THEORY OF GAMMA RAY BURSTERS

G.S.Bisnovatyi-Kogan
Space Research Institute
Acad. Sci. USSR, Moscow,
Profsoyuznaja 84/32,
USSR

ABSTRACT. Gamma ray bursters are interpreted as nuclear explosions under the surface of neutron stars. The explosions occur after transportation of the matter with non-equilibrium composition during starquakes in outer layers where the matter becomes unstable and explodes as a result of a developing chain reaction. In the nonequilibrium matter nuclear charge Z decreases with increasing density, contrary to the equilibrium composition. Formation of a shock wave and total energy output are calculated. Parameters of the mighty burst of 5 March 1979 are estimated. Formation of observed lines in different partions of the γ-range and a possible nature of accompanying optical bursts are discussed with the proposed model as a basis.

1. INTRODUCTION

Soon after the discovery of gamma ray bursters [1] about ten very different theories have been proposed for their explanation 3 . The discovery of a pulsar stage in the gamma ray burst of 5 March 1979 [3] was a strong support to the theory related to neutron stars [4,5] . Intensive investigations of gamma-ray bursters in late 70s-early 80s gave vast information about complex temporal and spectral behaviour of gamma-ray bursts, their statistical properties connected with the log N – log S diagram, exact localization on the sky, etc. [6-9] . Despite numerous attempts of optical identification no burster have ever been associated with any stationary optical source [7,8] . Neither radio nor X-ray sources have been found in the error boxes of several well-localized sources *). In this indicates that the neutron stars, responsible for gamma-ray

_____

*) The projection [7]of the 5 March 1979 burster on the edge of SNR N 49 in LMC seems accidental.

bursts are single and very old with moderate $(B \lesssim 10^{10}$ Gs) magnetic fields. The model of bursts from such objects has been developed in [4,5, 10-14] . It is necessary in this model that a neutron star have a nonequilibrium layer of superheavy elements, stable at high densities and unstable at low ones. The transfer of the nonequilibrium matter to low densities must occur during starquakes which are often observed in young neutron stars (Crab and Vela pulsars) and may be very rare in old ones. This may explain almost total absence of recurrence in gamma bursters.

It is impossible now to explain with only one theoretical model all striking features of gamma-ray bursters. We try here to fit only the most important features: the energy supply, short rising time, including formation of γ-lines, emission in hard and soft regions. We give quantitative estimations of this characteristics and several observational predictions. The construction of the model seems to be a hard job , but it could have been enormously harder if the connection with the neutron stars had not been firmly established.

2. FORMATION OF A NONEQUILIBRIUM LAYER AND ITS STRUCTURE

The dense matter may have an Equilibrium Composition only at high temperatures when all possible channels of reactions are open. The channels become shut during cooling so that strictly speaking, the equilibrium in the cold matter (minimum energy state) is impossible. The cold matter composition is always nonequilibrium and depends on the way it reaches the state with given ρ and (low) T.

Two extreme approaches have been considered: 1) contraction of the cold matter [10,15-18] which occurs during the accretion on a neutron star; 2) cooling of the matter at a given density, which occurs after the neutron star is formed.

The contraction of cold matter continues with A=const and decreasing Z up to the neutron drip line where the stripping energy of the neutron is $Q_n = 0$.

Further the contraction leads to cold evaporation of neutrons and decreasing both A and Z along the neutron drip line. Using nuclear parameters from [19] and beginning the compression from iron Fe^{56} we obtain the nucleus

$(A,Z) = (56,16)$ at $\rho = 4,2 \cdot 10^{11}$ g/cm^3 on the neutron drip line. Calculations [18] based on the nuclear matter theory from [20] give nuclei along the neutron drip line

from $(A,Z) = (56,16)$ at $\rho = 5,01 \ 10^{11}$ g/cm^3 up to

$(A,Z) = (32,9)$ at $\rho = 1,41 \cdot 10^{12}$ g/cm^3. As estimated in [18], further contration leads to fusion of the nuclei in picnonuclesr reactions.

Analytical estimations of parameters along the neutron drip line were made in [15,16]. The stripping energy of the proton Q_p :

$$Q_p(A,Z) = (m_{A,Z-1} - m_{A,Z})c^2 + Q_n(A,Z-1) - (m_n - m_p)c^2 \qquad (1)$$

is approximated along the neutron drip line by relation

$$Q_p = 33 - Z/7 \text{ Mev}, \quad A = 4Z, \quad Z \gtrless 6 . \qquad (2)$$

Using consition of beta-equilibrium

$$(m_{A,Z-1} - m_{A,Z})c^2 = \mathcal{E}_{fe} + m_e c^2 \qquad (3)$$

and expression for Fermi-energy $\mathcal{E}_{fe}$, we obtain from (1)-(3) the relation between Z and ρ at $Q_n = 0$:

$$\left[1 + \left(\frac{Z\rho}{10^6 A_o} \right)^{2/3} \right]^{1/2} = 1.96(33 - \frac{Z}{7}) + 2.54, \quad A = 4Z \qquad (4)$$

The compositions along the neutron drip line from (4) are: $(A,Z) = (56,14)$ at $\rho = 10^{12}$ g/cm^3 up to $(A,Z) = (24,6)$ at $\rho = 2.6 \cdot 10^{12}$ g/cm^3.

