Gamma-rays from White Dwarfs within Globular Clusters?

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Abstract: Recently a population of Globular Clusters have been established as gamma-ray sources by the Fermi-LAT telescope. We investigate possible production of gamma-rays by relativistic electrons injected from the population of White Dwarfs within the globular cluster. Large numbers of these compact objects should be present within the globular clusters. We calculate the expected gamma-ray spectra produced by these relativistic electrons in the Inverse Compton scattering of stellar radiation field and the microwave background radiation within the globular clusters. We conclude that gamma-rays produced by electrons accelerated by the whole population of White Dwarfs might be responsible for a part of the observed emission from Globular Clusters.

Keywords: globular clusters - stars: white dwarfs - gamma-rays: theory

1 Introduction

Globular Clusters (GCs) are huge concentrations of $\sim 10^5 - 10^6$ old stars contained within a spherical volume with a radius of a few parsecs. Since GCs are very old objects, they contain remnants of evolution of stars with masses $>1 M_\odot$, i.e. millisecond pulsars (MSPs), Cataclysmic Variables (i.e. accreting White Dwarfs), Low Mass X-ray Binaries, and possibly also stellar mass or intermediate mass black holes. Several Globular Clusters have been recently established as sources of GeV $\gamma$-rays in the observations with the Fermi-LAT telescope (Abdo et al. 2009a, Abdo et al. 2009b, Kong et al. 2010, Tam et al. 2011, see for review Bednarek 2010). The $\gamma$-ray spectra of GCs seemed to show features very similar to the recently discovered population of the millisecond pulsars (MSPs), i.e. very flat spectra with an exponential cut-off at a few GeV (Abdo et al. 2010). However such features may not be common in the case of all $\gamma$-ray emitting GCs since some of recently discovered objects show also spectra which clearly extend above $\sim 10$ GeV, without clear evidences of the cutoffs (Tam et al. 2011). Therefore, the origin of $\gamma$-rays may not be only related to processes occurring within the inner magnetospheres of MSPs. The possibility of high energy $\gamma$-ray emission extending up to TeV energies has been also expected (Bednarek & Sitarek 2007, Venter et al. 2009, Cheng et al. 2010).

Although the relation of the MSP content within the GCs to their $\gamma$-ray emission seems to be very likely we wonder whether other sources within the GCs may also contribute to the observed $\gamma$-ray flux. In this paper we investigate the possibility of acceleration of electrons within the inner magnetospheres of non-accreting White Dwarfs (WDs). These electrons might diffuse within the GC producing high energy $\gamma$-rays by scattering stellar radiation and the Microwave Background Radiation (MBR) in the IC process as considered in Bednarek & Sitarek (2007).

