Vol. B20 (1989) ACTA PHYSICA POLONICA No 11

STRANGE STARS: ARE THEY BARE?*

By W. Doroba†

Cracow Branch of the N. Copernicus Astronomical Center, Reymonta 4, 30-059 Kraków, Poland
Polish Academy of Sciences, Warsaw

(*Received June 19, 1989*)

We study the fate of outer layers of a dense star which underwent transition to a strange star. "Burning" occurring while the star is hot can significantly reduce the amount of material covering quark matter interior. Crust of the resulting strange star can be much thinner than the outer crust of a neutron star, but obtaining a bare strange star in this way is not possible.

PACS numbers: 97.60.-s, 14.80.Dq

1. *Introduction*

Strange matter, quark matter consisting of roughly equal numbers of u, d and s quarks has been conjectured [1] to be absolutely stable. At low temperatures, even without any external pressure, conversion of all kinds of nuclei into droplets of strange quark matter (SQM) with baryon number above certain critical value $A_{\min}$ (estimated to be about few tens) would be then energetically preferred. Properties of SQM have been investigated [2] in terms of simple MIT bag model, which describes quarks in SQM as strongly degenerate relativistic Fermi seas, contained inside a bag of constant energy per volume B. Effects of quarks' interactions other than long range attraction mimicked by B can be taken into account perturbatively as corrections in α_c — strong coupling constant. Only strange quark mass m_s is not negligible compared to quarks' chemical potentials and its abundance is slightly smaller. Admixture of electrons needed to neutralize the system ($Y_e \leqslant 3 \cdot 10^{-4}$, Y_e — number of electrons per unit baryon number) results in the creation of a repulsive Coulomb barrier [2, 3] for positively charged nuclei, what would prevent created somehow SQM seed from swallowing up surrounding ordinary matter. Properties of SQM for the sets of values which parameters B, m_s, α_c can possibly assume suggest that the existence of absolutely stable SQM is from the point of view of this model quite likely.

If the conjecture was indeed correct, then neutron stars, the only objects where SQM could possibly form now, could convert to quark stars [3, 4]. While the conversion of

* Work supported in part by research grants CPBP 01.03 and 01.09.

† Deceased

neutron matter core into SQM once somehow initiated should sooner or later be accomplished, the fate of the outer layers of the star (its outer crust), where pressure is not high enough to cause free neutrons to drip out of nuclei, remains to be determined. Absence of the crust would leave the strange star with bare quark surface which may exhibit extraordinary properties [3] (one can however hardly think when it could be able to radiate at a rate exceeding Eddington limit as suggested in Ref. [3]), but at the same time, the star's structure would then be so simple, that it may be difficult to explain various properties observed in compact objects. Presence of a crust may be of some help (not big however, since such a crust would be very thin anyway). One needs to know the structure of outer layers of a star to analyse its cooling. They determine the relation between internal and surface temperatures, and also efficiency of surface photon emission mechanism. It can be important as differences in cooling rates (because of different neutrino emissivities) between neutron matter and SQM present perhaps the most promising way to distinguish between those two possible cases.

Our aim is to investigate the fate of outer layers of a dense star which underwent transition to a strange star. In Section 2 we briefly review two mechanisms which could lead to the destruction of star's crust. Later we concentrate on the scenario of "burning down" of the crust while the star is hot, and we analyse relevant factors. The rate at which energy is removed from the region where burning occurs is calculated in Section 3. In subsequent sections we estimate flux of particles which can be transferred from the crust to SQM. We find that it is not possible to obtain sufficient flux of neutrons alone (Section 4) and charged particles need to be transported to SQM as well (Sections 5 and 6). Finally in Section 7 we present expected course of burning process and its outcome.

2. *Star's crust, and how it can be removed*

As an outer crust of a strange star we will consider the region where density of electron gas (from ionized atoms) is lower then that of electrons inside SQM, and hence electrostatic potential rises on the way from the crust to the edge of SQM. This increase, acting as a Coulomb barrier V_C, is (at $T = 0$) equal [3]:

$$V_C = \tfrac{3}{4}\, p_{e_{SQM}} + \tfrac{1}{4}\, \frac{p_{e_c}^4}{p_{e_{SQM}}^3} - p_{e_c}, \tag{1}$$

where $p_{e_{SQM}}$ and p_{e_c} are Fermi momenta of (relativistic) electron gas inside SQM and the crust respectively. Electrostatic potential at the surface is slightly changed at nonzero temperature but temperature would have to be as high as tens of MeV for this change to be substantial [5]. So the layer we call crust is characterized by baryon number densities less then:

$$p_{e_{SQM}}^3 / 3\pi^2 Y_e, \tag{2}$$

or neutron drip density (if $p_{e_{SQM}} > p_{e_{nd}} \simeq 25$ MeV — rather unlikely value for absolutely stable SQM).

