QCD AGAINST BLACK HOLES OF STELLAR MASS *

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Abstract

In course of the consolidation of nucleon (neutron) spacing inside a compact star, two key factors are expected to come into play side by side: the lack of self-stabilization against shutting into black hole (BH) and forthcoming phase transition - color deconfinement and QCD-vacuum reconstruction - within the nuclear matter the star is composed of. These phenomena bring the star to evolve in the quite different (opposite) ways and should be taken into account at once, as the gravitational compression is considered. Under the above transition, which is expected to occur within any super-massive neutron star (NS), the hadronic-phase (HPh) vacuum - a coherent state of gluon- and chiral $q\bar{q}$-condensates - turns, first near the star center, into the "empty" (perturbation) subhadronic-phase (SHPh) one and, thus, pre-existing (very high) vacuum pressure falls there down rather abruptly; as a result, the "cold" star starts collapsing almost freely into the new vacuum. If the stellar mass is sufficiently large, then this implosion is shown to result in an enormous heating within the star central domain (up to a temperature about 100-200 MeV or, maybe, even higher), what makes the pressure from within to grow up, predominantly due to degeneracy breaking and multiple $q\bar{q}$-pair production. Thus, a "flaming wall" could arise, which withstands the further collapsing and brings the star off the irrevocable shutting into BH. Instead, the star either forms a transient quasi-steady state (just the case of relatively low star mass) and, losing its mass, evolves gradually into the "normal" steady NS, or is doomed for self-liquidation in full (at higher masses).

* This is mainly the updated version of ref. [7] which is, in particular, free from some unnecessary assumptions.
Two (incompatible) mechanisms underlying possible instability of a supermassive compact star are confronted below. Once it has arisen, they bring the star to evolve in absolutely alternative ways: the first (gravitationally-motivated) one, which is rather familiar, "pushes" it into a BH, whereas the second (QCD-motivated) one implies HPh $\rightarrow$ SHPh transition within the nuclear matter (it is considered here in more detail) and, if activated in advance, "seeks" to prevent it from approaching the BH horizon. In what follows, some indicative reasonings in favor of the BH-eliminating scenario are put forward.

0.1 Phase transition in nuclear medium

The main peculiarity of QCD is that, at non-extremal conditions (not very high pressure and/or temperature), the vacuum state is composed of the quark-gluon condensate of high (negative) energy density, $\varepsilon_{\text{vac}}^0 \simeq -5 \times 10^{-3}\text{GeV}^4$, which shows itself up evidently in a number of elementary particle interactions $[1, 2, 3, 4]$, and, hence, of the same modulo (but positive) pressure, $P_{\text{vac}}^0 = -\varepsilon_{\text{vac}}^0$. One can also express this fact by the statement that the QCD Hamiltonian is nearly diagonalized with the following set of eigenstates: vacuum condensate (the necessary entity) plus any possible configurations of nucleons and other hadrons which refer to a given baryon number $B$. The accent is made here on the word "nearly", which emphasizes the negligibility of the residual interaction between the real particles and vacuum condensate under consideration of macroscopical (thermodynamical) processes at the "ordinary" conditions, which are realized, actually, within any rarefied media - up to the within of the steady neutron stars (with masses $M_{\text{NS}}$ below the observed upper limit, $M_{\text{NS}} \simeq 2M_\odot$). To this extent, the vacuum condensate may be considered "a spectator", which marks the zero-energy (and pressure) level. However, this idealization ceases to be physically relevant, when the gravitational compression makes the nuclear medium, first of all near the star center, sufficiently dense: then, two entities - the condensate and substance $\mathbb{1}$ - start to affect each other considerably and destructively. As a result, the vacuum condensate is no longer being a spectator, in the end it vanishes as well as the nucleon mass (the nucleons disintegrate into the massless quarks), and the eigenstates of QCD Hamiltonian become the proper configurations of colored particles - deconfined quarks and gluons. In other words, the nuclear matter transforms into SHPh. This "metamorphosis" is necessarily to be taken into account as the evolution of a NS of ultraboundary mass ($M_{\text{NS}} \geq \overline{M}_{\text{NS}}$) is considered.

$^1$For brevity, this term is addressed to everything, except of the vacuum condensate itself.
The key question is: whether some conditions exist which allow the NS nuclear matter to transform from HPh to SHPh without losing stability? In other words, is there a way of passing the interphase boundary (layer) without undergoing an enormous heating up? If yes, then no objections were, most probably, remained in the eyeshot against the statement that any sufficiently massive NS must finally shut into a BH\(^2\). However, according to the reasons given below, one has to say: No - the HPh $\rightarrow$ SHPh transition must show up certain unremovable explosion features [5, 6, 7].

