ELECTRODYNAMICS OF THE MAGNETOSPHERES OF COLLAPSING STARS

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The particles acceleration and its non-thermal emission in the magnetospheres of collapsing stars are considered. The magnetic field in magnetosphere increases considerably, when the star is compressed under the collapse. The charged particles will be accelerated in this field. These particles will generate radiation when moving in the magnetic field. The effect can be observed by means of modern instruments [7]. The radiation flux grows during a stellar collapse in millions times and can be observed in the form of radiation pulse with duration equal to the stellar collapse time. This flux depends on the distance to the star, its magnetic field, and the particle spectrum in the magnetosphere. In this paper the radiation fluxes are calculated for various collapsing stars with the initial dipole magnetic fields and the initial power-series, relativistic Maxwell, and Boltzmann particles energy distributions in the magnetosphere.

INTRODUCTION

Collapse begins when the mass of stellar core exceeds the Chandrasekhar bound, and the star become dynamically unstable. The star will compress and its radius will decrease. After that, the star can evolve by several ways. The first way is that a star explodes and loses its mass. The collapse of a massive star ($M_\odot \leq 3 \div 6M_\odot$) may results in the formation of a neutron star or a black hole. The neutron star formation can accompany by the explosion and loss of mass. This phenomenon is observed as a supernova star. The star with smaller mass collapses to a white dwarf [10, 11], the process may be accompanied by the formation of a planetary nebula. The second way is realized when a star collapses without the loss of mass. In this case it is very difficult to observe the collapse and hitherto there are no strong astronomical data conforming the evidence of this stage.

A star emits the electromagnetic radiation under the collapse. In this paper the non-thermal radiation from the collapsing stars with the initial dipole magnetic field at the non-relativistic stage is studied and the method for the observation of collapse using the data on this radiation is proposed.

MAGNETOSPHERES OF COLLAPSING STARS

The external electromagnetic field of a collapsing star is given by [2, 7]

$$B(r,\theta,t) = (1/2)F_0 R r^{-3}\left(1+3\cos^2\theta\right)^{1/2} \tag{1}$$

Here $F_0 = B_0 R_0^2$ is the initial magnetic flux of star with the radius R having the initial radius R_0 and the initial magnetic field B_0.

The field structure and particles dynamics in the magnetosphere are influenced by three factors: particles pressure, collisions, and star rotation. As follows with the detail analysis [7], these effects can be neglected during the collapse.

The initial concentrations of charged particles in the magnetosphere have been chosen as the power-series, relativistic Maxwell, and Boltzmann distributions which can be described, respectively, by the formulas

$$N_1(E) = K_C E^{-\gamma}; \tag{2}$$

$$N_2(E) = K_M E^2 \exp(-E/kT); \tag{3}$$

$$N_3(E) = K_B \exp(-E/kT). \tag{4}$$

Here K_C, K_M, K_B are the spectral coefficients; k is the Boltzmann constant; E is the particles energy and T is the temperature in the magnetosphere; γ is the power spectrum.

PARTICLE DYNAMICS AND SPECTRUM CHANGE IN THE MAGNETOSPHERE

The particles dynamics and their acceleration during the collapse are considered by means of the method of adiabatic invariant so as magnetosphere plasmas is frozen in magnetic field and is a collision-free. The particles energy change in this case as the results of two mechanisms. The first mechanism is a betatron acceleration of particles in the variable magnetic field, the second one is a bremsstrahlung energy loss in this field. For the resulting rate of particle energy change in the magnetosphere we get [7]:

$$\frac{dE}{dR} = \left(\frac{dE}{dR}\right)_a + \left(\frac{dE}{dR}\right)_s = a_1 \left(\frac{2GM}{R_*}\right)^{\frac{1}{2}} \left(\frac{R_* - 1}{R^3}\right)^{\frac{1}{2}} E - a_2 F_0^2 R^2 E^2 r^{-6}, \tag{5}$$

Here $a_1 = (5k_1/3)(3\cos^4\theta + 1.2\cos^2\theta - 1)(1+3\cos^2\theta)^{-2}$; $a_2 = (e^4/6m^4c^7)(1+3\cos^2\theta)\sin^2\theta$; k_1=2 and k_1 =1 for relativistic and non-relativistic particles, respectively; $R_* = R_0/R$; G is the gravitational constant, M is the mass of collapsing star.

