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INSTITUTE FOR HIGH ENERGY PHYSICS

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S.S. Gershtein*

OSCILLATING STRUCTURE OF γ -BURSTS
AND THEIR POSSIBLE ORIGIN

E-mail: gershtein@mx.ihep.su

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Abstract

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As it is well-known that the hydrodynamic collapse of the massive star iron core should lead to the production of a hot neutron star. The assumption is made that the thermonuclear burning of the envelope matter, accreting onto the hot neutron star, can proceed in the oscillatory regime (analogously to that happens during heat explosion of the carbon-oxygen cores of stars with smaller masses).

Local density oscillations in the vicinity of the neutron star surface can generate shock waves, in which the stratification of the electron-positron plasma from the rest of the matter can happen due to the light pressure. In the case of the spherically symmetric collapse of the compact star it can lead to the production of the expanding relativistic fireball shells with characteristic oscillation time of $\sim 10^{-2}$ s, observed in the cosmological γ -bursts (GRB), can occur.

It is pointed out that nonrotating massive Wolf-Rayet's (WR) stars could be the source for the GRB, whose collapses, according to a number of observations, can happen without any noticeable ejection of the envelope.

Аннотация

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Высказывается предположение, что термоядерное горение вещества оболочки массивной компактной звезды, аккрецирующего на горячую нейтронную звезду, образовавшуюся в результате сферически симметричного коллапса железного ядра звезды, может происходить в осцилляционном режиме (подобно тому, как это происходит при тепловом взрыве углеродно-кислородных ядер звезд меньших масс). Локальные осцилляции плотности вблизи поверхности нейтронной звезды могут генерировать ударные волны, в которых происходит стратификация электрон-позитронной плазмы от остального вещества и образование оболочек расширяющегося релятивистского файерболла с характерным временем осцилляций порядка 10^{-2} с, наблюдаемых в космологических γ -всплесках (GRB).

Указывается, что прародителями GRB могут быть невращающиеся массивные звезды Вольфа Райе (WR), коллапс которых, согласно ряду наблюдательных данных, может происходить без сколько-нибудь значительного выброса оболочки.

1. Introduction. Fireball model

The observed γ -bursts (GRB — Gamma Ray Burst) are extremely interesting and still unexplained phenomenon (see reviews [1-4] and refs. therein).

Optical identification of the γ -bursts with “host” galaxies has proved that, at least, part of them occurs in the galaxies with red shift of $Z \geq 1$, i.e. is of cosmological origin. This agrees well with a fully isotropic distribution of GRB over the sky and with statistic distribution of the burst events over their intensity.

Optical identification of GRB has allowed one to determine the distance to them and establish that a huge energy of $\sim 10^{52} \div 10^{54}$ erg. in the γ -range (30-500 keV) is emitted in this phenomenon. Many of the observed GRB characteristics are explained in the framework of the “fireball” model [5-7], i.e. in terms of the electron-positron cloud, expanding with ultrarelativistic velocities. Ultrarelativistic velocities of the expansion (naturally appearing in the electron-positron plasma) [6], allow one to solve the problem of the GRB source compactness [6-8] and match the nonthermal GRB spectrum with a short characteristic time of the GRB variability ($\delta t \sim 10$ ms.)¹. Basing on the fireball model, one has succeeded to explain both the observed effects of the long-lasting optical GRB afterglow, which appears as a result of the interaction between relativistic expanding fireball and inter-stars medium [11], and the effect of the early afterglow, which intersects in time with the GRB of high duration [12-14]. Thus, the model of the relativistic fireball containing a small number of baryons allows one to agree with the observed GRB characteristics and explain the accompanying phenomena. However, some of the questions remain unresolved yet:

1. The mechanism of the fireball production.
2. Large energy in the fireball.
3. The presence in some GRB's of a large number ($\sim 10^2 \div 10^3$) of pulsation of the γ emission intensity with a characteristic time of $\delta t \approx 10$ ms. We believe that this effect could serve as a basic key to resolve the γ -bursts puzzle. In this paper we attract the attention to the fact that the oscillations of the γ -quantum flux can naturally appear during the hydrodynamic collapse of some compact, massive, and nonrotating stars at a final stage of their evolution.