Physical motivation for this choice is, actually, quite simple - it is based on the crucial difference between EoSs for substance and vacuum: the former one is, evidently, $P \leq \varepsilon/3$, whereas the latter one is much harder, $P_{\text{vac}} = -\varepsilon_{\text{vac}}$. Since the NS periphery consists of a nuclear matter in (still relatively rarefied) HPh, the total (vacuum + substance) pressure there is expected to be slightly higher than that inside the vacuum alone, $P^0_{\text{vac}} = |\varepsilon^0_{\text{vac}}|$. Obviously, it cannot be lower near the (not collapsing) star center. Consequently, if the transition into SHPh (with empty vacuum) occurred there, then the substance energy density (now it becomes the total one) is, wittingly, higher than $3|\varepsilon^0_{\text{vac}}|$. Meanwhile, near the outside of the phase transition boundary (where HPh is still retained!), the substance energy density, in any case, may not exceed that of the closely-packed nucleon (neutron) medium, because, otherwise, the particle wave functions would overlap so much that the individual nucleons lose their identity and may no longer confine the quarks they were constructed from before. That is why $\varepsilon \leq \varepsilon_n \simeq |\varepsilon^0_{\text{vac}}|$ there, $\varepsilon_n$ being the mean energy (mass) density within an isolated neutron. Thus, the phase transition under consideration is definitely associated with, at least, tripling the substance energy density. The only reason for such a sharp enhancement seems to be very fast heating the medium which is followed by degeneration breaking and multiple production of $q\bar{q}$-pairs and gluons.

One can easily suggest the qualitative dynamics of this transformation: as the color charges are getting randomly unleashed, they start to violate the long-range correlations in color field, which are responsible for vacuum condensate appearance; the condensate suffers of damages\(^5\) and its pressure diminishes (the EoS of the entire substance-vacuum

\(^2\)Actually, namely this logical sequence is meant when the OTO prediction of the "imminent" existence of stellar mass BH’s is declared.

\(^3\)By the way, within the framework of the Bag model, namely the pressure $P^0_{\text{vac}}$ is responsible for making such the nucleons (and other baryons) as they are really.

\(^4\)That is tunneling (percolation), what may, probably, result effectively in color deconfinement somewhat earlier.

\(^5\)One can say, figuratively, that the energy necessary for the condensate destruction is mainly taken at the price of vanishing of nucleon masses. This indicates once more the deep interconnection between the
configuration softens); that is why the gravitational collapse is accelerating which completes the condensate destruction and makes the nuclear substance to heat up strongly, initially near the star center, enforcing it to transform into non-degenerate state of SHPh, as a result the pressure of the substance there being increased again. Then, the collapse may stop and even turn into a turbulent swelling, unless the BH horizon had time to emerge before in course of star compression. In what follows, our goal is to show that, actually, there is not enough time for it to do. But firstly, some simple estimates are made of how the ultraboundary mass, $M_{NS} > M_{NS}$ and corresponding radius $r$ of the central domain taken by SHPh are interrelated.

For brevity, in what follows, the SHPh-domain hot quark-gluon plasma (QGP) is referred a nearly perfect gas, which consists of the unremovable "primordial" quarks (carrying the net baryon-over-antibaryon surplus) as well as of the multiply produced gluons and $q\bar{q}$-pairs, baryonic chemical potential $\mu_B$ thus tending to zero. If the QGP domain is much less than the total star volume, then the obvious energy-conservation equation reads:

$$-AG \frac{M_{NS}^2}{R_{NS}^2} dR_{NS} \simeq 4\pi \sigma_{QGP} \langle T^4 \rangle (1 + \frac{\left|\varepsilon^0_{vac}\right| - \varepsilon_n}{\sigma_{QGP} \langle T^4 \rangle}) r^2 dr,$$

where on the left-hand side stands the work made by the gravitational field ($M_{NS}$ and $R_{NS}$ are the NS mass and its radius, respectively, and the value of coefficient $A$ is confined in between of its non-relativistic and ultra-relativistic limits, $\frac{6}{7} \leq A \leq \frac{3}{2}$), whereas on the right-hand side stands the energy increase within the central QGP domain of a radius $r \ll R_{NS}$ and mean temperature $\langle T^4 \rangle$,

$$\sigma_{QGP} = \frac{\pi^2}{30}[2 \times 8 + 2 \times 3 \times 2 \times (2 \div 3) \times \frac{7}{8} + (12 \div 16)]$$

being the weight factor of (2 ÷ 3)-flavor QGP (8 gluons of spin 1 and (3 + \bar{3}) colored quarks of spin 1/2, plus photon and lepton contribution (the last item)). In the accordance真空凝聚态和中子质量在HPh.