Alcock, Fahri and Olinto [3] investigated crust's stability against quantum tunneling of ions through the potential barrier (at zero temperature). They found that the transition probability is negligible, so whenever the barrier exists (which is the case when density of electrons inside SQM is bigger than that in the crust), it should not be penetrated by ions. This result seems to be correct but overlooks another possibility of removing the crust, its "burning down" when the star is hot.

Baym et al. [6] entertaining the possibility that Cygnus X-3 is such a strange star addressed the question of conversion of it's crust to SQM. They expect, that ordinary matter will be absorbed through the interface and converted to quark matter, provided the matter encountered is sufficiently neutron rich, or if the temperature of the star remains high enough that there are some particles in the nuclear matter with kinetic energies sufficient to overcome the Coulomb barrier of strange matter. As the SQM burns its way outward, it may preheat the matter in front and generate enough particles with kinetic energies above the Coulomb barrier to maintain burning. They estimate that it is indeed possible, but we think the arguments they use are not correct. Rate at which particles can go through the barrier, suppressed due to Boltzmann factors, is compared with the speed of "formation front" of SQM. Calculation of this speed is based on the rate of conversion of nonstrange quarks into strange ones (which is underestimated). As this speed is found to be low (10^{-2}–10^{-1} cm/sec), the supply of particles may catch up with it.

If one wants the crust to be removed, it is however not desirable to find strong constraints on rate at which conversion to SQM can occur. If conversion was so slow, it would be difficult to maintain high temperature (Baym et al. assume temperature $T = 0.1$–1.0 MeV), and number of particles able to go through the barrier would drop. We think that "burning" scenario needs revision, and in subsequent sections we will analyse the factors which we expect to determine its outcome.

3. *Energy loses during burning*

Flux of particles capable of crossing potential barrier and reaching SQM surface is reduced by a factor $e^{-ZV_C/T}$ compared to the number which would strike this surface at the same time in the absence of the barrier (Z — number of protons in given kind of nuclei). At increased temperature not only particles are provided with higher thermal energies, but also dissociation of heavy nuclei produces neutrons which do not feel Coulomb repulsion and protons with minimal $Z = 1$. As temperature drops this supply of baryons to SQM is cut off. Burning can then occur only at sufficiently high temperatures, and we will have to check whether enough energy is released to maintain this temperature, and if not, how fast the temperature would decrease.

At temperatures $T \sim 1$ MeV, which will be important in our analysis, energy is emitted mainly in neutrinos (and antineutrinos). Neutrino mean free path in SQM is at this energy scale of order of a few kilometers [7], so the neutrinos carrying away energy released by burning will freely escape the star. Because of much higher density, bigger energies of reacting particles, and good transport properties of SQM we expect that neutrino emission from this medium will dominate energy loses.

Neutrino emissivity of quark matter was found to be large [7, 8]:

$$e = \tfrac{914}{315} G_F^2 \cos^2 \theta_C \alpha_c p_d p_u p_e T^6 \equiv \varepsilon T^6, \tag{3}$$

$$e = 4.1 \times 10^{36} (\alpha_c/0.1)\,(p_q/235\text{ MeV})^2 (p_e/10\text{ MeV})\,(T/1\text{ MeV})^6 \text{MeV cm}^{-3}\text{ sec}^{-1} \tag{4}$$

(p_i — Fermi momentum of particle i in SQM). SQM will cool rather fast, reaching temperature T in the time

$$t \simeq \mathscr{E}/2e \simeq 1.32(1\text{ MeV}/T)^4 (0.1/\alpha_c)\,(10\text{ MeV}/p_e)\text{ sec} \equiv t_0 \times (1\text{ MeV}/T)^4, \tag{5}$$

where $\mathscr{E}$ is (thermal) energy density which in this degenerate system ($\mu_q \gg T$) is $\mathscr{E} \simeq \frac{3}{2}\mu^2 T^2$.

