Long Gamma Ray Bursts from Quark Stars

P. Haensel and J.L. Zdunik

N. Copernicus Astronomical Center, 00-716 Warszawa, Poland

Summary. — If strange quark matter (SQM) is the true ground state of hadronic matter, then conversion of neutron stars (NS) into quark stars (QS) could release some $10^{53}$ erg. We describe a scenario of burning of a NS into a hot, differentially rotating QS. Emission of released non-baryonic energy through the QS surface is discussed. The role of magnetobuoyancy of SQM is mentioned. The outflow of $\gamma e^+e^-$ lasting for up to $\sim 1000$ s could be at the origin of long GRBs. Advantages of hot, differentially rotating QS as an inner engine of long GRBs are reviewed.

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1. – Introduction

Atomic nuclei are droplets of nuclear matter. From the point of view of quark structure of matter, nuclear matter is composed of triplets of quarks confined to small bubbles of the QCD vacuum. These confined triplets are $uud=\text{protons}$ and $ddu=\text{neutrons}$. Nuclei and electrons form atoms, and the minimum energy per nucleon at zero pressure for atomic matter (thermal contribution being negligible) is reached for a body-centered cubic crystal of $^{56}$Fe, with energy per nucleon (including nucleon rest energy) $E(^{56}\text{Fe}) = 930.4$ MeV. But is this a true ground state of matter built of quarks? A hypothesis that the true ground state of hadronic matter differs from $^{56}$Fe, and is actually much denser quark matter, was advanced since 1970s [1, 2](also Terazawa (1979), as quoted in [3]). In this true ground state, self-bound at $P = 0$, nuclear matter is replaced by a plasma of the $u$, $d$, and $s$ quarks, the presence of the $s$ quarks being crucial for lowering the energy due to the Pauli principle. The baryon number of a drop of the $uds$ plasma of $N_q$ quarks is $A = N_q/3$, and for a sufficiently large (so that surface and Coulomb energies are much smaller than the bulk one $\propto A$) drop of $uds$ plasma $E(uds) < 930.4\text{MeV}$. In contrast to atomic nuclei, the size of self-bound droplets of strange quark matter (SQM) is not limited by Coulomb forces, and for $A \sim 10^{57}$ they become huge spheres of SQM called quark stars(QS) [2]. Structure and astrophysics of QS was first studied in detail in [1, 4]. In contrast to neutron stars (NS), which are bound by gravitation, QS are bound by the QCD forces. However, for $A \sim 10^{58}$ the
quark star mass $M_{\text{QS}} > M_\odot$, while its radius $R \sim 10$ km. Under such conditions, gravitation becomes important. Space-time curvature implies then the existence of maximum allowable mass for QSs, which turns out to be quite similar to that predicted for NSs, $\sim 2 M_\odot$.

If SQM is indeed the true ground state of hadronic matter, then NS would be metastable with respect to conversion $\text{NS} \rightarrow \text{QS}$, the conversion process releasing $\sim 10^{53}$ erg. As we will argue, a newly born QS is a promising source of an ultrarelativistic energy outflow which could then produce long gamma ray burst (GRB). Since 1986 many papers on GRBs from QS appeared and many different scenarios exploiting unique properties of QS were proposed (see, e.g., [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]). Here we discuss a specific model of QS as an inner engine of long GRBs, stressing its advantages over standard models involving NS. Applications to observed long GRBs are presented by Drago, Pagliara, and Parenti [22] in these proceedings.

2. – Conversion of neutron star into quark star

Conversion $\text{NS} \rightarrow \text{QS}$ is initiated by nucleation of a droplet of SQM in nuclear matter near the NS center. This process is catalyzed by high density and temperature, and could occur near the center of a newly born NS, formed in gravitational collapse of a core of a massive star. It could also be triggered in an accreting NS, after its central density reaches some critical value.