When cooling proceeds at a constant density much higher A and Z values may be reached [15,16]. They depend on the free-neutron concentration which may be found from the calculations of the kinetic of cooling. Such calculations have not been made, so we suppose that the mass concentration of neutrons is $X_n = \frac{1}{2}$. The final composition along the neutron drip line, using (1)-(3), is [15,16] :

$$Z = 7 \left\{ 33 - 0.511 \left[\left(\frac{\rho}{\mu_{\overset{.}{z}} 10^6} \right)^{2/3} + 1 \right]^{1/2} + 1.293 \right\} ,$$

$$\mu_{\overset{.}{z}} = A/Z(1-X_n); \quad A = 4Z \tag{5}$$

The curve $Z(\rho)$ for $X_n = \frac{1}{2}$ is presented in Fig.1. The value $Q_{p,max}$ is reached for C_{24} when $\rho = \rho_2 = 2.24 \cdot 10^{12} \mathrm{g/cm}^3$. At $\rho = \rho_1 = 1.2 \; 10^{11} \; \mathrm{g/cm}^3$, when $Z = 150$ we have $Z^2/A = Z/4 = 37.5$ with the fission time $\mathcal{T}_f = 3 \cdot 10^7$ years. At densities $\rho < \rho_1$ and $\rho > \rho_2$ new seed nuclei are formed and matter becomes almost equilib- rium. How the nonequilibrium composition forms during co- oling is schematically in shown the Fig. 2 from [16].
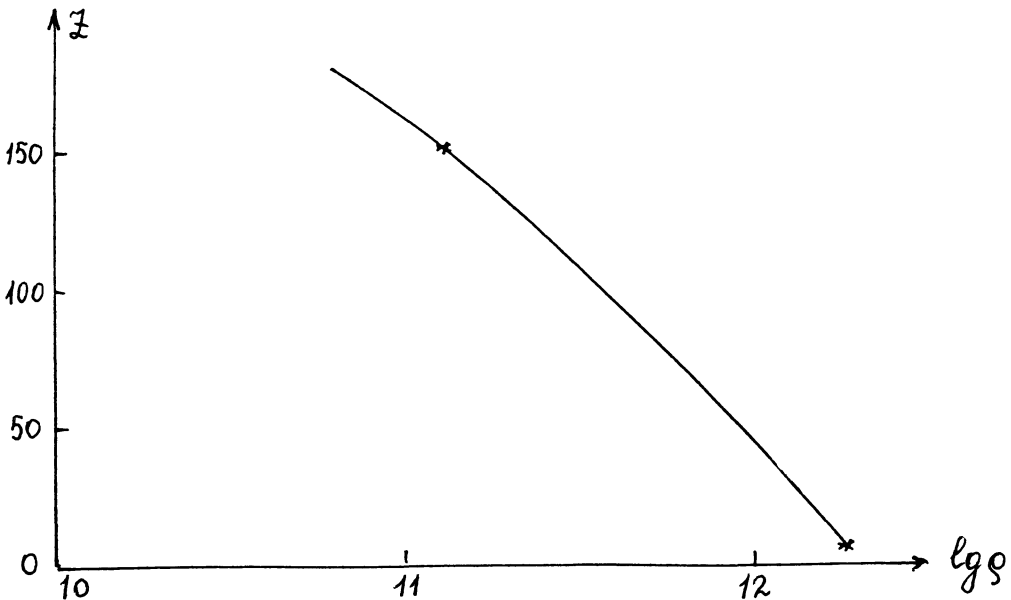

Fig. 1. Composition of neutron star envelope after cooling for $X_n = \frac{1}{2}$, nonequilibrium layer is situated at densities in between the asterisks

Note that the nonequilibrium pressure is ~ 1.5 times higher than the equilibrium one at the same density. The total mass and energy stored in this layer are [16]:
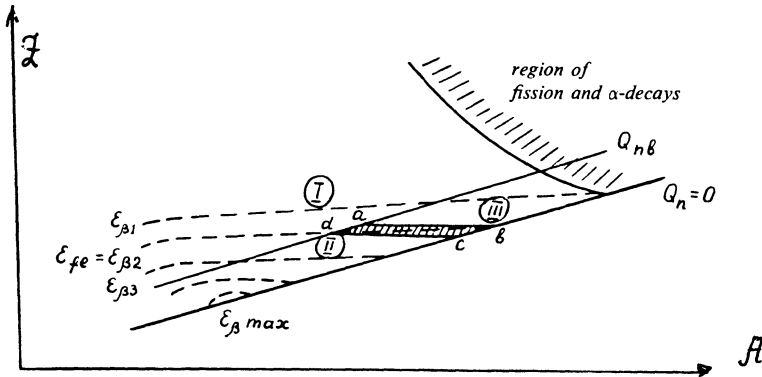
Fig. 2. Formation of non-equilibrium composition; photo-
stripping of neutrons is impossible in region I,
where $Q_n > Q_{nb}$; in region II - $Q_n < Q_{nb}$, $\mathcal{E}_{fe} < \mathcal{E}_\beta$,
and in region III - $Q_n < Q_{nb}$, $\mathcal{E}_{fe} > \mathcal{E}_\beta$. On the dash
lines $\mathcal{E}_\beta = Q_p - Q_n = const$, $\mathcal{E}_{\beta 1} < \mathcal{E}_{\beta 2} < \mathcal{E}_{\beta max}$. Nuc-
lei are situated within the shaded region abcd
at given values of $Q_{nb}(T)$ and $\mathcal{E}_{fe}(\rho)$

$$m_{tot} \simeq 10^{29} \text{ g}, \quad E_{tot} \simeq 3 \cdot 10^{47} \text{ ergs} \quad \text{for } \eta = 3 \cdot 10^{-3} c^2.$$

$$(6)$$

## 3. NUCLEAR EXPLOSION IN THE OUTER LAYERS OF THE NEUTRON STAR ENVELOPE

A very sharp increase of luminosity observed in the 5 March
1979 burst ($\mathcal{T}_r < 2.5 \cdot 10^{-4}$ s [21]) is incompatible with

a thermonuclear explosion of the accreted material, where
the rise times 0.2-1 s and the spectrum explain well the
properties of much softer X-ray bursters identified with
neutron stars in low-mass binary systems [22]. The nuclear
fission beneath the surface of the neutron star leads to
an explosion due to the chain reaction to formmation of
the shoch wave and very sharp increase of luminosity in
good accordance with observations.

a) Development of a chain reaction [13]