Now we will ask the question about the rate, at which energy will be emitted from superficial layer of SQM, when temperature at the surface is kept constant. All transport problems considered here are one dimensional (we will assume SQM to extend from $x = -\infty$ deep inside the star to it's edge at $x = 0$). Energy conservation expressed in the frame comoving with SQM's front for the steady state gives

$$-v\partial_x \mathscr{E} = -\varepsilon T^6 + \partial_x (K \partial_x T), \tag{6}$$

where K is the thermal conductivity coefficient and v — speed of the front. K coefficient of SQM behaves like T^{-1}, which can be understood as extension of the result of elementary kinetic theory:

$$K = \tfrac{1}{3} C\bar{v} l \tag{7}$$

to the degenerate case, with specific heat $C = 3\mu_q^2 T$ and mean free path l enhanced because of Pauli blocking $l = l_0(\mu_q/T)^2$. Velocity of quarks is essentially equal to the speed of light $\bar{v} = 1$ and we will assume $l_0 = 0.18$ fm, which reproduces K value calculated in Ref. [9]. Then

$$K = \frac{\mu_q^4 c l_0}{T} \equiv \frac{\kappa}{T}, \tag{8}$$

with

$$\kappa = 2.12 \times 10^{38} (\mu_q/235\text{ MeV})^4 (l_0/0.18\text{ fm})\text{ MeV cm}^{-1}\text{sec}^{-1}. \tag{9}$$

Energy emission rate h (per unit surface area) for given fixed temperature T at the surface is

$$h = \int_{-\infty}^{0} \varepsilon T^6(x)dx = v\mathscr{E}(T(0)) + K\partial_x T(0). \tag{10}$$

Second term corresponds to the energy pulled from the surface by the conduction. It dominates when v is small. The value h assumes when motion of the front can be neglected is

$$h_c = (\tfrac{1}{3}\kappa\varepsilon T^6)^{\frac{1}{2}}, \tag{11}$$

where T denotes temperature at the surface. With κ and ε values given above, (11) makes:

$$h_c = 1.7\times 10^{37}(\mu_q/235\ \mathrm{MeV})^3(l_0/0.18\ \mathrm{fm})^{\frac{1}{2}}(\alpha_c/0.1)^{\frac{1}{2}}$$
$$\times(p_e/10\ \mathrm{MeV})^{\frac{1}{2}}(T/1\ \mathrm{MeV})^3\ \mathrm{MeV\ cm^{-2}\ sec^{-1}}. \tag{12}$$

When speed v rises h_c becomes eventually overwhelmed by the term $v\mathscr{E}(T)$, describing energy needed to heat newly formed surface layer to the required temperature. It is independent of ε and κ, as v increases hot layer properly widens. Front's speed is

$$v = j_b/n_{SQM}, \tag{13}$$

where n_{SQM} is the density of baryon number in SQM, and j_b is the flux of baryon number absorbed. Then in high v regime

$$h = j_b\mathscr{E}(T)/n_{SQM} = j_b\,\tfrac{3}{2}\,\pi^2\,\frac{T}{\mu_q}\,T. \tag{14}$$

Absorption of each baryon entering SQM releases typically energy much bigger then is needed to warm up one baryon to MeV temperatures in a degenerate system ($T/\mu_q \ll 1$). So in this high v regime, energy emission from SQM will not result in dropping of the surface temperature.

Problems in sustaining temperature can occur, when supply of particles which can be transformed to SQM is for some reason constrained. We have then to compare energy released by conversion of this baryons with h_c given by Eq. (12) to check wehther it can balance the losses.

4. *Neutronization in the crust*

Presence of free neutrons may suggest a way of transferring baryons to SQM which avoids potential barrier, namely transporting to its surface only neutrons. Flavor composition in surface layer of SQM needs to be equilibrated, mainly by producing strange quarks from d ones in reaction:

$$\mathrm{u}+\mathrm{d} \to \mathrm{s}+\mathrm{u}. \tag{15}$$

Limits on the conversion speed resulting from this requirement are not very restrictive [10], and it is limited supply of neutrons that constraints efficiency of such mechanism. In this process SQM would have to absorb not only the neutrons released by splitting the nuclei. Such process (apart from having natural limit of reducing crust's mass by about half) produces flux of neutrons which declines as neutron-deficient layer close to the absorbing surface widens. To obtain stationary supply of neutrons they need to be produced in beta reactions. We can estimate efficiency of such a way of transporting baryons to SQM. In stationary state $n_n(x)$, density of (free) neutrons at a distance x from interface, satisfies the equation:

