COLLAPSING STARS AS POWERFUL SOURCES OF NON-THERMAL ELECTROMAGNETIC RADIATION

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Abstract

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

Keywords: collapsing stars, particle acceleration, non-thermal emission, relativistic jets.

1. Introduction

There are three ways to observe the stars on the stage of gravitational collapse detecting: 1) neutrinos, 2) the gravitational waves, and 3) electromagnetic radiation from collapsing stars. The only one neutrino signal from supernova star was detected in 1987 from SN 1987 A (Bionta et al., 1987, Hirata et al., 1987). No gravitational waves are detected today from astrophysical objects. Electromagnetic and gravitational radiation from collapsing relativistic stars is analyzed in papers Gunningam et al. (1978, 1979, 1980), and Moncrief (1980). Numerical solutions the wave equations are presented for the waveforms, energies, and spectra of the emitted radiation. The results show that the radiation is independent of the internal dynamics of the collapsing star. Henriksen et al. (1979) calculated the dipole radiation from an exploding (or collapsing), homogeneous, uniformly rotating spheroid. They found that $\sim 2.4 \times 10^{40}$ ergs is radiated by an object with a mass of 1.4 M_0, an initial magnetic field of 10^8 gauss, and an initial density of 10^9 g cm^{-3} collapsing to a black hole. The radiation frequency is ~ 1 kHz, and such low frequency radiation cannot be observed directly near Earth. In paper Ruffert and Janka (1999) was simulated the formation of the accretion torus after two neutron stars have merged, and assume that the compact remnant with a baryonic mass of about $3M_\odot$ has collapsed into a black hole. Authors find that the torus formed after neutron star merging and the neutrino emission with a total luminosity near 10^{53} erg/ s. Neutrino-antineutrino annihilation deposits energy in the vicinity of the torus at a rate of (3–5) 10^{50}erg/ s and the emission period of 0.02–0.1 s. Authors show that accretion on the black hole formed after neutron star merging can yield enough energy by neutrino-antineutrino annihilation to account for weak, short gamma-ray bursts. Macfadyen and Woosley (1999) explored the evolution of rotating helium stars with mass $M_s > M_\odot$, in which iron-core collapse does not produce a successful out-going shock but instead forms a black hole. These are the best candidates for producing gamma-ray bursts (GRBs). Authors studied the formation of accretion disk and the strong relativistic outflows jets in the polar regions, the associate flow patterns. After the jet breaks through the surface of the star, highly relativistic flow can emerge. These outflows, powered by viscous dissipation in the disk, have energy of up to a few times 10^{51} *erg/s*. But energetic GRBs shorter than a few seconds will be difficult to produce in this model. Electromagnetic pulse from final gravitational stellar collapse is computed in paper Morley and Schmidt (2002) both for medium size cores undergoing hydrodynamic bounce and large size cores undergoing black hole formation. Authors show that there must exit two classes of neutron stars, separated by maximum allowable masses: those that collapsed as solitary stars (dynamical mass limit) and those that collapsed in binary systems allowing mass accretion (static neutron star mass). In this paper is 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 signals in this frequency regime cannot penetrate earth's ionosphere. The evolution in general relativity of the electromagnetic field of a magnetic star that collapses from rest to a Schwarzschild black hole have solved in paper Baumgarte and Shapiro (2003). The matter is assumed to be perfectly conducting and threaded by a dipole magnetic field at the onset of collapse. The evolution of the magnetic and electric fields is determined analytically in the matter interior and numerically in the vacuum exterior. At late times the longitudinal magnetic field in the exterior has been transformed into a transverse electromagnetic wave. A part of the electromagnetic radiation is captured by the hole and the rest propagates outward to large distances. New perspectives in physics and astrophysics from the theoretical understanding of Gamma-Ray Bursts are explored in papers Remo Ruffini at al. (2003, 2005a, 2007). The next fundamental physics new regimes are explored: (1) the process of energy extraction from black holes; (2) the quantum and general relativistic effects of matter-antimatter creation near the black hole