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The stars with low masses (in the range $\sim 0.8-8 M_\odot$) should finish their life as the White Dwarfs (WDs). We estimate the initial mass function of stars by the function, $dN/dM = N_0 M^{-\beta}$, with $\beta = 2.35$ above $0.5 M_\odot$ (Salpeter 1955, Kroupa 2001) and $\beta = 1.3$ below $0.5 M_\odot$ (Kroupa 2001). The normalization factor is estimated on, $N_0 \approx 7 \times 10^4 M_\odot^{-2}$, by assuming the total mass of stars within the GC equal to $M_{GC} \approx 3 \times 10^5 M_\odot$ and the minimum mass of stars on 0.08 $M_\odot$. In such a case the number of WDs which appeared within the GC is estimated on $N_{WD} \sim 7 \times 10^4$. We conclude that the number of WDs within specific GC can be a few hundred times larger than the number of the MSPs expected within the GC. Note, that a part of these WDs, which form the compact binary systems, can merge during the lifetime of the GC. As a result a population of massive WDs (with the mass close to the Chandrasekar limit) is expected within the GCs. These WDs should have small radii ($\sim 10^8$ cm), short periods (due to the large angular momentum of the WD-WD binary systems), and strong surface magnetic fields ($\sim 10^9$ G). The second population of magnetic WDs can appear as a result of evolution of stars with masses $2 - 3 M_\odot$, so called A type stars. These two populations have different characteristics parameters and time distribution within GCs.
The rotational energy loss rate of the WD is, \( E_{\text{rot}} = B_{\text{WD}}^2 \Omega_{\text{WD}}^2 P_{\text{WD}}^2 / (6c^3) \approx 1.5 \times 10^{31} B_{\text{WD}}^2 P_{\text{WD}}^4 \) erg s\(^{-1}\), where the angular velocity of the WD is \( \Omega_{\text{WD}} = 2\pi / P_{\text{WD}} \) and \( P_{\text{WD}} = 5 \times 10^8 \) cm. The rotational energy budget of the WD is, \( E_{\text{rot}} = 0.5 I_{\text{WD}} \Omega_{\text{WD}}^2 \approx 4 \times 10^{47} P_{\text{WD}}^2 \) erg s\(^{-1}\), where the moment of inertia of the WD is \( I = 0.4 M_{\text{WD}} R_{\text{WD}}^2 \approx 2 \times 10^{46} \) g cm\(^2\). Therefore, for typical parameters \((B_8 = 1\) and \(P_2 = 1\)), the WD is able to inject relativistic electrons continuously during the characteristic time, \( \tau_{\gamma} = E_{\text{rot}} / E_{\gamma} \approx 1.6 P_{\text{WD}}^2 / B_8^2 \) Gyr. By comparing this time scale with the characteristic rotational energy loss time scale of the WD with specific parameters \((\tau_{\gamma WD} = \tau_{MWD})\), we conclude that the old WDs should have at present the periods longer than, \( P_2 \approx 2.5 B_8 \tau_{10} \), where \( \tau_{MWD} = 10 \tau_{10} \) Gyr. However, the magnetic field of the WDs might also decay on the time scale which is usually expected in the range of \( 3 - 10 \) Gyr. We apply the simple exponential decay law for this process, i.e. \( B_{\text{WD}}(T) = B_0 \exp(-T/\tau_d) \), where \( B_0 \) is the surface magnetic field of the WD at birth, \( \tau_d \) is the decay time, and \( T \) is time. The evolution of the rotational period of this WD is then determined by \( P^2(T) = P_0^2 + 4.6 B_0^2 \tau_d [1 - \exp(-2T/\tau_d)] \) s\(^2\).

In the case of the WDs from mergers in binary systems the above formulae should be modified by changing the radius of the WD from \( 5 \times 10^8 \) cm to \( 10^9 \) cm and its mass from \( 0.8 M_\odot \) to \( 1.4 M_\odot \). The initial rotational periods of the WDs, formed during merger of two WDs, can be estimated by assuming that the angular momentum of the WD binary system has been conserved during merger. Let us assume that the initial orbital period of the WD-WD binary system was \( \tau_{\text{orb}} = \tau_{10} \) days and the masses of the WDs were \( M_{\text{WD}} = 1 M_\odot \). Then, the rotational period of the WD formed during the merger can be as short as, \( T_{\text{WD}} = (2\pi R_{\text{WD}})/(2.51/2) (32 \pi^2 / G^2 M_{\text{WD}} \tau_{\text{WD}}) \approx 0.3 R_8 M_{\text{WD}}^{-1} \frac{\tau_d}{\sqrt{R_{\text{WD}}}} \) s, where the radius of the WD is \( R_{\text{WD}} = 10^8 R_8 \) cm.