¹It is very important here that the bound on the number of baryons contained, which has to be small enough [9,10], is the condition for the ultrarelativistic expansion of lepton-photon plasma.

2. The possibility of the oscillator burning of thermonuclear fuel during the process of hydrodynamic collapse

It is well-known that the production of a sufficiently large iron core in the process of the star evolution is the reason for the hydrodynamic collapse of massive stars with masses $M \geq 10M_{\odot}$. In this case the star core, having exhausted the source of thermonuclear energy, tends to compress and heat. The resulting increase of pressure, however, is unable to stop the compression, since the thermal energy is spent on the endothermal reaction of the iron nucleus decay and further — on the core neutronization. As a result, the core compression is transferred to the catastrophic hydrodynamic collapse, which is followed by the production of the hot neutron star. According to the idea by Fowler and Hoyle [16], the accretion of the nuclear fuel, which is left in the star envelope, onto the hot neutron star leads to its explosion and pollution manifesting itself as the burst of supernova. However, selfconsistent hydrodynamic calculations did not prove this assumption. It turned out that a consequent account for the neutrino emission leads to the delay of the collapse, which stops only when the core matter becomes nontransparent to the neutrino radiation. As a result of this delay, the burning of the accreting nuclear fuel occurs in a deep gravitational potential and, thus, the emitted thermonuclear energy is insufficient for the envelope ejection [17] (see, for instance, review [18] and refs. therein). Shock wave, occurring during the collapse delay, dumps only a small fraction of the envelope with the energy about 10^{49} erg [19], which is two orders of magnitude less than a characteristic energy of the supernova explosion, 10^{51} erg. Thus, this phenomenon was named as "soundless" or silent collapse. Further attempts to explain the supernova bursts at the spherically symmetric collapse of massive stars had not led to a desirable result [20] and now most of the specialists tend to the idea that the observed supernovas bursts with massive early-supernova are anyway connected with effects of the collapsing star rotation: magnetic pressure onto the envelope, the Relay-Taylor instability, or breakage of the neutron star into two components (see, for instance, [21-22]).

However, one should take into account that the burning of the thermonuclear fuel during its accretion onto a hot neutron star can have the oscillating behavior. This effect is well-known and manifest itself in the consideration of the final evolution stage of stars with small masses, $3M_{\odot} \leq M \leq 10M_{\odot}$. In such stars the oxygen-carbon core with a degenerated electronic gas is produced as a result of the evolution. In this case the thermal explosion in the degenerated star core is the reason for the instability, when the core mass achieves the value close to the Chandler limit [23]. In this case the oscillating character of thermonuclear fuel burning could be easily understood, if one takes into account a relatively small calorific power of this fuel with carbon-oxygen and so on content. The energy emitted during the thermal explosion leads to the elimination of degeneracy and the increase of thermal pressure resulting in the star expansion. As a result of the expansion, the star temperature is decreased. This leads to the consequent compression of the star and enhancement of the thermonuclear burning which, in its turn, leads to the expansion, etc. All said above can be illustrated in Fig. 1, where one can see the results of calculations [24]. The observed oscillation not only retained, but had been enhanced due to the account for convection, thus leading to the delayed detonation with explosion energy $\sim 10^{51}$ erg (report by V.S. Imshennik, the seminar devoted to the memory of S.I. Syrovatsky, March 2, 2000).

Fig. 1. Time dependence of the central density and temperature in the process of the carbon burst. The pulsing regime of the carbon burning with subsequent separation of star core fragments is clearly seen [18,24].