Let us suppose that during a starquake the matter from the
layer at $\rho_1 < \rho < \rho_2$ is transported to a lower-density re-

gion $\rho \ll \rho_1$ with the depth $d \ll 10^4$ cm [*]. We now as-
sume for simplicity, that initially the matter consists of
the kind of nuclei (A,Z) which are stable against fissi-

on and α-decay, but not against β^--decay at $\rho \ll 10^{10}$ g/cm^3.
The interaction of these nuclei with rapid neutrons lead
to the formation of slow neutrons, so these nuclei act as
a moderator material. This property of the nuclei (A,Z)
follows from the fact that the nonequilibrium layer at
$\rho_1 < \rho < \rho_2$ is stable even in the presence of chance rapid

neutrons. The nucleus (A,Z) takes part in two reactions:

$$(A,Z) \longrightarrow (A,Z+1) + e^- + \tilde{\gamma} \, ,$$

$$(A,Z) + n_r \longrightarrow (A,Z)^* + n_s \, ,$$
(7)
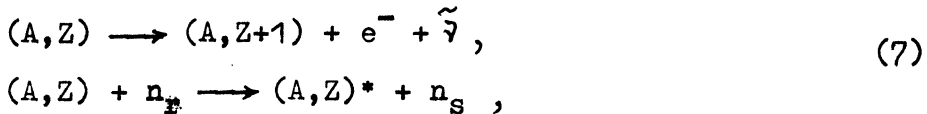
where n_r and n_s are rapid and slow neutrons. Nuclei
$(A,Z+1)$ are stable to the spontaneous fission and α-de-
cay, but unstable to β^--decay and the fission induced by
rapid neutrons. So we have

$$(A, Z+1) \longrightarrow (A,Z+2) + e^- + \tilde{\gamma} \, ,$$

$$(A,Z+1) + n_r \longleftrightarrow (A_1 Z_1) + (A_2 Z_2) + (\alpha +1)n_r \, .$$
(8)
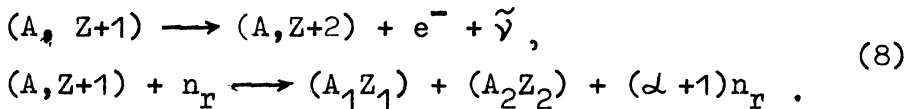
The nucleus $(A,Z+2)$ is unstable to β^--decay and sponta-
neous fission and yields γ rapid neutrons in one fis-
sion:

$$(A,Z+2) \longrightarrow (A,Z+3) + e^- + \tilde{\gamma} \, ,$$

$$(A,Z+2) \longrightarrow (A_3,Z_3) + (A_4,Z_4) + \gamma \, n_r \, .$$
(9)
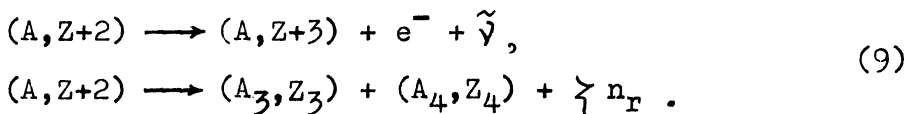
The picture of the development of explosion is as follows.
When bulk of the matter consisting of nuclei (A,Z) comes
to a region with low density $\rho \ll 10^{10}$ g/cm^3, the β^--

decay begins, its probability being W_β^Z. When a suffici-
ent amount of nuclei $(A,Z+1)$ is stored, the absorption
of rapid neutrons by the moderator, characterized by the
average cross-section multiplied by velocity $\langle \sigma V \rangle_z$, be-
comes less intense. The production of rapid neutrons in

[*] This transportation does not need energy supply becau-
se the entropy of a neutron star is close to constant (ze-
ro) which mean that there exists neutral equilibrium to
convective (exchange) motion.

the induced fission (8) of (A,Z+1) characterized by $\langle \sigma v \rangle_{z+1}$ and spontaneous fission (9) of (A,Z+2) which follows immediatly the β^- -decay of (A,Z+1) with probability W^{z+1}, prevails as compared with their absorption, a chain reaction develops and a nuclear exposion occurs.

For approximate values [13] ($V_n \simeq 3 \cdot 10^9$ cm s^{-1} for $E_{n_r} \simeq$ 10 MeV):

$$W^z_\beta \simeq 10^3 \text{ s}^{-1} , \quad W^{z+1}_\beta \simeq 10^2 \text{ s}^{-1} ,$$

$$\langle \sigma v \rangle_z \simeq 10^{-15} \text{ cm}^3 \text{ s}^{-1} , \quad \langle \sigma v \rangle_{z+1} \simeq \frac{1}{3} 10^{-17} \text{cm}^3 \text{ s}^{-1}$$

$$\alpha = \gamma \simeq 3 \tag{10}$$

the chain reaction begins when

$$\frac{X_{Z+1}}{X_Z} \simeq \frac{\langle \sigma v \rangle_z}{\alpha \langle \sigma v \rangle_{z+1}} \simeq 100 \tag{11}$$

and concentration of rapid neutrons X_r is

$$X_r = \frac{\gamma \cdot W^{z+1}_\beta}{(\rho/m_p) \alpha \langle \sigma v \rangle_{z+1}} \simeq 5 \cdot 10^{-15} \text{ for } \rho = 10^6 \text{ g} \cdot \text{cm}^{-3} \tag{12}$$

Chain reaction begins

$$\frac{\ln 100}{W^z_\beta} \simeq 5 \cdot 10^{-3} \text{ s} \tag{13}$$

after the starquake and develops practically instantly, so that

$$\tau_{ch} \ll \tilde{\tau}_h \simeq \frac{d}{V_s} \frac{10^4}{10^{10}} = 10^{-6} \text{ s} \tag{14}$$

The average energy output (essiciency) in the fission of superheavy nuclei may be estimated [15] as $\eta =$ $= 3 \cdot 10^{-3} c^2$ ergs/g . Instant heating leads to the formation of a shock wave which may initiate gamma ray burst when it reaches the surface.

b) Formation and output of the shock wave

Hydrodynamical calculations of the shock wave propagation in the neutron star envelope have been done in [14] in a spherically symmetric approximation. The system of equations in Lagrangian coordinates is:

$$\frac{\partial r}{\partial t} = u, \quad \frac{\partial r}{\partial m} = \frac{1}{4\pi \rho r^2} \; ,$$

$$\frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial p}{\partial m} - \frac{Gm}{r^2} \; , \tag{15}$$

$$\frac{\partial \mathcal{E}}{\partial t} = -4\pi p \frac{\partial(ur^2)}{\partial m} + q(m,t) - f_\nu(\rho,\tau) \; .$$

