Astrophysical Bounds on the Properties of Strange Quark Matter

M. Jändel ¹⁾

CERN - Geneva

Abstract

Constraints on the size of the Coulomb barrier and the universal abundance of stable strange quark matter are calculated assuming that the evolution of stars and the nucleosynthesis at stellar sites are not dominated by strange quark matter. The results are applied to find the minimum required beam energy and sensitivity in a heavy ion activation search for strange quark matter in laboratory samples.

¹⁾ CERN, CH- 1211 Geneva 23, Switzerland

Strange-quark matter (SQM) is a hypothetical stable phase of baryonic matter consisting of almost equal numbers of u , d and s quarks. The concept of SQM has been used to provide explanations for the missing dark matter in cosmology [1], the puzzling properties of the compact cosmic-ray source Cygnus X-3 [2] and the extraordinarily violent 1979 March 5 gamma-ray burst [3]. General theoretical arguments and recent model calculations [4] suggest that SQM could be the ground state of QCD at nonvanishing baryon number. Theoretical uncertainties prevent, however, any firm conclusion.

The behaviour of a lump of SQM in a stellar core or in a laboratory experiment depends on a few basic attributes such as the size, the mass, the Coulomb barrier and energetically preferred size. Rough estimates of these properties can be made. The relation between SQM size and baryon number is,

$$R_s = a A_s^{1/3}, \quad (1)$$

where R_s and A_s are the radius and baryon number respectively. Model calculations [4] indicate that $.87 \text{ fm} < a < 1.22 \text{ fm}$. Here $a = .98 \text{ fm}$ is assumed whenever a definite value is required. A lump of SQM with R_s smaller than the electron Compton wave length is usually called a strangelet.

Predictions of SQM electrostatic properties are very model-dependent. Witten argued [1] that the SQM surface Coulomb potential V_c could be as large as 50 MeV. Strange quark matter, in or between the stars, would then be completely shielded against absorption of atomic nuclei. Farhi and

Jaffe [4] gives no definite prediction for the value of V_c . A reasonable variation of model parameters allows the charge carried by quarks to be either positive or negative. A lump of SQM could hence be surrounded by a compensating cloud of either electrons or positrons. As negatively charged SQM in any cosmic abundance would have catastrophic consequences it is, however, usually assumed that $V_c > 0$.

Any lump of SQM larger than a few fermi could be stable against emission of nuclei. It is, however, quite possible that some specific baryon number A_g is energetically favoured. SQM with $A_s = A_g$ would then be the ground state of baryonic matter. Significantly larger lumps of SQM would decay by fission. The sign of the SQM surface tension is, however, not known. Coulomb effects gives a negative contribution but strong interaction effects could easily lead to a total positive sign of the surface tension [4].

A small preferred size caused by Coulomb effects would be about as large as the electromagnetic screening length λ_{em} in SQM. Using the Thomas-Fermi approximation we find that $\lambda_{em} \approx 5$ fm for reasonable MIT bag model parameters. The preferred SQM baryon number would then be about 10^3 . This is in agreement with observations if Centauro events [5] are caused by strangelets. A detailed theoretical discussion of SQM electrostatics is not within the scope of this paper and will be presented elsewhere. To be independent of model calculations we shall study a wide range of most stable sizes.

Strange matter that is embedded in the hot core of a star will absorb nuclei in proportion to the total SQM surface Y . For sufficiently small A_g the available SQM surface is always proportional to the total SQM baryon number. Since the rate of increase is proportional to the total abundance there will be a bacterial growth of SQM inside the stellar core. We shall refer to this scenario as the strangelet model. If the SQM surface tension is positive a seed strangelet can grow to an unlimited size. The SQM

growth rate in stars is then slower than in the strangelet model. This case shall be referred to as the bulk model.

