GAMMA-RAY BURSTS: A CENTAURO'S CRY?

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Gamma-ray bursts are enigmatic flashes of gamma-rays at cosmological distances, so bright that the implied energetics is astounding: energies of order of about solar rest-energy are liberated in a time scale of the order of seconds in space regions only a few kilometres in size. Central engines capable to produce such enormous explosions, leading to a highly relativistic expending fireballs, remain a mystery. Here we propose a new candidate for the gamma-ray bursts central engine.

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Centauros are unusual cosmic-ray events firstly observed in 1972 at the Chacaltaya high mountain laboratory [1]. Detector used in this experiment consisted of upper and lower chambers separated by the carbon target. Usually the upper chamber detects much more particles than the lower chamber, because the electromagnetic component of the shower, initiated by the primary cosmic-ray interaction at some altitude above the detector, is strongly suppressed by the carbon layer. The first Centauro event with the contrary situation came as a big surprise. It had a striking imbalance between electromagnetic and hadron components and can be interpreted as a production of 74 hadrons and only one electromagnetic (e/γ) particle. Therefore, in Centauro events one cannot guess the lower part of the detector response from the upper one — hence the name.

In a sense, gamma-ray bursts are also like Centauros — from their observed upper parts it is not easy to guess the inside central engine. Let us see if we can give some depth to this metaphor.

The clue is provided by one of "our most perfect physical theories" [2] — quantum chromodynamics (QCD). At low energies the QCD effective coupling constant is large and usual perturbation theory methods do not work. But, fortunately, many features of the low-energy dynamics are dictated by symmetries of the QCD Lagrangian and their breaking patterns. This enables us to substitute QCD at these energies by some effective theory, for example, by linear sigma model [3].

In two flavour case, the Lagrangian of the linear sigma model has the form

$$L = \frac{1}{2}\,\partial_\mu\sigma\,\partial^\mu\sigma + \frac{1}{2}\,\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} - \frac{\lambda}{4}\left(\sigma^2+\vec{\pi}^{\,2}-v^2\right)^2 + H\sigma\,. \qquad (1)$$

Here $\lambda \sim 20$, $v \sim 90$ MeV and $H \sim (120\ \text{MeV})^3$ are free parameters of the model and they can be fixed by using the pion and sigma meson masses and PCAC relation as inputs [4] (note that [4] is a pedagogical review article where relevant citations to the original papers can be found). In the absence of the last term, the linear sigma model potential has "Mexican hat" shape. Therefore, in this chiral limit the vacuum state is degenerate and chiral symmetry is spontaneously broken as the sigma field develops a nonzero vacuum expectation value.

At finite temperature the thermal fluctuations modify the potential [5]. In a crude, but intuitively transparent approximation the modified potential takes the form (in the chiral limit. See [4] for explanations)

$$V = \frac{\lambda}{4}\left(\sigma^2+\vec{\pi}^2+\frac{T^2}{4}-v^2\right)^2 . \qquad (2)$$

The σ-condensate, which minimizes the energy, now becomes

$$\langle\sigma\rangle = \sqrt{v^2-\frac{T^2}{4}}$$

and completely melts away at the critical temperature $T_{\rm c} = 2v \approx 180$ MeV. Above this phase transition point the chiral symmetry is restored. Note that this critical temperature is not accurate by about 20–30 percents. In reality the temperature dependence of the effective potential is quite complicated — see references cited in [4]. But these subtleties are completely irrelevant for our purposes — we are just preparing a stage for the main idea which will follow.

The last term $L_{\rm SB} = H\sigma$ in the Lagrangian (1) explicitly violates the chiral symmetry and originates from the nonzero quark masses. It tilts the "Mexican hat" and removes the vacuum degeneracy. As a result, σ-condensate does not melt away completely. However, near the critical point the residual value of the σ-condensate is quite small and irrelevant [4].

In the fireball, produced by a primary cosmic-ray particle interaction with air nuclei, the initial temperature can reach $T_{\rm c}$. Then the chiral symmetry is restored and the sigma field condensate melts away (up to small corrections due to finite quark masses) in some small volume. But the fireball expends quickly and the inside temperature suddenly drops to zero. At that the fields do not have enough time to follow this sudden change in the environment and, therefore, immediately after the quench the system finds itself in a highly out of equilibrium situation for the zero temperature Lagrangian — near the top of the "Mexican hat".