An approximate equation of state in the analytical form [23] has been used:

$$P = 3.09 \cdot 10^{12} \rho^{5/3} \frac{1+1.59 \cdot 10^{-3} \rho^{1/3}}{(1+3.18 \cdot 10^{-3} \rho^{1/3})^2} + \rho \mathcal{R} T +$$

$$+ \frac{aT^4}{3} \quad dyn/cm^2 \; , \tag{16}$$

$$\mathcal{E} = 4.635 \cdot 10^{12} \rho^{2/3} (1+3.18 \cdot 10^{-3} \rho^{1/3})^{-1} + \frac{3}{2} \mathcal{R} T +$$

$$+ \frac{aT^4}{3} \quad ergs/g \; ,$$

which is valid for $\rho \lesssim 3 \cdot 10^9$ g/cm^3, $\mathcal{R} = k_B/\mu m_p$ – gas constant, $\mu = 1$, a – energy density constant. The neutrino emission rate $f_\nu(\rho,T)$ takes into account URCA processes and interpolates numerical calculations from [24].
    Only the region with $\rho < 3 \cdot 10^9$ g/cm^3 has been considered in calculations. The star is supposed to be initially cold and in static equilibrium:

$$u = 0, \quad \frac{\partial u}{\partial t} = 0, \quad T = 0 \quad at \quad t = 0 \; . \tag{17}$$

    The explosion was characterized by the energy E_{tot}, which was produced very rapidly $t_b \ll t$ in a spherical layer whose upper edge is at a depth h_0 under the surface. The mass of this layer m_b and the depth of its bottom h_1 are determined uniquely by the efficiency η: $m_b = E_{tot}/\eta$. So, in this layer

$$q(m,t) = \frac{\eta}{t_b} \quad , \quad 0 \leqslant t \leqslant t_b \quad ,$$

$$= 0 \qquad \qquad t > t_b \quad , \tag{18}$$

with $t_b \simeq 10^{-8}$ s . At $\quad t = t_b \quad$ the temperature distribution is determined by using (16):

$$\tfrac{3}{2} \mathcal{R} T_b + a\, T_b^4 / \rho = \eta \quad . \tag{19}$$

Typical distributions of parameters at $t=0$ and $t=t_b$ are given in Fig. 3. The results of numerical calculations
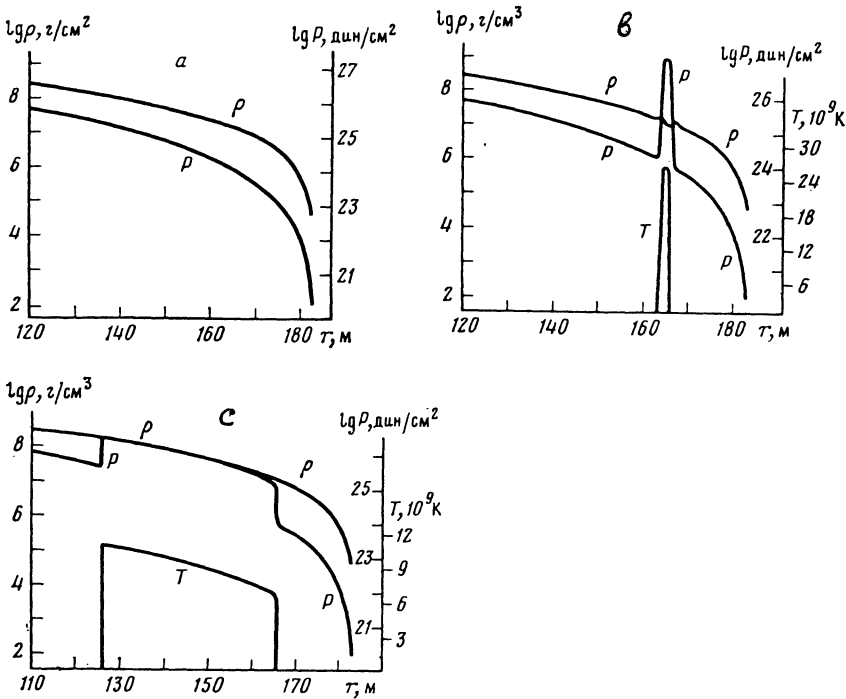

Fig. 3. Density, pressure and temperature distributions
in the envelope of the neutron star with $M=1M_\odot$,
$R=10$ km . The distance r_3 is measured from
the level $\rho = 3 \cdot 10^9$ g/cm^3. a) t=0 with T=0,
b)t=t_b, variant 1 from table 1, c) t=t_b, variant
6 from table 1.

are presented in Table 1 and Fig. 4. The surface tempera-
ture at the moment when the shock wave reaches the surface
with optical depth $\tau = 1$ was estimated in [14], using

Table 1. Explosion parameters in the envelope of the neutron star with $M = 1M_\odot$, $R = 10$ km

N	η/c^2	E_{tot} ergs	h_o-h meters	$m_b/M_\odot$	$M_{hyd}/M_\odot$ (% m_b)	$\dfrac{u_{edge}}{u_p}$
1	0.3	10^{43}	18-20	$1.86 \cdot 10^{-11}$	$8.7 \cdot 10^{-13}$ (4.7)	> 1
2	0.03	10^{43}	18-30	$1.86 \cdot 10^{-10}$	$3.0 \cdot 10^{-14}$ (0.016)	> 1
3	0.008	10^{43}	18-40	$6.94 \cdot 10^{-10}$	$(\lesssim 10^{-3})$	0.64
4	0.008	10^{43}	40-50	$6.94 \cdot 10^{-10}$	$(\lesssim 10^{-3})$	0.86
5	0.003	10^{42}	10-30	$1.86 \cdot 10^{-10}$	$(\lesssim 10^{-5})$	0.34
6	0.003	10^{43}	18-58	$1.86 \cdot 10^{-9}$	$(\lesssim 10^{-5})$	0.34
7	0.003	10^{43}	68-76	$1.86 \cdot 10^{-9}$	$(\lesssim 10^{-5})$	0.61
8	0.003	10^{44}	20-174	$1.86 \cdot 10^{-8}$	$(\lesssim 10^{-5})$	0.36

selfsimilar solution by the method, proposed in [5]

$$p \simeq k_2^2 \rho \, h^{-0.6} \; , \quad \rho \simeq k_1 h^{1.5} \; , \quad u = 0.7 \, k_2 h^{-0.3} \; . \quad (20)$$