Atomic nuclei could, in principle, decay to SQM but this would be a multi-order weak interaction process and hence highly suppressed. Witten suggested [1] that SQM could be created in the early universe. Recent calculations [6] indicate, however, that any primordial SQM would have decayed completely by evaporation of neutrons before the universe was one second old. SQM could appear spontaneously in dense neutron-rich matter. A first generation of supernovae could therefore produce seeds of SQM and eject them into the interstellar medium. Later generations of stars would then contain such seeds from the beginning of their evolution. Witten speculated [1] that SQM can be ejected in collisions between neutron stars or during mass transfers in binary systems containing a compact star. The universal abundance of SQM was estimated to be $10^{-6} - 10^{-20}$ depending on the production mechanism.

Seeds of SQM could, under favorable conditions, grow and multiply by absorbing normal matter from stars. A wealth of astronomical evidence confirm, however, that the burning of light nuclei into heavier nuclei and not the burning of nuclei into SQM is the main energy source for stars. Stellar nucleosynthesis can also be understood without any reference to SQM. Theories of SQM are hence constrained by conventional astrophysics. For a given initial SQM concentration in stars we shall obtain a lower limit for the SQM Coulomb barrier.

Neutron capture processes in stars provides bounds on the universal SQM abundance. The results depend on the seed size and both the strangelet and the bulk-model are considered. We assume that SQM is deeply bound so that neutrons or nuclei are not evaporated at normal stellar temperatures.

The growth of SQM in a stellar core is described by $X(t)$, the SQM fraction of the total baryon number at time t . A young star is assumed to contain an initial SQM fraction X_0 in the form of seed strangelets each having an average baryon number A_0 . The number of absorbed nucleons per unit SQM surface and unit time F depends on the physical conditions in the star and on the SQM Coulomb potential.

In the bulk model the baryon number of each SQM seed will increase by $dA_s = 4\pi a^2 A_s^{2/3} F dt$ during a time interval dt . The seed baryon number A_s grows hence according to,

$$A_s(t) = A_0 \left(t/3\tau + 1 \right)^3,$$

$$\tau^{-1} = 4\pi a^2 A_0^{-1/3} F,$$

where τ is the the time scale of SQM growth. As each seed grows independently we find that $X \sim A_s$ so that

$$X(t) = X_0 \left(t/3\tau + 1 \right)^3. \quad (2)$$

In the strangelet model there is a preferred strangelet baryon number A_g . Any significantly larger lump of SQM decays by fission. It follows that $A_0 = A_g$. The total SQM baryon number A_s in a stellar core increases according to $dA_s = (A_s/A_g) Y_0 F dt$ where $Y_0 = 4\pi a^2 A_g^{2/3}$ is the strangelet surface area. The SQM abundance must hence increase exponentially:

$$X(t) = X_0 e^{t/\tau}. \quad (3)$$

To calculate F we use a Maxwellian velocity distribution and a geometrical nucleus-strangelet cross section. The contribution to F from the capture of nuclei of charge Z , mass m , and number density N at temperature T is,

$$F = (2\pi m)^{-1/2} T^{-3/2} A N \int_0^{\infty} e^{-E/T} P(E) E dE. \quad (4)$$

The quantum mechanical barrier penetration probability $P(E)$ is,

$$P(E) = (1 + e^{2G})^{-1},$$

$$G = \int_{R_0}^{R_s} (2m(ZV(r) - E))^{1/2} dr, \quad (5)$$

where R_0 is the classical turning-point.

The form of the SQM Coulomb potential $V(r)$ depends on how R_s compares with the electron Compton wave length λ_e . A strangelet with $A_s < \lambda_e$ carries its electron cloud outside. The external Coulomb potential is then $V(r) = \alpha Z_s / r$. For lumps with $R_s > \lambda_e$ we can use the Thomas-Fermi approximation $V(r) \approx \mu$ where μ is the electron chemical potential. Ignoring the electron mass we insert the electron density $n = \mu^3 / 3\pi^2$ in the Poisson equation finding $\Delta V = (4\alpha / 3\pi) V^3$. For large lumps,

$$V(r) \approx \sqrt{\frac{3\pi}{2\alpha}} \frac{1}{r+b}, \quad (6)$$

where r is the distance from the SQM surface.

