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COSMOLOGICAL γ-RAY BURSTS FROM COLLAPSE OF A NEUTRON STAR INDUCED BY A PRIMORDIAL BLACK HOLE

E.V.Derishev[1], *V.V.Kocharovsky*[2], *Vl.V.Kocharovsky*[2]

Institute of Applied Physics RAS
603600 Nizhny Novgorod, Russia

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We outline a detailed analysis of a novel scenario, in which gamma-ray bursts are of intergalactic origin and arise from induced collapse of an isolated neutron star triggered by a primordial black hole. The energy released from the phase transition of accreted nucleon matter into the quark-gluon plasma is transferred by degenerate neutrinos to the star's surface, where neutrinos annihilate into an electron-positron plasma and produce an inverted temperature layer that preserves a fireball from undue baryonic pollution. Possible observational tests include the absence of apparent cosmological time dilation, primary location of γ-ray bursts outside of galaxies, specific shape of $\log N - \log S$ dependence with a large peak near redshift $z \sim 10$, emission of $\sim 10^{-3}$ of total energy in the form of 100 GeV photons, bimodal distribution of durations, very weak accompanying pulse of gravitational radiation, etc.

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Introduction. The problem of γ-ray bursts (GRBs) (see, e.g., [1, 2]) remains a chalenging controversial issue of modern astrophysics, though a general agreement that they are of cosmological origin seems to appear. If so, the burst rate for the whole Universe is at least 800 events per year (only one third of them is observed). Each GRB lasts for 0.1-100 s ($\sim$ 10 s on average) and has a broad spectrum with maximum energy emitted in 200 keV region.

Many suggestions were made to explain the subsecond release of a huge amount of energy $\gtrsim 10^{51}$ ergs in the proper spectral range (e.g., [3, 4]). It should be noted that for two bursts, GRB971214 and GRB990123, the estimated value of energy release approaches 10^{54} ergs assuming isotropic emission. Since it is very divergent from the average value ($10^{51} - 10^{52}$ ergs) inferred from the analysis of $\log N - \log S$ curve [5], these bursts may be of different origin.

At present, the bulk of theories involves the stellar progenitors for GRBs, and there are intrinsic difficulties in scenarios of this kind [6]. The most subtle one is inevitable baryonic pollution of a hot electron-positron (e^-e^+) relativistic wind (fireball), whereas the lower limit on the final Lorentz factor of plasma outflow (equal to the inverse initial fraction of baryons' rest energy to the energy of thermal plasma) is $\Gamma \gtrsim 100$ [7].

In standard fireball models there is another problem, related to the presence of a powerful neutron stream [8]. The latter makes impossible bursts shorter than the apparent lifetime of neutrons, $\sim$ 5 s in usual models. To get rid of the problem one needs a fireball with very high Lorentz factor $\sim 10^3$, allowing velocity decoupling between the proton and neutron flows.

Stellar cosmological models place bursters inside galaxies, and this constitutes two more problems: few bright galaxies observed in the error boxes of bright GRBs [9]

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[1] e-mail: derishev@appl.sci-nnov.ru

[2] e-mail: kochar@appl.sci-nnov.ru

and null result of the search for cosmological time dilation in the subsets of bright and dim bursts [10]. Both problems could be avoided if sources are predominantly located in the intergalactic space. In this case expansion of the Universe affects not only the observed GRB duration, but also the shock deceleration time in the local frame (due to time dependence of the intergalactic gas density). Two changes follow the opposite laws inversely proportional to each other, so that no apparent time dilation is expected.

In this paper we propose a novel scenario for cosmological GRBs, which can resolve these difficulties. It is based on the collapse of an isolated neutron star (NS) interacting with a primordial black hole (PBH). PBHs, another great enigma of contemporary cosmology, are relics of the early Universe, and their existence is related to large metric and density perturbations at that stage. The initial mass distribution of PBHs depends on the spectrum of primordial fluctuations [11], and in the scale-invariant Harrison – Zeldovich case $dn/dm \propto m^{-5/2}$. Those black holes which were lighter than $m_* \simeq 5 \cdot 10^{14}$g became extinct due to quantum evaporation. So, PBHs having masses around m_* are the most abundant now, but their total number is unknown and the best upper limit on average density, derived from studying cosmic ray background [12], is $n_0 < 10^4$ pc^{-3}. The MHD plasma regime of PBH evaporation leads to GRBs, but they constitute a small fraction of all bursts [13].

