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THE PHYSICS OF STRANGE MATTER

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ABSTRACT

Strange matter may be the ground state of matter. We review the phenomenology and astrophysical implications of strange matter, and discuss the possible ways for testing the strange matter hypothesis.

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1. INTRODUCTION

It has long been known that hadronic matter under very high pressure may undergo a phase transition to quark matter, but the idea that quark matter with strangeness can be stable at zero pressure was suggested only recently.[1]

Let's imagine we subject protons and neutrons to such high pressures that a phase transition to quark matter occurs. The baryon number of this high density phase would be in the form of up and down quarks. If the pressure is then returned to zero the quark matter state of up and down quarks will go back to a hadronic state of protons and neutrons. In heavy nuclei, protons and neutrons are the relevant degrees of freedom, not up and down quarks. Therefore, at low pressures, the energy per baryon of two-flavor quark matter, ϵ_{2QM}, is higher than the energy per baryon of nuclear matter, $\epsilon_{NM} < \epsilon_{2QM}$.

If high density quark matter exists long enough for weak interactions to take place, some up and down quarks will become strange quarks as long as the strange quark mass, m_s, lies below the chemical potential of the up and down quark matter system, μ_{2QM}. The presence of strange quarks increases the number of degrees of freedom in the system, therefore decreasing the energy per baryon (or chemical potential) of the system. In other words, if $m_s < \mu_{2QM}$, the energy per baryon of three-flavor quark matter, ϵ_{3QM}, is below that of two-flavor quark matter, $\epsilon_{3QM} < \epsilon_{2QM}$. When the pressure is then taken to zero, the three-flavor quark matter was expected to return to a nuclear matter phase. We know that both ϵ_{NM} and ϵ_{3QM} lie below ϵ_{2QM}, but we don't know how to compare ϵ_{NM} with ϵ_{3QM}. It is possible that, at zero pressure, three-flavor quark matter is stable, ($\epsilon_{3QM} < \epsilon_{NM}$), and therefore the ground state of matter. Stable three-flavor quark matter is called *strange matter.*[2]

So why aren't we all made of strange matter? The process described above for reaching the strange matter stage is not easily realized. Without the intermediate high density state, the conversion of nuclear matter into strange matter would require very high-order simultaneous weak interactions. The lowering of the chemical potential of a quark matter system by introducing a third degree of freedom can compensate for the increase in quark masses (due to m_s) only for a system with large baryon number, A, greater than some A_{min}. Strange matter is not stable for baryon number below A_{min}; for instance, for $A = 1$, we have the decay $\Lambda \to N\pi$. As long as A_{min} is greater than a hundred or so, we need not worry about the stability of ordinary (non-strange) matter.

In what follows, we review the current status of the strange matter hypothesis. First, strange matter and its phenomenology are discussed in a bag model framework. Second, some of the searches for such a state of matter are reviewed. Third, the astrophysical implications of strange matter and possible astrophysical observations that might lead to a resolution of the strange matter question are discussed.

2. STRANGE MATTER

In principle the theory of the strong interactions should contain the answer to the question of whether strange matter is stable. Unfortunately, as we are all too aware, QCD is not the friendliest theory when it comes to straight answers. We need to rely on alternative simplified models to test the idea at least qualitatively.

If strange matter is stable, it can exist over a wide range of masses: we have argued that there is a minimum baryon number for strange matter stability, but the maximum baryon number is only determined by gravitational instability. Strange matter can vary from nuclear size to whole neutron stars! In what follows, we will first discuss strange matter in bulk (for which surface effects can be neglected) and then we will address low-baryon number strange matter, or *strangelets*. (We will assume that finite temperature effects can be neglected.)

2.1 Bulk Strange Matter

Farhi and Jaffe[2] (FJ) studied strange matter via the MIT bag model and found sizeable regions of parameter space for which strange matter is stable. Following their approach, we can model strange matter as a zero-temperature Fermi gas of up (u), down (d), and strange (s) quarks, confined to a bag of vacuum energy B, and neutralized by electrons (e). The pressure for each component of the system, including perturbative QCD corrections up to one-gluon exchange ($O(\alpha_c)$), can be written as:

$$P_u = \frac{\mu_u^4}{4\pi^2}\left(1 - \frac{2\alpha_c}{\pi}\right) \quad , \tag{1}$$

$$P_d = \frac{\mu_d^4}{4\pi^2}\left(1 - \frac{2\alpha_c}{\pi}\right) \quad , \tag{2}$$

$$P_s = \frac{1}{4\pi^2}\left\{\mu_s\left(\mu_s^2 - m_s^2\right)^{1/2}\left(\mu_s^2 - \frac{5}{2}m_s^2\right)\right.$$

$$
\begin{aligned}
&+\frac{3}{2}m_s^4\ln\left[\frac{\mu_s+(\mu_s^2-m_s^2)^{1/2}}{m_s}\right] \\
&-\frac{2\alpha_c}{\pi}\left[3\left(\mu_s\left(\mu_s^2-m_s^2\right)^{1/2}-m_s^2\ln\left[\frac{\mu_s+(\mu_s^2-m_s^2)^{1/2}}{\mu_s}\right]\right)^2\right. \\
&-2\left(\mu_s^2-m_s^2\right)^2-3m_s^4\ln^2\frac{m_s}{\mu_s} \\
&\left.\left.+6\ln\frac{\rho_R}{\mu_s}\left(\mu_s m_s^2\left(\mu_s^2-m_s^2\right)^{1/2}-m_s^4\ln\left[\frac{\mu_s+(\mu_s^2-m_s^2)^{1/2}}{m_s}\right]\right)\right]\right\} \quad , \qquad (3)
\end{aligned}
$$