$$D\partial_x\partial_x n_n(x)+R_n(x)+v\partial_x n_n(x) = 0, \tag{16}$$

where D is neutrons' diffusion coefficient, $R_n(x)$ rate at which neutrons are produced at a place where their density is smaller then equilibrium one, and v is the rate at which crust subsides on the SQM's surface. It yields following estimate on the flux of neutrons reaching SQM's surface:

$$j_n \leqslant (2Dn_n R_n)^{\frac{1}{2}}, \tag{17}$$

n_n being the density of (free) neutrons far from the interface, and R_n — maximum production rate. Diffusion coefficient, $D = \bar{v}l/3$, can be estimated putting $l \simeq (n_b\sigma)^{-1}$ with $\sigma \simeq 10^{-24}\ \mathrm{cm}^{-2}$ appropriate for n energies of order of 1 MeV (n_b — baryon number density), and thermal velocities $\bar{v} \simeq (3\ T/m_n)^{\frac{1}{2}}$. Rate R_β of β-reaction converting protons into neutrons in the presence of degenerate (relativistic) electrons with chemical potential μ_e, calculated in the approximation treating all protons as unbound and neglecting inverse reaction, is $R_\beta \simeq 1.6 \times 10^{28}\ (\mu_e/1\ \mathrm{MeV})^8\ \mathrm{sec}^{-1}\ \mathrm{cm}^{-3}$ [11]. Rate R_n is bigger then R_β by a factor Y_e^{-1}, as to the neutrons produced in the weak reaction we can add without changing the composition those liberated from split nuclei (dissociation is a much faster process). Finally we find the following constraint for j_n:

$$j_n \leqslant 7.4 \times 10^{30} (T/1\ \mathrm{MeV})^{\frac{1}{2}} (\mu_e/1\ \mathrm{MeV})^4 (n_n/Y_e n)^{\frac{1}{2}}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}.$$

Factor $(n_n/n_b)^{\frac{1}{2}}$ decays exponentially with T^{-1} when we are below neutron drip densities (also μ_e in hot matter is lower then in the cold one producing the same pressure). We find that this neutron flux is much to small to supply baryons efficient enough to maintain high temperature. In our estimate we have not taken into account convection in the crust, which can considerably improve transport of neutrons to SQM's surface. Unless neutron flux is increased this way many orders of magnitude this mechanism would not allow for burning of the crust, especially its outer parts. We will not analyse it further as we can point out to another mechanism, which seems to be much more efficient.

5. Electron annihilation in SQM

Results of the previous two sections suggest that the deleptonization of nuclear matter conversed to SQM should also be performed inside SQM, where we can expect it to be more efficient. In the next section we will investigate how particles cross potential barrier to reach the surface of SQM, and now we will analyse deleptonization.

Number of electrons per baryon in matter "eaten" from the crust $Y_e \sim 0.3$ is orders of magnitude bigger then corresponding value for equilibrium SQM, which means that practically every incoming electron must be annihilated. This is achieved in reactions:

$$\mathrm{u} + \mathrm{e} \to \mathrm{d} + \nu, \tag{18a}$$

and analogous one with s quark in the place of d:

$$\mathrm{u} + \mathrm{e} \to \mathrm{s} + \nu. \tag{18b}$$

Since $p_e, p_\nu \ll p_q$ electron annihilation has typically smaller phase space then strangeness production in reaction (15), and increased electron density in the surface layer of SQM (needed to create this phase space) heightens Coulomb barrier. Rates for these two reactions calculated in the approximation that all particles are massless, Fermi distributions taken as θ functions, and μ_e much less then chemical potential μ_q of quarks are:

$$R_{ue\to d(s)\nu} = \frac{1}{30\pi^5} G_F^2 \begin{pmatrix} \cos^2\theta_C \\ \sin^2\theta_C \end{pmatrix} \mu_q^2(\mu_e+\mu_u-\mu_{d(s)})^6. \tag{19}$$