horizon; (3) the physics of ultrarelativisitc shock waves with Lorentz gamma factor > 100. From the point of view of astronomy and astrophysics also new regimes are explored: (i) the occurrence of gravitational collapse to a black hole from a critical mass core of mass $M > 10 M_{\odot}$, which clearly differs from the values of the critical mass encountered in the study of stars "catalyzed at the endpoint of thermonuclear evolution" (white dwarfs and neutron stars); (ii) the extremely high efficiency of the spherical collapse to a black hole, where almost 99.99% of the core mass collapses leaving negligible remnant; (iii) the necessity of developing a fine tuning in the final phases of thermonuclear evolution of the stars, both for the star collapsing to the black hole and the surrounding ones, in order to explain the possible occurrence of the "induced gravitational collapse". New regimes are as well encountered from the point of view of nature of GRBs: (I) the basic structure of GRBs is uniquely composed by a proper-GRB (P-GRB) and the afterglow; (II) the long bursts are then simply explained as the peak of the afterglow (the EAPE) and their observed time variability is explained in terms of inhomogeneities in the interstellar medium (ISM); (III) the short bursts are identified with the P-GRBs and the crucial information on general relativistic and vacuum polarization effects are encoded in their spectra and intensity time variability. These GRBs are emitted by vacuum polarization process in the dyadosphere of black hole with the creation of the optically thick self accelerating electron-positron plasma. 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 in paper Ruffini at al. (2005b). 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 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. The relevance of these theoretical results for the understanding of short gamma-ray bursts is outlined. 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 $\approx 0.1 - 1\, M_{\odot}$ 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. Fujimoto at al.(2006) performed two-dimensional, axisymmetric, magnetohydrodynamic simulations of the collapse of a rotating star of $40\, M_{\odot}$ and in the light of the collapsar model of gamma-ray burst. They investigated the formation of an accretion disk around a black hole and the jet production near the hole. The fields inside the disk propagate to the polar region along the inner boundary near the black hole through the Alfv´en wave, and eventually drive the jet. Uzdensky and Macfadyen (2006, 2007) proposed a magnetic mechanism for the collimated explosion of massive stars relevant for long-duration gamma-ray bursts (GRBs), X-ray Flashes (XRFs) and asymmetric core collapse supernovae. In this model a massive rotating star after the core has collapsed to form a collapsar with a black hole accretion disk or a millisecond magnetar. Hypermassive neutron star collapse as central engine for short gamma-ray bursts was considered in paper Shibata at al. (2006). A hypermassive neutron star is formed after the merger of a neutron star binary. Authors find that a hypermassive neutron star undergoes 'delayed' collapse to a rotating black hole as a result of angular momentum transport via magnetic braking and the magnetorotational instability. The outcome is a black hole surrounded by a massive, hot torus with a collimated magnetic field. The torus accretes onto the BH at a quasi-steady accretion rate $10 M_{\odot}/s$; the lifetime of the torus is 10 ms. The torus has a temperature 10^{12} K, leading to copious neutrino-antineutrino radiation. This collapse scenario is a promising for generating short-duration gamma-ray bursts and an accompanying burst of gravitational waves and neutrinos. Dessart et al. (2007) present 2D magnetohydrodynamics simulations of the Accretion-Induced Collapse (AIC) of a rapidly-rotating $1.92 M_{\odot}$ white dwarf. They determinated the dynamical role of MHD processes after the formation of a millisecond-period protoneutron star, and they find that magnetic stresses can lead to a powerful explosion with an energy of a few Bethe with an associated ejecta mass of $0.1 M_{\odot}$. The core is spun after bounce, and the rotational energy extracted from the core is channeled into magnetic energy that generates a strong magnetically-driven wind, rather than a weak neutrino-driven wind. Baryon loading of the ejecta, while this wind prevails, precludes it from becoming relativistic. This suggests that γ -ray burst is not expected to emerge from such AICs during the early protoneutron star phase.