$$
P_e=\frac{\mu_e^4}{12\pi^2} \quad , \qquad (4)
$$

where the chemical potential for each species is μ_i ($i = u, d, s, e$), and ρ_R is the renormalization point (see ref. 2). The number density of each species is $n_i = \partial P_i/\partial\mu_i$. The total pressure, energy density, and baryon number of the system will then be:

$$
P=\sum_i P_i - B \quad , \qquad (5)
$$

$$
\rho=\sum_i(\mu_i n_i - P_i) + B \quad , \qquad (6)
$$

$$
n_B=\frac{n_u+n_d+n_s}{3} \quad . \qquad (7)
$$

Chemical equilibrium is insured by the following weak interactions: $u \rightarrow d($ or $s) + e^+ + \bar{\nu}$, $d(s) + e \rightarrow u + \nu$, $u + e^- \rightarrow d(s) + \nu$, $d(s) \rightarrow u + e^- + \bar{\nu}$, and $u + d \leftrightarrow u + s$, which imply $\mu_u + \mu_e = \mu_d = \mu_s$, where the neutrinos are assumed to escape the system ($\mu_\nu = 0$). Charge neutrality imposes one more constraint upon the system: $2n_u - n_d - n_s - 3n_e = 0$. These two constraints leave the system with only one free parameter, say $\mu \equiv \mu_d = \mu_s$.

Strange matter is stable at zero pressure if the energy per baryon number of strange matter is less than the nucleon mass, *i.e.,* $\rho/n_B = \epsilon_{3QM} < 939$ MeV. (Actually, for strange matter to be the ground state of matter, we require $\epsilon_{3QM} < 930$ MeV, the energy per baryon number of ^{56}Fe.) Using the equations above, we can calculate ϵ_{3QM} as a function of B, m_s, and α_c. In Fig. 1, we show contours of fixed ϵ_{3QM} in the m_s versus B plane (with $\alpha_c = 0$). There is a wide range of values of B and m_s within which strange matter is stable. The binding energy of strange matter relative to ^{56}Fe is $\Delta = 930$ MeV$-\epsilon_{3QM}$. For $\alpha_c = 0$, 145 MeV $< B^{1/4} <$ 165 MeV, and $m_s <$ 300 MeV, there are stable solutions for strange matter. The lower limit on B is due to the requirement that two-flavor quark matter not be absolutely stable: for $\alpha_c = 0$, this requires $B > 145$ MeV. The upper bound on B for strange matter stability is reached at $m_s = 0$. The mass of the strange quark is not well determined, but it is expected to lie between 100 and 400 MeV.[2] The window of strange matter stability in the m_s versus B plane also changes as the value of α_c is increased (see ref.2).

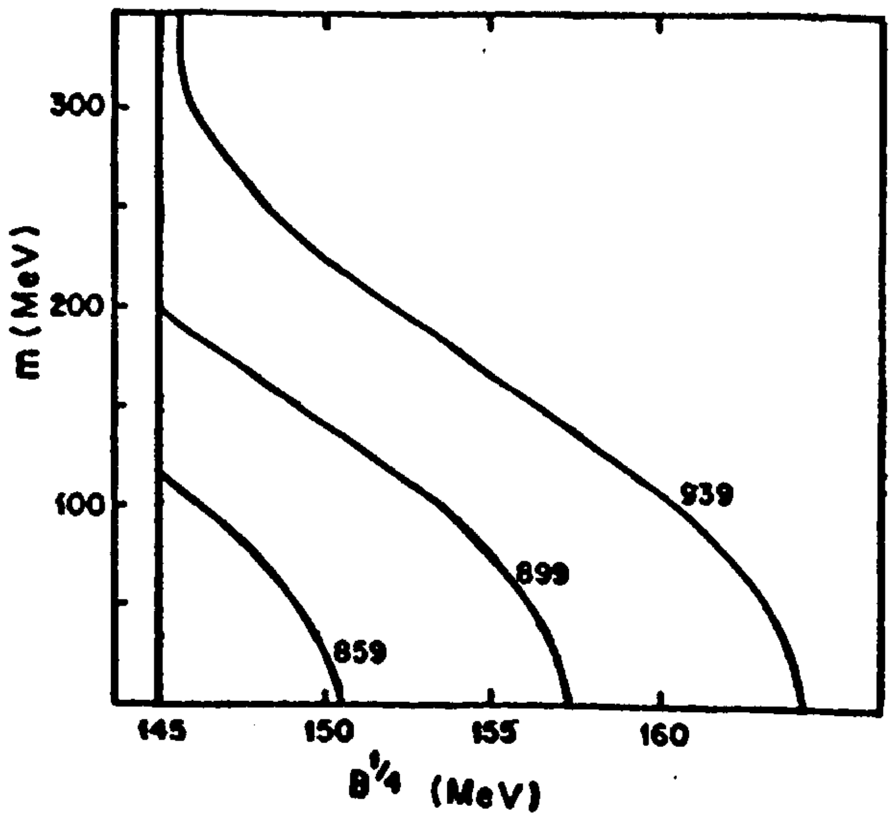


Figure 1. m_s versus B plane, for $\epsilon_{3QM} = 939MeV, 899MeV, 859MeV$ and $\alpha_c = 0$.