If $\mu_u \gg \mu_s$ (composition far from equilibrium) second reaction has additional phase space and:

$$R_{ue\to s\nu} = \frac{1}{30\pi^5} G_F^2 \sin^2\theta_C \mu_q^2(\mu_e^6+6\mu_e^5(\mu_u-\mu_s)+15\mu_e^4(\mu_u-\mu_s)^2), \tag{20}$$

but nonstrange process should dominate anyway. We can perform now a simplified calculation of the rate at which electrons are annihilated in the surface layer at SQM's front. Chemical potentials there are shifted from their equilibrium values (which satisfy β-equilibrium condition $\bar{\mu}_u+\bar{\mu}_e = \bar{\mu}_d = \bar{\mu}_s$):

$$\mu_i(x) = \bar{\mu}_i+\Delta\mu_i(x), \tag{21}$$

where i denotes u, d, s or e. Because $\mu_q \gg \mu_e$ in neutral system we expect that $\Delta\mu_q$ should be typically much smaller than $\Delta\mu_e$, and we will ignore it in expressions for reaction rates. When the motion of SQM's front is neglected (it increases the rate but only slightly) charge neutrality condition for the steady state implies

$$D_q n_e'' - R = 0, \tag{22}$$

with

$$R \equiv (R_{ue\to d\nu}+R_{ue\to s\nu}) \simeq \frac{1}{30\pi^5} G_F^2\bar{\mu}_q^2\Delta\mu_e^6,$$

and D_q — diffusion coefficient of quarks, taken to be the same for each quark flavour ($D = \bar{v}l/3$, with $\bar{v} = 1$ and $l = l_0(\mu/T)^2$). Electrons are relativistic:

$$n_e = (\bar{\mu}_e+\Delta\mu_e)^3/3\pi^2.$$

We can solve Eq. (22) and find the flux j_e of electrons annihilated:

$$j_e = \int_{-\infty}^{0} R(\Delta\mu_e(x))dx,$$

$$j_e = \left(\frac{2}{7\pi^2}\,\frac{l_0}{3}\left(\frac{\mu_q}{T}\right)^2 \frac{1}{30\pi^5} G_F^2\mu_q^2\bar{\mu}_e^2\Delta\mu_e^7\left(1+\tfrac{7}{4}\left(\frac{\Delta\mu_e}{\bar{\mu}_e}\right)+\tfrac{7}{9}\left(\frac{\Delta\mu_e}{\bar{\mu}_e}\right)^2\right)\right)^{\frac{1}{2}}. \tag{23}$$

Flux of baryon number which can be absorbed by SQM will be a factor $1/Y_e$ larger:

$$j_b = j_e/Y_e, \tag{24}$$

where Y_e refers to the matter in the crust (we assume $Y_e = 26/56$).

6. *Flux of particles reaching SQM*

We will calculate now the flux of baryons transferred from the crust to SQM. All these particles can be treated at temperatures and pressures of interest as nonrelativistic Maxwell-Boltzmann gases. Flux of nuclei (A, Z) hitting SQM's surface is:

$$j_{(A,Z)} = \left(\frac{T}{2\pi m_{(A,Z)}}\right)^{\frac{1}{2}} e^{-ZV_C/T} n_{(A,Z)},$$

where $n_{(A,Z)}$ denotes their density at the interface. Because of the factor $e^{-ZV_C/T}$ resulting from the existence of Coulomb barrier, protons are the only charged particles capable of transporting baryon number in nonnegligible quantities. We assume that each nucleon reaching the surface of SQM is absorbed.

At the same time some baryons will be evaporated from SQM. Chemical potential of neutrons in equilibrium with SQM is:

$$\mu_{\mathrm{nvap}} \simeq m_{\mathrm{n}} - W, \tag{25}$$

where W is the energy released by conversion of one neutron to SQM at zero temperature and pressure. Chemical potentials of all other particles in equilibrium "vapor" are determined through β-equilibrium ($\mu_{\mathrm{p}} + \mu_{\mathrm{e}} = \mu_{\mathrm{n}}$) and charge neutrality conditions.

Density of neutron "vapor":

$$n_{\mathrm{nvap}} = 2\left(\frac{m_{\mathrm{n}} T}{2\pi}\right)^{\frac{3}{2}} e^{-W/T},$$

is plotted in Fig. 1 together with that of protons and total baryon number density of such equilibrium baryon gas. Resulting net flux of particles from the crust to SQM is:

$$j_{\mathrm{p}} = \left(\frac{T}{2\pi m_{\mathrm{p}}}\right)^{\frac{1}{2}} e^{-V_C/T}(n_{\mathrm{p}} - n_{\mathrm{pvap}})$$

in the case of protons and:

$$j_{\mathrm{n}} = \left(\frac{T}{2\pi m_{\mathrm{n}}}\right)^{\frac{1}{2}} (n_{\mathrm{n}} - n_{\mathrm{nvap}})$$