In this paper we consider the generation of the non-thermal radiation from collapsing stars with the heterogeneous magnetospheres. This radiation will be generated when the stellar magnetosphere compress 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 (Kryvdyk, 1999). The frequencies of this radiation are very high (from gamma-rays to radio waves) and therefore they can be detected near Earth.

2. Magnetosphere of collapsing star

We consider the particle dynamics and their radiation from collapsing stars having magnetospheres with the three initial particle heterogeneous distribution in magnetosphere (power-series (P), relativistic Maxwell (M) and Boltzmann (B) distributions):

$$N_P(E) = K_p r^{-3} E^{-\gamma} \tag{1}$$

$$N_M(E) = K_M r^{-3} E^2 e^{-E/kT} \tag{2}$$

$$N_B(E) = K_B r^{-3} e^{-E/kT} \tag{3}$$

Here K_P, K_M, K_B are spectral coefficients, *k*- Boltzmann constant, *E* and *T*- particles energy and temperature, *r*- distance from a centre of star.
The external electromagnetic fields of collapsing stars will change as (Ginzburg and Ozernoy, 1964, Kryvdyk, 1999)

$$\begin{aligned} B(r,\theta,R) &= (1/2)F_0 R r^{-3}(1+3\cos^2\theta)^{1/2}, \\ E_\varphi &= -\frac{1}{cr^2}\frac{\partial\mu}{\partial t}\sin\theta. \end{aligned} \tag{4}$$

Where θ is polar angle, *R(t)*- radius of collapsing stars, $\mu(t) = (1/2)F_0 R(t)$ is a magnetic momentum of the collapsing star, $F_0 = R_0 B_0^2$ – their initial magnetic flux.

The particle energy will change as results of the two mechanisms: 1)a betatron acceleration $(dE/dR)_a$ in the variable magnetic field and 2) bremsstrahlung energy losses $(dE/dR)_s$ in this field.

The rate of particle energy changes in the magnetosphere is (Kryvdyk, 1999)

$$\frac{dE}{dR} = \left(\frac{dE}{dR}\right)_a - \left(\frac{dE}{dR}\right)_S = A_1(\theta)\frac{E}{R} + A_2(\theta)R^2E^2r^{-6}((R_* - 1)/RR_*))^{-1/2} \tag{5}$$

Here $A_1(\theta) = (5/3)k_1(3\cos^4\theta + 1.2\cos^2\theta - 1)(1+3\cos^2\theta)^{-2}$,

$A_2(\theta) = (e^4/6m^4c^7)(B_0R_0)^2(2GM)^{-1/2}(1+3\cos^2\theta)\sin^2\theta$.

$k_1 = 2$ and $k_1 = 1$ for relativistic and non-relativistic particles respectively, $R_* = R_0/R$.

The relation of the rate of the particle energy increase to the rate of the particle energy energy decrease is

$$Q = \left(\frac{dE}{dR}\right)_a \Big/ \left(\frac{dE}{dR}\right)_s = \frac{A_1(\theta)}{A_2(\theta)}\frac{1}{E}\frac{(R_* - 1)^{1/2}}{R_*^{1/2}}R^{5/2}\left(\frac{r}{R}\right)^6 \tag{6}$$

When $Q>1$ the particle energy grow; $Q=1$ the energy is constant; and $Q<1$, the energy decreases. The energy for $Q=1$ are given in Table 1. This energy is the highest possible energy, when energy losses do not influence on the particle spectrum in the magnetosphere. For particles with the greater energy will dominate the bremsstrahlung energy losses.

