Gamma-ray emission during supernova outbursts

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Mechanisms are proposed for the nonthermal γ-ray emission generated in the shock wave front in a supernova outburst. Both mechanisms are due to nuclear collisions in the shock wave front. The internuclear mechanism of γ-ray emission in the energy range of $\lesssim 10$ MeV is realized in collisions with excitation of nuclei. At high shock wave velocities π^0 mesons can be formed in the collisions of nuclei, and their decays yield hard γ-ray emission with an energy of ~ 70 MeV: the nuclear-meson mechanism. The ratio of intensities of the two mechanisms is sensitive to the shock wave velocity and the chemical composition of the supernova envelope. A study of the correlation of the predicted γ-ray burst with neutrino and x-ray bursts and with the optical light curve of a supernova can yield important information about the properties of the presupernova.

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As is known, supernova outbursts are characterized by emission in the optical and x-ray ranges. Although only 1% of the entire energy of a supernova explosion goes into radiant energy, it yields important information about the processes occurring during the explosion. In Refs. 1-3 calculations and estimates were made of the emission in the x-ray and γ-ray ranges during the emergence at the surface of a star of the shock wave formed in the explosion of the core. According to these reports, the emission is due to the heating of the surface of the star during the emergence of the relativistic shock wave. Nonthermal mechanisms of γ-ray emission are also possible in a supernova explosion. For example, γ-ray emission in the energy range of 2.8-4 MeV in the decay of excited levels of Fe^{56} formed in the β^+ decay of Co^{56} is considered in Ref. 4.

Possible mechanisms of nonthermal γ-ray emission during the propagation of subrelativistic shock waves in the envelopes of exploding stars are suggested in our report.

The proposed mechanisms are essentially connected with the structure of the shock wave front. If the radiation pressure is low compared with the ion pressure, the shock front consists of the narrow region of a viscous jump, where the kinetic energy of directional motion of matter changes into thermal energy of nuclei, and a relaxation region, where the establishment of thermal equilibrium between nuclei, electrons, and radiation occurs.[1)] The size of the region of the viscous jump decreases with an increase in temperature, and hence in radiation pressure. When $P_\gamma > 4.55P_i$ the region of the viscous jump disappears.[6] But the region in which the absorption of directional momentum occurs remains. We will call this region, which coincides with the region of the viscous jump when $P_\gamma < 4.55P_i$, the shock zone. The characteristic size l of the shock zone is on the order of one or several mean free paths of nuclei. Under conditions when the propagation of the shock wave is accompanied by the development of plasma instabilities, the size of the shock zone and the amplitude of the shock wave can be decreased. The following physical picture is valid for the shock zone: a flux of particles with a velocity on the order of the shock wave velocity shoots through the material,[2)] with the energies of the bombarding particles able to reach several tens of megaelectron volts per nucleon, depending on the shock wave velocity.

The processes of proton–ion and ion–ion collisions in the shock zone are the sources of the γ-ray emission due to the excitation and decay of nuclei (the internuclear mechanism of γ-ray emission).

If the energy of the collision particles exceeds the threshold for the creation of π^0 mesons, then the processes of decay of π mesons formed in these collisions will be a source of neutrino emission and hard γ-ray emission (the nuclear–meson mechanism).[3)] It is important that in collisions of heavy nuclei π mesons can be created at energies per nucleon considerably lower than the threshold for the creation of pions in collisions of free nucleons.

It is interesting to note that processes of particle collisions in a shock zone have been used in the mechanism[8] of noncosmological production of deuterium through the splitting of He^4 by high-energy particles. In Ref. 9 the D + D reaction in a shock zone was considered as a mechanism for neutrino emission from the region of an axial plasma jet in a noncylindrical z pinch.

Let us estimate the intensity of the γ-ray emission from π^0 decays. From the equations of conservation of momentum and energy and from the continuity equation, neglecting the pressure and specific energy ahead of the front, we can obtain the relation[8]

$$\rho_s=\rho_i\frac{\gamma+1}{\gamma-1};\quad v_s=v_i\frac{\gamma-1}{\gamma+1};\quad P_s=\frac{2\rho_i v_i^2}{\gamma+1},\tag{1}$$

where γ is the adiabatic index, P is the pressure, ρ is the density, and $(\gamma-1)\rho_S U_S = P_S$, with U_S being the specific internal energy.