### 3 Relativistic electrons from White Dwarfs

The maximum Lorentz factors of electrons accelerated in the WD inner magnetosphere along the electric field induced through the open magnetic field lines can be estimated from (Goldreich & Julian 1969), \( \gamma_{\text{max}} = \xi e B_{\text{WD}}^2 \Omega_{\text{WD}}^2 P_{\text{WD}}^2 / (2m_e c^2) \approx 1.6 \times 10^7 \xi B_8 P_{\text{WD}}^2 \), where \( \xi \) is the acceleration efficiency, \( e \) is the electron charge, \( c \) is the velocity of light, and \( m_e \) is the electron rest mass. However, the acceleration process can be limited by the energy losses on curvature emission due to the curvature of the magnetic field lines in the inner WD magnetosphere. We estimate the parameter range of the WDs for which the curvature energy losses are not able to limit their acceleration. The following condition has to be fulfilled, \( \lambda_{\text{cr}} > R_{\text{LC}} \) where \( \lambda_{\text{cr}} = m_e c^2 \gamma_{\text{max}} / \dot{E}_{\text{cr}} \) is the electron energy loss mean free path on the curvature radiation. The curvature energy losses are given by, \( \dot{E}_{\text{cr}} = 2 e^2 \gamma_{\text{max}}^4 / 3 R_{\text{cr}}^2 \), where the curvature radius of the magnetic field lines is estimated from \( R_{\text{cr}} = \sqrt{R_{\text{WD}} R_{\text{LC}}} \approx 1.5 \times 10^{10} P_{\text{WD}}^{1/2} \) cm, \( R_{\text{LC}} = c P_{\text{WD}} / 2\pi \) is the light cylinder radius. The curvature losses are not able to limit the electron acceleration in the WD magnetosphere for the range of parameters fulfilling the condition, \( B_8 < 0.84 P_{\text{WD}}^2 / \xi \). If this equation is not fulfilled, then electrons are injected from the inner WD magnetosphere with the Lorentz factors \( \gamma_{\text{sat}} \), which can be clearly lower than \( \gamma_{\text{max}} \). This limiting Lorentz factor can be estimated from the condition \( \lambda_{\text{cr}}(\gamma_{\text{sat}}) = R_{\text{LC}} \), and is equal to, \( \gamma_{\text{sat}} \approx 1 \times 10^4 \). Note that it is independent on the WD parameters in the case of realistic curvature of the magnetic field lines. Electrons with such Lorentz factors can produce curvature photons with characteristic energies \( E_{\gamma} = 3 \epsilon \gamma_{\text{sat}}^3 / (4\pi R_{\text{cr}}) \approx 5.3 \epsilon P_{\text{WD}}^{-1/2} \) MeV.

\( \gamma \)-rays can be efficiently converted into \( e^\pm \) pairs in the magnetic field of the WD if the following condition is fulfilled (Ruderman & Sutherland 1975), \( (E_{\gamma}^2 / 2m_e c^2) (B / B_{\text{cr}}) > 1/2 \), where \( B_{\text{cr}} = 4.4 \times 10^{13} \) G is the critical magnetic field strength. Electrons with the Lorentz factors, \( \gamma_{\text{sat}} \), following the magnetic field with curvature, \( R_{\text{cr}} \), can not fulfill the above condition for realistic values of the surface magnetic field since \( B_8 > 5.4 \times 10^2 P_{\text{WD}}^2 / \xi \). Only in the case of almost instantaneous acceleration of electrons relatively close to the WD surface (without curvature losses included), the energies of curvature \( \gamma \)-rays produced by these electrons can be as large as, \( E_{\gamma} = (3/4\pi)(h)(c)/(R_{\text{cr}}) \approx 8 \epsilon^3 B_8^3 P_{\text{WD}}^{13/8} \) MeV, where \( h \) is the Planck constant. Applying the curvature of the WD magnetic field lines in the inner magnetosphere, \( R_{\text{cr}} \), as expected in the dipole model, we get the limit, \( B_8 < 7.8 \epsilon^{-3/4} P_{\text{WD}}^{13/8} \), for which curvature \( \gamma \)-rays can create \( e^\pm \) pairs in magnetic field. As a result the magnetic \( e^\pm \) pair cascades develop along the certain magnetic field lines within the WD inner magnetosphere. They can quench the acceleration of electrons to large energies along these lines.