The magnetic moment $\mu(t)$ of collapsing stars changes as

$$\frac{d\mu}{dt} = \frac{1}{2}F_0\frac{dR}{dt} = \frac{1}{2}F_0(2GM(R_* - 1)/RR_*)^{1/2} \tag{7}$$

as results of the decreases their radius $R(t)$ under the influence of gravitational field according to the law of free fall $dR/dt = (2GM(R_* - 1)/RR_*)^{1/2}$.

For the heterogeneous distribution the particle dynamics can be investigated using the equation of transitions particle in the regular magnetic fields (Ginzburg and Syrovatskij, 1964)

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial E}(N\frac{dE}{dt}) + \frac{\partial}{dr}(N\frac{\partial r}{\partial t}) = 0 \tag{8}$$

For the new variable $R = R(t)$ this equation becomes

$$\frac{\partial N}{\partial R} + \frac{1}{r^2}\frac{1}{R}f_2(\theta)\frac{\partial}{\partial r}(Nr^3) - \frac{1}{R}\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(Nf_3(\theta)) + \frac{\partial}{\partial E}(N\frac{dE}{dR}) = 0, \tag{9}$$

Here $f_2(\theta) = \sin^2\theta(1 + 3\cos^2\theta)^{-1}$, $f_3(\theta) = (1 + 3\cos^4\theta)(1 + 3\cos^2\theta)^{-2}$.

Eq. (9) can not be solved in the general case and so two special cases are considered: (i) when energy losses do not influence on the particle spectrum in the magnetosphere and (ii) when the energy losses determine the particle spectrum.

The solution of Eq. (9) in these two cases is given by

$$N^i{}_P(E,R,r) = K_p r_*^{-3} E_*^{-\gamma} R_*^{-\beta_P}, \tag{10}$$

$$N^i{}_M(E,R,r) = K_M r_*^{-3} E_*^2 R_*^{-\beta_M} e^{-E/kT} \tag{11}$$

$$N^i{}_B(E,R,r) = K_B r_*^{-3} R_*^{-\beta_B} e^{-E/kT} \tag{12}$$

$$N^{ii}{}_P(E,R,r) = K_p r_*^{-3} e^{-\gamma_P} \tag{13}$$

$$N^{ii}{}_M(E,R,r) = K_M r_*^{-3} E_*^2 e^{-\gamma_M} \tag{14}$$

$$N^{ii}{}_B(E,R,r) = K_B r_*^{-3} R_*^{-\beta_B} e^{-E/kT} \tag{15}$$

Here $E_* = E/E_0$; $r_* = r_0/r$; $\gamma_P = \gamma(1 - \gamma_1)$; $\gamma_M = \gamma_B = (1 - \gamma_1)E/kT$; $\beta_P = A_1(\theta)(\gamma - 1)$; $\beta_M = A_1(\theta)(E/kT \ln E_* - 3)$; $\beta_B = A_1(\theta)(E/kT \ln E_* - 1)$; $\gamma_1 = A_2(\theta)F(R,R_*)r^{-6}E$; $F(R,R_*) = \frac{1}{3}R^3(R_* - 1)^{1/2} + \frac{5}{12}R^3R_*(R_* - 1)^{1/2} + \frac{5}{8}R^3R_*^2(R_* - 1)^{1/2} + \frac{5}{8}R^3R_*^3\arctan(R_* - 1)^{1/2}$.

Eqs. (10) - (12) determine the particle spectrum in the magnetosphere and its evolution during the initial stage of the collapse when the energy losses can be neglected. We will consider this case in this paper. Eqs. (13) - (15) determine the particles spectrum on the final stage of the collapse, when the magnetic field attains an extreme value and the energy losses influence the particle spectrum considerably. This case we will consider in a later paper.

The transformation of the stellar magnetosphere during collapse is shown on Fig.1. We can see that the initial stellar magnetosphere transforms during collapse and the polar jets are formed in magnetosphere already on the initial stage of collapse. The particles density and its energy in polar jets grow during collapse (see Fig.2). Thus we can see that the jets from collapsing stars can be formed already the explosion of supernova stars.