6In this connection, one has to point out that thermal neutrinos get essentially stuck at the relevant densities of nuclear matter and, therefore, the energy transport towards the star outside is an extremely slow process (a few hours vs a typical hydrodynamic-time scale, which is, probably, of some fractions of a second).

7It is just the above-mentioned "competition to stay ahead" between the two types of instabilities.

8The direct lattice MC simulations have shown that, in this case, the thermodynamics of the real subhadronic medium mimics properties of such a gas within the accuracy of 20%. Thus, the reasoning we put forward below keeps valid anyway.

9Below, we put $A = 1$, since, in fact, the ultra-relativistic limit is rather inaccessible for the HPh-medium. For the same reason, the eq.(1) also neglects the role of particle pressure.

10Some numerical lift results from the fact that the temperature (see below) and $s\bar{s}$- and $\mu^+\mu^-$-pair masses
with what was mentioned above, the inequality

$$\sigma_{QGP}\langle T^4 \rangle \geq 3|\varepsilon^0_{\text{vac}}|$$  \hspace{1cm} (2)

should take place, wherefrom one can find a lower limit for the mean QGP temperature:

$$\langle T^4 \rangle^{1/4} \geq 160\text{MeV}$$  \hspace{1cm} (3)

This temperature is, at least, about 20-30 times higher than typical temperatures of supernova explosions and, therefore, of the neutron medium outside the SHPh. Thus, the hydrodynamic (fast process) balance can be achieved (if it ever possible) only at the cost of an enormous thermal disbalance. It is worth mentioning here an encouraging correlation between the above estimate and result of well known lattice MC simulation [8], which indicates, at $\mu_B = 0$, the HPh $\rightarrow$ SHPh crossover within the temperature range $140\text{MeV} \leq T \leq 200\text{MeV}$.

Being combined, the relations (2) and $\varepsilon_n \simeq |\varepsilon^0_{\text{vac}}|$ suggest that one can neglect the second term in the brackets on the right-hand side of eq.(1) \footnote{Anyway, this level of accuracy is suitable in the relevant estimates.}. Thus, integrating eq.(1), one obtains

$$GM_{NS}^2R_{NS} = \simeq \frac{4\pi}{3}\sigma_{QGP}\langle T^4 \rangle r^3 + C,$$  \hspace{1cm} (4)

where $C$ is defined by $\overline{M_{NS}}$ - the value of mass upper limit for the really steady ("cold" everywhere, i.e., $r = 0$) NSs: $C \simeq (0.5 \div 1)M_\odot$ for $\overline{M_{NS}} \simeq (1.5 \div 2.5)M_\odot$ and $R_{NS} \simeq (8 \div 10)$ km, respectively \footnote{The current observations favor definitely the lower of these estimates.}. Of course, the transient "quasi-steady" heterogenic mode of a high-mass NS nuclear medium, described by eq.(4), could be thought as physically realizable, only if $r \ll R_{NS}$, thus HPh $\rightarrow$ SHPh transition being not too violent (i.e., if the temperature profile is not too sharp \footnote{12}). Then, it seems sensible to imagine a rather quiet combustion within the supermassive NS which does not turn into detonation in full. This process is, undoubtedly, accompanied by some eruptions of star substance and/or gamma bursts, both being the more powerful the more noticeable is the difference $(M_{NS} - \overline{M_{NS}})$; this "volcano activity" results in a diminishing of star mass and is expired as $M_{NS}$ approaches $\overline{M_{NS}}$. At still larger initial values of $M_{NS}$, the eq.(4) asks formally for $r \simeq R$, but it means nothing else than the fact that the very approximation adopted ceases to be admissible. Instead, may occur of the same order, thus the relevant freedom degrees being only half-alive. What is, principally, more essential is that, unlike the QGP-fireball produced in heavy ion collisions, the photons and leptons participate now on an equal with quarks and gluons in the establishing of an equilibrium state.
one can reasonably expect that no room remains now for the achievement of a transient hydrodynamic balance and more or less quiet evolution: in this case, one can expect the development of powerful shock waves, which should forward NS towards the catastrophic self-destruction.

0.2 BHs of the lowest mass, NSs of the highest mass and large band gap in between. No way for compact star $\rightarrow$ BH evolution.