Constants k_2 and k_1 are estimated from numerical calculations. Applying (20) at $\tau = \int_0^h \varkappa \rho \, dh = 1$, where numerical calculations failed, we obtain the surface temperature $T_s = 150$ KeV for models in Table 1 with $\eta = 0.003$. This surface temperature leads to supercritical luminosity and strong mass loss. Supposing that the momentum of radiation is transformed into the momentum of matter running away with velocity close to parabolic one

$u_p = (2GM/R)^{1/2} \simeq 0.54 \, c$, we obtain for the total mass loss m_{out} :

$$m_{out} \simeq \frac{\alpha \, E_{tot}}{0.54 c^2} \simeq 2 \cdot 10^{22} \alpha \, (E_{tot}/10^{43}) \qquad g \qquad (21)$$

where $\alpha = 0.5-1$ is part of the energy emitted in the su-
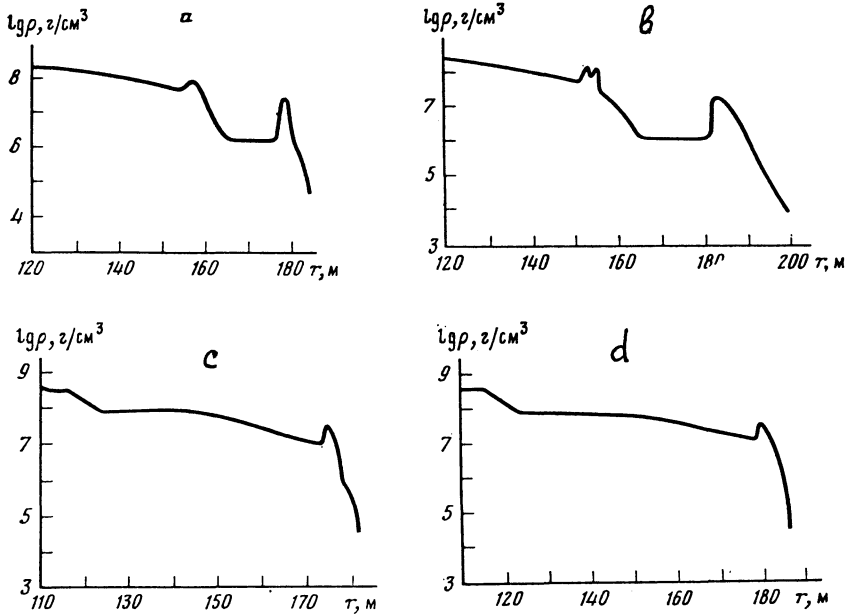
Fig. 4. Density distribution at different moments of the development of the explosion in the star with $M=1M_\odot$, R=10 km. Variant 1 from table 1: a) $t=20t_b$ - before the output of the shock wave to the surface; b) $t=30t_b$ - after the output. Variant 6 from table 1: c) $t = 130t_b$ - before the output; d) $t=160t_b$ after the output

percritical regime. For $\eta = 0.003 \ c^2$ the part of the running-away matter is equal to $\sim 0.007\alpha$ of the exploded one. Note that in real events the diameter of the bulk of exploding matter is equal about its depth h, so the numbers for energy in Table 1 should be multiplied by

$$\frac{h^2}{4\pi R^2} \simeq 10^9 \ / \ (4\pi \cdot 10^{12}) \simeq 10^{-4} \tag{22}$$

for $h = 3 \cdot 10^4$ cm and R = 10 km. The amount of mass ejected by the supercritical wind from (21) is much larger than a hydrodynamical outburst m_{hyd} by the shoch wave in Table 1.

4. MODEL OF THE GAMMA RAY BURST 5 MARCH 1979

The observed flux $Q_\gamma = 1.3 \cdot 10^{-3}$ ergs/cm^2 from this sour-

ce leads to the following total energy outputs for diffe-
rent assumed distances d_{LMC} and d_{Gal} :

$$q_{tot} = 4.5 \cdot 10^{44} \text{ ergs for } d_{LMC} = 55 \text{ kpc}$$

$$(23)$$

$$q_{tot} = 1.5 \cdot 10^{39} \text{ ergs for } d_{Gal} = 100 \text{ pc} .$$

The observed luminosity on the pulsar stage is

$$L_{puls,LMC} = 3.6 \cdot 10^{42} \text{ ergs/s} \gg L_{edd} ,$$

$$(24)$$

$$L_{puls,Gal} = 1.2 \cdot 10^{37} \text{ ergs/s} < L_{edd} .$$

The rotational energy of the neutron star with the obser-
ved period p = 8.1 s is

$$E_{rot} \lesssim \frac{1}{2} I_{max} \Omega^2 \simeq 5 \cdot 10^{44} \text{ ergs} \simeq q_{tot \ LMC} . \quad (25)$$

Having in mind that not more than $0.02 \ E_{rot}$ (energy of
the crust) may be released during a starquake we may exclu-
de the possibility of rotational energy supply in the ca-
se of LMC. The explosion of the nonequilibrium matter of
such a scale seems to be also improbable. The observed
behavior of the burst source on the pulsar stage is ra-
ther regular [3, 21] and cannot be related with strongly
supercritical regime, where violent outbursts of matter
and strong irregularities of luminosity must be expected.
So we adopt the galactical origin of this burst .