The particle dynamics and their spectrum changing in the magnetosphere in form of the equation for particle transitions in the regular magnetic field are considered as [7]

$$\frac{\partial N}{\partial R} = f_1(E,R)\frac{\partial N}{\partial E} + f_2(E,R)N = 0. \tag{6}$$

Here $f_1(E,R) = ER^{-1}[a_1 - a_2F_0^2[R^7R_*/2GM(R_*-1)]^{1/2}Er^{-6}$; $f_2(E,R) = R^{-1}\{a_1 - 2[\,R^7(R_*-1)]^{\,1/2}E\}$.

In paper [7] Eq. (6) has solved for the two special cases. In the first case it is assumed that energy losses do not influence the particles spectrum in the magnetosphere. Then the second term in the right part of Eq. (5) can neglected and the solution of Eq. (6) for the initials distribution (2)–(4) are as follows:

$$N_1^{'}(E,R) = K_p E^{-\gamma} R_*^{-\beta_1}; \tag{7}$$

$$N_2^{'}(E,R) = K_M E^2 R_*^{-\beta_2} \exp(-E/kT); \tag{8}$$

$$N_3^{'}(E,R) = K_B R_*^{-\beta_3} \exp(-E/kT), \tag{9}$$

Here $\beta_1 = a_1(\gamma - 1)$; $\beta_2 = a_1(E/kT \ln E - 3)$; $\beta_3 = a_1(E/kT \ln E - 1)$.

Eqs. (7)–(9) determine the particle spectrum in the magnetosphere and its evolution during collapse for the first case when the energy losses can be neglected. This case is typical for the initial stage of the collapse and we will consider it in this paper. The second case is realized in the final stage of the collapse, when the magnetic field attains the extremely value and the energy losses influence considerably on the particle spectrum. We will consider this case in later on but not in this paper.

NON–THERMAL RADIATION FROM COLLAPSING STARS

For the power-series, relativistic Maxwell, and Boltzmann distributions (7)–(9) the ratio between the radiation flux from collapsing stars and its initial radiation flux, respectively, [7] are following:

$$I_{\nu P}/I_{\nu P0} = (\nu/\nu_0)^{(1-\gamma)/2} R_*^{\gamma-2} \int (R_*)^{-a_1(\gamma-2)} \sin\theta d\theta, \tag{10}$$

$$I_{\nu M}/I_{\nu M0} = R_*^{-3}(\nu/\nu_0)(1/kT) \int R_*^{-\beta_2} \exp(-E/kT) \sin\theta dE d\theta, \tag{11}$$

$$I_{\nu B}/I_{\nu B0} = R_*^{-3}(kT)(\nu/\nu_0) \int R_*^{-\beta_3} E^{-2} \exp(-E/kT) \sin\theta dE d\theta \tag{12}$$

Using Eqs. (10)–(12) the radiation flux from collapsing stars can be calculated. The ratio between the radiation flux from collapsing stars and its initial flux for different radius R_* and temperature $1\,eV \le kT \le 9\,eV$ by $\nu/\nu_0 = 1$ are given in Tables 1–2. This value is obtained by the numerical integration of Eqs. (10)–(12) in the range $2\ eV \le E \le 1000\ eV$, $0 \le \theta \le \pi/2$ for different radius R_*, temperature kT and index γ.

Table 1: The value $I_{\nu P}/I_{\nu P0}$ for various R$_*$ and γ by $\nu/\nu_0 = 1$

γ	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0
R_*					$I_{\nu P}/I_{\nu P0}$				
10	4.75	12	32.6	93.7	281	864	2710	8600	27600
40	14.6	76.1	443	2740	17500	1.15e5	7.60e5	5.09e6	3.43e7
80	26.7	203	1740	15700	1.46e5	1.38e5	1.33e7	1.29e8	1.26e9
100	32.6	281	2710	27600	2.89e5	3.09e6	3.35e7	3.67e8	4.04e9
200	61.2	774	10900	1.61e5	2.46e6	3.81e7	5.98e8	9.47e9	1.51e11
400	117	2170	44400	9.56e5	2.11e7	4.74e8	1.08e10	2.47e11	5.71e12
600	172	3980	1.02e5*	2.72e6	7.45e7	2.08e8	5.87e10	1.67e12	4.80e13
800	226	6140	1.83e5	5.71e6	1.83e8	5.94e8	1.96e11	6.50e12	2.17e14
1000	281	8600	2.89e5	1.02e7	3.67e8	1.34e10	4.98e11	1.86e13	7.03e14