A typical expected latent heat associated with $\text{NS} \rightarrow \text{QS}$ is $Q \sim 50$ MeV/nucleon. Predicted energy release is therefore $E_{\text{conv}}(\text{NS} \rightarrow \text{QS}) \sim 10^{53}$ erg. This energy release can be re-vitalized by sporadic accretion. As the density profile within QS is very different from that in NS, conversion implies strong differential rotation of a newborn QS. Typical energy contained in differential rotation (calculated at constant $A$ and angular momentum $J$) is $\Delta E_{\text{diff. rot}} = c^2 (M_{\text{diff. rot}} - M_{\text{rigid}})A_J \sim 10^{52}$ erg. All in all, the thermal energy, plus the energy in differential rotation of a newly born QS, form a huge energy reservoir to generate $\gamma e^+e^-$ fireball with Lorenz factor $\Gamma > 100$, which could be at the origin of a long GRB.

Let us consider kinetics of burning of a NS into a QS. Neutron star is basically composed of a liquid core containing some 99% of stellar mass and a partially solid crust. For simplicity, we will consider a core composed of nucleons and electrons. A nucleated droplet of SQM at the NS center grows by absorption of nucleons, which dissociate into quarks, $n \rightarrow u + d + d, \quad p \rightarrow d + u + u$. Then quark matter equilibrates via $u + d \rightarrow s + u, \quad u + e \rightarrow d + \nu_e$. Both processes are highly exothermic, releasing a total of $\sim 50$ MeV/nucleon. The SQM front progresses outwards. This front can be shown to be convectively unstable and consequently progresses as a strong deflagration, converting baryon core into quark core rapidly but still subsonically, never producing a detonation [23]. The bottom of the NS crust, containing nuclei, is reached in 10 ms. The quark core is heated to $\sim 5 \times 10^{11}$ K and is opaque to neutrinos, which are trapped inside it.

Let us first consider the burning of NS crust into SQM assuming a diffusive regime. The temperature behind the SQM front is $T_Q \sim 10^{11}$ K, and the thickness of the burning layer where the non-equilibrium reactions take place in quark matter (on the Q-side), $\delta_Q$, is much thinner than the layer of neutron star which is preheated, molten, and convectively mixed with original crust matter. The thickness of this convective layer of the crust ahead of the expanding SQM is denoted by $\delta_N$. The temperature of the crust before preheating is $T_{\text{crust}} \sim 10^9 - 10^{10}$ K, while $\delta_Q \ll \delta_N \sim 1$ cm. Let us stress that preheating up to $T_Q$ leads to dissociation of nuclei into nucleons which greatly facilitates
conversion into SQM. Generally, preheating and convective mixing strongly accelerates the burning of the crust into SQM. Because of the high density gradient within the crust, its total burning moves the SQM front only 30 m outwards. We estimate that this takes 0.01 s, so that the SQM front moves at 3 km/s only. Because the temperature at the SQM front is $T_Q \sim 10^{11}$ K, the very outer layer of NS, of mass $M_{ej} = 4\pi R^2 P_{\gamma}/g$ where $g \sim 3 \times 10^{14}$ cm/s$^2$, will be ejected by the photon pressure. Under prevailing conditions, $M_{ej} \sim 10^{-6} M_\odot$.

3. – Ultrarelativistic energy outflow from the quark star surface

Quarks, of number density $n_q \sim 10^{39}$ cm$^{-3}$, are confined in a huge bubble ($R \sim 10$ km) of the QCD vacuum (by strong interaction). This results in a very sharp SQM surface, of thickness of the order of the range of strong interactions $\sim 10^{-13}$ cm. However, electrons are not interacting strongly. Their number density in SQM is $n_e \sim 10^{-4} n_q$ \[4\,5\] and they are bound to quarks (which have a net positive charge) by electric forces. This results in an "electrosphere" of electron gas, of thickness $10^{-11}$ cm, extending above the...
SQM surface (5, Fig. 1). The surface layer of a newly born QS is very hot, with $T_S \sim 10^{10} - 10^{11}$ K. We assume that this does not lead to a significant evaporation of nucleons from QS. This assumption is valid when the binding energy of a nucleon in SQM, $W_N$, satisfies $W_N \gg k_B T_S$.

