Gamma-ray flash from relativistic shock break out at the surface of Hypernova star

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The observational signatures of relativistic shock break-out at the surface of Hypernova star are investigated. The interaction of accelerated particles with the particles of circumstellar medium is considered. Particularly we analyze a gamma-ray flash as a result of inelastic proton-proton collisions. The parameters of the flash are calculated and conditions of its detection are estimated.

1. INTRODUCTION

The current opinion connects the nature of long gamma-ray bursts (GRBs) with death of massive star — Hypernova [1] or collapsar [2]. The observational evidences of the connection between GRBs and SNe include a few cases, starting from GRB 980425, when an unusual Type Ic Supernova was revealed in the error box of this GRB [3–5]. Later there were discovered SNe–GRBs counterparts for another GRBs: GRB 021211 [6], GRB 030329 [7], GRB 031203 [8].

In Hypernova model together with two collimated ultrarelativistic jets a mildly relativistic spherical shock break-out at the surface of progenitor is expected [5]. As it was shown in [9] hydrodynamically accelerated by relativistic shock wave matter of outermost layers of SNIa presupernova (protons) acquire moderate Lorentz factors $\gamma \sim 10 – 100$ and cause a powerful flash of gamma-radiation via inelastic proton-proton interaction with interstellar (circumstellar) gas. In our work we investigate the gamma-ray flash from interaction between accelerated matter and interstellar medium in case of Hypernova explosion.

2. HYDRODYNAMICAL ACCELERATION OF OUTERMOST LAYERS OF HYPERNOVA

The collapse of prehypernova core results in strong shock wave, moving through the star interior and breaking out at the surface, accelerating the outer layers of star up to relativistic velocities. In order to estimate the expected characteristics of accelerated particles we take as a representative case
the CO6 model of progenitor star considered in [5,10,11]. As it is shown in [10], the acceleration process
includes two stages: acceleration of matter by shock wave, where Lorentz factor of accelerated particles \( \gamma_1 \)
increases with decreasing of density \( \rho(r) \) in envelope of star \( \gamma_1 \sim \rho(r)^{-\alpha} \) and additional acceleration due
to subsequent “expansion in vacuum” to Lorentz factor \( \gamma_2 \sim \gamma_1^b \), where parameters \( a \) and \( b \) lie in the
ranges \( 0.2 < a < 0.232, 2.0 < b < 2.73 \) [9]. The resulting integral energy spectrum of relativistic particles, i.e. the
number of particles \( N_p \) with energy, larger than \( T_p \) will be power-law \( N_p(>T_p) \sim T_p^{\delta} \) with \( \delta = 4/(3ab) \) [9]
and another parameters of relativistic flow are presented in Table 1, where \( \gamma_p^{\text{max}} \) and \( T_p^{\text{max}} \) are maximum
final Lorentz factor and kinetic energy of accelerated protons, \( N_p(>T_p) \) and \( W_p(>T_p) \) are number and
total energy of particles with energy greater than \( T_p \).

### 3. GAMMA-RAY PRODUCTION

Now we shell consider the interaction between thin spherically-symmetric shell of accelerated particles (protons) and circumstellar matter. We assume that Hypernova star with radius \( R_s \) is surrounded by the wind with the wind number density at shell position \( r \approx R_s + ct \) as function of time \( t \) lasted from break-out moment

\[
n_{\text{iism}}(t) = n_{\text{iism}}^0 \left( \frac{R_s}{R_s + ct} \right)^2,
\]

where \( c \) is the velocity of light, \( n_{\text{iism}}^0 = 5 \cdot 10^{13} \text{ cm}^{-3} \) in order to have typical grammage \( x \sim 1 \text{ g/cm}^2 \)
(optical depth is of order of \( x/x_{\text{max}} \), where \( x_{\text{max}} = 70 \text{ g/cm}^2 \) is the interaction path length of incident proton in circumstellar medium).

The rate of creation of neutral pions with kinetic energy \( T_\pi \) that are produced in the shell via pp-collision (production spectrum) is [12]

\[
N_\pi(T_\pi, t) = \min[N_{\pi1}(T_\pi, t), N_{\pi2}(T_\pi, t)] \quad [\text{GeV}^{-1} \text{s}^{-1}],
\]

where

\[
\begin{align*}
N_{\pi1}(T_\pi, t) &= \int_{T_p^{\text{min}}}^{\infty} N_p(T_p) c n_{\text{iism}}(t) \frac{d\sigma(T_p, T_\pi)}{dT_\pi} dT_p, \\
N_{\pi2}(T_\pi, t) &= 4\pi (R_s + ct)^2 n_{\text{iism}}(t) \int \frac{\dot{N}_{\pi1}(T_\pi, t)}{\dot{N}_{\pi1}(T_\pi, t)}/dT_\pi,
\end{align*}
\]

d\sigma(T_p, T_\pi)/dT_\pi is the differential cross section for neutral pion production from p–p collisions,
\( T_p^{\text{min}} = 2m_p c^2 (1 + m_\pi/4m_p) \approx 0.29 \text{ GeV} \) is the minimum kinetic energy of proton to be enough to create
the neutral pion, \( m_\pi \) and \( m_p \) are the masses of pion and proton, respectively.

