Non-thermal electromagnetic radiation from pulsating and collapsing magnetized white dwarfs

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Abstract. The non-thermal electromagnetic radiation from pulsating and collapsing magnetized white dwarfs is considered. This radiation generates when the star magnetosphere compresses during collapse and its magnetic field greatly increases. The electric field produced involves acceleration of charged particles, which generates radiation when moving in the magnetic field. Thus the pulsating and collapsing magnetized white dwarfs can be powerful sources of electromagnetic pulses. These pulses can be observed by means of modern instruments (radio, X- and gamma- telescopes).

1. Introduction

During their collapse stars emit gravitational and electromagnetic waves. In Dar et al. (1992), the acceleration non-relativistic nuclei and the generation gamma-ray bursts from accretion-induced collapse white dwarfs to neutron star was considered. As follows from this paper results, accretion induced collapse may be an important source of cosmic ray and cosmological gamma-ray bursts. De Couveia Dal Pino and Lazarian (2001a,b) have proposed that ultra high-energy cosmic rays observed above the Greisen-Zatsepin-Kuzmin (GZK) limit could be mostly protons accelerated in reconnection sites just above the magnetosphere of newborn millisecond pulsars, originated by accretion-induced collapse. Dermer and Atoyan (2006) considered the collapse of neutron stars to black holes in binary systems as a model for short gamma ray bursts. They found that the accretion of \( \approx 0.1 \sim 1 \text{ M}_\odot \) of material by a neutron star through Roche lobe overflow of its companion, or through white-dwarf/neutron-star coalescence in a low mass binary system, could be enough to exceed the critical mass of a neutron star and trigger its collapse to a black hole, leading to the production of a short gamma-ray burst. Henriksen et al. (1979) calculated the dipole radiation from an exploding (or collapsing), homogeneous, uniformly rotating spheroid. They found that \( \sim 2.4 \times 10^{40} \text{ ergs} \) are radiated by an object with a mass of \( 1.4 \text{ M}_\odot \), an initial magnetic field of \( 10^8 \text{ gauss} \), and an initial density of \( 10^9 \text{ g cm}^{-3} \) collapsing to a black hole. The radiation frequency is \( \sim 1 \text{ kHz} \), and such low frequency radiation cannot be observed directly near Earth. MacFadyen and Woosley (1999) explored the evolution of rotating helium stars with mass \( M_\ast > M_\odot \), in which iron-core collapse does not produce a successful outgoing shock but instead forms a black hole. These are the best candidates for producing gamma-ray bursts (GRBs). Authors studied the formation of an accretion disk and the strong relativistic outflow jets in the polar regions. These outflows, powered by viscous dissipation in the disk, have energy of up to a few times \( 10^{51} \text{ erg/s} \).

The electromagnetic pulse from final gravitational stellar collapse is computed by Morley and Schmidt (2002). In this paper they calculated the electromagnetic energy radiated by stellar objects that bounce and become stable neutron stars, and stellar objects so massive that they become black holes. Due to the peak of the spectral curve around the wavelength 2 km, the receiver will have to be a satellite able to detect a broadband spectrum within the electromagnetic pulse. The theoretical predictions for the signatures of the electromagnetic radiation emitted during the process of the gravitational collapse of a stellar core to a black hole are studied by Ruffini at al. (2005). The last phases of this gravitational collapse are studied, leading to the formation of a black hole with a subcritical electromagnetic field,
and an outgoing pulse of an initially optically thick e+e−–photon plasma. Such a pulse reaches transparency at Lorentz gamma factors of 102–104. Authors find a clear signature in the outgoing electromagnetic signal.

In this paper we consider the generation of non-thermal radiation from collapsing magnetized white dwarfs with heterogeneous magnetospheres. This radiation will be generated when the stellar magnetosphere is compressed during the collapse and its magnetic field increases considerably. A cyclic electric field is produced and the charged particles will accelerate. Moving in the magnetic field, these particles will generate radiation. The frequencies of this radiation span a wide range (from gamma-rays to radio waves) and therefore they can be detected near Earth.

2. Magnetosphere of a collapsing star
The external electromagnetic fields of a collapsing white dwarf will change as (Ginzburg 1964, Kryvdyk 1999)

$$B(r, \theta, R) = \left(1/2\right) E_0 R_r^2 (1 + 3 \cos^2 \theta)^{1/2},$$

$$E_\psi = -\frac{1}{c r^2} \frac{\partial \mu}{\partial r} \sin \theta. \quad (1)$$

where $\theta$ is the polar angle, $R(t)$ the radius of the collapsing star, $\mu(t) = (1/2) R_0 B_0^2 R(t)$ the magnetic momentum of the collapsing star.