Hence, the velocity of the material passing through the shock wave front changes by an amount u equal to $u = v_i - v_S = {}^6/_7 v_i$ for $\gamma = {}^4/_3$ and $u = {}^3/_4 v_i$ for $\gamma = {}^5/_3$, where v_i coincides with the propagation velocity of the shock

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wave in the coordinate system connected with the front. The velocity v_i can be obtained either from numerical calculations of shock wave propagation in the outer layers of stars or from self-similar solutions for the propagation of a shock wave through matter with a decreasing density. Selected values for the velocities v will be given below.

Let us write the kinetic equation for the creation of π mesons in internuclear collisions in the physical model under consideration. As we said above, it can be assumed that a flux of particles having an energy $\varepsilon = m_p u^2/2$ per nucleon falls onto stationary matter. Then the kinetic equation has the form

$$\frac{dn_\pi}{dt}=\sum_{ij}\frac{X_iX_j}{A_iA_j}\frac{\rho_i\rho_*}{m_p^2}\sigma_\pi^{ij}u, \tag{2}$$

where σ_π^{ij} is the cross section for the creation of a pion in the collision of nuclei with mass numbers A_i and A_j and with the respective weight concentrations X_i and X_j. Let us estimate the ratio of the times of decay of a free π^0 meson and of its capture by a nucleus:

$$\frac{\tau_\pi}{\tau_n}\approx\frac{m_p\tau_\pi}{\sigma_{n\pi}\rho v_\pi}, \tag{3}$$

where we set the cross section for π^0 absorption by nuclei at $\sigma_{n\pi} \approx 10^{-24}$ cm^2 and $\tau_{\pi 0} \approx 10^{-16}$ sec. Hence, $\tau_{\pi 0}/\tau_n < 1$ at densities $\rho \leq 10^6$ g cm^3 and π^0 is able to decay into two γ.

For the emission intensity of the γ-ray line with $E_\gamma \approx 67.5$ MeV (the line will have broad wings owing to the motion of the decaying pion, formed far from the creation threshold) we have

$$L_\gamma\approx\sum_{i,j}VE_\pi^{ij}\frac{dn_\pi^{ij}}{dt}, \tag{4}$$

where E_π^{ij} is the total energy of the decaying pion, $E_\pi^{ij} \approx m_\pi c^2$, and $V = 4\pi R^2 ?$.

Then from Eq. (4), with allowance for the relation $dt = dr/v_i$ and (1), we obtain the following expression for the total energy $\mathscr{E}$ of γ-ray emission:

$$\mathscr{E}=\sum_{ij}\frac{X_iX_j}{A_iA_j}E_\pi^{ij}\frac{\sigma_\pi^{ij}}{\beta_n\sigma_n}\frac{\Delta M}{m_p}\frac{2}{\gamma+1}, \tag{5}$$

where

$$\Delta M=4\pi\int_{r_0}^{r_1}\rho r^2dr, \tag{6}$$

where $\beta_n = l_n/l$, where l_n is the mean free path of a nucleus. The lower limit of integration r_0 is determined by the condition that the shock wave velocity be sufficient for the creation of π mesons: $r_0 = r_\pi$. But if $r_\pi \ll R$ (the radius of the star), then the outer layers of material will be opaque to the γ-ray quanta formed. In this case $r_0 = r_\gamma$, where r_γ is determined by the relation

$$\tau=\frac{\sigma_\gamma(\varepsilon_\gamma)}{m_p}\int_{r_\gamma}^{R}\rho dr\approx 1. \tag{7}$$

The upper limit r_1 in (6) corresponds to $\tau \approx 1$ for thermal photons, which corresponds to violation of the "condition of adiabaticity" of the shock wave. When $r > r_1$ the kinetic energy of the shock wave can change into thermal emission.[1]

We note that the annihilation of positrons from the decays of π^+ mesons through the change $\pi^+ \to \mu^+\nu$; $\mu^+ \to e^+\nu\bar{\nu}$ will also be a source of hard γ-ray emission.[10] The total emission energy can be determined from Eq. (5) with E_π^{ij} replaced by the corresponding total energy released in the annihilation of fast positrons and equal to ~30–40 MeV. The decays of charged π mesons are accompanied by the emission of neutrinos, and the total energy emitted can also be estimated from Eq. (5) with E_π^{ij} replaced by $E_\nu \approx (35\text{–}40)$ MeV and with allowance for the fact that the material of the outer layers of a star is transparent to neutrinos. Therefore, the entire region in which the shock wave velocity is high enough for pion creation contributes to the neutrino emission. [In Eq. (6) $r_0 = r_\pi$ always.]