3. Non-thermal emission from collapsing stars

The ratio $I_{*\nu} = I_\nu / I_{\nu 0}$ between the radiation flux I_ν 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

$$I_{*P} = r_*^{-3}(\nu_*)^{(1-\gamma)/2} R_*^{\gamma-2} \int_0^{\pi/2}\int_0^{\infty} R_*^{-\beta_P} \sin\theta d\theta dE, \tag{16}$$

$$I_{*M} = r_*^{-3}\nu_* R_*^{-3}(kT)^{-1} \int_0^{\pi/2}\int_0^{\infty} R_*^{-\beta_M} e^{-E/kT} \sin\theta d\theta dE \tag{17}$$

$$I_{*B} = r_*^{-3}\nu_* R_*^{-3}(kT) \int_0^{\pi/2}\int_0^{\infty} R_*^{-\beta_B} E^{-2} e^{-E/kT} \sin\theta d\theta dE. \tag{18}$$

Using Eqs. (16) - (18), the radiation flux from the magnetospheres of collapsing stars with variable dipole magnetic fields can be calculated. These ratios are given in tables 2-3. The ratios between the radiation flux from the collapsing stars with radius R and their initial flux by frequency $\nu_* = \nu/\nu_0 = 1$ are:

$$\begin{array}{lll} 2 \le I_{*P} \le 3.09\times 10^{6} & \text{for } 2.2 \le \gamma \le 3.4, & 10 \le R_* \le 100, \\ 1 \le I_{*M} \le 2.89\times 10^{10} & \text{for } 1\ eV \le kT \le 4eV, & 34 \le R_* \le 145, \\ 1 \le I_{*B} \le 1.29\times 10^{12} & \text{for } 1\ eV \le kT \le 4eV, & 34 \le R_* \le 145. \end{array} \tag{19}$$

These values are obtained by the numerical integration of the equations (16)-(18) for $2\ eV \le E \le 10^9\ eV$ and the different R_*, kT, γ. The temporal changes of the flux radiation during collapse are shown in Fig.3. As follows from these results, the flux radiation increases during collapse, and on the final stage collapse the stars are the very powerful sources of the non-thermal radiation.

4. Plasma influence on radiation

Now we will investigate of a plasma influence on the radiation in magnetosphere collapsing star. Plasma will influence on radiation by frequencies $\nu \le \nu_s$ (Paholhik, 1973). Here ν_s is critical frequency:

$$\nu_s = 2\nu_0^2 / 2\nu_L \sin\mu_0 = 2N_e / B, \tag{20}$$

$\nu_0 = (e^2 N_e/\pi m)^{1/2}$ and $\nu_L = (eB/2\pi mc)$ is plasma and Larmor frequencies, μ_0 is angle between the direction to observer and magnetic field B, N_e is the density of electron in plasma. The radiation will be absorbed at the frequency $\nu \le \nu_s$, therefore the steep slope will be observed on the low frequencies. This effect has observed in the some sources of the non-thermal radiation (Paholhik, 1973).

We estimate a frequency ν_s for the radiation in magnetosphere of collapsing star with magnetic fields (4) and the particles distribution (10)-(12).

Substituting the relations (4) and (10)-(12) into (20), we obtain

$$\nu_{sP} = \frac{40 K_P E^{-\gamma}}{R_0^2 B_0^2} \frac{R_*^{-\beta_P+1}}{(1+3\cos^2\theta)^{1/2}}, \tag{21}$$

$$\nu_{sM} = \frac{40 K_M E^2 e^{-E/kT}}{R_0^2 B_0^2} \frac{R_*^{-\beta_M+1}}{(1+3\cos^2\theta)^{1/2}}, \tag{22}$$

$$\nu_{sB} = \frac{40 K_B e^{-E/kT}}{R_0^2 B_0^2} \frac{R_*^{-\beta_B+1}}{(1+3\cos^2\theta)^{1/2}}. \tag{23}$$