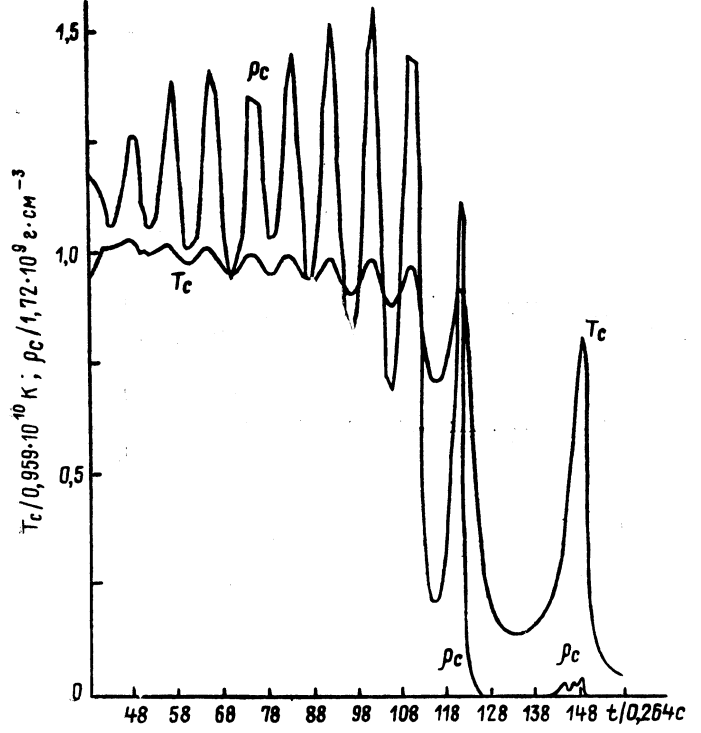
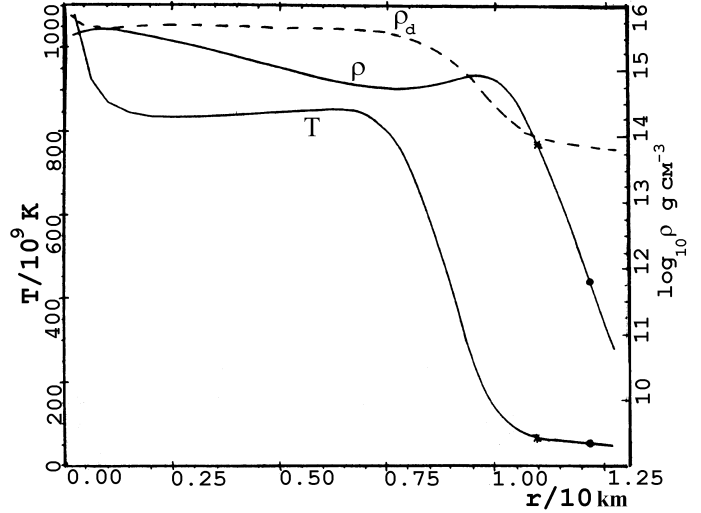


Fig. 2. The density and temperature distributions over the hot neutron star surface (dashed line corresponds to the degeneracy density). The location of the neutrino photosphere is shown by the star marker, the black marker shows the boundary of the neutron core [19].



It is possible that such oscillations appear as well in the layers of the thermonuclear fuel accreting onto a hot neutron star. In contrast to the case discussed above, they can have only a local character, evolving in layers, adjacent to the surface of the hot neutron star. The period of these oscillations can be estimated by the arguments of dimension

$$\tau \sim \frac{1}{\sqrt{G_N \bar{\rho}}}, \quad (1)$$

where G_N is the gravitational constant, $\bar{\rho}$ is the matter density in the vicinity of the neutron star. According to the calculations (see Fig. 2), $\bar{\rho} \sim 10^{11} \text{ g/cm}^3$. Thus, the period of oscillations turns out to be equal to

$$\tau \sim 10^{-2} \text{ s}, \quad (2)$$

which coincides intriguingly with an oscillation period of the γ -quantum flux in some GRB². Density and temperature oscillations close to the surface of hot neutron star have to generate diverging shock waves in the surrounding envelope (with decreasing density vs. radius increase), repeating with the oscillation frequency.

