Acceleration of the Cosmic Rays by Stellar Collapse

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Abstract

The cosmic-rays acceleration in the magnetospheres of collapsing stars with initial dipole magnetic fields and a certain initial energy distribution of charged particles in a magnetosphere (power-series, relativistic Maxwell, and Boltzmann distributions) are considered . When the star magnetosphere compressing under the collapse its magnetic field considerably increases. The cyclic electric field thus produced involving acceleration of charged particles. The analysis of particles dynamics and its acceleration in the stellar magnetosphere under collapse show that the collapsing stars can by powerful sources of cosmic rays and non-thermal radiation.

1. Magnetospheres of collapsing stars

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

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

Here $F_o = B_o R_o^2$ is the initial magnetic flux of star with the radius R having the initial radius R_o and the initial magnetic field B_o. The initial concentrations of charged particles in the magnetosphere have 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.

2. Particles dynamics and their spectrum in magnetosphere

The particles dynamics and their acceleration during the collapse are considered by means of the method of adiabatic invariant so as magnetosphere plas-

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mas is frozen in magnetic field and collision-free. The particles energy change in this case as the results of two mechanisms. First mechanism is a betatron acceleration of particles in the variable magnetic field, second one is the bremsstrahlung energy losses in this field. For the resulting rate of particle energy change in the magnetosphere we get [7]:

$$\frac{dE}{dR}=(\frac{dE}{dR})_a+(\frac{dE}{dR})_s=a_1(\frac{2GM}{R_*})^{\frac{1}{2}}(\frac{R_*-1}{R^3})^{\frac{1}{2}}E-a_2F_0^2R^2E^2r^{-6}, \tag{5}$$

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; $R_*=R_o/R$; G is 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 $f_1(E,R)=ER^{-1}[a_1-a_2F_o^2[R^7R_*/2GM(R_*-1)]^{1/2}Er^{-6}$; $f_2(E,R)=R^{-1}\{a_1-2[R^7(R_*-1)]^{1/2}E\}$. In paper [7] Eq.(6) has solved for 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:

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

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

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

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 considered it in this paper.

3. Cosmic rays flux from collapsing stars in Galaxy

The initial particle energy E_i choose during stellar collapse to the final energy E_f which determinate with adiabatic invariant as $E_f=(B_f/B_i)E_i-$ for nonrelativistic particles, $E_f=(B_f/B_i)^{1/2}E_i-$ for relativistic particles. Were B_i and B_f is the initial and final magnetic fields Respectively. The value $B_f/B_i=10^{12}$. Final particle energy $E_f=10^{12}E_i-$ for nonrelativistic particles, $E_f=10^6E_i-$ for relativistic particles. The middle velocity of the acceleration particles for the all collapsing star in Galaxy is $N_a = nV_a\nu$. Here n and V_a is the particles density and volume of the magnetosphere collapsing star, ν is a collapse stars frequency in the Galaxy. For the collapsing stars with the magnetospheres

$$N_a = 10^{36} - 10^{38} particles/\sec$$

For the pulsars in Galaxy the variosly estimation give $N_p = 10^{42} particles/\sec$

4. 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]

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

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

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

Using Eqs. (10) - (12) the radiation flux from the collapsing stars can be calculated. The ratio between the radiation flux from collapsing stars and its initial flux by $\nu/\nu_0 = 1$ are in the ranges:

$1 \leq I_{\nu P}/I_{\nu P0} \leq 1.34 \times 10^{10}$ for $2.4 \leq \gamma \leq 3.4$, $10 \leq R_* \leq 1000$;
$1 \leq J_{\nu M}/J_{\nu M0} \leq 4.86 \times 10^5$ for $1\ eV \leq kT \leq 9\ eV$, $145 \leq R_* \leq 850$;
$1 \leq J_{\nu B}/J_{\nu B0} \leq 2.23 \times 10^{11}$ for $1\ eV \leq kT \leq 9\ eV$, $145 \leq R_* \leq 850$.

These values obtained by the numerical integration of the equations for the ratio between the radiation flux in the range $2\ eV \leq E \leq 10^9\ eV$, $0 \leq \theta \leq \pi/2$ for the different radius R_*, temperature kT and index γ.

5. Conclusions

The general conclusions from the obtained results are next. The stellar magnetic field will increased considerable during the collapse. The charged particles can be accelerated in this magnetic field and their will emitted the electromagnetic waves in the wide frequency range from radio waves to gamma rays. The radiation flux grows during collapse and reach the maximum at the final stage of collapse. We can observed this radiation as the radiation impulses in the wide frequency range. The pulse duration completes with the collapse time defining the initial mass and initial radius of collapsing star. The intensity of these impulses are very strong, and the radiation flux from collapsing stars at the final stage of collapse exceed the initial flux in millions times. We can see that the radiation fluxes for stars with the initial fluxes in range [1-6, 8, 9]

$10^{-22} erg/cm^2 s\ Hz\ \leq I_{\nu o} \leq 10^{-30} erg/cm^2 s\ Hz$ can increase to $10^{-16} erg/cm^2 s\ Hz\ \leq I_{\nu o} \leq 10^{-24} erg/cm^2 s\ Hz$ and more. Thus the collapsing stars can be the powerful sources of the charged particles and the non-thermal radiation impulses.

6. References

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