for neutrons. Burning can proceed only when it means steering towards equilibrium ($n_i > n_{i_{\mathrm{vap}}}$). Neutrons do not feel Coulomb repulsion and their density close to the interface will be reduced. In stationary case (and without efficient neutronization in the crust) neutron flux can be only $(1 - Y_{\mathrm{e}})/Y_{\mathrm{e}}$ times that of protons, so at SQM's surface neutron density should be only slightly bigger than its "vapor" value. Transfer of protons is a limiting factor and the total flux of baryons will be:

$$j_{\mathrm{b}} \simeq \frac{1}{Y_{\mathrm{e}}}\left(\frac{T}{2\pi m_{\mathrm{u}}}\right)^{\frac{1}{2}} e^{-V/T}(n_{\mathrm{p}} - n_{\mathrm{pvap}}). \tag{26}$$

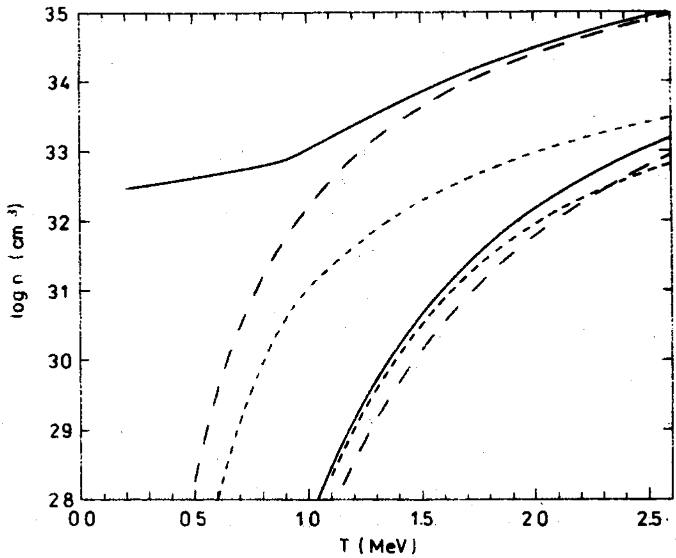

Fig. 1. Baryon gas in equilibrium with SQM. Logarithms of neutron (long dashes), proton (short dashes) and total baryon number (solid) densities versus temperature when SQM is ($W = 20$ MeV), or is not ($W = 8$ MeV, upper curves) absolutely stable

We calculate the height of Coulomb barrier from Eq. (1). We put there for $p_{e_{SQM}}$ the value of electron chemical potential at the surface $\mu_{e_{SQM}} = \bar{\mu}_e + \Delta\mu_e$ (Eq. (21) — electrons in SQM are relativistic). Similarly we will assume $p_{e_c} = (3\pi^2 n_{e_c})^{\frac{1}{3}}$, where n_{e_c} is the density of electron gas in the crust (it is incorrect when electrons in the crust are nondegenerate and/or nonrelativistic but in this case reduction of V_C they produce is not significant anyway).

For given temperature and composition of matter at the interface we find $\Delta\mu_e$ value for stationary flow of baryons (rate of electron annihilation in the surface layer of SQM equal to their inflow with protons).

7. *Burning of the crust*

Process of burning of the crust can be best represented in the (P, T) plane, where P is the pressure at crust's base. It is pressure P which determines the mass M of remaining crust. M is a tiny fraction of star's mass M_s and crust is thin compared to star's radius. SQM's density changes very weakly with temperature, so there will not be any significant contraction of SQM's bag filling the star while cooling. We will use Newtonian gravity approximation:

$$\frac{GM_sM}{R^2} = 4\pi R^2 P, \tag{27}$$

where R is star's radius. For our strange star we will assume sizes typical for neutron stars, namely:

$$M_s \simeq 1.4\, M_\odot = 2.8\times 10^{33}\mathrm{g}, \quad R \simeq 10\ \mathrm{km},$$

and so gravitational potential on the surface $GM_s/R \simeq 0.2$.