We first calculate F for the potential $V(r) = \alpha Z_s / r$. Barrier penetration rather than direct capture from the high-energy tail of the Maxwell distribution dominates for sufficiently small strangelets. Using essentially the methods of Gamow and Teller [7] we note that there is a sharp maximum in the integrand of (4) due to the competition between the Maxwell factor

$\exp(-E/T)$ and the Gamow factor $\exp(-2G)$. Expanding the integrand in the neighborhood of the maximum at $E = E_m$ we find after integration,

$$\begin{aligned} F &= \frac{(2\pi\alpha)^{1/3}}{\sqrt{3}} (Z Z_s T/m)^{1/3} A N e^{Q_1 - 3E_m/T}, \\ E_m &= \left(\frac{\pi\alpha}{\sqrt{2}} Z Z_s T \sqrt{m} \right)^{2/3}, \\ Q_1 &= 4\sqrt{2}\alpha (Z Z_s m)^{1/2} A_0^{1/6}. \end{aligned} \quad (7)$$

This expression is accurate if E_m is smaller than the Coulomb barrier $E_c = ZV(R_s)$. The difference between (7) and the result in [7] for thermonuclear reaction rates is due to our choice of a geometrical rather than a wave mechanical cross-section.

For the case of large lumps of SQM with electrons within we calculate first, using the potential (6), the constant G in the Gamow factor finding,

$$G = \sqrt{\frac{3\pi m}{\alpha E_c}} \left(\frac{\pi}{2} \sqrt{\frac{E_c}{E}} - 1 \right). \quad (8)$$

Expanding the integrand in (4) as before we get,

$$\begin{aligned} F &= \sqrt{\pi} (2/9\alpha)^{1/6} (T/m)^{1/3} A N e^{Q_1 - 3E_m/T}, \\ E_m &= \pi (3/4\alpha)^{1/3} (m T^2)^{1/3}, \\ Q_1 &= \sqrt{12\pi/\alpha} (m/E_c)^{1/2}. \end{aligned} \quad (9)$$

If $E_m > E_c$ classically allowed capture contribute significantly to F . Inserting $P(E) = \theta(E_c)$ in (4) we get,

$$F = \frac{E_c + T}{\sqrt{2\pi m T}} A N e^{-E_c/T} \quad (10)$$

Using the proper form of F in (2) and (3) we now determine under what conditions stars will be consumed by strange matter. The SQM seed baryon number is chosen within the range $10^2 - 10^{16}$. Heavier lumps of SQM than $A_s = 10^{16}$ could not be present in laboratory samples since they would sink to the centre of the Earth [8]. The lower limit is based on theoretical prejudice and on the fact that observed strange hadrons are unstable. Initial SQM mass fractions within the interval $10^{-2} - 10^{-26}$ are considered here.

For the stellar core chemical composition, temperature T , density ρ and the duration t of each burning stage we use a recent stellar evolution model calculation [9] for a population I star of 25 solar masses. A star of this size develops through successive thermonuclear burning stages from hydrogen burning to silicon burning and undergoes presumably also a final explosive phase. It is assumed here that the chemical composition, central temperature and density are stable during each burning stage. To be conservative the lower limit $V_{\min}$ of the SQM Coulomb barrier is determined from the condition $X(t) = 1$ for $V_c = V_{\min}$. The structure of the star would obviously change significantly long before the entire core is converted to SQM.

Small variations in ρ and t due to for example the choice of a different stellar structure model or a different stellar mass are not important since $V_{\min}$ depends logarithmically on these properties. The dependence on T is linear but the value of the core temperature is quite stable for a given burning stage within a wide range of model calculations at different stellar masses. Results are presented for each burning stage. If alternative models for stellar evolution and nucleosynthesis that include SQM as an active component are constructed some of these limits might be invalidated.