If $r_0 = r_\gamma \approx R \approx r_1$ in Eq. (6), then

$$\Delta M=4\pi R^2\int_{r_\gamma}^{r_1}\rho dr\approx 4\pi R^2\int_{r_\gamma}^{R}\rho dr=\frac{4\pi R^2}{\sigma_\gamma(\varepsilon_\gamma)}m_p$$

and

$$\mathscr{E}=\sum\frac{X_iX_j}{A_iA_j}E_\pi^{ij}\frac{\sigma_\gamma^{ij}}{\beta_n\sigma_n}\frac{4\pi R^2}{\sigma_\gamma(\varepsilon_\gamma)}\frac{2}{\gamma+1}, \tag{8}$$

where R is the radius of the star and $\sigma_\gamma(\varepsilon_\gamma)$ is the cross section for the absorption of γ quanta with an energy ε_γ.

Equation (5) also allows one to estimate the intensity of γ-ray emission with $E_\gamma \lessapprox 10$ MeV due to the internuclear mechanism.[4]

For this $E_\pi^{ij}\sigma_\pi^{ij}$ must be replaced by $E_\gamma^{ij}\sigma_\gamma^{ij}$, where E_γ^{ij} is the average energy of γ-ray quanta from nuclear transitions in collisions of nuclei of type i with nuclei of type j while σ_γ^{ij} is the total cross section for the formation of γ-ray quanta in such collisions. Since processes of emission of γ-ray quanta in internuclear collisions have a far lower threshold than processes of pion creation, $r_0 = r_\gamma$ in Eq. (6), and for the total energy of γ-ray emission due to the internuclear mechanism we have

$$\mathscr{E}=\sum_{ij}\frac{X_iX_j}{A_iA_j}E_\gamma^{ij}\frac{\sigma_\gamma^{ij}}{\beta_n\sigma_n}\frac{4\pi R^2}{\sigma_\gamma(E_\gamma^{ij})}\frac{2}{\gamma+1}. \tag{9}$$

The total energies of γ-ray emission due to the nuclear–meson and internuclear mechanisms are essentially determined by the cross sections for the creation of π^0 and γ-ray quanta, respectively. These processes will be determined by different nuclear effects, depending on the propagation velocity of the shock wave and hence the energy of the nuclei colliding in the shock zone.

At energies $E \geq 60\text{–}70$ MeV/nucleon the creation of

π^0 in nuclear collisions is due to collisions between nucleons in the region of interpenetration of the colliding nuclei, with the creation of π^0 at E less than the threshold for their creation in collisions of free nucleons being connected with the Fermi motion of nucleons inside the nuclei.[11] At E < 60 MeV/nucleon the creation of π^0 mesons evidently can occur only through collective effects in the scattering of an incident nucleus on nucleon associations in the target nucleus. Unfortunately, both experimental data and theoretical estimates of the yield of π^0 mesons are absent for this energy region.

With reasonable chemical compositions of envelopes the main elements heavier than helium are carbon and oxygen. Therefore, we will be confined to these three elements in further discussions. In proton–nucleus and helium–nucleus collisions, when the incident particle has energies of from several megaelectron volts per nucleon to several tens of megaelectron volts per nucleon, the creation of γ-ray quanta is connected predominantly with the process of excitation of the target nucleus in the bound state. Since bound excited states are absent in He^4, bremsstrahlung photons are formed in the collision of protons or α particles with He^4 and the cross section for this process is small.[12] Therefore, the main source of γ-ray quanta will be $(p, p'\gamma)$ and $(\alpha, \alpha'\gamma)$ processes on O^{16} and C^{12}. The γ-ray quanta are emitted predominantly by the following excited states: in C^{12} they are the levels with energies E = 4.4 and 12.7 MeV, while in O^{16} they are E = 6.13, 6.92, 7.12, and 8.87 MeV and two levels in the region of 11 MeV.