Position in (P, T) plane determines composition of matter at the interface. As discussed in the previous section neutron chemical potential must be close to its "vapor" value (25). In equilibrium (with respect to strong reactions) this condition uniquely relates composition and pressure. Contributions to the pressure come from baryon gas — a Maxwell--Boltzmann gas with $P_{\mathrm{bar}} = n_{\mathrm{bar}}T$, n_{bar} being the total density of particles containing baryons, electron (and positron) gas and radiation:

$$P = P_{\mathrm{bar}}+P_{\mathrm{el}}+P_{\mathrm{rad}}.$$

To determine whether energy released during burning can cover the loses in neutrino emission we also have to know how much energy is released per each intercepted baryon. Some fraction of released energy need to be supplied to the crust in order to preheat it to the required temperature — it can change the structure of the crust. This energy can be returned later when hot matter is absorbed. We can calculate released energy in an idealized case of a column of ordinary matter, kept at constant pressure P, with temperature which is high at the contact layer, and falls down as we move away from the interface with SQM. When some baryons are transferred to SQM and temperature distribution remains unchanged (column of matter must be appropriately long), result is the same as if we removed the same number of baryons from the cold end of the column. So our prescription is to find chemical potential per baryon in cold nuclear matter, producing the same pressure as that present at the interface. In our calculations cold nuclear matter means ^{56}Fe nuclei in electron gas (with no electrostatic corrections included). Energy released per baryon W_b is then:

$$W_b = W+\tfrac{1}{56}(m_{\mathrm{Fe}}+26\mu_e)-m_n,$$

where m_{Fe} denotes mass of Fe nucleus, and μ_e — chemical potential of electrons in their degenerate gas. Work done by the force exerting pressure (in the star it is gravity acting on higher layers of the crust) has its contribution to W_b.

Condition

$$j_b W_b = h_c$$

delimits the region in (P, T) plane where burning releases enough energy to cover the loses for emission (curve a in Fig. 2). In fact, this borderline should be slightly shifted towards higher P regions as we neglected that the neutrinos emitted from the layer of flavour nonequilibrium may have nonthermal energies. Including this correction should not significantly change the final result of burning (which is not very sensitive to W value for absolutely stabile SQM, cf. Fig. 3).

Points above curve a describe a crust with base dense enough to burn releasing more heat than can be emitted at given temperature. Temperature then rises, so the corresponding

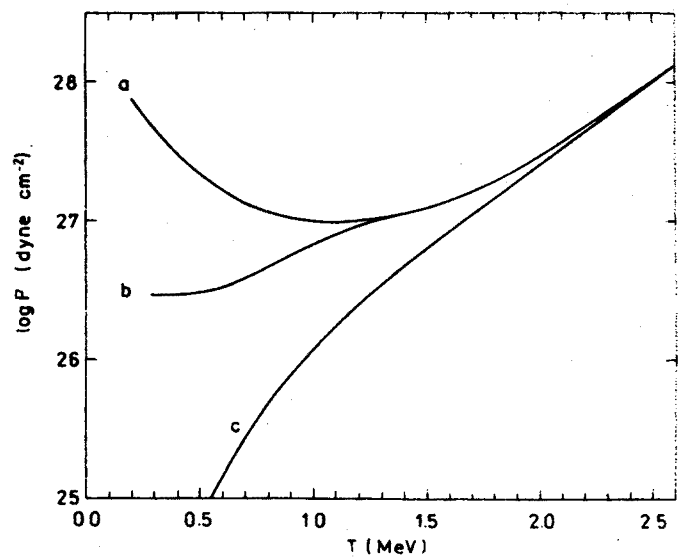

Fig. 2. Pressure at the interface versus temperature. Points above curve a correspond to "burning" which releases more energy than can be emitted at this temperature (dense crust). Oppositely, curve c describes the crust with baryon gas in equilibrium with SQM (in the region below, crust is rather created then removed). Curve b follows the decrease in P (resulting from the interception of baryons by SQM) when temperature changes according to Eq. (5). Figure is drawn for strongly bound SQM ($W = 20$ MeV) with (equilibrium) electron chemical potential equal to 14 MeV

point moves to the right until it reaches borderline. We expect it then to slide down along a. At lower temperatures it is more difficult to push baryons through the potential barrier, and P on our "equilibrium" curve rises again. History of the crust is described by the curve with nonincreasing P — crust's mass is always reduced by burning (unless we start from below curve c in Fig. 2 e.g. from hot and for some reason bare quark bag). At some moment supply of particles to SQM becomes insufficient to balance the loses and temperature at the interface no longer waits until burning of the layer of given density is completed, but decreases at a rate well approximated by the expression for "free cooling" (5). It does not immediately cut off particle supply, and we shall follow changes in P taking place in this phase. With $M \simeq Nm_u$, (N — baryon number of the crust, m_u — unit mass) (5) and (27) give for this "free cooling" trajectory:

$$\frac{dP}{dT} = \frac{4t_0}{T^5}\left(\frac{GM_s}{R}\right)\frac{m_u}{R}j_b. \tag{28}$$

When "heat equilibrium" curve a flattens system switches to this "free cooling" trajectory b at a point where it slope starts to be bigger.

