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

V.V. Marchenko, B.I. Hnatyk

Astronomical Observatory of Taras Shevchenko Kyiv National University

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.

ГАММА-СПАЛАХ ПРИ ВИХОДІ РЕЛЯТИВІСТСЬКОЇ УДАРНОЇ ХВИЛІ НА ПОВЕРХНЮ ГІПЕРНОВОЇ ЗОРІ, Марченко В.В., Гнатик Б.І. — В роботі досліджено спостережувальні прояви виходу релятивістської ударної хвилі на поверхню гіпернової. Розглянуто взаємодію прискореної речовини зовнішніх шарів зорі з навколозоряним середовищем. Проаналізовано генерацію гамма-випромінювання внаслідок непружних p–p зіткнень. Оцінено параметри потоку гамма-випромінювання та можливість його детектування сучасними та майбутніми космічними місіями

ГАММА-ВСПЛЕСК ПРИ ВЫХОДЕ РЕЛЯТИВИСТСКОЙ УДАРНОЙ ВОЛНЫ НА ПОВЕРХНОСТЬ ГИПЕРНОВОЙ ЗВЕЗДЫ, Марченко В.В., Гнатык Б.И. — В работе исследованы наблюдательные проявления выхода релятивистской ударной волны на поверхность гипернововой. Рассмотрено взаимодействие ускоренного вещества внешней оболочки звезды с околозвездной средой. Проанализирована генерация гамма-излучения в результате неупругих p–p взаимодействий. Оценены параметры потока гамма-излучения и возможность его детектирования современными и будущими космическими миссиями.

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

Table 1. Parameters of hydrodynamically accelerated protons

Parameter	$a=0.2,\ b=2.0$	$a=0.232,\ b=2.73$
δ	3.7	2.6
$\gamma_2^{\max}$	22.8	265.45
$T_p^{\max}$ $[GeV]$	20.3	246.2
$N_p(>0.29\ GeV)$	$1.28\cdot10^{52}$	$3.67\cdot10^{53}$
$W_p(>0.29\ GeV)$ $[erg]$	$7.98\cdot10^{48}$	$2.57\cdot10^{49}$
$W_p(>2\ GeV)$ $[erg]$	$3.24\cdot10^{46}$	$7.22\cdot10^{47}$

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 γ_1 increases with decreasing of density $\rho(r)$ in envelope of star $\gamma_1 \sim \rho(r)^{-a}$ 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 $\gamma_2^{\max}$ and $T_p^{\max}$ 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

$$n_{ism}(t) = n_{ism}^0 \left(\frac{R_s}{R_s + ct}\right)^2, \tag{1}$$

where c is the velocity of light, $n_{ism}^0 = 5\cdot10^{13}$ cm^{-3} in order to have typical grammage $x \sim 1$ g/cm^2 (optical depth is of order of $x/x_{\max}$, where $x_{\max} = 70$ g/cm^2 is the interaction path length of incident proton in curcumstellar medium).

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

$$\dot{N}_\pi(T_\pi, t) = \min[\dot{N}_{\pi 1}(T_\pi, t), \dot{N}_{\pi 2}(T_\pi, t)] \quad [GeV^{-1} s^{-1}], \tag{2}$$

where

$$\dot{N}_{\pi 1}(T_\pi, t) = \int_{T_p^{\min}}^{\infty} N_p(T_p) c n_{ism}(t) \frac{d\sigma(T_p, T_\pi)}{dT_\pi} dT_p,$$

$$\dot{N}_{\pi 2}(T_\pi, t) = 4\pi (R_s + ct)^2 n_{ism}(t) \frac{\dot{N}_{\pi 1}(T_\pi, t)}{\int \dot{N}_{\pi 1}(T_\pi, t) dT_\pi},$$

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

$$\frac{d\sigma(T_p, T_\pi)}{dT_\pi} = \exp\left(K_1 + \frac{K_2}{T_p^{0.4}} + \frac{K_3}{T_\pi^{0.2}} + \frac{K_4}{T_\pi^{0.4}}\right) \quad [mb\ GeV^{-1}], \tag{3}$$

where $K_1 = -5.8$, $K_2 = -1.82$, $K_3 = 13.5$, $K_4 = -4.5$.