The exist-ance of spectral features in this burst
indicates that optical depth $\tau \lesssim 1$ during their for-
mation. We suppose [4,10] that the spectrum of a γ-ray
burst is a mixture of the emission of a hot spot on the
surface of the neutron star and of an expanding cloud
which becomes transparent to γ-radiation at $t \gtrsim t_e$.
Spectral features are forming at the $t = t_0 > t_e$. For
the cloud expanding with velocity $V_c \simeq 0.5 \ c$ and suppo-
sing $\tau_c < 1$ at $t = t_0$ we estimate cloud parameters as:

$$R_c \simeq V_c t_0 \simeq 1.5 \cdot 10^9 \ (\frac{t_0}{0.1c}) ,$$

$$\rho_c \simeq \frac{\mu_e m_p}{R_c \sigma_e} \quad \tau_c \simeq \frac{10^{-8}}{t_{0.1}} \tau_c \quad g/cm^3 , \quad (25)$$

$$M_c = \frac{4\pi}{3}\, \rho_c R_c^3 = 1.4 \cdot 10^{20}\, t_{0.1}^2\, \tau_c \quad g \quad,$$

$$t_{0.1} = t_0/0.1 \quad sec$$

Here we used $\sigma_e = 0.4\, \sigma_T \simeq 2.6 \cdot 10^{-25}$ cm^2 for $E_\gamma \simeq$ 0.6 MeV and $\mu_e = 2.3$. If we suppose that nonthermal emission is generated in the expanding cloud with efficiency $\frac{1}{4}\eta = \frac{1}{4}\, 3 \cdot 10^{-3}$, then we obtain:

$$E_{nonth} = \frac{3 \cdot 10^{-3}}{4}\, M_c\, c^2 \simeq 10^{38} (t_{0.1})^2\, \tau_c \quad ergs \quad . \quad (26)$$

The total energy of the burst is about two orders of magnitude larger and is equal to

$$E_{tot} \simeq 10^{40} t_{0.1}^2\, \tau_c \quad ergs \tag{27}$$

For the integral flux on the Earth $F_c \simeq 1.3 \cdot 10^{-3}$ ergs/cm^2, we estimate the distance as

$$d \simeq (E_{tot}/4\pi\, F_c)^{1/2} \simeq 8 \cdot 10^{20}\, t_{0.1} \tau_c^{1/2}{}_{cm} \simeq 260\, t_{0.1} \tau_c^{1/2}{}_{pc} \tag{28}$$

On the pulsar stage the spectum is well approximated by the radiation of optically thin plasma with T = 4 · 10^{8}K [3], so that the emission region should be represented by a corona on the surface of the neutron star. The existence of a corona may be connected with the mechanical flux from a convective layer in the stellar envelope developed after the explosion, and the magnetic field may be important for mechanical energy transformation into heat, like in the heating of the solar corona.

Let us estimate coronal parameters [11,12] . The density distribution in the isothermal corona is represented by a barometric formula

$$\rho = \rho_0\, e^{-(\mu m_p/kT)(GM/R_{ns}^2)x} = \rho_0\, e^{-(X/113)} \quad . \quad (29)$$

The flux of free-free emission from the unit surface is

equal to

$$F_{cor} = \int_0^\infty 1.4 \cdot 10^{-27} Z^2 \sqrt{T_c} \; n_e n_i dx \approx 8 \cdot 10^{-22} Z \; n_{eo}^2 \qquad (30)$$
$$n_e = Z n_i \qquad\qquad ergs/cm^2 \; s \quad .$$

The value of F_{cor} must be less than a critical Eddington flux F_{Edd}, so

$$F_{cor} = 8 \cdot 10^{-22} Z n_{eo}^2 = \mathcal{E} F_{edd} = \mathcal{E} \, 4 \cdot 10^{24} \frac{\mu_e \, m_p}{G_T} \quad , \qquad (31)$$

$$\mathcal{E} < 1, \quad n_{eo} = 2.8 \cdot 10^{22} \sqrt{\mathcal{E}} \quad , \quad \mu_e = 2.3 \quad .$$

We take $\mathcal{E} \leq 0.1$ so that when compton corrections to the spectrum are neglible [11]. On the pulsar stage, the flux on the Earth l_e is equal to $l_e \approx 10^{-5}$ ergs/cm^{2}s . If about half the neutron star surface is heated, then for $\mathcal{E} = 0.07$, $\mu_e = 2.3$ we have from (31):

$$l_e = \frac{1}{2} \left(\frac{R_{ns}}{d} \right)^2 F_{cor} \; , \; d = \left(\frac{F_{cor}}{2l_e} \right)^{\frac{1}{2}} R_{ns} =$$
$$= 2.6 \cdot 10^{20} \; cm = 85 \; pc \quad . \qquad (32)$$

Comparing (32) with (28) and (27) we have

$$t_{0.1} \tau_c^{\frac{1}{2}} \simeq 1/3 \; , \quad E_{tot} \simeq 10^{39} \; ergs \quad ,$$

$$\tau_c < 1 \implies t_o > 0.033 \; , \qquad (33)$$

$$t_o < 0.2 \; s \implies \tau_c > 0.02 \; .$$

The value of E_{tot} is much less than a total energy reserve of nonequilibrium layer in (6). The qualitative picture of the development of this burst is shown in Fig. 5.
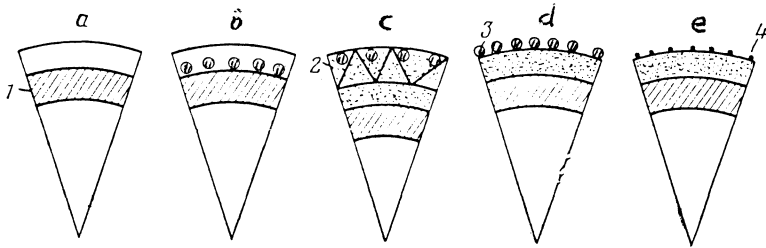
Fig. 5. Schematic picture of gamma-ray burst formation
5 March 1979; a - envelope in static equilibrium,
1 - nonequilibrium layer; b - after starquake, c -
after nuclear explosion, 2 - shock wave, d - ex-
pansion of the cloud (3) and explosions there, e -
pulsar stage, 4 - hot corona

5. SPECTRAL FEATURES IN THE EMISSION OF GAMMA-RAY BURSTS

Several kinds of features have been observed in the spectra
of gamma-ray bursts. The first are emission features in
the hard region which are broad $\Delta E \simeq E$ and have maxima at
$E \simeq 400-500$ KeV, close to the e^+e^- - annihilation line [25]
It was supposed in [25], that these features are emitted
in optically thin not regions, separated from the regions
which emit most of their energy in softer photons. In our
model this region may be an expanding cloud or more probab-
ly a corona on the initial stage of the burst, when its
temperature may be sufficiently high for intense thermal
birth of e^+e^- - pairs.