Final pressure achieved during burning can be translated into baryon number density of the ^{56}Fe matter at the base of the crust, when it is cooled down. It is shown in Fig. 3 for various values of electron chemical potential in (equilibrium) SQM together with corresponding values for the situation when no burning of the crust occurs (chemical po-

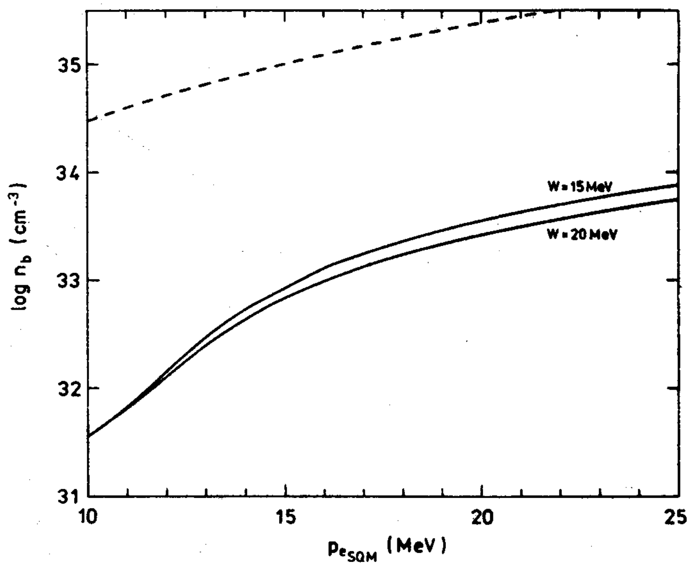

Fig. 3. Baryon number density at the base of the crust, cooled down after burning process is completed (solid curves) for $W = 20$ MeV, $W = 15$ MeV and various values of electron Fermi momentum in (equilibrium) SQM. If no burning could occur this density would be described by the dashed curve

tential the same for gas inside SQM and the crust). In all our calculations concerning the matter in the crust we took into account protons, neutrons, alpha particles and ^{56}Fe nuclei (ground states) as its only constituents, which should be a reasonable approximation at temperatures and densities relevant to our analysis. Our results should be treated as order of magnitude estimates anyway (apart from approximations made, we neglected some other factors which may be important, e.g. star's rotation).

Burning can substantially reduce the crust. This should be particularly important when final mass density at the crust's base can be lower then about 10^{10} g cm^{-3} (it corresponds to baryon number density $\sim 6 \times 10^{33}$ cm^{-3}) — it changes the relation between internal and surface temperature of a star (regions of bigger densities are expected to become isothermal in both neutron and strange stars, cf. Ref. [3] and references therein). If accretion of some material onto the star occurs without heating of lower parts of its crust enough to initiate the burning, then crust can grow up to the size corresponding to upper curve in Fig. 3.

It also seems impossible to form a bare quark star.

REFERENCES

[1] E. Witten, *Phys. Rev.* **D30**, 272 (1984).
[2] E. Fahri, R. L. Jaffe, *Phys. Rev.* **D30**, 2379 (1984).
[3] C. Alcock, E. Fahri, A. V. Olinto, *Astrophys. J.* **310**, 261 (1986).
[4] P. Haensel, J. L. Zdunik, R. Schaeffer, *Astron. Ap.* **160**, 121 (1986).
[5] T. Chmaj, W. Słomiński, *Phys. Rev.* **D40**, 165 (1989).

[6] G. Baym, R. L. Jaffe, E. W. Kolb, L. McLerran, T. Walker, *Phys. Lett.* **106B**, 181 (1985).
[7] N. Iwamoto, *Ann. Phys.* (N. Y.) **141**, 1 (1982).
[8] N. Iwamoto, *Phys. Rev. Lett.* **44**, 1637 (1980).
[9] P. Haensel, A. J. Jerzak *Acta Phys. Pol.* **B20**, 2, 141 (1989).
[10] A. V. Olinto, *Phys. Lett.* **192B**, 71 (1987).
[11] S. L. Shapiro, S. A. Teukolsky, *Black Holes, White Dwarfs, and Neutron Stars*, J. Wiley Pub., New York 1983.