For each successive burning stage the charge of the fuel nuclei, the core temperature and the density increase while the typical time-scale decreases. The outcome of this competition is usually that $V_{\min}$ will be larger for later evolutionary stages. Hydrogen burning in the $M = 25 M_{\odot}$ star lasts for 1.2×10^7 yr. This duration is much shorter than for a low mass star like the sun. The core temperature of the sun is, however, lower than that of the $25 M_{\odot}$ star. Solar limits is therefore typically 25% lower than for the heavier star. At the next burning stage the SQM growth competes with the triple- α process which depends on a three-body resonance. $V_{\min}$ is in general about three times higher than in the previous stage. Carbon burning provides only slightly more significant results.

The neon burning chain starts with the endothermic photo-disintegration reaction,

Free α -particles are then absorbed by ^{20}Ne , ^{24}Mg and possibly also by SQM. Although the fraction of α -particles is quite small this is more than compensated for by their small charge. SQM grows hence mainly by absorbing α -particles. We have used the detailed neon burning calculation in [10]. For a $16 M_{\odot}$ star neon burning take place at $T = 1.5 \times 10^9 \text{K}$ a total density of $3 \times 10^6 \text{gcm}^{-3}$ and a ^4He density of $6.3 \times 10^{-5} \text{gcm}^{-3}$. The duration of this stage is $4.3 \times 10^6 \text{s}$.

The most significant results is obtained for α -particle absorption during silicon burning. At temperature $T = 3 \times 10^9$ silicon is photo-disintegrated according to,

Heavier elements such as iron are then produced by the capture of α -particles and intermediate beta-decay processes. The alpha-abundance is well estimated by assuming chemical equilibrium between the ^{28}Si and ^4He populations [11]. The number density of α -particles is given by,

$$\log n_\alpha = 32.75 + \frac{1}{7} \log \rho_{\text{Si}} + \frac{9}{7} \log T_9 - 27.69/T_9, \quad (13)$$

where ρ_{Si} is the mass density of silicon. For the $25 M_\odot$ star we find $n_\alpha = 2.74 \times 10^{24} \text{cm}^{-3}$.

A realistic heavy ion activation experiment would be sensitive to SQM mass fractions larger than about 10^{-11} [12]. Since the fraction of heavy elements in a pop. I star is about 2% this corresponds to a SQM seed concentration of about $X_0 = 10^{-13}$. Values of V_{min} have been calculated for this case and the results are displayed in Figs. 1 and 2 for the strangelet and bulk model respectively. We have argued that $A_0 = 10^3$ would be a reasonable guess for the seed size. For silicon burning with $X_0 = 10^{-13}$ and $A_0 = 10^3$ we find $V_{\text{min}} = 3.65 \text{ MeV}$ in the bulk model and $V_{\text{min}} = 7.58 \text{ MeV}$ in the strangelet model. In both models V_{min} decreases with increasing A_0 . For the maximum seed baryon number that can be supported by terrestrial materials we obtain $V_{\text{min}} = 2.11 \text{ MeV}$ and $V_{\text{min}} = 3.31 \text{ MeV}$ in the bulk and strangelet model respectively. The effect of changing X_0 within the interval $10^{-2} - 10^{-26}$ is displayed in Fig. 3 for silicon burning in the bulk model. Assuming $A_0 = 10^3$ we find $V_{\text{min}} = 4.93 \text{ MeV}$ for $X_0 = 10^{-2}$ and $V_{\text{min}} = 2.11 \text{ MeV}$ for $X_0 = 10^{-26}$. The initial SQM abundance is much less important in the strangelet model. With the X_0 interval as above the variation in V_{min} is less than 10% of the $X_0 = 10^{-13}$ values.