3. The possibility of the electro-positron plasma stratification

One of the most important effects, which should be taken into account in the description of shock waves passing through the star envelope, is a possible stratification of the electron-positron plasma, which happens without any violation of the electroneutrality of ordinary matter (nuclei and electrons, which compensate their electric charge). Such stratification is possible under condition of light pressure in a propagating shock wave, as the Eddington limit for electron-positron plasma is 3600 times lower than that for an ordinary matter with nuclei $A \simeq 2Z$. So, the electron-positron plasma, when exiting to the star surface, will contain a relatively low concentration of baryons (which is just needed to agree the fireball model and observed data). It should also be noted that under condition of the rarefacted star atmosphere the equilibrium electron-positron plasma can appear at relatively low temperatures, since under these conditions at $kT \ll m_e c^2$:

$$\begin{aligned} n_{e+} \approx n_{e-} &\approx \frac{1}{(2\pi^3)^{1/2}} \left(\frac{m_e c}{\hbar} \right)^3 e^{-1/x} x^{3/2} \\ x &= \frac{kT}{m_e c^2} \ll 1 \end{aligned} \quad (3)$$

while in the dense matter the positron concentration will be proportional to $\exp - \left(\frac{2m_e c^2}{kT} \right)$ (see, for instance, [26]). The fact that sufficiently high temperatures ($kT \geq m_e c^2$) are achieved close to the center of the collapsing star is proved by the presence of the process of explosive nucleosynthesis of the ^{56}Ni nuclei with subsequent production of ^{56}Co , as it comes from the observation data on SN1987 [21,27] (according to the calculations [19], in the region of neutrinosphere $kT \simeq 5, 6$ MeV).

When leaving the star atmosphere, the expanded cloud of electron-positron plasma inevitably gains the ultrarelativistic character (see [6]). This, as is well-known, leads to the variations of γ -radiation momentum, received by a remote observer

$$\delta t \simeq \frac{R}{2c\Gamma^2}, \quad (4)$$

where R is the cloud radius, $\Gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor, corresponding to the expansion velocity, v . It is evident that the oscillation of the γ -quantum flux will be observed, if

$$\delta t \leq \tau. \quad (5)$$

In the opposite case ($\delta t \gg \tau$), the oscillations in the γ -quantum flux for a remote observer are smeared. This helps to explain the fact that there are no observed oscillations in some GRB's.

²It should be noted that the conditions for oscillation excitation [25] are also realized in the hot neutron stars, produced as a result of the iron core collapse. However, their frequency is, at least, two orders of magnitude more.

Stratification of the electron-positron plasma from ordinary matter should lead to the situation, when each oscillation in the vicinity of the neutron star will produce shock waves in the form of two shells expanding with different velocities. Here, it could happen that the electron-positron shell, emitted in the following oscillation can overtake that one containing baryons and emitted in the previous oscillation. Thus, there can be an interaction of shock waves inside the fireball itself [12,13,28,29,30].

Ultrarelativistic character of the fireball expansion ($\Gamma \sim 10^2$) allows one to conclude that at observed values of $\delta t \sim 10^{-2}$ s the fireball size can be large enough (and the plasma density is low enough, correspondingly), to consider the fireball as a “thin” source. This allows one to explain the nonthermal (power) spectrum of GRB. “Intrinsic” shock waves, producing the fireball, can also generate high energy particles by means of a well-known mechanism of acceleration. This can explain the observation the high energy γ -quanta (up to 18 GeV) in some GRB’s.

4. Possible progenitors of GRB

The scenario of the oscillation origin in GRB developed above confines the class of objects, which could be the progenitors of GRB.

First, these should be sufficiently massive stars with masses $M > (15 - 20)M_{\odot}$. Quite stage of such star evolution has to be ended within a time period about 10^6 years or less. A star mass, large enough, is also required to explain the GRB energy.

Second, these should be nonrotating (or with low angular velocity) stars. It seems that stars with high angular velocity should explode due to the effects connected with their rotation, as ordinary supernovas of the type II with ejection of relatively massive envelope [31].

And third, these should be compact stars devoid of extent hydrogen and, probably, in part, helium envelope, which is able to prevent the outer ejection of the electron-positron plasma due to the processes of positron annihilation.