The particle energy will change as a result of two mechanisms: 1) a betatron acceleration in the variable magnetic field and 2) bremsstrahlung energy losses in this field.

The equation of particle transitions in the regular magnetic field of the heterogeneous magnetosphere was solved by Kryvdyk (2005) for two special cases: (i) when energy losses do not influence the particle spectrum in the magnetosphere and (ii) when the energy losses determine the particle spectrum.

The solution of this equation, for the first case and for three initial particle heterogeneous distributions in the magnetosphere (power-series (P), relativistic Maxwell (M) and Boltzmann (B) distributions) is given by Kryvdyk (2005)

$$N^i_p(E, R, r) = K^i_p r^{-3} E^{-\gamma} R^{-\beta_p}, \quad (2)$$

$$N^i_M(E, R, r) = K^i_M r^{-3} E^{-\gamma} R^{-\beta_M} e^{-E/kT}, \quad (3)$$

$$N^i_B(E, R, r) = K^i_B r^{-3} R^{-\beta_B} e^{-E/kT} \quad (4)$$

Here $E_*= E/E_0$; $R_*= R_0/R$; $r_* = r_0/r$; $\beta_p = A_p(\gamma - 1)$; $\beta_M = A_M(E/kT \ln E_* - 3)$; $\beta_B = A_B(\gamma - 1)(E/kT \ln E_* - 1)$; $A_p(\gamma) = (5/3) k_t (3 \cos^4 \theta + 1.2 \cos^2 \theta - 1)(1 + 3 \cos^2 \theta)^{\gamma}$; $k_t = 2$ and $k_t = 1$ for relativistic and non-relativistic particles respectively.

Eqs. (2) - (4) determine the particle spectrum in the magnetosphere and its evolution during collapse for the initial stage of the collapse, when the energy losses can be neglected. We will consider this case in this paper. During the final collapse, the magnetic field grows to extreme values, and the energy losses will influence the particle spectrum considerably. This case will be considered in a future paper.

3. Non-thermal emission from collapsing magnetized white dwarfs
The ratio $I_\nu = I_\nu / I_{\nu 0}$ between the radiation flux $I_\nu$ from collapsing stars with radius $R$ and its initial radiation flux $I_{\nu 0}$ (by $R = R_0$) for the power-series (P), relativistic Maxwell (M) and Boltzmann (B) distributions are (Kryvdyk 2005)
\[ I_p = r_p^{-3} (v_p)^{(1-\gamma)/2} R_p^{\gamma-2} \int_0^{\pi/2} \int_0^{r_p} R_p \sin \theta \, d\theta \, dE, \]  

\[ I_M = r_M^{-3} v_M R_M^{-3} (kT)^{-1} \int_0^{\pi/2} \int_0^{r_M} \rho e^{-E/kT} \sin \theta \, d\theta \, dE \]  

\[ I_S = r_S^{-3} v_S R_S^{-3} (kT) \int_0^{\pi/2} \int_0^{r_S} \beta E^{-2} e^{-E/kT} \sin \theta \, d\theta \, dE. \]

**Figure 1.** Pulses of the electromagnetic radiation from WD collapse for different $R_0/R$ and $\theta$
Using Eqs. (5) - (7), the radiation flux from the magnetospheres of collapsing stars with variable dipole magnetic fields can be calculated. The temporal changes of the flux radiation during collapse are shown in Fig.1. As follows from these results, the flux radiation increases during collapse, and during the final collapse stage the stars are very powerful sources of non-thermal radiation.

4. Conclusions
We can extract the following conclusions from the results obtained. The magnetic field will increase during the collapse. The charged particles will accelerate to relativistic energy in the magnetospheres of collapsing stars. These particles will emit electromagnetic waves in the wide frequency range from radio waves to gamma rays. The radiation from collapsing magnetized white dwarfs can be observed as electromagnetic pulses in a wide frequency range, from radio to gamma rays. The pulse duration is equal to the time of stellar collapse defined from the mass and the radius of the collapsing star. The intensity of this pulse is very strong. The radiation flux from collapsing stars exceeds the initial flux by factors of millions at the final stage of the collapse.

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