In the energy range from 8 to 40 MeV the cross sections of the $(p, p'\gamma)$ and $(\alpha, \alpha'\gamma)$ reactions on C^{12} with excitation of the 4.4 MeV level are large, exceeding 1 b at the lower limit and falling to several millibarns at the upper limit.[13,14]

The cross sections for the excitation of the enumerated levels of the O^{16} nucleus also reach several tens of millibarns in the same energy range of the incident proton. At an energy on the order of 100 MeV and higher the γ-ray quanta are formed both in the $(p, p'\gamma)$ or $(\alpha, \alpha'\gamma)$ reactions and from the $(p, p'x\gamma)$ and $(\alpha, \alpha'x\gamma)$ reactions of knocking out of the nucleus of a fragment x consisting of a nucleon or a group of nucleons.[15,16] The cross sections for these processes are about 100 mb.

In contrast to the process of emission of γ-ray quanta, the process of pion formation will be connected with the collision of two helium nuclei (by virtue of their high concentration). From theoretical calculations based on the mechanism proposed in Ref. 11 and from experimental data[17] we find that for ε = 100, 200, and 300 MeV/nucleon this cross section will be

$$\sigma(He^4+He^4\to\pi^0+\ldots)=0.02;\ 0.7;\ 2.8\ \text{mb}. \tag{10}$$

respectively.

Let us estimate the total energy of γ-ray emission from Eqs. (5), (8), and (9) for two models of a supernova explosion: 1) the explosion of a core with a massive extended envelope, $M_{en} \gg M_c$; 2) the explosion of a core in a compact model with $M_{en} \ll M_c$. It is assumed[18] that these models correspond to two different types of supernova explosions. Numerical calculations[2,3] of the emergence of shock waves in such envelopes show that considerably lower velocities are reached in an extended envelope than in the compact model. In a compact envelope the velocities can reach sublight values near the surface of the star, so that the intensity of γ-ray emission is determined by Eqs. (8) and (9).

Assuming that the chemical composition of a compact envelope is the same as the observed chemical composition of the Crab Nebula (X = 0.14, Y = 0.86, Z $\approx 10^{-2}$), from Eqs. (8) and (9) with $R = 10^9$ cm we obtain $E(E_\gamma \approx 100\ \text{MeV}) = 10^{39}\cdot 1/\beta_n$ erg and $E(E_\gamma \approx 10\ \text{MeV}) = 10^{35}\cdot 1/\beta_n$ erg. In this case the process of π^0 formation in the collision of helium nuclei dominates in the nuclear–meson mechanism of formation of γ-ray quanta with $E_\gamma \approx$ 100 MeV. The internuclear mechanism proves to be less efficient, since processes of collision of He^4 nuclei and protons with heavier elements are the source of the γ-ray emission. Moreover, the effective region of γ-ray emission with $E_\gamma \le 10$ MeV is an order of magnitude smaller than the size of the region of emission due to the nuclear–meson mechanism because of the greater opacity of the material to softer γ-ray quanta. At $E_\gamma \lessdot 150$ MeV the opacity of material with the chemical composition under consideration is determined by processes of Compton scattering of photons on electrons.

We note that, in contrast to γ-ray emission in the accretion of material onto black holes and neutron stars, where the gravitational shift and the Doppler effect shift the spectrum in the red direction, the spectrum of the emission from a shock zone proves to be shifted into the violet region because of the Doppler effect for the outward-moving shock front. The outward propagation of the shock front also assures a predominant outward direction for the γ-ray quanta formed.

The explosion of a supernova with a compact envelope will be characterized by a short γ-ray burst. The characteristic time of emission is $t \approx l_\gamma/v_i$, where l_γ is the mean free path of the γ-ray quanta while $v_i \approx c$. When the density of the outer part of the envelope is $\rho \approx 10^{-3}$ g·cm^{-3} we have $t \approx 10^{-5}$ sec.