The stars of the Wolf-Rayet type (WR) meet all these requirements — they are the most massive compact starts, which have almost lost all their hydrogen and, in part, helium envelope during their evolution. It is possible that, namely, due to the loss of the bulk of their envelope these stars have lost their rotatory impulse. Anyway, the rotation is observed only for 15% of the WR-stars [32]. In the studies by A.M. Cherepashchuk et al. (see [33] and refs. therein) it was found that one could neglect the decrease of the WR-star masses in the process of their further evolution (which is caused by the stellar wind). It allows one to compare the masses of the WR-stars and their CO-nuclei with the masses of the relativistic objects (neutron stars and “black holes”), for which the WR-stars are the progenitors. Basing on the masses measurement of the X-ray sources in double systems, A.M. Cherepashchuk has drawn an extremely important conclusion that the distribution of the X-ray sources masses is of a clear bimodal character. There is a mass gap between the neutron stars — pulsars, whose masses range in the narrow band $(1 - 2)M_{\odot}$ with an average mass of $(1.35 \pm 0.15)M_{\odot}$, and masses of candidates to black holes, which are distributed in the range of $(5 \div 15)M_{\odot}$ and have an average mass of $(8 \div 10)M_{\odot}$. The bimodal mass distribution and the presence of the gap serves as an indication of a different origin of these objects. As for the massive candidates to black holes, the correlation (discovered by A.M. Cherepashchuk [33]) between their masses and masses of the WR-stars, which are in the range of $(5 - 55)M_{\odot}$ and for which an average value of their CO-nuclei is $(8 \div 12)M_{\odot}$, close to that of the observed candidates to black holes, seems to be very important to understand their origin. Thus, there are arguments to assume that, at least, some of the WR-stars collapse into massive

objects through the “soundless” collapse without any significant ejection of their envelope. In the first turn it concerns more evolved WC-stars with rich content of C-nuclei in their envelope (produced due to the thermonuclear burning of helium) and with an average mass of $13,4 M_{\odot}$. The data presented in [33] are the strong argument in favour of the assumption formulated by P.Conti in 1982 [34] that the WR-stars more often disappear in the form of “whimper”, rather than explosion³.

The compact structure of the WR-stars allows one to assume that the electron-positron plasma shells, which appear due to the stratification in shock waves, can leave the star surface, and even a small part of the large gravitational energy emitted in the massive star collapse can explain the GRB energy.

5. The GRB energy

To determine the GRB energy, it is necessary to have self-consistent hydrodynamic calculations of the process of soundless massive star collapse with account for a possibility of the e^+e^- -plasma stratification from the rest of the matter. However, one can try to estimate a possible GRB energy from physical (though, not very reliable) arguments. If, as a result of the collapse into the hot neutron star with mass $M = 1,5M_{\odot}$, the gravitational energy $\epsilon \approx 5 \cdot 10^{53}$ erg. is emitted in the form of neutrino radiation, then for masses $M = (15 \div 20)M_{\odot}$ (in the case without the envelope ejection) one can expect the energy emission about $\epsilon \simeq 10^{56}$ erg.⁴ So, to provide the GRB energy $\sim 10^{53}$ erg., it is sufficient to have (e^+e^-) -plasma ejection accumulating $\sim 0,1\%$ of emitted gravitational energy. An analogous estimate can be obtained using (taking some risk) the calculation results of the hydrodynamic collapse of the iron-oxygen star core [18]. Though the shock wave generated in this process is subjected to the attenuation due to neutrino radiation and its power is not sufficient to explain the supernova explosion, nevertheless, the energy of the emitted shell can be $\sim 10^{49}$ erg. For the obtained velocity of the shell expansion of $v \sim 1.5 \cdot 10^3$ km/s, the mass of the ejected shell is $\Delta M \simeq 0,44M_{\odot}$. Were such mass being ejected in the form of the e^+e^- -plasma, the energy of $8 \cdot 10^{53}$ erg. should be emitted during its subsequent annihilation. The comparison given here is not proved well, but it gives an idea on a possible effect value. Thus, the bulk of the GRB energy in the mechanism considered has the gravitational origin. The heating of the collapsing star leads to the production of the dense and hot e^+e^- -plasma, and energy emitted in oscillatory burning of the thermonuclear fuel is spent to generate shock waves pushing the e^+e^- -plasma beyond the star.