The new scenario not only explains GRBs, but also provides a link between them and PBHs. We expect that it will become a sensitive indicator for PBHs' existence, 3 – 5 orders of magnitude more powerful than the present day tests.

We investigated the model thoroughly, but in a short Letter is not possible to present it in detail. So, we give a short description of the whole scenario and focus on the most essential physical point – the neutrino transfer from the quark-nucleon interface. In conclusion we propose accessible observational tests that are capable to distinguish an actual GRB model.

The induced collapse scenario. During contraction of a protostellar cloud, some PBHs along with other dark matter species are gravitationally captured in the cloud, and a valuable fraction of PBHs resides inside a newly born star. After the supernova explosion, PBHs with orbits close to the collapsed core remain bound to it [6]. The lifetime of such orbits is limited by gravitational emission and tidal deceleration, and we find that there are enough PBHs that will fall inside NSs within the age of the Universe.

The efficiency of the capturing process crucially depends on the dispersion of PBHs' velocities [14], which took the smallest value just before galaxies were formed. Given the protostellar ($\rho_* \sim 10^{-23}$ g/cm^3) and presupernova core ($\rho_c \sim 10^8$ g/cm^3) densities, we estimate the probability that a NS becomes a GRB source:

$$P_{GRB} \simeq 0.3 \left(\frac{R_i}{R_0}\right) \left(\frac{R_i}{R_*}\right)^3 \frac{\Omega_{PBH}}{\Omega_b} \frac{M_{NS}}{m_*}. \qquad (1)$$

Here $R_i = R_c(\rho_c/\rho_*)^{1/4}$ is a radius of the PBH orbit just after trapping in the protostellar cloud, $R_c \simeq 3 \cdot 10^8$cm a radius of the core, R_* a radius of part of the protostellar cloud with $M \simeq 1.5 M_\odot$, Ω_b and Ω_{PBH} are the mass fractions of baryons and PBHs. The probability must be about few per cent to explain the present-day GRB rate (assuming that $\sim 30\%$ of all bursts are actually observed), so we estimate $\Omega_{PBH} \sim 2 - 5 \cdot 10^{-8}\Omega_b \sim 10^{-9}$, an order of magnitude less than the current upper limit. Small-scale clastering of dark matter prior to the formation of first stars [15] may significantly increase the probability of PBH capture.

Thus, almost all the progenitors should belong to the pregalactic population of stars [16]. These early Population III stars have been captured later by forming galaxies, but NSs are born with a kick velocity of several hundreed km/s, which in many cases is sufficient to escape gravitation of a nearby protogalaxy. Therefore, GRBs have predominantly intergalactic origin.

The fall-down time of PBH plotted as a function of its periastron distance steeply rises by orders of magnitude when this distance changes by less than 10% crossing the radius of NS. As a result, PBHs which induce GRBs are spread over fall-down times in such a manner that there is a peak which traces the formation of Population III stars. PBHs on orbits passing through NSs were swallowed almost immediately at the redshift $z \sim 10$ and gave rise to a distinct population of GRBs. More than 90% of all PBH-NS binaries ever formed have not produced GRBs yet. They will give rise to future bursts with steadily decreasing rate.

Decelerated by tidal friction, PBH settles at rest in the centre of NS, establishing almost stationary infall of nucleons. A moderate compression applied to dense nucleon matter causes its transition into quark-gluon plasma at the density $\sim (1-2)\cdot 10^{15}\,\mathrm{cm}^{-3}$ [17]. The latter occurs at a distance $10 - 100 r_g$ (r_g is the radius of event horizon for a central black hole), depending on the actual conditions in the NS core. Close to the event horizon the accretion flow consists of ultrarelativistic particles only (quarks, gluons, photons, etc.) and has velocity of sound equal to $c/\sqrt{3}$, so that the mass growth rate of black hole is $\dot{m} \simeq 6\sqrt{3}\pi\rho_n r_g^2 c$, where ρ_n is an undisturbed density of nucleon matter. According to this explosive instability equation, the time before the final implosion, $\tau_{\rm im} \simeq$ $\simeq 4\cdot 10^6\,(m_*/m)$ years, is small in comparison with the age of the Universe for $m \sim m_*$. During the whole latent period of PBH – triggered GRB, excluding the last 30 s, no more than 0.1 per cent of the total energy is released.