Here

$$\beta_P = A_1(\theta)(\gamma - 1),$$

$$\beta_M = A_1(\theta)(E / kT \ln E_* - 3),$$

$$\beta_B = A_1(\theta)(E / kT \ln E_* - 1),$$

$$A_1(\theta) = (5/3)k_1(3\cos^4\theta + 1.2\cos^2\theta - 1)(1 + 3\cos^2\theta)^{-2}$$

The numerical value of the function $A_1(\theta)$ for relativistic particles is give in table 4. The function $A_1(\theta)$ decrease from the value 0.33 in polar regions ($\theta = 0$) to the value -1.67 in the equatorial regions. Since

$$\nu_s \sim (R_0 / R)^{A_1(\theta)}, \tag{24}$$

the frequency ν_s is depended strongly from polar angle θ.
In polar regions ($\theta = 0$)

$$\nu_s \sim (R_0 / R)^{0.33} \tag{25}$$

On the equator ($\theta = \pi/2$)

$$\nu_s \sim (R_0 / R)^{-1.67} \tag{26}$$

As follows from these results, the radiation will absorb the most in the equatorial regions by the across propagation in the magnetic fields. The frequency ν_s increase during collapse, therefore we will observe the more hard of the radiation spectrum from the equatorial regions. In polar regions ν_s is less depended from (R_0/R), therefore the frequency ν_s increase during collapse considerable slow. As a result the radiation from the polar regions will be observed in more wide the frequency range than from the equatorial regions.

Conclusions

We can make the next conclusions from the obtaining results. The magnetic field will increase very strong during collapse. The charged particles will accelerate to relativistic energy in the magnetospheres of collapsing stars. These particles will emit the electromagnetic waves in the wide frequency range, from radio waves to gamma rays. The radiation flux increases during collapse in millions and more compared with the initial flux. The most rapidly the flux increases for the collapsing stars with the low- temperature magnetospheres. The flux increases for these stars by millions times when the stellar radius decrease by ten times (Table 3). For the stars with magnetospheres with the middle temperature the flux start to increase when the stellar radius decrease by few ten times, and for the stars with the high-temperature magnetospheres the flux start to increase when the stellar radius decreases by hundred times. For stars with Boltzmann distribution the radiation flux increase more rapidly than for stars with the relativistic Maxwell distribution.

The radiation from collapsing stars can be observed as the electromagnetic pulses in the all frequency range, from radio to gamma ray bursts. The pulse duration equal to the time of stellar collapses defined from the mass and radius of collapsing stars. The intensity of this pulse is very strong. The radiation flux from collapsing stars exceeds of the initial flux in millions at the final stage of collapse (see Tables 2-3).

Thus the collapsing stars can be the powerful sources of the non-thermal radiation pulses. Where can these pulses are observed? First of all they may be among the powerful gamma and X-ray bursts which can be connected with massive stars collapsing to black holes. These pulses can be observed also from the presupernova stars on the stage of gravitational collapse.

Thus the collapsing stars can emit the high-frequency radiation pulses. What problems can arise by a realization of the observational program for search these pulses? First of all we can not prognosticate of the time and the location collapsing stars on coelosphere, since the theory of stellar evolution is not enables to make it. Therefore we can not indicate exactly where and when the collapsing star can arise. This fact is a principal problem for the observational program of a search of collapsing stars. Second problem is how the radiation pulse from collapsing stars can be discerned among the great numbers of bursts with the unknown origin. This subject will be investigated in the next papers.

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Table 1. The value $E(ev)$ for which $Q=1$ under various R and r/R .

$R(cm)$	10^9	10^8	10^7	10^6
$r/R=5$	4.6×10^9	1.5×10^7	4.6×10^4	1.5×10^2
10	3.0×10^{11}	1.0×10^9	3.0×10^6	1.0×10^4
50	4.6×10^{14}	1.5×10^{12}	4.6×10^9	1.5×10^7
100	3.0×10^{17}	1.0×10^{15}	3.0×10^{12}	1.0×10^{10}

Table 2. The values $I_{\nu P} / I_{\nu P0}$ for different R_*, γ .