The above discussed conditions are marked in Fig. 1. We can distinguish a few regimes for the acceleration of electrons in the inner WD magnetosphere. For the parameters above the dotted line, the energies of curvature \( \gamma \)-rays are sufficient enough for their conversion into \( e^\pm \) pairs in the magnetic field of the WD. Produced \( e^\pm \) pairs saturate the electric field induced in rotating magnetosphere, preventing acceleration of \( e^\pm \) pairs to energies comparable to the maximum potential drop through the open magnetosphere. As a result, primary electrons are accelerated to relatively low energies but plenty of \( e^\pm \) pairs escape through the light cylinder. Below the dotted line electrons can be accelerated to large energies. Above the dashed line their acceleration is limited by the curvature energy losses (so called saturated acceleration). Below dashed line electrons reach the maximum energies corresponding to full potential drop available along the open field lines. Therefore, for the parameters of the WDs below the dotted line electrons are injected through the light cylinder with large Lorentz factors. The rotating WD produce collimated pulses of radiation.
Figure 1: Conditions for the acceleration of electrons in the inner White Dwarf magnetosphere as a function of the surface magnetic field of the WD, $B$, and its rotational period, $P$: for the WDs formated as a result of stellar evolution (figure on the left) and originated from the WD-WD mergers within the compact binary systems (figure on the right). The condition for $e^+$ pair production by the curvature $\gamma$-rays in the magnetic field of the inner WD magnetosphere (dotted line). The condition for saturation (or not saturation) of electron acceleration by curvature energy losses (dashed line). The WD should operate as a pulsar above the dashed line. The final parameters of the WD which has been created within the Globular Cluster and slowed down during its lifetime due to the rotational energy losses are marked by the dot-dashed line. The acceleration parameter is assumed to be equal to $\xi = 1$.

The electrons accelerated in the WD magnetosphere takes a part, $\eta$, of the rotational energy loss rate of the WD equal to $E_{\text{rot}}$. Then, the power contained in relativistic electrons can be related to the WD energy loss rate by, $P_{\text{inj}} = \eta E_{\text{rot}}$ in the case of the WDs with unsaturated acceleration of electrons in the inner magnetospheres and by $P_{\text{inj}} = \eta (\gamma_{\text{max}}/\gamma_{\text{sat}}) E_{\text{rot}}$ in the case of saturated acceleration. We estimate the number of injected relativistic electrons by normalizing their spectra to the above estimated power, $P_{\text{inj}}^\text{unsat}$ and $P_{\text{inj}}^\text{sat}$, respectively.

The magnetic WDs (MWDs) created in the merger events have similar magnetic moments to those formed from magnetic stars but their rotational periods are expected to be clearly shorter, due to the large angular momentum of the binary system. On the other hand, the curvature of the magnetic field lines should be smaller due to their larger masses and smaller radii of the WDs. Therefore, in principle they could accelerate electrons to larger energies in their inner magnetospheres $E_{\text{max}} = 1.3 \times 10^8 \xi B_5 P_2^{-2}$. The basic parameters of these WDs from mergers can significantly differ from those appeared as a result of stellar evolution. We apply for them following values: $M_{\text{WD}} = 1.4 M_\odot$ and $R_{\text{WD}} = 10^8$ cm.

The condition for the saturation of electron acceleration in the case of the WDs from mergers now becomes, $B_5 > 62 P_2^{13/8}/\xi$. In the case of saturated acceleration, electrons move in the inner magnetosphere with the equilibrium Lorentz factor, $\gamma_{\text{sat}} \approx 8 \times 10^6$, and the characteristic energies of curvature $\gamma$-rays are $E_{\gamma}^\text{sat} = 2 \text{ MeV}$. The condition for developing cascades in the WD magnetosphere now becomes the following, $B_5 > 240 P_2^{13/8}$, These conditions for the acceleration of electrons in the magnetospheres of MWDs created in mergers are shown in Fig. 1. Their characteristic residence time within the GC estimated from the rotational energy loss time is $\tau_{\text{WD}} \approx 130 P_2^2/B_5^2$ Gys. We estimate that WDs from mergers created soon after GC formation should have at present rotational periods longer than $P_2 \approx 0.28 B_5$.