Calculations of the explosion of a supernova with a massive extended envelope lead to velocities of shock wave propagation not exceeding $v_i \lessdot c/3$, i.e., the particle energy in the shock zone does not exceed 50-60 MeV/nucleon. At such energies a calculation of the contribution of the nuclear–meson mechanism to the γ-ray emission is hindered by the uncertainties in the cross section for π^0 formation discussed above. For a rough estimate we will assume that $\sigma_\pi/\sigma_n \approx 10^{-8}$ (also see Ref. 7).

Then from Eq. (8) for $R \approx 10^{15}$ cm, under the assumption of a normal chemical composition of the enveope, we have $E(E_\gamma = 100\ \text{MeV}) = 10^{41}\cdot 1/\beta_n$ erg. The characteristic time of emission is $\tau = l_\gamma/v_i \approx R/v_i = 10^5$ sec. In this case processes of π^0 formation in the collisions of He^4 with heavy nuclei make the main contribution to the nuclear–meson γ-ray emission. For the internuclear emission we obtain from Eq. (9)

$$E(E_\gamma \lessdot 10\ MeV) = 10^{47}\ 1/\beta_n\ \text{erg}.$$

Processes of collision of protons with heavy helium nuclei make the main contribution to the internuclear γ-ray emission.

These estimates show that the emergence of a shock wave into the envelope of a supernova can be accompanied by γ-ray emission in the ranges of $E_\gamma \lesssim 10$ MeV and $E_\gamma \approx 100$ MeV. Observations of such γ-ray emission and the study of its time characteristics make it possible to obtain important information about the properties of supernova explosions and the structure of presupernovae. The total energy of γ-ray emission and the duration of the γ-ray pulse are determined by the size of the presupernova, $\sim R^2$ and $\sim R$, respectively. The observation of γ-ray emission in the range of $E_\gamma \approx 100$ MeV would serve as confirmation of the presence of subrelativistic velocities of shock wave propagation in supernoval envelopes. The observation of γ-ray lines in the range of $E_\gamma \lesssim 10$ MeV would permit the obtainment of information about the chemical composition of presupernova envelopes.

An investigation of the correlation of the neutrino emission during the collapse of the central core, the x-ray and γ-ray emission in the supernova explosion, and the light curves of supernovae could serve as a detailed test of models of the formation of neutron stars and of supernova explosions and of presupernova models. The collapse of the core of a star is characterized by a powerful neutrino pulse with a total energy of $\sim 10^{53}$ erg and a duration of 0.1-10 sec (Ref. 19). The emergence of a shock wave at the surface of a star is accompanied by the nonthermal γ-ray emission discussed in the present report and by hard thermal (x-ray[2,3] or, possibly,[1] even soft γ-ray) emission. The durations of the corresponding bursts are characterized by the quantity R/c, determining the time of arrival at the observer of the radiation from all parts of the surface turned toward him, and the leading front of the nonthermal γ-ray pulse should be in advance of the leading front of the x-ray pulse by $\Delta t \approx l_\gamma/v_i$. The delay of these pulses relative to the ν pulse is determined by the time of emergence of the shock wave at the surface and characterizes the size of the presupernova. We note that in the explosion of a supernova without a remnant the neutrino emission may be practically unobservable.[18]

If the optical emission of a supernova is directly connected with the emergence of the shock wave at the outside, then the maximum of the supernova light curve sets in following the γ-ray and x-ray pulse after a time interval of $\sim l_X/v_i$ (l_X is the mean free path of the x-ray quanta). But if the emission in the visible range is due to an additional mechanism of slow energy release, then the maximum of the light curve may be delayed by 10-30 days relative to the x-ray and γ-ray pulses. Thus, the observation of these correlations allows one to draw very definite conclusions about the mechanism of supernova outbursts, with the correlated γ-ray and x-ray pulses serving as a forerunner of the supernova outburst in the visible range and their correlation with the neutrino pulse indicating a connection between supernova outbursts and the formation of pulsars.

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1)Since the magnetic field is small in the material through which the shock wave propagates, a collisionless shock wave is not formed.[5]
2)The material through which the shock wave propagates is stationary.
3)A short qualitative discussion of this mechanism is contained in Ref. 7.
4)The authors thank G. V. Chibisov, who drew their attention to the possible efficiency of this mechanism.

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