The superdense SQM surface of temperature $T_S \sim 10^{10} - 10^{11}$ K is a very efficient emitter of photons and $e^+e^-$ pairs (see [24] and references therein). Notice, that as quarks are bound not by gravitation but by the (strong) QCD forces, and there is no atmosphere, but an electrosphere of a thickness of $\sim 10^{-11}$ cm hold by huge electric forces ($10^{18}$ V/cm), the photon flux emerging from QS surface is not bounded by the Eddington limit. There are three main mechanisms of photon and $e^+e^-$ pair emission. Their contribution to the photon-pair luminosity of a QS are:

(eq) Equilibrium transverse plasmons, propagating within $\nu_{\text{plas}} \sim 20$ MeV/ℏ, this component of the photon flux, denoted by eq in Fig. 2, is completely negligible for $T_S < 10^{10}$ K.

(pair) Pair emission and annihilation. Pairs are efficiently formed in the huge electric field in the surface layer, and for $5 \times 10^9$ K $< T_S < 5 \times 10^{10}$ K give a dominant contribution to the energy outflow, see Fig. 2.

(neq) Photons produced in Bremsstrahlung $qq$ and $ee$ processes in the surface layer.

Finally, we have $\nu \rightarrow e^+e^-$ above the SQM surface. Actually, sharp QS surface creates ideal conditions for efficient $\nu \rightarrow e^+e^-$ pair production. However, its contribution, so important for NS, is not important for hot QS, because even at $10^{11}$ K it yields only $\sim 1\%$ of the total luminosity.

4. – Differential rotation and magnetobuoyancy

QS has a nearly constant density, while in NS we have $\rho_{\text{center}}/\rho_{\text{surf}} \sim 10^{14}$. Therefore, a rigidly rotating NS converts into a strongly differentially rotating hot QS. As the electrical conductivity of SQM is huge, this makes ideal conditions to generate toroidal magnetic field $B_{\text{tor}}$ by winding an initial poloidal $B_{\text{pol}}$, amplified later by the magnetorotational instability. A schematic picture of magnetized toroids inside a rotating QS is shown in Fig. 3. Pressure equilibrium requires $P = P_i + B^2/(8\pi)$ which implies matter density difference $\rho_i - \rho = -B^2/(8\pi c_s^2)$, where $c_s \approx 0.6c$ is the sound speed in quark matter. Effective total mass-energy density deficit within the toroid, relative to the ambient medium, is $(\Delta \rho)_i = - (c^2 - c_s^2) B^2/(8\pi c_s^2)$. A magnetized toroid, pushed up by buoyancy, floats along the rotation axis towards the QS surface, Fig. 3.

4.1. Stratification and anti-buoyancy: electrons present. – Electron fraction in SQM $x = n_e/n_b$ increases outwards [4]. A floating “magnetized ring” gets off beta equilibrium. At ambient $P$, a non-equilibrated quark matter weights more than the equilibrated one. Therefore, stratification opposes buoyancy of a magnetized SQM (Fig. 4). Consider an element of SQM initially at pressure $P_1$ and with equilibrium composition $x_1 = x^{eq}(P_1)$, moving upwards, with fixed $x = x_1$, to $P \ll P_1$ through the equilibrated medium with $x = x^{eq}(P)$ (Fig. 4). The anti-buoyancy factor is then defined by $f_{ab}(P_1;P) = [\rho(P,x_1) - \rho^{eq}(P)]/\rho^{eq}(P)$, where $\rho^{eq}(P) \equiv \rho(P,x^{eq}(P))$. By construction, $f_{ab}(P_1;P_1) = 0$.