Table 2. Parameters of gamma-ray flash

Parameter	$a=0.2,\ b=2.0$	$a=0.232,\ b=2.73$
N_γ^{tot}	$8.09\cdot10^{47}$	$1.2\cdot10^{48}$
W_γ^{tot} $[erg]$	$2.91\cdot10^{45}$	$4.43\cdot10^{46}$

The production spectrum of gamma-rays with energy E_γ is [12]

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

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

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

$$\dot{N}_\gamma^{tot}(t)=\int_0^\infty \dot{N}_\gamma(E_\gamma)dE_\gamma\ [s^{-1}], \qquad \dot{W}_\gamma^{tot}(t)=\int_0^\infty \dot{N}_\gamma(E_\gamma)E_\gamma dE_\gamma \quad [erg\ s^{-1}] \tag{5}$$

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

$$N_\gamma^{tot}=\int_0^\infty \dot{N}_\gamma^{tot}(t)dt, \qquad W_\gamma^{tot}=\int_0^\infty \dot{W}_\gamma^{tot}(t)dt \tag{6}$$

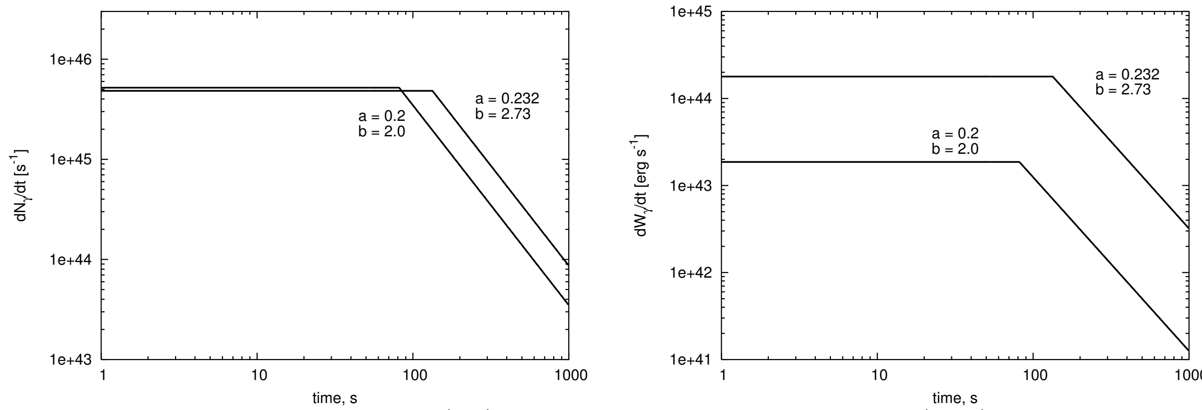

Fig. 1. Light curve (left) and energy in gamma rays per second (right).

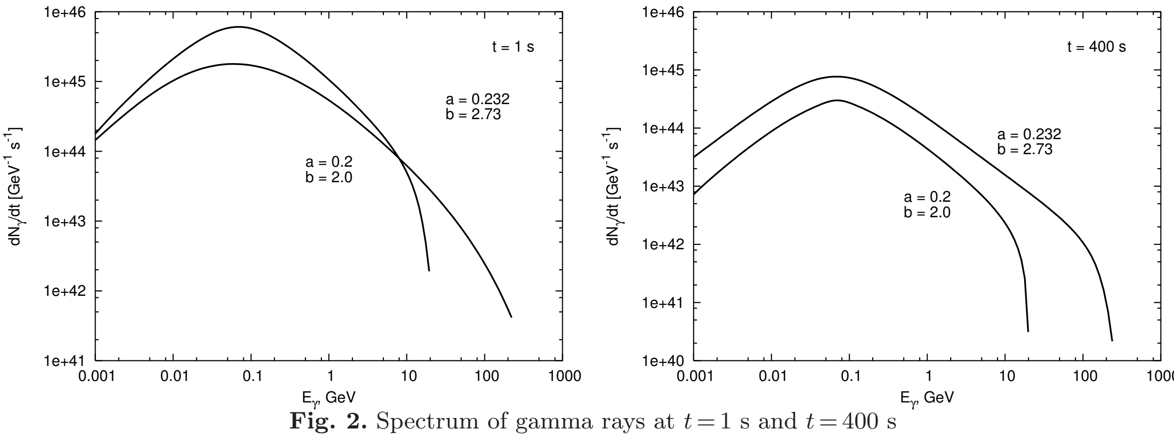

Fig. 2. Spectrum of gamma rays at $t=1$ s and $t=400$ s

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] ($F^{thr}_{GLAST} = 6 \cdot 10^{-9}$ cm^{-2}s^{-1}, $F^{thr}_{EGRET} = 10^{-7}$ cm^{-2}s^{-1}) we find the distances from which we are able to detect such gamma-flash by this missions $D^{\max}_{EGRET} = 20.2$ Mpc, $D^{\max}_{GLAST} = 82.3$ Mpc.

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