Nucleons, destroyed under the extreme pressure in the accretion flow, produce a primary plasma consisting of u-quarks and approximately the double number of d-quarks, while the equilibrium composition is made of roughly equal numbers of u-, d-, and s-quarks. It is the energy released in $d \to s$ transition that heats the quark-gluon plasma and powers the burst through neutrino emission. The plasma beneath the phase transition boundary is heated up to $\simeq 50$ MeV, as can be obtained by equating its thermal energy and the energy difference between initial and final compositions. The outer part of the star remains cold and neutrinos and antineutrinos form a degenerate gas with low effective scattering cross-section. Reactions $\nu\bar{\nu} \to \pi^0\gamma$ and $\nu\bar{\nu} \to 3\gamma$ do not take place due to high energy threshold in the first case and small cross-section in the second case. So, neutrinos do not annihilate until they reach the surface layer of NS where the Fermi level of electrons is low enough to permit the process $\nu\bar{\nu} \to e^+e^-$. The role of three-particle processes is small in comparison with elastic scattering. The latter alone deposits inside NS an amount of energy which would be sufficient to heat the entire star up to 10 MeV, if this thermal energy were not advected by the accretion flow into the black hole. Thanks to the effect of advection, a hot nucleon matter is confined in a thin shell ($\lesssim 0.3\,\mathrm{km}$) around the quark core.

The main annihilation process $\nu\bar{\nu} \to e^+e^-$ begins at a depth 0.5-1 km, where neutrino gas is degenerate, and it takes some time – and distance – to heat the flow to the temperature which corresponds to the conversion of $\simeq 50\%$ of the neutrinos' energy to the energy of thermal $e^+ - e^-$ plasma. As a result, an inverted temperature layer is formed, that overlaps the region where the e^-e^+-wind begins. To get into this wind, baryons have to pass along positive temperature gradient ∇T, where the radiation energy density increases as T^4 while the mass density decreases. Under such conditions the velocity of baryon flow in the sonic point, $[(\partial p/\partial r)/(\partial\rho/\partial r)]^{1/2}$, is many times smaller than the adiabatic velocity of sound for the case when radiation pressure dominates. Since the density at the sonic point is completely defined by neutrino luminosity, the mass ejection rate in the presence of the inverted temperature layer is much smaller, reducing considerably the baryon pollution of the fireball. The Lorentz factor of an outflow in this case may reach several thousands and is limited by the total mass of nucleons laying above the sonic point.

After this stage our scenario joins the standard fireball models assuming formation of a shock in the surrounding medium, but with the principal modification dictated by the ultrarelativistic neutron flow which carries as much energy as usually considered proton-electron flow [8]. Depending on parameters, the neutron flow may decouple from proton one or may not, so that the cosmological GRBs have bimodal distribution of durations. Decoupling may lead to multi-peaked lightcurves [18] and causes the pion production in inelastic proton-neutron collisions. The latter results in the emission of $\sim 10^{-3}$ fraction of the total GRB energy in the form of energetic quanta originated from the decay of neutral pions and blueshifted to ~ 100 GeV.

Neutrino transfer. Now let us detail the energy transfer from the hot quark-gluon plasma in the NS core to the surface of star. In the GRB case a transfer time is much less than an induced collapse one. So, the neutrino flow is quasi-stationary and the pressure gradient is equal to the rate of momentum density losses. In the case of spherical symmetry this gives

$$\frac{d\mu}{dR} = -\frac{3}{16\pi}\sigma_0 N_n \Sigma \lambda_c^2 h f, \tag{2}$$

where μ is the neutrino chemical potential, $\sigma_0 \simeq 1.8\cdot 10^{-44}\mathrm{cm}^2$, N_n the neutron density, $\lambda_c = h/m_e c$ the Compton wavelength of the electron, h the Planck constant, and f the neutrino flux density. The effective cross-section for scattering of degenerate neutrinos $\Sigma = (2m_e c^2/\mu)^2\sigma_{eff}/\sigma_0$ has the thermal component [19]

$$\Sigma_T = \frac{1+2g_a^2}{4}\frac{\chi}{\mu}\frac{m_n c}{p_F^n}, \quad g_a \simeq 1.254, \tag{3}$$

where $\chi = \pi^2 T^2/4\varepsilon_F^n$ is thermal energy per neutron, m_n the neutron mass, ε_F^n and p_F^n are the Fermi energy and momentum of neutrons ($T \ll \mu, \varepsilon_F^n$), and the non-thermal component

$$\Sigma_N = 0.24\left(\frac{m_n c}{p_F^n}\right)^2 \frac{\mu}{p_F^n c}\left(\frac{\delta}{\mu}\right)^2, \quad \delta \ll \mu, \tag{4}$$

which may be easily calculated in the limit of heavy neutrons and zero temperature. Here δ is a dipole moment of the deviation of neutrino Fermi surface $\varepsilon_F^\nu = \mu + \delta\cos\theta$ from the equilibrium level due to non-zero flux. In the case of interest both thermal and non-thermal parts are small ($\sigma_{eff} \ll \sigma_0$), and the total value Σ is simply their sum.