The bag model analysis is highly suggestive, but certainly not conclusive. For instance, the use of perturbation theory in the strong coupling limit is certainly risky. Thus the stability of strange matter is uncertain, but this need not prevent us from studying its properties.

In the limit $m_s \to 0$, strange matter is neutral, with no need for electrons.

For larger strange quark mass, $m_s \gg m_u$ and m_d, strange quarks are usually less abundant than up and down quarks, so a small fraction of electrons permeate the quark matter medium, neutralizing it.

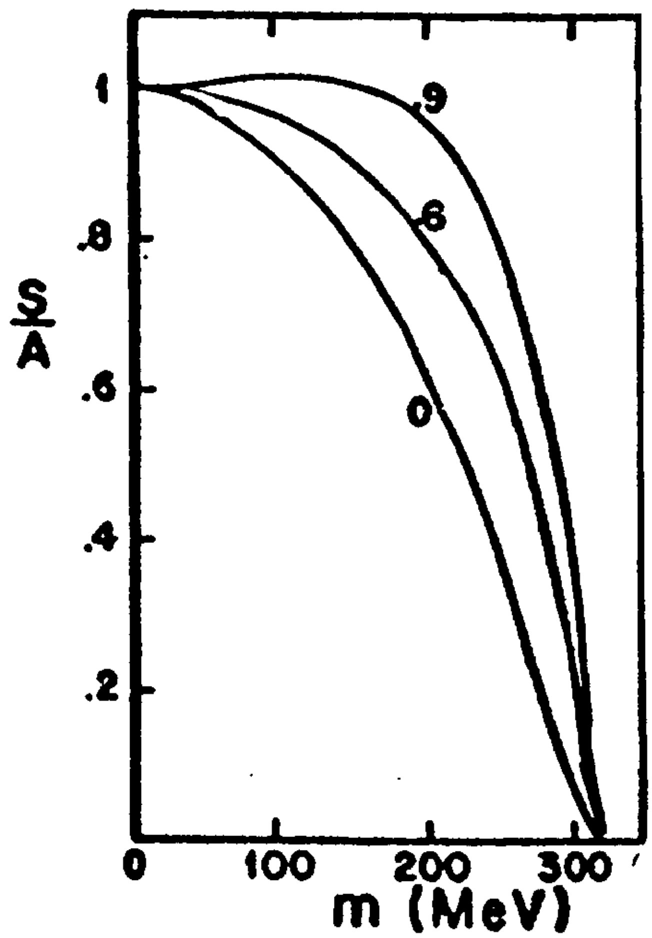


Figure 2. Strangeness per baryon number S/A as a function of m_s for $\alpha_c = 0, 0.6, 0.9$ and $\epsilon_{3QM} = 899 MeV$

The strangeness per baryon number as a function of m_s, for fixed $\epsilon_{3QM} = 899 MeV$, is shown in Fig.2. For low m_s, $-S/A \to 1$, while $-S/A \to 0$ as $m_s \to 330 MeV$. The case of high α_c has a curious behaviour, $-S/A > 1$ for some range in m_s. In quark matter, one-gluon exchange is repulsive. However, the repulsive interaction is weaker for massive quarks than for massless quarks. One-gluon exchange therefore shifts the chemical equilibrium in the direction of more strange quarks.

As a result, for large α_c, quark matter can be negatively charged, which would lead to disaster: if strange matter ever came in contact with our environment, it would convert everything to strange matter.

As long as strange matter is positively charged, it can coexist with hadronic matter due to the Coulomb barrier that keeps them apart. A proton must overcome this barrier to penetrate the strange matter region, where it would be converted to strange matter, while a neutron can be absorbed directly and readily become part of strange matter. Matter on Earth is composed of positively charged nuclei and can coexist with strange matter. However, in the interior of a neutron star, as the name implies, matter is composed mainly of neutrons – a strange matter lump in that environment will convert most of the star into a *strange star*.[3,4,5]

2.2 Strangelets

Nuggets of strange matter containing enough quarks such that the Fermi gas approximation is valid, but small enough that the effects of surface tension cannot be neglected, are called strangelets. For baryon number between 10^2 and 10^7, the typical size of these strangelets ranges between 5 and 200 fm. These strangelets are smaller than the electron Compton wavelength; the electron cloud extends beyond the quark matter surface, and Coulomb effects become important.

The charge-to-baryon-number ratio (Z/A) for strangelets is much lower than for nuclei. The Coulomb energy vanishes for $m_s = 0$ and increases with increasing m_s. Even for finite m_s the charge density is small, and strangelets can support much larger charges than nuclei. For example, a charge of 1000 is reasonable and would correspond to baryon number 10^6 (radius of 112 fm). Since Z grows only slowly with A, one would expect many stable strange isotopes for each value of Z.