At the same time, the horizon of a radius $R_{\text{BH}}$ is, obviously, emerged at the condition $\frac{2GM_{\text{BH}}}{R_{\text{BH}}}=1$, or, what is the same,

$$R_{\text{BH}} = \left[\frac{3}{8\pi G \langle \varepsilon_{\text{BH}} \rangle}\right]^{1/2},$$

(5)

where $M_{\text{BH}}$ and $\langle \varepsilon_{\text{BH}} \rangle$ are the BH mass and its mean energy density, respectively. For getting the lower estimate of $R_{\text{BH}}$ (in the context of compact star collapse), one has to take into account that $\langle \varepsilon_{\text{BH}} \rangle \leq \varepsilon_n \simeq |\varepsilon_{\text{vac}}^0|$, since, otherwise, the phase transition instability followed by the aforementioned consequences is expected to activate before. Thus, one obtains for $R_g = \min R_{\text{BH}}$ and $M_g = \min M_{\text{BH}}$

$$R_g \geq 12 \text{ km or } M_g \geq 4 M_\odot$$

This is, actually, an underestimation (most probably, a considerable one) because the star interior density is higher than the peripheral one, and, therefore, the hot SHPh matter starts forming there even earlier. Thus, the NSs of highest mass, ($M_{\text{NS}} \simeq \overline{M_{\text{NS}}} \leq 2 M_\odot$), which are observed so far (and had a perspective to turn into BH), and the hypothetical BHs of lowest mass predicted by GR are separated by a very significant gap. What kind of star organization could set up in between? If the NS mass still were imagined to access $4 M_\odot$, then eq.(4) tells immediately that \( r \simeq R_{\text{NS}} \), what means nothing else than, in fact, no sensible solutions exist at all. The only reasonable interpretation of this fact is, seemingly, that any collapsing star of a mass $M$, which considerably exceeds $2 M_\odot$, is doomed for the complete destruction just after (hydrodynamic time scale!) the nucleon packing becomes sufficiently compact. Thus, a large (semi-phenomenologically/semi-theoretically motivated)

\[^{13}\text{From the more general point of view, the variety of possible ways of stopping the star collapse demonstrates nothing else than that there are different ways of symmetry (in this context - of the chiral one) breaking along with medium cooling and getting more rarefied: the no-order-parameter SHPh turns into the HPh, which shows up clearly an order parameter - for it can be chosen, say, the inverse radius of color confinement.}\]
band gap, $\Delta \geq 2 M_\odot$, between the allowed NS (even transient one) and BH masses blocks the way for compact star $\rightarrow$ BH evolution.

We put aside everything that relates to the formation of less compact BH of substantially larger $M_{BH}$ and $R_{BH}$ (both are $\sim \langle \varepsilon_{BH} \rangle^{-1/2}$), since, in this case, a more detailed information on star dynamics should be involved. What can be said from the general considerations, is that shutting to BH of such a type is, seemingly, an event of even lower probability. Essentially, the matter is that the conditions, which make horizon to emerge, are linked to the global features of the star nuclear medium (the values of $M/R$ and averaged energy density $\langle \varepsilon \rangle$), whereas the HPh $\rightarrow$ SHPh transition instability is linked directly to the local values of $\varepsilon$, which, undoubtedly, increase towards the star center. Since the relevant EoS is rather soft (the medium is non-relativistic and thus $P \ll \varepsilon/3$), one can expect this increase to be sufficiently steep for making the proactive development of HPh $\rightarrow$ SHPh transition instability near the star center.

It is worth also mentioning, in this connection, that some factors unaccounted above - unavoidable energy density fluctuations, expected star rotation and its non-sphericity and, especially, binary-star configuration - should, obviously, result in diminishing the margin of star stability, thus making the above arguments against attainability of BH-horizon even more defensible.

1 Conclusion

The QCD-induced mechanism of NS instability is discussed which is incompatible with the gravitational one. The NSs of highest masses are proven to be in face of instability associated with QCD-vacuum transformation under HPh $\rightarrow$ SHPh transition, which could manifest itself, in particular, through the softening of EoS towards the star center. This instability seems to develop before BH horizon emerges somewhere within the star body, what makes rather improbable the very accessibility of a BH configuration at the end of collapsing star evolution.

Since the temperature of substance in SHPh formed near the star center is more than one order higher than that of the supernova explosions, the relevant energy release could be up to several orders higher. That is why one cannot rule out that some poorly understood observation data on very distant (“young”) and most powerful GRB’s - like GRB 090423 [11], GRB 080916C [12], GRB 080319B (“naked eye”) [13], Sw 1644+57 [14], etc. - (which
are associated sometimes with insatiable "eating up" the stellar substance by situated (supposedly) nearby BH) are linked, actually, with the above phase instability within the neutron stars themselves.

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