The second type of features has been observed in a
softer region $E_\gamma = 30-60$ KeV mostly in absorption [26]
and has been interpreted there as cyclotron absorption.
It seems improbable for an old neutron star to have very
high magnetic field $3 \cdot 10^{12} - 10^{13}$ Gs, nesessary for cyc-
lotron spectral features to form in this region. Besides,
such a large field prevents output of hard photons with
$E_\gamma \gtrless 2$ MeV observed in the spectra of bursts. In our mo-
del these features may be naturally interpreted as absorp-
tion lines of very heavy elements with $Z \simeq 55$ in an ex-
panding cloud. These elements are produced in fission of
superheavy nuclei. For example, Ba_{56}^{40}, I_{53} with A =
= 131-135 and Ce_{58} with A = 143,144 are the main ele-
ments produced in fission of U^{235} [27] . The ionization
potential of the last K-electron $I_Z \simeq 13.6 \, Z^2$ eV $\simeq$
42.6 eV for Ba_{56}. In the cloud expanding with V = 0.4 c

the blue shifted absorption line may be located close to
the observed one at 60 KeV. Temporal behaviour of this ab-
sorption feature in some bursts [25] which gradually dis-
sapeared is well explained by the absorption in the expan-
ding cloud, which should disappear when the density in the

cloud becomes small. If iron Fe^{56} is the most abumdant
element in the cloud, then we may expect in some cases
strong absorption in the softer region $E \gtrsim 13$ KeV during
the cloud expansion.

In the hard region $E \gtrsim 1$ MeV spectral features may be
expected which are associated with the emission of excited
nuclei. Most probable is D^2 line with $E_\gamma = 2.2$ MeV .
Such a line may be formed in our model, because free neut-
rons are formed during the fission of superheavy nuclei
[10]. Indications to the presence of this line have been
found in the spectra of the 7 March 1979 burst in some
spectra obtained over short periods $\Delta t \lesssim 1$ sec in the
Soviet-French signe experiment on Venera 11 and 12 probes.

6. OPTICAL EMISSION ACCOMPANYING GAMMA BURST

Intense investigations of the error-box of the 5 March
1979 gamma-ray burst lead to a discovery of optical
flashes which may be connected with gamma ray bursts [28].
The shape of one of these flashes on 8 Feb. 1984 is close
to that of the main burst (Fig. 6). Several weaker recurrent
gamma events have been observed in the same direction [29]
The optical flash may be associated with one of the re-
current rather feeble gamma-ray bursts.

The shape of this optical flash is well interpreted
by the optical emission of the expanding cloud. The emis-
sion prior to the maximum (Fig. 6) may be connected with
a Reyleigh-Jeans region of thermal emission of the cloud
which is opaque in the optical region. The optical emis-
sion after the maximum may be interpreted as free-free
radiation of optically thin iron plasma cloud, irradiated
by the gamma-ray emission of the neutron star. Estimati-
ons made together with A.F.Illarionov, show that optical
emission of the transparant cloud may be about

$5 \cdot 10^{-4}$ times the gamma luminosity of the neutron star.

REFERENCES

1. Klebesadel R., Strong I., Olson R., Astrophys J. Lett.,
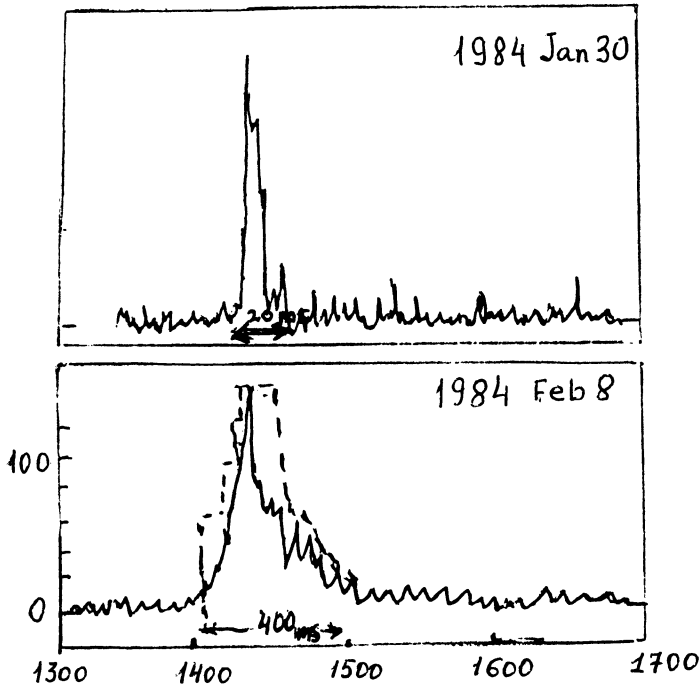   1973, 182, L85.

Fig. 6. Optical flash 8 Feb. 1984 and gamma-ray burst
        5 March 1979 coming from the same region of the
        sky. The times of beginning of both flashes are
        brought into coincide as well as their maxima due
        to choosen luminocity scales

2. Prilutskii O.F., Rozental I.L., Usov V.V., Uspechi Fiz.
   Nauk, 1975, 116, 517.
3. Mazets E.P., Golenetskii S.V., Ilyinskii K.N., Pa-
   nov V.N., Aptekar R.L., Gurjan Yu.A., Sokolova Z.Ya.,
   Charitonova T.V., Pisma Astron. Zh., 1979, 5, 307.
4. Bisnovatyi-Kogan G.S., Gamma-Ray bursts from neutron
   stars, Report on COSPAR/IAU Symposium on "Fast Transi-
   ents in X and gamma-ray astronomy", May 29-31, 1975,
   Varna, Bulgaria; Space Res. Inst. preprint D-203,1975.
5. Bisnovatyi-Kogan G.S., Imshennik V.S., Nadyozhin D.K.,
   Chechetkin V.M. Astrophys. Space Sci., 1975, 35, 23,
6. Mazets E.P. et al. Catalog of cosmic gamma ray bursts
   from the Konus experiment data. Astrophys. Space Sci.,
   1981, vol. 80, N 1.
7. Vedrenne G. Cosmic γ-ray bursts, Phil. Trans. R. Soc.
   Lond. 1981, A301, 645.
8. Hurley K., Adv. Space Res., 1983, 3, 163.
9. Rozental I.L., Usov V.V., Estulin I.V., Uspechi Fiz. Na
   uk, 1983, 140, 97.
10.Bisnovatyi-Kogan G.S.,Chechetkin V.M. Sov. Phys. Usp.,
   1979, 22, 89.