The chemical behaviour of strangelets with positive charge less than 100 is that of unusually heavy but otherwise ordinary atoms. Electrons surround the core in atomic orbitals and the Bohr radius of the innermost shell can be much larger than the size of the strangelet.

For small A, surface effects can increase the energy per baryon substantially and instabilities can arise. The energy required to remove a baryon from a strangelet is a good measure of stability; if it exceeds the mass of a nucleon, m_N, neutrons evaporate from the surface. If it is less than m_N but more than $m_\alpha/4$, then α particles are emitted, though this process is inhibited by a Coulomb barrier.

Strangelets with low baryon number can decay by a complicated chain of radioactive decays. For some typical choices of parameters Farhi & Jaffe[2] find that for $A < 1900$ strangelets decay by α emission, and for $A < 320$ strangelets emit nucleons. Low-A strangelets might be quasistable and decay radioactively by chains of α, β, and nucleon emission. For even smaller baryon number (A less than 100), shell effects become important, and stability is even less likely. Emission of α-particles drives strangelets out of flavor equilibrium and ceases until weak decays reestablish equilibrium. This process resembles the radioactive decay of a heavy nucleus like Uranium. The α process is much faster in strangelets because the Coulomb barrier is lower. On the other hand, the β process is slower because strangeness-changing weak interactions are inhibited by a factor of $sin^2\theta_c = 0.04$. Eventually, as strangelets decay, emission of protons and neutrons becomes possible. Anomalous patterns of radioactive decay might be a signature for strange matter.[6]

3. STRANGE MATTER SEARCHES

The possibility of strange matter stability opens up a wide range of phenomenology. Some strangelets may be found as heavy isotopes around us, while relativistic strangelets may be traversing the Earth like bullets shot through butter. Several experimental searches have been proposed to look for strangelets. Some of them are described below.

3.1 Heavy-Ion Activation

Heavy-ion accelerators provide one means of searching for small abundances of strangelets in terrestrial materials. These experiments were aimed at detecting the energy released by nuclei converting into strange matter.

A ~ 20 MV Coulomb barrier ordinarily prevents strangelets from reacting with nuclei. However, a heavy-ion accelerator can accelerate heavy nuclei to kinetic energies well in excess of 60 MeV per baryon. A Uranium nucleus with kinetic energy per baryon of ~ 100 MeV will easily penetrate the Coulomb barrier and interact strongly with a strangelet.

The subsequent development depends only weakly on the baryon number A of the strangelet. For $A >> 10^3$, the nucleus will be absorbed into the strangelet, and a rapid sequence of β decays will establish weak equilibrium. The excess energy, comprising most of the kinetic energy of the projectile plus the binding energy of the strange matter, will be distributed among the internal excitations of the strangelet. There are so many of these excitations that we may say that the energy is converted into heat. This heat (~ 5 GeV) will most likely be lost radiatively in photons of energy ≤ 1 MeV. This flash of photons would be a unique signature of the presence of a strangelet.

Heavy-ion activation experiments were performed at Brookhaven National Laboratory with null results.[7] The problem with generalizing their findings is that there is no reliable guidance for selecting the material that might have been contaminated by strangelets.

3.2 Mass Spectroscopy

The ratio of charge to baryon number for strangelets, Z/A, is much less than that of ordinary nuclei. Very small strangelets may occur in normal matter, where their chemistry would be determined by their charge Z. The nuclear chemistry of these strangelets would reveal them to be extremely heavy isotopes of the chemical elements selected for study.

Mass spectographs are precise devices of extreme sensitivity over relatively narrow ranges of Z/A. The masses of these strangelets are so much higher than the masses of the equivalent ions that, most likely, the typical spectrograph magnet would barely deflect them. A special modification of the experiment is needed, given the uncertain Z/A of the object being looked for.

Searches have been performed and are still underway for heavy isotopes.[7]

3.3 Creation of Strangelets in Heavy-Ion Colliders

The possibility of creating a quark-gluon plasma in the laboratory is one of the principal motivations for the study of relativistic heavy-ion collisions. Should a phase transition to the quark-gluon plasma be observed in the collision of two heavy ions, a powerful new tool for studying QCD will become available.

Liu & Shaw[8] suggested that strangelets (or perhaps metastable droplets of quark matter) might be formed in heavy-ion collisions. The probability that a given droplet might form is difficult to compute, and the results turn out to be highly model-dependent.

The high temperatures involved in heavy-ion collisions make it difficult for a strange matter nugget to survive. The creation of strangelets requires the generation of strange quarks, which occurs by thermal production of $s\bar{s}$ pairs. The s and $\bar{s}$ quarks must separate before condensation from the quark-gluon plasma, in order to prevent their annihilation. Strangeness separation and fast cooling are necessary conditions for strangelet formation (and survival) in such a high entropy, high temperature environment. Even if strangelets cannot survive heavy-ion collisions, the study of the quark-gluon plasma may shed light on the general nature of the strong interactions and may indirectly yield a better understanding of the high-density, low-entropy region of the phase diagram (where strange matter would live).