In equation (2) we take into account, that the total number of interactions per second with ambient protons (or the total rate of creation of pions \( N_\pi(\pi) \)) can not be greater than number of interstellar ambient protons, that are engulfed by shell per second. For the differential cross section we have used the parameterizations proposed in [15]

\[
\frac{d\sigma(T_p, T_\pi)}{dT_\pi} = \exp \left( K_1 + \frac{K_2}{T_p^{0.82}} + \frac{K_3}{T_p^{1.2}} + \frac{K_4}{T_p^{4.4}} \right) \quad [\text{mb GeV}^{-1}],
\]

where \( K_1 = -5.8, K_2 = -1.82, K_3 = 13.5, K_4 = -4.5 \).

Table 1. Parameters of hydrodynamically accelerated protons

| Parameter | \( a = 0.2 \), \( b = 2.0 \) | \( a = 0.232 \), \( b = 2.73 \) |
|-----------|----------------------------|----------------------------|
| \( \delta \) | 3.7                       | 2.6                       |
| \( \gamma_p^{\text{max}} \)  | 22.8                      | 265.45                    |
| \( T_p^{\text{max}} \) [GeV] | 20.3                      | 246.2                     |
| \( N_p(>0.29 \text{ GeV}) \) | 1.28 \cdot 10^{52}       | 3.67 \cdot 10^{53}       |
| \( W_p(>0.29 \text{ GeV}) \) [erg] | 7.98 \cdot 10^{48}    | 2.57 \cdot 10^{49}    |
| \( W_p(>2 \text{ GeV}) \) [erg] | 3.24 \cdot 10^{46}      | 7.22 \cdot 10^{47}      |

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Table 2. Parameters of gamma-ray flash

| Parameter | \( a \) | \( b \) | \( a \) | \( b \) |
|-----------|--------|--------|--------|--------|
| \( N_{\gamma}^\text{tot} \) [\( \text{erg} \)] | \( 8.09 \cdot 10^{47} \) | \( 2.91 \cdot 10^{45} \) | \( 1.2 \cdot 10^{48} \) | \( 4.43 \cdot 10^{46} \) |

The production spectrum of gamma-rays with energy \( E_\gamma \) is [12]

\[
\dot{N}_\gamma(E_\gamma, t) = 2 \int_{E_\gamma^{\text{min}}}^{\infty} \frac{\dot{N}_\pi(T_\pi, t)}{\sqrt{E_\pi^2 - m_\pi^2 c^4/4E_\gamma}} dE_\pi \quad [\text{GeV}^{-1} \text{s}^{-1}],
\]

where \( E_\pi \) is the total energy of pion, \( E_\gamma^{\text{min}} = E_\gamma + m_\pi^2 c^4/4E_\gamma \) and is presented on Figure 2.

The total number of generated gamma photons per second (light curve) and their energy are

\[
\dot{N}_\gamma^\text{tot}(t) = \int_0^\infty \dot{N}_\gamma(E_\gamma) dE_\gamma \quad [\text{s}^{-1}], \quad \dot{W}_\gamma^\text{tot}(t) = \int_0^\infty \dot{N}_\gamma(E_\gamma) E_\gamma dE_\gamma \quad [\text{erg s}^{-1}]
\]

and is presented in Figure 1. The total number of gamma photons that are produced during the shell–CSM interaction and their energy are

\[
N_\gamma^\text{tot} = \int_0^\infty \dot{N}_\gamma^\text{tot}(t) dt, \quad W_\gamma^\text{tot} = \int_0^\infty \dot{W}_\gamma^\text{tot}(t) dt
\]
4. DISCUSSION AND CONCLUSIONS

We show, that analogously to the case of SNIa outburst [9] relativistic shock break out at the surface of Hypernova star is accompanied by hydrodynamical acceleration of outermost layers of presupernova up to relativistic velocities and by the gamma ray flash from pp-interaction of relativistic particles with circumstellar medium. This flash can be detectable by existing and under constructing space missions. For GLAST and EGRET sensitivities [16,17] ($F^{th}_{\text{GLAST}} = 6 \cdot 10^{-9} \text{ cm}^{-2} \text{s}^{-1}$, $F^{th}_{\text{EGRET}} = 10^{-7} \text{ cm}^{-2} \text{s}^{-1}$) we find the distances from which we are able to detect such gamma-flash by this missions $D_{\text{max,EGRET}} = 20.2 \text{ Mpc}$, $D_{\text{max,GLAST}} = 82.3 \text{ Mpc}$.

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