Neutrons would be easily absorbed by SQM since they are not influenced by the Coulomb barrier. Assuming a geometrical absorption cross-section the parameter F in (2) and (3) is equal to the neutron flux.

Consider first the fate of SQM seeds in a high-flux nuclear fission reactor. The neutron flux is about $F = 10^{13} \text{ cm}^{-3}\text{s}^{-1}$. The exposure time could be as large as 20 yr if some SQM seeds are present in the construction material of the reactor core. The maximal SQM growth is then .02% which is much too small to be detected.

Trans-iron nuclei are produced in stars mainly through the s-process and the r-process. The s-process is thought to be related to the He-burning region in red giant stars. The time-integrated neutron flux has been found to be $.30 \text{ mb}^{-1}$ [13]. To avoid SQM dominance at the s-process site the condition $X_0 < 5.7 \times 10^{-4} A_0$ must be satisfied in the bulk model. The corresponding limits in the strangelet model are $X_0 < 4.1 \times 10^{-4}$ if $A_g = 10^2$ and $X_0 < 2.7\%$ if $A_g = 10^3$. For larger strangelets the results are even less significant.

The r-process neutron density is about 10^{24} cm^{-3} and the temperature is 10^9 K . The duration of the r-process is about 50 seconds [11]. Assuming a thermal energy distribution of neutrons we can calculate the neutron flux. Inserting the result in (2) we obtain,

$$X_0 < 10^{-25} A_0, \quad (14)$$

This result is combined with silicon burning limits in Fig. 3. In the strangelet model X_0 values within $10^{-2} - 10^{-26}$ would lead to a complete SQM take-over at the r-process site. Note, however, that the r-process neutron flux is not known with any precision. Estimated values within the range $10^{19} - 10^{31} \text{ cm}^{-3}$ [14] can be found in the literature. The corresponding variation in the numerical factor in (14) is $10^{-10} - 10^{-46}$.

The results in Figs. 1-3 serve as a constraint on theoretical models and as a guide for the planning of experiments to search for SQM. We conclude that the beam energy per unit projectile charge should not be

chosen lower than 8 MeV in a heavy ion activation experiment. In order to avoid background events due to nuclear inelastic reactions an upper limit for the beam energy of 14 MeV/Z was suggested in [12]. A high experimental sensitivity is required if the r-process estimate (14) is accurate. In order to detect $A_s = 10^{12}$ strangelets one must for example be able to measure SQM mass fractions smaller than 10^{-13} .

Strangelet fission could be caused by the capture of a heavy nuclear projectile. Strangelets that grows in a stellar core would spend a large fraction of the time close to the fission threshold since V_c is proportional to $A_s^{2/3}$ if Z_s/A_s is constant. The absorption of neutrons and helium nuclei in stars provides much less excitation energy than the capture of a heavy nucleus. Induced fission of strangelets could hence be a large fraction of SQM-related events in accelerator experiments. The fission fragments would have just a few keV of kinetic energy per unit baryon number but the released surface energy would provide a signal for such events.

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FIGURE CAPTIONS

Fig. 1 : Lower limit $V_{\min}$ of the strangelet Coulomb barrier versus most stable strangelet baryon number A_g for various stellar burning stages. The initial strangelet fraction is 10^{-13} .

Fig. 2 : Lower limit $V_{\min}$ of the bulk SQM Coulomb barrier versus SQM seed baryon number A_0 for various stellar burning stages. The initial seed fraction is 10^{-13} .

Fig. 3 : The lower limit $V_{\min}$ of the bulk SQM Coulomb barrier versus initial seed fraction X_0 , calculated in the case of stellar silicon burning, is displayed for the values 10^3 , 10^6 , 10^9 , 10^{12} and 10^{15} of the seed baryon number A_0 . Only X_0 values below the dashed line are allowed according to the r-process limit (14).

Fig. 1

Fig. 2

Fig. 3