3.4 Cosmic Rays

If strangelets are formed in our galaxy, for example in the coalescence of strange stars, it is very likely that they will be detected as cosmic rays. There have been many searches for strangelets in cosmic rays; they are summarized in Fig.3.

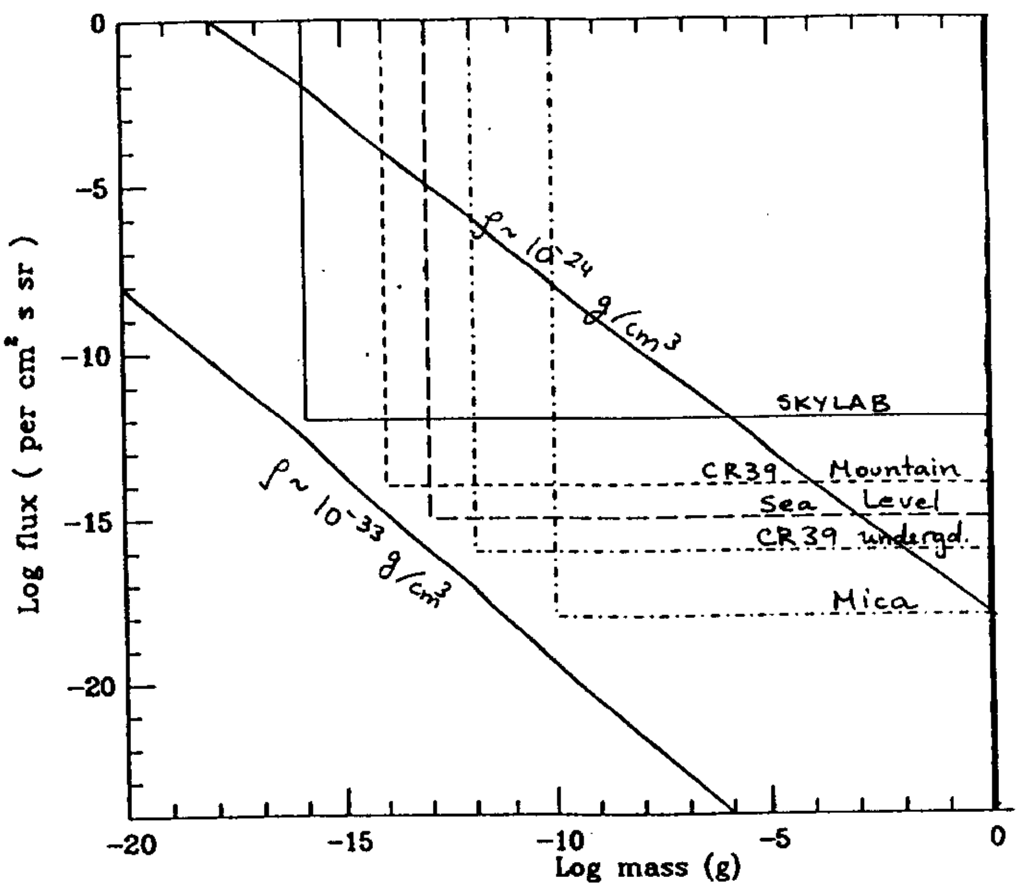


Figure 3. Limits on the flux of strangelets from different experiments.

Strangelets can have large Z and small Z/A. For $Z > 100$ there is no background. No events with $Z > 100$ have been reported, limiting the flux of strangelets to less than $\sim 10^{-12}/\text{cm}^2$ sr sec. Two candidate events with large A and small Z/A have been reported.

3.5 "Strange" Events

In the astronomical literature one finds many examples of phenomena that are both puzzling and extremely unusual or unique. Their interest derives in large measure from the fact that they do not belong to any known class of phenomena. Strange matter has been invoked in models for three such "special events."

3.5.1 Centauro Cosmic-Ray Events

The Centauro cosmic-ray events are cosmic rays in which the primary particle appears to fragment almost exclusively into large numbers of baryons.[9] It is important to stress that this phenomenology is extremely unusual.

It has been suggested[10,11] that the primary particle in these events is a glob of quark matter with baryon number $\sim 10^3$ and kinetic energy per baryon between 10^3 and $10^4 GeV$. This notion becomes much more plausible if the glob of quark matter is stable, which it would be under the strange matter hypothesis.

Witten suggested that collisions of strange matter stars would be the likely origin for such lumps of strange matter. This is certainly a plausible hypothesis, since such collisions must occur with reasonable frequency in our galaxy. Of the $\sim 10^3$ known pulsars, three are in close binary systems with another compact object. At least one of these, PSR 1913 + 16, has an orbit that will decay in less than 10^9 years. The resulting collision will be violent, and some material may be expelled. Friedman and Caldwell estimated the spectrum of strangelets created in such coalescence events.[12] The expulsion velocities will typically be $\sim 0.1c$, so any large lump will leave the galaxy immediately. Smaller strangelets will be arrested by the galactic magnetic field, and may ultimately give rise to Centauro events. The efficiency of this process could be very low and yet still account for the observed flux at Earth.