The vacuum expectation values develop while the system begins to roll down towards the valley of the potential. But all the information about the "correct" orientation of the chiral order parameter (along the sigma direction) is lost during the phase transition. Besides, the fireball inside region is temporally shielded from the outside "normal" world by a thin shell of hot hadronic debris of the fireball. Therefore we have every reason to expect that by the time the fields reach the "Mexican hat" brim the chiral order parameter will be misaligned. Afterwards, then the shielding shell disappears, such disoriented chiral condensate (DCC) relaxes to the ordinary vacuum by emitting a coherent burst of low energy pions [4,6–9] (the DCC literature is vast, we cite only some recent reviews).

The formation and decay of the DCC bubble appears to be an attractive explanation of the Centauro puzzle, although not without difficulties [1, 10]. In accelerator based experiments Centauros were searched but not yet found [1]. These efforts will be continued in the majority of future heavy-ion experiments and, hopefully, we will know soon whether the DCC phenomenon really exists.

Now let us return to the gamma-ray bursts [11–14] and put our main card on the table: if a macroscopic DCC region might be formed in some violent cosmic event, its subsequent decay will provide a highly efficient source of a pure radiation energy without the baryon loading problem.

Observational evidence suggests that at least long gamma-ray bursts are associated with star-forming regions and thus most probably with the death (collapse) of massive stars [15]. During supernova core collapse, temperatures can be as high as about 40 MeV [16], but this is still much lower than the critical temperature T_{c} discussed above. How can the desired chiral phase transition then happen?

The value of T_{c}, extracted from the simple arguments concerning high-temperature behaviour of the linear σ-model, assumes low density environment, while in supernova core the density is high. Therefore, in contrast to the cosmic-ray and heavy-ion experiments, we need high density QCD, not the high temperature one.

At high density, one also expects the restoration of chiral symmetry. This is especially transparent in the MIT bag-model picture of nucleons as droplets of chiral symmetry restored phase, within which the quark density is nonzero, immersed in a sea of nonperturbative vacuum with no quarks but nonzero chiral condensate. While squeezing a lump of hadronic matter, as the outer pressure increases, the chiral symmetry restored phase occupies more and more fraction of the volume. At last individual bags begin to overlap and finally they unify in a one big bag containing all the quarks. In such so called quark–gluon plasma (QGP) phase, the chiral symmetry is restored up to effects of nonzero quark masses.

The real situation is not as simple, however. The phase structure of high-density QCD turns out to be surprisingly reach and its study is an active research field at present [17–20]. A main result is that at high-densities one expects formation of diquark condensates and development of colour superconductivity, due to Fermi surface generic instability against attractive interactions.

In the colour superconductive phase, the chiral symmetry can be both restored, as in the so called two flavour colour superconductivity (2SC) phase, and spontaneously violated, as in the colour-flavour-locked (CFL) phase. In latter case, however, the chiral symmetry breaking mechanism is different from the ordinary one at low densities. It turns out that in the CFL phase some discrete chiral symmetry remains unbroken up to small instanton-induced effects [21, 22]. This residual (approximate) symmetry renders difficult the development of ordinary $\langle \bar{q}_{\rm L} q_{\rm R} \rangle$ chiral condensate and as a result its magnitude is much less than in the ordinary QCD vacuum [23].

Therefore, it seems plausible that the transient phase transition, triggered by a high-density, can also lead to formation of DCC bubbles. Let us take a closer look at some speculative scenarios how this may happen.

Interesting and still open fascinating possibility is the hypothetic stability of three-flavour quark matter (strange matter) [24, 25]. If the strange matter is indeed the true ground state of hadronic matter, instead of ^{56}Fe, then strange stars may exist [26]. Neutron star (NS) will be converted into strange star (SS), if a strange matter seed is created inside the neutron star, big enough to overcome surface energy cost. In fact, NS$\rightarrow$ SS conversion was suggested as a candidate for the gamma-ray bursts central engine [28–33] (we cite only some relevant references, others can be traced through them).

A newborn neutron star can increase its central density because of accretion or spin-down. When the density becomes sufficiently high, the deconfinement phase transition happens and two-flavour (u and d) quark matter is formed in the inner core [27]. But the two-flavour quark matter is unstable and converts into three-flavour strange matter via weak interactions very rapidly, with a time scale below 10^{-7} s [34]. Once a strange matter seed is formed, it will start to grow and swallow the surrounding neutron matter. Combustion is limited by quark diffusion and might be, in principle, slow [35], if not the hydrodynamical instabilities [36] which, most probably, will turn the conversion of neutron matter into detonation. The whole star will be digested in a time period maybe as short as 10^{-3} s [31].

