RELATIVISTIC SHOCK BREAK OUT AT THE SURFACE OF HYPERNOVA STAR

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ABSTRACT. The hydrodynamics of relativistic shock break out at the surface of Hypernova star is investigated. The characteristics of hydrodynamically accelerated external layers of star (energy spectrum of accelerated particles etc.) are estimated.

Keywords: Stars: Hypernova; gamma rays: GRB; hydrodynamics: relativistic shock waves.

1. Introduction

The gamma-ray bursts (GRBs) were discovered in the late sixties, but only detection of an optical afterglows in 1997 led to the measurement of redshifts for some long GRBs and revealed their cosmological nature (Meszaros, 2002). The first strong evidence for the connection between GRBs and SNe was provided by GRB 980425, when an unusual Type Ic supernova was seen in the error box of the GRB (Galama et al., 1998; Woosley et al., 1999). After that there were discovered another SNe that proved the GRB-SN connection – GRB 021211 (Valle et al., 2003), GRB 030329 (Stanek et al., 2003), GRB 031203 (Malesani et al., 2004).

The most popular model for long GRB is connected with death of massive star – Hypernova (Paczynski, 1998) or collapsar (MacFadyen and Woosley, 1999). In this model together with a collimated ultrarelativistic jets a mildly relativistic spherical shock break out at the surface of progenitor is expected (Woosley et al., 1999). In our work we investigate the hydrodynamics of shock break-out and determine characteristics of hydrodynamically accelerated external layers of progenitor.

2. Relativistic shock break out at the surface of star

In our work we use the CO6 model of progenitor star considered in (Woosley et al., 1999; Tan et al., 2001). It is the bare carbon-oxygen core $M_s = 6.55 M_\odot$ of $25 M_\odot$ main sequence star. The star radius is $R_s = 1.22 \times 10^{10}\ cm$.

The motion of relativistic shock wave in the outer layers of the stellar envelope can be described by an analytical approximation proposed in (Gnatyk, 1985; Berezinsky et al., 1996):

$$\Gamma_s \beta_s = (\Gamma_s \beta_s)_i \left(\frac{\rho(r)}{\rho(r_i)} \right)^{-a} \propto \left(\frac{F(r)}{F(r_i)} \right)^{-3a/4}, \quad (1)$$

where $\beta_s = u_s/c$ is the dimensionless velocity of the shock front, $\Gamma_s = \left(1 - \beta_s^2\right)^{-1/2}$ is the Lorentz factor of the shock front, c is the velocity of light, $\rho(r)$ is the density of Hypernova stellar envelope as a function of distance to the center of the star r, $F(r)$ is the fraction of the stellar mass beyond the radial distance r and index "i" refers to initial values of corresponding parameters. Dimensionless parameter a is restricted by two values: $a = 0.2$ and $a = 0.232$ (Gnatyk, 1985). For outer layers of star we use a polytropic model of density distribution (Tan et al., 2001)

$$\rho(r) = \rho_0 (1 - r/R_s)^3, \quad \rho_0 = 910\ g/cm^3 \quad (2)$$

The connection between Lorentz factor of shock wave itself Γ_s and Lorentz factor of matter behind the shock γ_2 is given by the following equation (Blandford and McKee, 1976)

$$\Gamma_s^2 = (4\gamma_2 - 1)^2 (\gamma_2 + 1)/(8\gamma_2 + 10), \quad (3)$$

where $\gamma_2 = \left(1 - \beta_2^2\right)^{-1/2}$ is the Lorentz factor and β_2 is the dimensionless velocity of the fluid behind the shock.

The maximum value of Lorentz factor of shock corresponds to the smallest value of F at which the shock still exists in the outer layers of Hypernova star. The shock breaks out at some radius r_{max} where the dissipation of energy due to the escape of photons or other particles becomes essential (Berezinsky et al., 1996). One can show, that $F_{min} = 4\pi R_s^2 x_{int}/M_s$, where x_{int} is the interaction pathlength of photons in g/cm^2. In our calculation we use $x_{int} = 1\ g/cm^2$, therefore, $F_{min} = 1.97 \times 10^{-13}$. For initial parameters of shock wave we take their typical values from numerical calculations (Tan et al., 2001): $F_i = F(r_i) = 1.3 \times 10^{-4}$,

$\beta_{s,i} = 0.3$. In this case $\Gamma_s^{max} = 6.75\,(10.92)$ and $\gamma_2^{max} = 4.77\,(7.73)$ for $a = 0.2$ (0.232), respectively.

The temperature of the gas behind the shock front is given by (Berezinsky et al., 1996)

$$T_2(r) = \left[\frac{4}{11a_K}\,(4\gamma_2+3)\,(\gamma_2-1)\,\rho(r)c^2\right]^{1/4} \qquad (4)$$

where a_K is the constant of the energy density of radiation. When the shock reaches the surface of the star, the temperature T_2^{sur} behind it at moment of break out is given by equations (4) with $\gamma_2 = \gamma_2^{max}$ and $r = r_{max}$. The burst of radiation (gamma ray flash) emerges from the star during the shock break out, when radiation energy trapped in the shock escapes through the transparent external layer of the star. The typical energy of the photons in the burst is

$$E_\gamma^{obs} \sim \gamma_2^{max} k T_2^{sur}, \qquad (5)$$

where k is the Boltzmann constant. The corresponding values of T_2^{sur} and E_γ^{obs} for $a = 0.2\,(0.232)$ are following: $T_2^{sur} = 4.97\,(8.95) \times 10^7\ K$, $E_\gamma^{obs} = 20.46\,(59.6)\ keV$.