3.5.2 Exotic Hadrons from Cygnus X-3

The special properties of strange stars inspired a model for some of the bizarre phenomena associated with Cygnus X-3.[3] Small strangelets produced at the surface of a strange star are accelerated electrodynamically to very high energies. Spallation reactions in the atmosphere of a companion star create some neutral strangelets (perhaps the $Z = 0,\ A = 2$ dilambda particle) that propagate to the Earth. Collisions in the atmosphere produce the neutrinos that in turn produce the deep underground muons reportedly seen in proton decay detectors.[13] The accelerated strangelets produce a very characteristic high-energy neutrino spectrum and a test of the strange star hypothesis might be possible.

The problem with this model is that it requires the strange matter to be exposed at the surface of the star. But Cygnus X-3 is an accreting compact star, as revealed by the X-ray emission. The strange star will certainly have a crust, and there will not be an exposed quark surface.

3.5.3 Very-High Luminosity Gamma-Ray Bursts

An extraordinary event was recorded by the interplanetary γ-ray sensor network on 5 March 1979.[14] This event exceeded by more than an order of magnitude the peak flux recorded from any other γ-ray event. The rise time of the γ-ray flux was $\leq 250\mu s$, more than 100 times faster than typical for γ-ray events. The rapid rise was followed by an intense phase of $\sim 0.15s$ duration. This in turn was followed by a much lower intensity phase, which was observed for about three minutes, during which the flux decayed exponentially with a characteristic time $\sim 50s$ and was periodically modulated with period $\sim 8s$. Precise determination of the arrival times of the burst photons at each of the nine spacecraft in the network allowed the source to be located on the sky in an "error box" $1' \times 2'$ in size. A young supernova remnant, N49 in the Large Magellanic Cloud, is found in the error box.[14]

The Large Magellanic Cloud is 50 *kpc* away. At this distance, the energetics of the event prove to be so extraordinary that the identification with N49 is customarily rejected.[16] In particular, the inferred luminosity is $\sim 10^6$ times the Eddington limit for a solar mass compact object, and the rise time is very much smaller than the time needed to drop $\sim 10^{25}$ gm of "normal" material onto a neutron star.

These considerations motivated a model[17] involving the particular properties of strange matter. In this scenario, a lump of strange matter of mass $\sim 10^{-8} M_{\odot}$ fell onto a strange star. Since the density of strange matter is so high, there was little tidal distortion of the lump by the gravitational field of the strange star, and the duration of the impact was very short, $\sim 1\mu s$; this accounts for the rapid onset of the γ-ray flash. The surface of the strange star was heated by the impact and radiated γ-rays with very high luminosity for $\sim 0.15s$. Since the strange matter surface is held together by the strong force rather than gravity, there is no conflict with violation of the Eddington limit, as there would be if the compact object was a neutron star. The lower intensity radiation that followed the original flash is attributed in this model to resettling of the strange star crust, and the $8s$ modulation is attributed to the rotation of the compact star.

4. STRANGE MATTER IN ASTROPHYSICS

Strange matter, if stable, could have important consequences for astrophysics and cosmology. We discuss several of these here.

4.1 Strange Matter in the Early Universe

When first proposed, strange matter lumps were thought to be produced in the quark-hadron phase transition in the early universe and thus to be good candidates for the dark matter in the universe. However, the survival of these low-entropy objects in the hot environment of the early universe is not easy.

Witten's model for the formation of strange matter in the early universe requires that the transition from a quark-gluon plasma to a gas of hadrons be via a first-order phase transition. As the universe cools through the first-order transition, there would be a brief epoch of coexistence between the quark and hadron phases. During this period, the temperature of the universe remains fixed at the coexistence temperature $T_c \simeq 100$ MeV. As the universe expands in the coexistence epoch, the fraction of the universe that is hadronic increases to unity, at which point the universe resumes cooling.

Bulk thermodynamic equilibrium between the two phases requires the exchange of entropy and baryon number across the phase boundary. Entropy is exchanged primarily by neutrinos and photons. Baryon number exchange could only occur via the association of three quarks into confined hadrons at the phase boundary, a process that has a characteristic scale of $\sim 1fm$. If this process of association is inefficient, then the baryon number of the universe would become trapped into shrinking regions of quark phase. One possible outcome of this would be the creation of lumps of strange matter, also known as quark nuggets.

Quark nuggets were an attractive candidate for the dark matter in the universe. They are a form of cold dark matter, since their velocities with respect to the mean Hubble expansion would be non-relativistic. In addition, the quark nuggets would be only weakly coupled to the photon gas that dominates the universe until $T \simeq 1eV$, so gravitational perturbations in the ensemble of nuggets can develop before the epoch of hydrogen recombination. Dark matter candidates with these properties are advantageous for theories of galaxy formation.[18]

Witten's model for the formation of quark nuggets was criticized by Applegate & Hogan.[19] However, the ultimate viability of this dark matter candidate was most seriously challenged by Alcock & Farhi[20], who showed that even if nuggets of strange matter are formed, they would evaporate as the universe cooled to $T \simeq 2$ MeV. This occurs as the universe crosses the region of the phase diagram between the quark-hadron phase transition and the strangelet region. The computation of the evaporation rate is at first sight straightforward, using detailed balance arguments to relate the neutron capture rate to the neutron evaporation rate at the surface of a nugget via the Saha equation. The evaporation rates turn out to be so large that the evaporation of large lumps is limited by the rate at which neutrino heating could supply the energy needed to emit the neutrons. Alcock & Farhi concluded that all lumps with baryon number $\leq 10^{52}$ would evaporate, while lumps larger than this could not have formed without violating causality at the epoch of formation.