The NS$\rightarrow$ SS conversion is accompanied by a release of huge amount of internal energy, comparable to the star's binding energy. For example, according to estimates [31], a neutron star with a mass $M_{\rm NS} = 1.409\,M_\odot$ and a radius $R_{\rm NS} = 11.0$ km, which has a gravitational binding energy of about 4.5×10^{53} erg, after the conversion produces the strange star with $M_{\rm SS} = 1.254\,M_\odot$ and $R_{\rm SS} = 10.5$ km. At that the expected amount of internal energy released is $(1.9-4.2)\times 10^{53}$ erg. As these estimates show, the liberated internal energy can constitute a significant fraction of the gravitational binding energy. Therefore a nascent strange matter will inflate somewhat before it reassembles itself into the strange star. Hence the appearance of vacuum bubbles inside strange matter seems inevitable. But which vacuum? The primordial chiral condensate disappears during the deconfinement phase transition and the consequent neutron matter burning into strange matter. The new vacuum inside the emergent bubbles is shielded for some time from the normal vacuum by the strange matter. Therefore, it seems natural to expect that the QCD vacuum will be disoriented inside these bubbles, that is DCC will be formed. Afterwards, when the DCC bubbles will come into contact with the ordinary vacuum, they will decay by emitting coherent pions.

Let us estimate how much energy can be stored in these DCC bubbles. Suppose DCC domain is formed inside the bubble with the misalignment angle θ. That is inside this DCC region one has

$$\langle\sigma\rangle_{\rm DCC} = f_\pi \cos\theta\,, \qquad \langle\vec{\pi}\rangle_{\rm DCC} = f_\pi \sin\theta\ \vec{n}\,,$$

where $\vec{n}$ is a unit vector in isospin space and $f_\pi \approx 93$ MeV is the pion decay constant. While in the normal vacuum

$$\langle\sigma\rangle = f_\pi\,, \qquad \langle\vec{\pi}\rangle = 0\,.$$

Energy density in the DCC region is higher than in the normal vacuum because of the symmetry breaking term $V_{\rm SB} = -H\sigma$. The difference equals (note that $H = f_\pi m_\pi^2$)

$$\Delta\varepsilon = -H\langle\sigma\rangle_{\rm DCC} + H\langle\sigma\rangle = Hf_\pi(1-\cos\theta) = 2f_\pi^2 m_\pi^2 \sin^2\frac{\theta}{2}\,.$$

As an estimator for the total volume of the produced DCC, we take the volume of the spherical shell with inner radius $R_{\rm SS}$ and outer radius $R_{\rm NS}$. Besides, $\sin^2\frac{\theta}{2}$ can be replaced by its mean value 0.5, because the misalignment angle θ changes randomly from domain to domain in the bubbles. Then the total energy content of the DCC bubbles equals

$$E_{\rm DCC} = \frac{4\pi}{3} f_\pi^2 m_\pi^2 (R_{\rm NS}^3 - R_{\rm SS}^3) \approx \frac{R_{\rm NS}^3 - R_{\rm SS}^3}{1\ {\rm km}^3}\ 1.5\times 10^{50}\ {\rm erg}\,. \qquad (3)$$

For $R_{\rm NS} = 11.0$ km and $R_{\rm SS} = 10.5$ km this estimation results in $E_{\rm DCC} \approx 2.6 \times 10^{52}$ erg – just right amount of energy to power a gamma-ray burst!

One can imagine another, even more speculative, scenario which could lead to formation of macroscopic DCC regions. The density in a supernova core can be raised to extreme values during the catastrophic gravitational collapse. It was argued [37] that even the electroweak symmetry has a chance to be restored in such collapse before the corresponding region is engulfed by a emergent black hole horizon. The subsequent baryon burning due to the baryon number violating processes, unsuppressed in the symmetric phase, was suggested as one more candidate for the gamma-ray bursts central engine [37].

The chiral symmetry will be restored much before the electroweak symmetry. However, to form the DCC regions one needs gravity suddenly to cease its deadly grasp of these chirally symmetric areas. Otherwise they will find their way into the central singularity with final fate obscure at present. Clearly, the latter is the only possibility offered by the classical theory of gravity.