γ	2.2	2.4	2.6	2.8	3.0	3.2	3,4
R_*				$I_{\nu p}/I_{\nu P}$			
10	2.02	4.75	12	32.6	93.7	281	864
20	2.63	8.2	29.5	117	494	2170	9740
40	3.37	14.6	76.1	443	2740	17500	1.15×10^5
60	3.92	20.7	135	981	7570	60300	4.91×10^5
80	4.36	26.7	203	1740	15700	1.46×10^5	1.38×10^6
100	4.75	32.7	281	2710	27600	2.89×10^5	3.09×10^6

Table 3. The values $I_{\nu B} / I_{\nu B0}$ and $I_{\nu M} / I_{\nu M0}$ for different R_* and kT

	$kT=1eV$			$kT=2eV$			$kT=4eV$	
R_*	$I_{\nu B}/ I_{\nu B0}$	$I_{\nu M}/I_{\nu M0}$	R_*	$I_{\nu B} / I_{\nu B0}$	$I_{\nu M}/I_{\nu M0}$	R_*	$I_{\nu B}/ I_{\nu B0}$	$I_{\nu M}/I_{\nu M0}$
34	16.4	1,11	60	4,44	1	105	2.8	1
36	86.2	6.04	65	70.8	1.43	110	17.1	1
38	491	35.2	70	1340	27.7	115	111	1
40	3010	221	75	29700	626	120	770	4.3
42	19800	1480	80	7.64×10^5	16400	125	5660	31.9
44	1.40×10^5	10600	85	2.26×10^7	4.92×10^5	130	44100	250
46	1.05×10^6	80900	90	7.67×10^8	1.69×10^7	135	3.63×10^5	2.07×10^3
48	8.35×10^6	6.54×10^5	95	2.96×10^{10}	6.58×10^8	140	3.15×10^6	1.81×10^4
50	7.06×10^7	5.61×10^6	100	1.29×10^{12}	2.89×10^{10}	145	2.88×10^7	1.67×10^5

Table 4. The numerical value of the function $A_l(\theta)$ for relativistic particles.

θ°	0	10	20	30	40	50	60	70	80	90
$A_l(\theta)$	0.33	0.32	0.30	0.25	0.16	0.002	-0.27	-0.75	-1.35	-1.67

Figure 1. Relativistic jets from collapsing stars for R_o/R=100.