This calculation was criticized by Madsen, Heiselberg & Riisager[21], who pointed out that since only neutrons (and some protons) are emitted at the strange matter surface, the u and d quarks are depleted but the s quarks are not. Evaporation would be limited by the rate at which equilibrium could be reestablished among the u, d, and s quarks. This rate of equilibration has since been computed by Heiselberg, Madsen, & Riisager[22] and is slow enough to supress surface evaporation significantly. These authors conclude that quark nuggets with baryon number as low as $\sim 10^{46}$ might survive evaporation. This number is smaller than the "causality limit" ($\sim 10^{49}$) but still much larger than the characteristic baryon numbers envisioned by Witten as being formed in the quark-hadron transition.

What was overlooked in this controversy was that the conversion of quark matter to hadron gas does not occur only at the surface. Strange matter at low pressure and high temperature ($T \geq 10$ MeV) is so far out of thermal equilibrium that bubbles of hadron gas spontaneously nucleate within the quark matter as well. These bubbles grow at rates that are limited only by the heating rate – the quark matter boils. Since this process occurs throughout the volume of the quark nugget, the weak equilibration limit is no longer significant, and the process is limited by the rate of heating by neutrinos; a baryon number limit similar to the original $\sim 10^{52}$ is obtained when this volume conversion process is taken into account.

Thus, strange matter cannot be the dark matter of the universe. Furthermore, since quark nuggets are so vulnerable at $T \simeq 20$ MeV, it seems unlikely that they would have formed in the first place, at $T \simeq 100$ MeV. This conclusion reflects the fact that the universe spends a significant amount of time in a region of the phase plane where normal hadrons are the favored constituents.

4.2 Strange stars

If the strange matter hypothesis is correct, neutron stars are metastable with respect to stars made of strange matter. This in turn means that the objects known to astronomers as neutron stars are probably made of strange matter, not of neutron matter, and should be called "strange stars."

4.2.1 Global Properties of Strange Stars

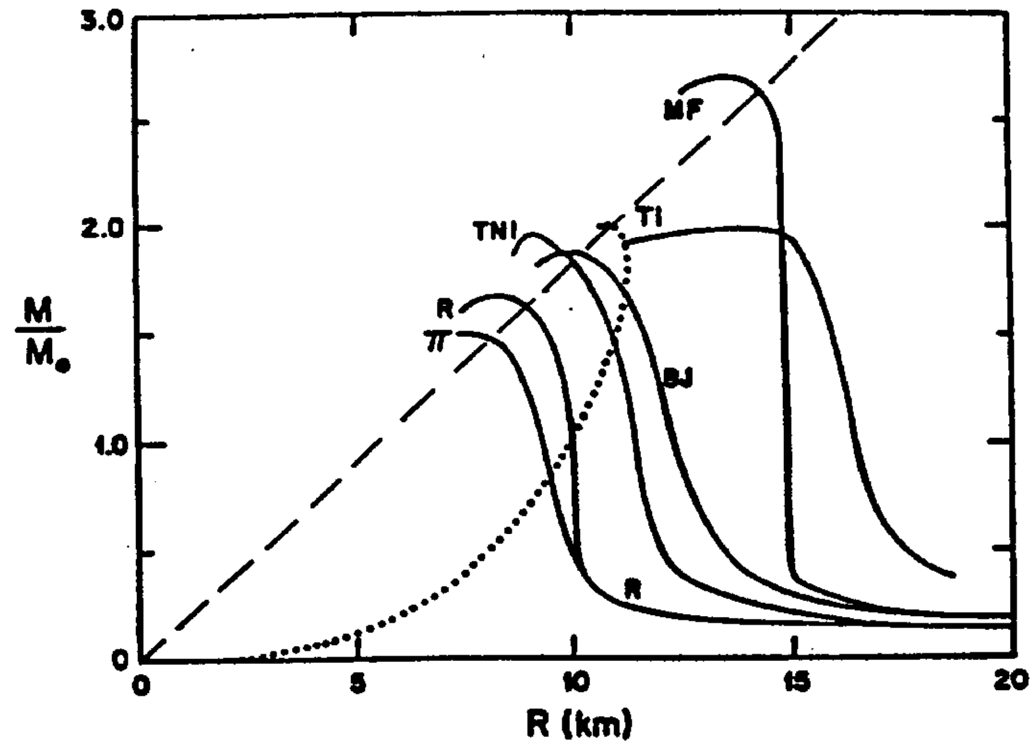
The global properties of strange stars have been described by Witten[1], Haensel, Zdunik & Schaeffer[4], and Alcock, Farhi & Olinto.[5] These objects have extremely simple structure, because the zero-temperature equation of state is, to high accuracy, $P = (\rho - 4B)/3$. This expression is exact in the bag model with massless quarks, independent of the number of flavors. The addition of mass to one of the flavors (the s quark) causes deviations no greater than 4% from this simple relation because, if the mass is dynamically important, the abundance of the massive quarks becomes small and their contribution to the equation of state is insignificant.