However, a challenging possibility, that General Relativity is just a low energy effective theory [38, 39], cannot be excluded. Therefore, the gravitational collapse may have completely different outcome than it is expected in Einstein gravity. The following analogy shows this picturesquely [39]. A stretched rubber sheet with a heavy ball on its models general relativity. The membrane is an analog of space-time, the ball corresponds to some gravitating object and the distortion of the rubber sheet surface represents the gravitational field. By declaring the laws of elasticity to be universally true, no matter how extreme the stretching, we expect that when the weight of the ball increases, so does the depression making small objects, which fall into this distortion, more and more inaccessible for us. In reality, however, the membrane ruptures if the ball becomes too heavy and the objects fall through.

In the condensed matter analogs of gravity, the vacuum state also does not remain stable in the presence of the horizon [40]. Besides, perturbations of the quantum vacuum, for example, due to QCD or electroweak phase transitions, can alter the cosmological constant, which in the effective gravity is not a constant but the evolving physical parameter [40]. Therefore, one cannot exclude that the gravitational collapse will be accompanied by much reacher phenomenology, like formation of DCC, or even more exotic false vacuum bubbles, than it is anticipated at present.

Although the effective gravity idea [38–42] is very attractive, the above mentioned possibility of DCC formation during a gravitational collapse is much more speculative than the scenario associated with the NS$\rightarrow$ SS transition. Therefore, let us summarize the latter:

- NS$\rightarrow$ SS transition happens probably very quickly due to detonation. In almost all volume, occupied by the initial NS, the strange matter is formed. But the strange matter has a higher density than the neutron matter. Therefore the produced strange matter cannot be completely continuous, it will have voids (vacuum bubbles) in its body.

- The voids will be formed also because the energy liberated during the NS$\rightarrow$ SS transition is very high: one expects the newborn strange matter to inflate somewhat before its lumps reunify and form the Strange Star.

- What we are interested in is the content of these voids. In usual QCD vacuum one has a nonzero chiral condensate $\langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} \rangle$ — in the linear sigma model language the corresponding quantity is a nonzero vacuum expectation value of the sigma field.

- But during deconfinement phase transition this chiral condensate disappears. Besides in various forms of quark matter this condensate is either absent (2SC), or is much smaller (CFL) compared to its value in the normal QCD vacuum at small density and temperature. So one can expect that just after the void bubble is formed inside the strange matter, the fields inside the bubble, both pions and sigma, do not have any vacuum expectation values, or these values are small.

- This situation is not stable inside the bubble, where we have a small ($\sim$zero) density and a small temperature environment, so that the fields dynamics is approximately governed by the zero temperature and density linear sigma model Lagrangian. The potential of this Lagrangian has a "Mexican hat" shape and the initial (small) values of the fields are located near its top. So the fields begin to roll down.

- When the fields reach the "Mexican hat" brim they can find themselves in a wrong place (from the point of view of the normal QCD vacuum). So the so called disoriented chiral condensate (DCC) may be formed.

- When the DCC bubble comes into contact to the normal QCD vacuum, it will decay by emitting pions. At that, if the DCC was oriented in the π^0 direction (in isospace), it will decay by emitting only neutral pions. If the initial orientation was perpendicular to the π^0 direction, the neutral pions will not appear at all, but one will have equal numbers of π^- and π^+.

- Strong electric and magnetic fields can prefer the DCC oriented in the π^0 direction due to chiral anomaly [43].

- A huge amount of produced π^0-s will create a wonderful relativistic fireball because of the decay $\pi^0 \to 2\gamma$ (or such a fireball will be formed also due to annihilation of π^- and π^+ pairs, if DCC not in all bubbles is oriented in the π^0 direction.

In fact the NS$\to$ SS transition is just one example which may lead to the formation of macroscopic amount of DCC bubbles. The main idea of the paper is more general: if in some energetic cosmic events a macroscopic amount of DCC bubbles can be formed, then we will have an effective GRB central engine at hand.

Physics is an experimental science. Therefore, the idea that the cosmic-ray Centauros and gamma-ray bursts both have a common QCD origin, however attractive, must confront scrutiny of the future heavy-ion and cosmic-ray experiments, as well as astrophysical observations. Remarkably, more than 135 theoretical models of the gamma-ray bursts were instantaneously destructed when the observational data from the Beppo-SAX satellite became available [44]. We hope that the idea presented in this article will be more fortunate.

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