*$1.02e5 = 1.02 \times 10^5$

Table 2: The value $J_{\nu M}/J_{\nu M0}$ and $J_{\nu B}/J_{\nu B0}$ for various R_* by $\nu/\nu_0 = 1$, $1eV \le kT \le 9eV$

	kT=1 eV			kT=5 eV			kT=9 eV	
R_*	$J_{\nu M}/J_{\nu M0}$	$J_{\nu B}/J_{\nu B0}$	R_*	$J_{\nu M}/J_{\nu M0}$	$J_{\nu B}/J_{\nu B0}$	R_*	$J_{\nu M}/J_{\nu M0}$	$J_{\nu B}/J_{\nu B0}$
37	6.04	204	145	1	405	300	1	54.3
38	14.5	491	150	2.8	1500	350	1	1360
39	35.2	1210	155	9.25	5420	400	1	22800
40	87.5	3019	160	29.7	19000	450	4.89	2.76e5
41	221	7660	165	93	65000	500	32.5	2.59e6
42	568	19800	170	283	2.16e5	550	181	1.98e7
43	1480	52200	175	838	6.96e5	600	872	1.27e8
44	3940	1.40e5	180	2420	2.19e6	650	3720	7.04e8
45	10600	3.79e5	185	6810	6.69e6	700	14300	3.45e9
46	29100	1.05e6	190	18700	1.99e7	750	49900	1.51e10
47	80900	2.93e6	195	50200	5.80e7	800	1.61e5	6.06e10
48	2.28e5	8.35e6	200	1.32e5	1.65e8	850	4.86e5	2.23e11

CONCLUSIONS

We can see from Tables 1–2 that the radiation flux grows during the collapse very rapidly (in millions times and especially in comparison with the initial flux). The radiation flux grows the most rapidly for collapsing stars with the cool magnetospheres ($kT \leq 1\ eV$). For these stars the flux increases in million times, when the stellar radius decreases in ten times (Table 2). For the magnetospheres with middle temperature ($1\ eV \leq kT \leq 3\ eV$) the flux grows at the later stage of a collapse. By the collapse of stars with the high-temperature magnetospheres the radiation flux grows at the still latest stage collapse, when the stellar radius decreases in hundreds times. The radiation flux from stars with Boltzmann distributions grows more rapidly in comparison with the stars having relativistic Maxwell distribution.

The general conclusions from the obtained results are the following. The stellar magnetic field will be increased considerable during the collapse. The charged particles can be accelerated in this magnetic field, which will emitted the electromagnetic waves in the wide frequency range from radio waves to gamma rays. The radiation flux grows during collapse and reaches the maximum at the final stage of a collapse. We can observe this radiation as the radiation impulses in the wide frequency range. The pulse duration completes with the collapse time determining the initial mass and initial radius of collapsing star. The intensity of these pulses are very strong, and the radiation flux from collapsing stars at the final stage of a collapse exceeds the initial flux in millions times. We can see (Table 1–2) that the radiation fluxes for stars with the initial fluxes in range [1]–[6], [8, 9] $10^{-22}\,\mathrm{erg/cm^2\,s\,Hz} \leq I_{\nu_0} \leq 10^{-30}\,\mathrm{erg/cm^2\,s\ Hz}$ can increase to $10^{-16}\,\mathrm{erg/cm^2\,s\,Hz} \leq I_{\nu_0} \leq 10^{-24}\,\mathrm{erg/cm^2\,s\,Hz}$ and more.

Thus, collapsing stars can be the powerful sources of the non-thermal radiation impulse. Where this impulse can be observed? First of all, in the middle of powerful gamma bursts and X bursts, which are not periodical and can be connected with the precollapse stars and the stars being at the stages of evolution those precede the neutron star formation and supernova explosion. The impulse non-thermal radiation can be observed also before explosion of nova and from the white dwarfs in double systems at the stage of accretion induced collapse. Periodical impulse of the non-thermal radiation can be generated by the pulsation of the stars with magnetic field as since in this case the charged particles can be accelerated and they can emitted the radiation.

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