One should also take into account a possible additive energy to the expanding e^+e^- -plasma due to neutrinos and antineutrinos radiated during the collapse process (since, during their scattering on the electrons and positrons they can pass the bulk of their energy to the latters). The question of γ -radiation spectra from GRB requires special treatment. It is quite possible that the absence of the 511 keV line from the e^+e^- -annihilation at rest is connected with the ultrarelativistic fireball expansion.

Discussions

On the basis of the observation data [33] there are forcible arguments to assume that massive, compact, and nonrotating stars of the Wolf-Rayet type [32] are subjected to the relativistic

³It is possible that some WR-stars are early supernovas 1b. (I would like to acknowledge this remark by V.S. Imshennik).

⁴It should be noted that a hot neutron star should be stable up to the mass of $M_{NS} \approx 70M_{\odot}$ [35].

collapse without any significant ejection of their envelope. This assumption agrees well with the fact that within the hydrodynamic calculations one fails to obtain the envelope ejection sufficient to explain the supernova bursts. The gravitational energy emitted during the relativistic collapse of such objects can be about $10^{55} \div 10^{56}$ erg.

The hypothesis developed in this paper is that the burning of the thermonuclear fuel accreting onto a hot neutron star can proceed in the oscillatory regime, which generate the shock waves, which, in their turn, push out the e^+e^- -plasma outside the star surface (in the presence of its stratification). This hypothesis explains qualitatively the origin of the relativistic fireball with a low baryon content and oscillations observed in GRB (moreover, the oscillation period is explained quantitatively in the order of magnitude). The duration of GRB (~ 20 s) agrees with the time of the outer envelope accretion onto the neutron star and the time of its cooling. A number of observed data, provided by B. Paczynski, in particular, the indication that GRB happens in the regions of intensive star production [36], tell in favour of the fact that the WR-stars can be the progenitors of GRB.

According to the hypothesis suggested in this paper, the collapse of the WR-star and ejection of the e^+e^- -plasma happens spherically symmetrically. A successful description of the optical afterglow during ~ 200 days [37], obtained in the framework of this hypothesis, proves the spherical symmetry of a number of the γ -bursts. (However, there are some indications of the fact in that jets can appear in some of GRB.)

In conclusion the author would like to thank G.V. Domogazky, A.M. Dyhne, A.A. Logunov, V.S. Imshennik, D.K. Nadezhin, K.A. Postnov for the stimulating interest to this work and valuable remarks. Special thanks to A.M. Cherepashchuk for letting me get to know his work and data on the WR-stars.

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Note added

During a hydrodynamical collapse the explosive burning of a thermonuclear fuel, which leads to local oscillations, could start before its accretion onto a hot neutron star. In this case the oscillation period can be roughly estimated as follows:

$$\tau \simeq 2\pi \sqrt{\frac{\Delta R}{g}},$$

where ΔR is the oscillation amplitude, g is the free fall acceleration onto the inner mass $M(R^*)$, which corresponds to the radius R^* of the explosive burning. Assuming the thermonuclear fuel calorific value of $q \simeq 1$ MeV/nucleon $\simeq 10^{-3}m_N c^2$ and $\Delta R \ll R^*$ one gets

$$g\Delta R \simeq 10^{-3}c^2,$$

and, hence, the τ value is estimated as

$$\tau \simeq 2 \cdot 10^2 \cdot \frac{\Delta R}{c}.$$

For $\tau \simeq 10^{-2}$ s the ΔR value is

$$\Delta R \simeq 1.5 \cdot 10^6 \text{ cm},$$

and the radius of the explosive burning

$$R^* \simeq 1.5 \cdot 10^7 \sqrt{\frac{M(R^*)}{M_\odot}} \text{ cm} .$$

Of course, to check this hypothesis, it is necessary to perform consecutive calculations of the hydrodynamical collapse.

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С.С.Герштейн

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