Eq. (2) with the values (3) and (4) must be accompanied by two more continuity equations for functions f and χ. For simplicity we assume $N_n =$ const and constant ratio of the radius of quark-gluon core to the radius of central black hole, $q = R_{in}/r_g$. Next, we involve the condition of zero neutrino losses, taking into account that their total flux differs at different radii due to non-zero value of derivative $\partial\mu/\partial t$, i.e., $dR_{in}/dt \neq 0$. This provides an equation for the flux f, the same for all six types of particles (ν_e, ν_μ, ν_τ and antiparticles) as far as they are considered massless.

On the way outside neutrinos remain degenerate with a temperature equal to that of local nucleon matter since any deviation from equilibrium causes rather strong scattering and energy transfer from neutrinos to neutrons. Balancing the thermal neutron energy flux $v_n N_n \chi$ and all neutrino energy fluxes $6\mu f$, where v_n is a fall-down velocity of nucleon matter, yields the last equation for $\chi(R)$.

In both equations we replace the time derivative $\partial/\partial t$ by $-Rr_g^{-1}(qdr_g/dt)\partial/\partial R$, that implies a self-similar scaling of profiles of μ and χ with increasing $R_{in}(t)$. This approximation does not affect significantly the numerical results, but reduces the problem to the system of three ordinary differential equations. The boundary conditions are as follows: $\mu = \mu_{in}$ at $R = R_{in}$, $\chi = 0$ and $f = k_{tr}(4\pi/3)(\mu/hc)^3 c/4$ at the NS surface $R \simeq R_{NS}$. Here a factor $k_{tr} < 1$ includes all possible opacities as compared with the free-streaming case $k_{tr} = 1$. For definiteness we take $\mu_{in} = 80$ MeV though results are not very sensitive to this value.

We have solved the neutrino transfer equations numerically and found that a hot nucleon matter with $T \sim 10$ MeV is localized within several hundreds of meters above the emitting quark surface, while the rest of NS remains cold, $T < 1$ MeV, allowing neutrino to escape almost freely; at such a temperature $\Sigma_N > \Sigma_T$. The final neutrino pulse has duration ~ 1 ms and typical neutrino energies $25-35$ MeV. Altogether, neutrinos provide $\sim 10^{51}$ erg in the form of relativistic electron-positron outflow. It should be noted that due to gravitational lensing some bursts may have apparent energy tens and hundreds times larger; this problem will be considered elsewhere.

Conclusion. We introduce the new kind of astrophysical objects, the PBH-NS binary, which arises naturally from Population III stars in pregalactic epoch. The evolution of such a binary leads to the induced collapse of NS, which we suggest as a source for cosmological GRBs.

The novel scenario can resolve many problems typical for cosmological models of GRBs, including the absence of time dilation, lack of large host galaxies, and small baryonic pollution of the fireball. The latter is possible thanks to the extraordinary physical conditions in collapsing NS, where the hot neutrino-emitting quark core and the region of efficient neutrino annihilation are separated by a layer of cold and hence transparent neutron matter. Under these conditions, an inverted temperature layer in the e^-e^+-plasma outflow is formed which serves as a barrier for baryons.

The induced collapse scenario gives several specific predictions. The simplest one to observe is a large peak near $z \sim 10$ corresponding to the first population of bursts and containing about a half of all GRBs, which took place so far. Then, the bimodal distribution of measured durations with a crossover at the value ~ 5 s should exist due to decoupling of the neutron and proton flows. We also suggest that ground-based observations of GRBs in 100-GeV range could give an opportunity to reveal physical conditions directly in a fireball, providing us with a new standard candle. Such observations are already within the sensitivity of modern instruments, but require at least 30° effective field of view to ensure one detection per year, taking into account 10% duty cycle for such telescopes. Finally, a very weak pulse of gravitational radiation is expected in our scenario, contrary to the model of coalescing NS binary.

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