3. Expansion in vacuum and additional acceleration of protons

Expansion in vacuum of hot shocked plasma of stelar envelope leads to additional acceleration of matter, and final Lorentz factor is (Berezinsky et al., 1996)

$$\gamma_f = \gamma_2^b + (4-b)(\gamma_2-b)/\gamma_2^2, \qquad (6)$$

where parameter b is restricted by values: $b = 2.0$ and $b = 2.73$. Maximum Lorentz factor of hydrodynamically accelerated particles of star envelope is

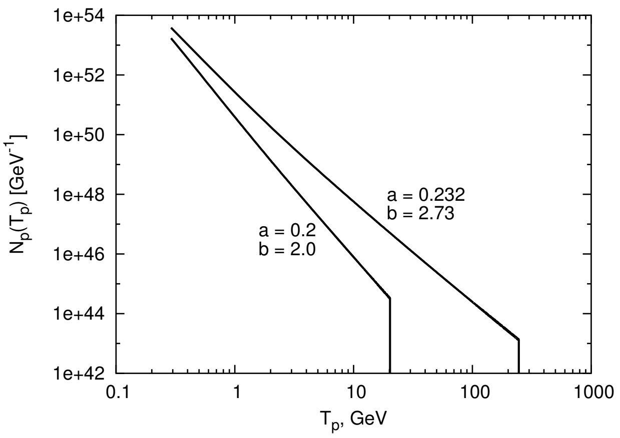

Figure 1: Differential energy spectrum of accelerated protons.

$$\gamma_f^{max} = \left[\frac{1}{2}\left(1 + (\Gamma_s\beta_s)_i^2\left(\frac{F_i}{F_{min}}\right)^{3a/2}\right)\right]^{b/2} \qquad (7)$$

Maximum value of kinetic energy of particles (protons of mass m_p) T_p is $T_p^{max} = m_p c^2\left(\gamma_f^{max} - 1\right)$. The differential energy spectrum of protons in the whole envelope is given by

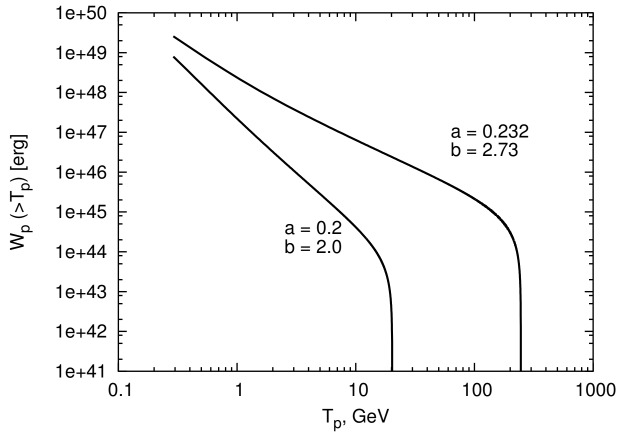

Figure 2: Integral energy spectrum of accelerated protons.

$$N_p(T_p) = \frac{M_s}{m_p}\,\frac{dF(T_p)}{dT_p}. \qquad (8)$$

It is power-low spectrum with spectral index $\delta^{diff} = 4.7\,(3.67)$ for minimum (maximum) values of a and b. The number and kinetic energy of protons with energy greater than T_p (integral spectra) are

$$N_p(>T_p) = \int_{T_p}^{T_p^{max}} N_p(T_p)\,dT_p, \qquad (9)$$

$$W_p(>T_p) = \int_{T_p}^{T_p^{max}} T_p N_p(T_p)\,dT_p. \qquad (10)$$

The differential (8) and integral (9) energy spectra are represented in Fig. 1 and Fig. 2 and parameters of hydrodynamically accelerated particles (protons) are given in Tab. 1 (T_p^{max} is given in GeV, W_p is in erg, $T_{p1} = 0.29\ GeV$, $T_{p2} = 2\ GeV$).

Table 1: Parameters of hydrodynamically accelerated protons

Parameters	$a = 0.2,\ b = 2.0$	$a = 0.232,\ b = 2.73$
γ_f^{max}	22.8	265.45
T_p^{max}	20.3	246.2
$N_p(>T_{p1})$	1.28×10^{52}	3.67×10^{53}
$W_p(>T_{p1})$	7.98×10^{48}	2.57×10^{49}
$W_p(>T_{p2})$	3.24×10^{46}	7.22×10^{47}

4. Conclusions

Relativistic shock break out at the surface of Hypernova star is accompanied by gamma ray flash and hydrodynamical acceleration of outermost layers of presupernova up to relativistic velocities. By analogy with the case of SN Ia outburst (Berezinsky et al., 1996) both the gamma ray flash and an interaction of relativistic particles with circumstellar medium can lead to signatures detectable by existing space missions.

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