{\rm p} \sim 100$ MSPs to energies at least $\sim$1 TeV. These limits put strong constraints on the high energy processes occurring in the inner pulsar magnetospheres and/or the acceleration mechanisms in the pulsar winds and the pulsar wind shocks.

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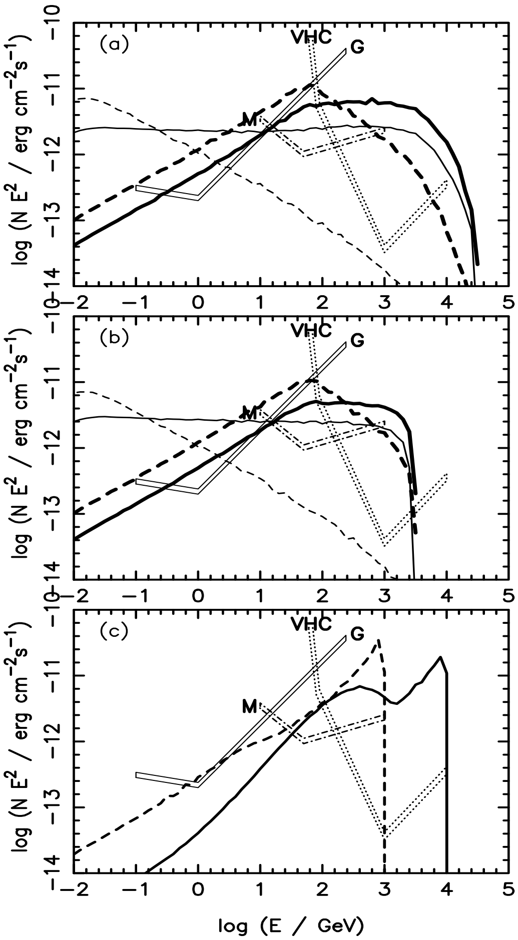

Figure 1: The differential gamma-ray spectra (SED) expected from NGC 5139 for different parameters of the injected spectrum of leptons: power-law spectrum with index 2 (solid curve), and 3 (dashed). The spectra have low energy cut-off at 1 GeV (thin) or 100 GeV (thick). Spectra produced by leptons with the upper energy cut-off at 30 TeV (figure (a)) and at 3 TeV (b). The energy conversion efficiency $\eta = 0.01$, 100 millisecond pulsars inside the globular cluster with the rotational periods equal to 4 ms and the surface magnetic fields equal to 10^9 G. Spectra for the case of mono-energetic leptons injected with energies 10 TeV and 1 TeV are shown in figure (c). The sensitivities of different γ-ray telescopes [7] are marked by a double dotted curve (C - CANGAROO, H - HESS, and V - VERITAS), a double dot-dashed (M - MAGIC, and expected HESS II in this energy range), and a double solid (G - GLAST).