4.2. Antibuoyancy for quark stars and neutron stars. – Factor $f_{ab}$ is very sensitive to the mass of strange quark $m_s$. At $T = 0$ we get $f_{ab} = 1 \times 10^{-7} \times [m_s c^2/(100 \text{MeV})]^{7/3}$.
Fig. 3. – Left panel. Floating of magnetized toroids due to their buoyancy. Quark star rotates around a vertical axis. \( \rho_i \) and \( \rho \) are matter density in the toroid and the ambient matter density, respectively. Right panel. Figure explaining the antibuoyancy due to stratification.

Thermal effects increase \( f_{ab} \). Let us define \( T_{11} = T/10^{11} \) K. For \( T_{11} > 1 \) and at fixed \( m_s \), thermal effects dominate, and one gets \( f^{QS}_{ab} \propto T_{11}^2 \) \[26\]. The values for NS are many orders of magnitude larger, \( f^{NS}_{ab} \sim 10^{-2} \) \[27, 26\].

### 4.3. Maximum \( B = B_f \) halted by stratification

Floating of magnetized toroid of SQM is halted if \( (\Delta \rho)_{ab} = \rho f_{ab} > (\Delta \rho)_{b} \). The toroid will float towards the QS surface, along the rotation axis, if \( B > B_f = \sqrt{8\pi f_{ab}\rho c^2 s} \) (Fig. 3). We have \( B_f \approx 10^{15} (f_{ab}/10^{-6})^{1/2} \) G. Therefore, for QS with \( T_{11} > 1 \) and \( m_s = 200 \) MeV/c\(^2\) we obtain \( B_f^{QS} = 5 \times 10^{15} T_{11} \) G \[26\]. For NS the critical value is \( B_f^{NS} = 10^{17} \) G \[27\].

After \( B_f^{QS} \) is reached, the magnetized toroid floats to the QS surface. The ultrarelativistic \( \gamma e^+e^- \) outflow from the QS surface follows. Using the arguments of \[27\], applied originally to NSs, one can show that the duration of the outflow, resulting from many cycles of the toroid generation and floating, can be as long as 1000 s.

In the case when QS is on the CFL superconducting state, there is a possibility of an CFL-enforced absence of electrons and no stratification. Then buoyancy is not opposed, and the floating of B-toroid and winding up are simultaneous. However, the floating is so slow, that the whole process of transport of frozen-in magnetic field to the QS surface, until \( E_{rot}^{diff} \sim 10^{52} \) erg is exhausted, takes hundreds of seconds.

### 5. Quark star inner engine vs. baryonic one

Let us summarize specific features of the inner engine of long GRBs based on the NS \( \rightarrow \) QS transition. This transition can take place in a newly born NS after a SNIc explosion, or in a spinning down or accreting NS. In the latter case, there is no SN accompanying the long GRB.

The process starts with a rapid conversion NS \( \rightarrow \) QS which can produce \( E_{therm} \sim 10^{53} \) erg and \( E_{rot}^{diff} \sim 10^{52} \) erg on a timescale \( \sim 0.01 \) s. There is no detonation, and matter ejection \( 10^{-6} M_\odot \) is insignificant. The quark surface acts as a membrane - only non-baryonic energy can flow through it. There is therefore no problem with Eddington limit for photons, so severe for NSs, where baryon loading cannot be avoided if \( L > L_{Edd} \). Moreover, the quark surface is sharp, which makes \( \nu\pi \rightarrow e^-e^+ \) process very efficient (in...
contrast to NS where this process causes a strong baryonic wind). A toroidal magnetic field, generated in a differential rotation, can power a long-time tail of energy outflow from the QS surface, without baryon pollution. For NS with $L >> L_{\text{Edd}}$ and neutrinosphere deep in stellar interior, a strong baryon pollution cannot be avoided.

Concluding, a hot differentially rotating QS could be an efficient inner engine of long GRBs (for application of this model to GRBs see [22] in these proceedings). Alas, we do not know whether QS exist.

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