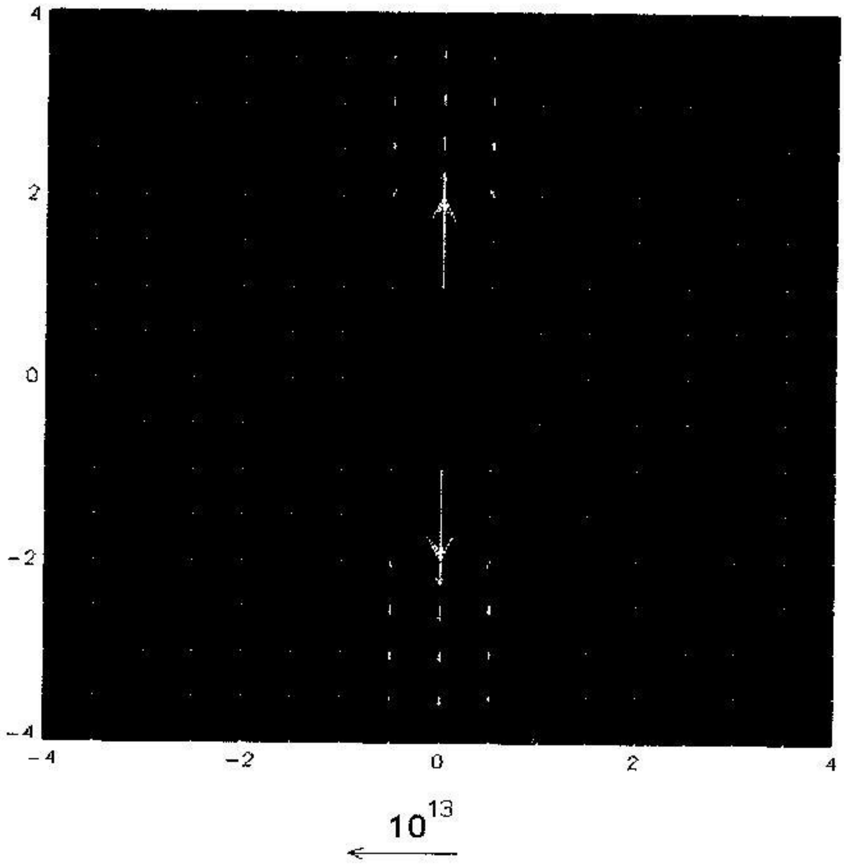

Figure 2. The particle distributions in magnetosphere of collapsing star for various R_o/R.

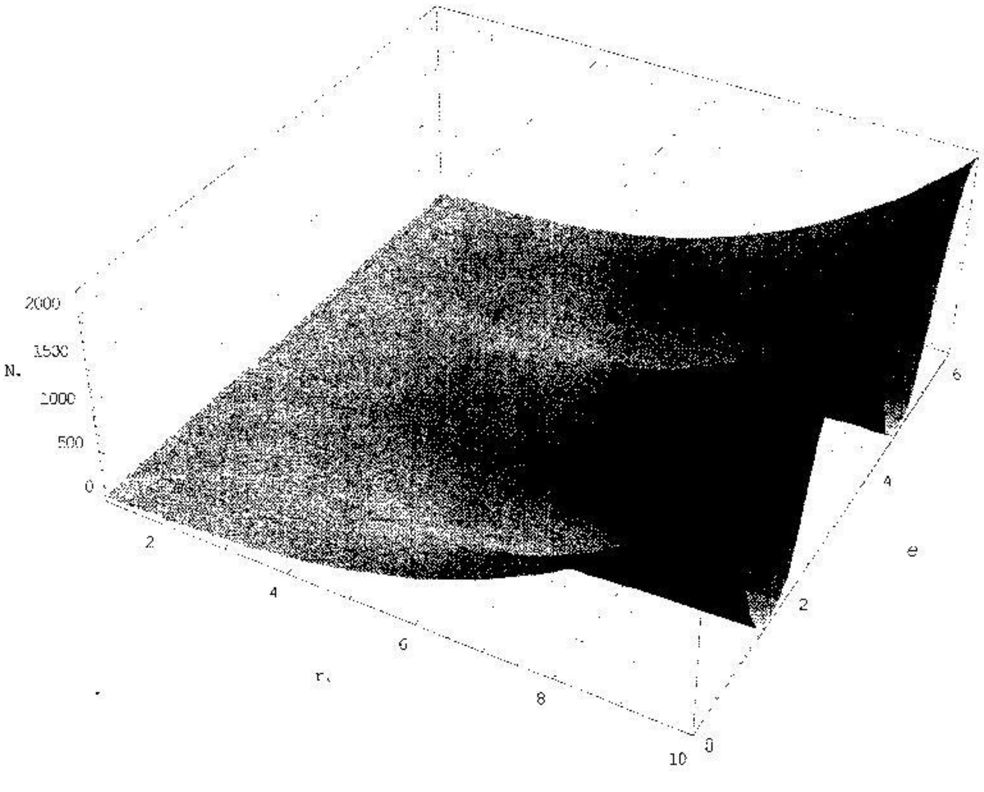

Figure 3. A increase of the electromagnetic radiation during collapse.