It is assumed that electrons are injected from WDs with the monoenergetic spectra determined by their parameters. We apply a simple model for the propagation of electrons within GC developed for the injection of electrons from the millisecond pulsars in GCs (see Bednarek & Sitarek 2007). Assuming the Bohm diffusion, electrons with specific energy, $E_e$, stay within the GC for the average time, $t_{\text{diff}} = R_{L_i}^2/D_{\text{diff}}$, where $D_{\text{diff}} = R_{L_i} c/3$ is the Bohm diffusion coefficient, $R_{L_i} = c p_e / e B_{\text{GC}}$ is the Larmor radius of electrons in the GC magnetic field $B_{\text{GC}} = 10^{-5} B_{-5}$ G, $p_e = 1 E_{\text{TeV}}/B_{-5}$ is the electron momentum and energy, and $R_{L_i}$ is the half mass radius of the GC. For the typical parameters of the GCs it has been shown that relativistic electrons spend enough time for frequent collisions with thermal photons. In order to calculate the $\gamma$-ray spectra from GCs, we apply the Monte Carlo method which helps us to follow the propagation of electrons and also describe the production of $\gamma$-rays in collisions with the MBR and the stellar radiation field which density decrease from the center of the GC (Bednarek & Sitarek 2007).
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We calculate the $\gamma$-ray spectra produced by relativistic electrons in the Inverse Compton process. The example results are shown for the GC at the distance of 7 kpc, containing $3 \times 10^5$ stars within the region with the core radius $R_c = 1.6$ pc and the half mass radius $R_h = 3$ pc. The magnetic field within the GC (which determines the diffusion process of leptons) is taken to be equal to $3 \times 10^{-6}$ G. The $\gamma$-ray fluxes expected from such GC due to comptonization of stellar and MBR fields by electrons which are injected by WDs with the range of initial periods (normalized to a single WD) are shown in Fig. 2. We show the $\gamma$-ray spectra in the case of the WDs which appear 12 Gyrs ago as a result of evolution of magnetic A type stars. The magnetic field of the WDs evolve on a time scale of 10 Gyrs (left figure). In the second calculations the WDs appear uniformly in time as a result of mergers within the binary systems and their surface magnetic field decays on a time scale of 3 Gyrs (right figure). The periods of the WDs and their surface magnetic fields evolve according to the formula shown above.

We confronted the expected $\gamma$-ray spectra with the 50 hr sensitivity of the future Cherenkov Telescope Array (CTA) which is of the order of $10^{-13}$ erg s$^{-1}$ at TeV energies. The CTA might be able to detect the TeV source with the power $\sim 5 \times 10^{32}$ erg s$^{-1}$ at the distance of 7 kpc. For example, the $\gamma$-ray emission expected from the population of WDs produced uniformly in time within the GC (right figure) might be detected by the CTA provided that about $2 \times 10^4$ MWDs is created during the lifetime of the GC. In the case of WDs formed soon after GC formation and with magnetic fields decaying on the time scale of 10 Gyrs (left figure), the detectability limit of the $\gamma$-rays from the MWDs should be a factor of a 2-3 less restrictive. Note that the $\gamma$-ray spectra extend to energies available by the CTA only in the case of efficient acceleration of electrons within the inner WD magnetosphere ($\xi > 0.03$). In the case of inefficient acceleration the WDs will be only able to contribute to the GeV energy range which in fact might be dominated by the $\gamma$-ray emission from the millisecond pulsar magnetospheres.

References