11. Bisnovatyi-Kogan G.S., Chechetkin V.M. Astron. Zh. USSR, 1981, 58, 561.
12. Bisnovatyi-Kogan G.S., Chechetkin V.M. Adv. Space Res. 1981, 1, 153.
13. Bisnovatyi-Kogan G.S., Chechetkin V.M. Astrophys. Space Sci., 1983, 89, 447.
14. Bisnovatyi-Kogan G.S., Blinnikov S.I., Zacharov A.F. Astron. Zh. USSR, 1984, 61, 104.
15. Bisnovatyi-Kogan G.S., Chechetkin V.M. ZhTF, Pisma, 1973, 17, 622.
16. Bisnovatyi-Kogan G.S. , Chechetkin V.M. Astrophys. Space Sci., 1974, 26, 25.
17. Vartanyan Yu.L., Ovakimova N.K. Soobsch . Burakan. Obs. 1976, N 49, p. 87.
18. Sato K. Prog. Theor. Phys. 1979, 62, 957.
19. Grootez H.V., Hilf E.R., Takahashi K., Af. data and nucl. data tables, 1976, 17, 418-427, 476-608.
20. Baym G., Bethe H., Pethick Gh. Nucl. Phys., 1971, A175, 225.
21. Cline T. et al. Astrophys. J. Let. 1980, 237, L1.
22. Joss P., Li F. Astrophys. J., 1980, 238, 287.
23. Bisnovatyi-Kogan G.S., Popov Yu.P., Samochin A.A. Astrophys. Space Sci., 1976, 41, 287.
24. Ivanova L.N., Imshennik V.S., Nadyozhin D.K. Nauch. Inf. Astron. Sov. Acad. Sci. USSR, 1969, 13, 3.
25. Golenetskii S.V. et al. Ioffe Phys.-Tech. Inst. preprint N 959, 1985.
26. Mazets E.P. et al. Ioffe Phys.-Tech. Inst., preprint N 687, 1980.
27. Shirokov Yu.M., Yudin N.P. Nuclear physics, 1980, Nauka, Moscow.
28. Pedersen H. et al. Nature, 1984, 312, 46.

DISCUSSION

E. Liang: You interpret the "cyclotron feature" as due to resonance lines of heavy elements I-Pb. Does this not require an unreasonably high concentration of heavy elements?

G. Bisnovatyi-Kogan: We need about 1% of heavy element to Fe ratio. This is much higher than solar abundance but may be obtainable in the expanding cloud after the fission chain reaction.

K. Hurley: How are the recurrent bursts from the 5 March source generated in this model?

G. Bisnovatyi-Kogan: The recurrent bursts have been observed only from 5 March 1979 gamma-ray burst position and they are at least 10^3 times weaker than it. Maybe, they are connected with residual activity of the neutron star after the strong starquake.

S. Woosley: The weak interaction time scale does not set a limit to the thermonuclear model for γ-ray bursts because helium may burn on a very rapid timescale at high density and temperature. Fryxell and Woosely have shown that a detonation wave will propagate around a neutron star in about a millisecond.

G. Bisnovatyi-Kogan: The helium flashes could explain X-ray bursters and it seems improbable that such different phenomena are produced by the same burning. You need a larger magnetic field for your model, which is prohibited by the observed hard γ-ray photons ($E_\gamma > 2-5$ MeV) which cannot escape from the neutron star with large field.

S. Woosley: What is the recurrence time scale for your model? What sets that time scale?

G. Bisnovatyi-Kogan: The recurrence time is expected to be between approximately 100-1000 years and is determined by the time between subsequent starquakes in old neutron stars.

D. Arnett: In core collapse we consider physical conditions very similar to these you quote: We estimate the relaxation time (to remove nonequilibrium) to be 2×10^{-5} sec. There seems to be a serious disagreement.

G. Binovatyi-Kogan: We consider the stages after formation of the neutron star and subsequent cooling. The nonequilibrium layer is formed after the temperature decreases and become less than $\sim 2 \times 10^9$ K, the time for the reactions between charged particles becomes very large, and the number of seed nuclei remains constant. At densities between $10^{11} - 10^{12}$ g/cm^3 the larger nonequilibrium exists for a very long time.

A. Burrows: Do I understand you to mean that many radio pulsars and, in particular, the Crab and Vela should be γ-ray bursters?

G. Bisnovatyi-Kogan: Crab and Vela must give the γ-ray bursts, but they are very feeble because of their large distances.

A. Burrows: How can matter deep in the crust penetrate all the way to the surface? What is the dynamics?

G. Bisnovatyi-Kogan: The matter of an old neutron star is almost at constant entropy (very small) and so is close to neutral stability relative to convection. The elastic energy released in the starquakes may be enough for convective motion which transports matter from the nonequilibrium layer to smaller densities where it becomes unstable.

S. Kulkarni: I would like you to clarify some points. If I understand you correctly, we ought to see a γ- and optical-burst from any neutron star when it glitches. So are you suggesting that is worthwhile comparing γ-ray burst catalogs and pulsar catalogs? In addition is it worthwhile cross-checking archival optical plates with radio pulsar positions?

G.S. Bisnovatyi-Kogan: That is right. But radio pulsars are too far away, so there is little chance of finding something.