This equation of state has the property that as $P \rightarrow 0$, $\rho \rightarrow 4B$. For $B = (145MeV)^4$ this means $\rho = 4 \times 10^{14} g/cm^3$, slightly greater than nuclear density. Thus, there is a sequence of objects with very low internal pressure and nearly uniform density. Their mass (M) vs. radius (R) relation is $M \propto R^3$.

The pressure at the center of one of these objects is $P_c = 2\pi G\rho^2 R^2/3$, where G is Newton's constant and Newtonian gravity has been assumed. For sufficiently large radius R, the pressure P_c approaches $4B/3$ and the density increases toward the center of the object. This effect becomes noticeable at $R \simeq 5km$, $M \simeq 0.1M_{\odot}$, and the mass–radius relation is very different from $M \propto R^3$ for objects with $R \simeq 10km$ and $M \simeq 1M_{\odot}$. Relativistic gravity also becomes important in these stars and the Oppenheimer-Volkoff equation for stellar structure must be used to compute the models.

The full mass–radius relation is shown in Fig. 4. The sequence terminates at the limit of dynamical stability, known as the Chandrasekhar limit (see ref.32 for a discussion of the dynamical stability of relativistic stars).

Figure 4.- Mass ($M/M_\odot$) versus radius (R) relation for strange stars (dotted line) and for a representative sample of neutron stars (solid lines). The labels on the solid curves refer to the equations of state discussed in the text.



The maximum mass and the radius of the maximum-mass star scale with the same power of B (namely $B^{-1/2}$). Therefore, sequences of stars for different values of B will have the same shape as in Fig. 4, with rescaled M and R axes. The slashed line in Fig.4 shows the maximum mass versus radius location for other star sequences when B is varied.

Figure 4 also shows some well-known mass radius relations for neutron stars, which are computed for a variety of different nuclear matter equations of state: MF is a mean field theory calculation; TI is a tensor-interaction model; BJ is a Bethe-Johnson model, which includes hyperons; R is a pure neutron model with a soft core interaction; π is the R model with pion condensate. These models were reviewed by Baym & Pethick.[23,24] These mass-radius relations are very different from that for strange stars, and the difference arises entirely because, for nuclear matter, $\rho \to 0$ as $P \to 0$. One would hope that such a large, qualitative difference could be exploited to discover the truth regarding the strange matter hypothesis.

All neutron/strange stars for which masses have been determined have masses near $1.4M_\odot$[25], where the two models of compact stars (neutron and strange) have very similar radii. Should a very low mass compact star be discovered, the two pictures would be distinguishable.

Another test is the limiting rotation rate for pulsars: extremely short pulsar periods would be indicative of high densities for neutron stars, and, therefore, of less conventional forms for the neutron star equation of state. With the recent sharp increase in fast pulsar discoveries, the limiting rotation rate for pulsars may be settled in the near future.

4.2.2 Surface Properties of Strange Stars

The fact that strange matter is absolutely stable raises the possibility that strange stars are made exclusively of strange matter, and that the surface of the star is exposed quark matter. Early discussions of strange stars[3,26] presumed that this would be the case, and some interesting consequences for the appearance of these objects are found. However, there is also the strong possibility that the surface of a strange star is made of the same material as the surface of a neutron star.

A bare strange surface has very unusual properties. The thickness of the "quark surface" is $\sim 1fm$; the integrity of this surface is ensured by the strong force. The electrons are held to the quark matter electrostatically, and the thickness of the "electron surface" is several hundred fermis; the electric field in this region is $\sim 5 \times 10^{17}$ V/cm. Since neither component is held in place gravitationally, the traditional "Eddington Limit" to the luminosity that a static surface may have does not apply, and these objects may (in principle) have photon luminosities much greater than $10^{38} erg/s$.

Alcock, Farhi & Olinto[5] concluded that a strange matter surface would have a low emissivity for X-ray photons. They reached this conclusion by calculating the dispersion relation for photons in strange matter. The result is much like the dispersion relation for photons in an electron plasma, but with characteristic "plasma frequency" $\omega_p = (8\pi\alpha/3)N_u^2/\rho_u$ (where α is the fine structure constant, N_u the number density of up quarks, ρ_u the energy density of up quarks). For typical parameters, $\omega_p \simeq 19$ MeV. This means that the surface of a bare strange star is highly reflective in the X-ray region and has a low emissivity. The emissivity has not yet been calculated.

There is a further consequence of the electrical properties of this surface. The very high electric field in the electron surface will exert a strong outward force on an ion. Clearly, a certain amount of normal ionic material can be supported by this electric field. It turns out that a crust of mass up to $\sim 5 \times 10^{28} g$ may be supported, with density at the inner edge up to $4 \times 10^{11} g/cm^3$.

This upper limit is set by the requirement that nuclear reactions between the crust and the strange matter must be prevented, or else the ions at the base of the crust would be converted to strange matter. This requirement is satisfied if there are no free neutrons in the crust [i.e., there is no "neutron drip"[27]] and there is a "gap" between the ions at the base of the crust and the quark surface in which a Coulomb barrier prevents direct reactions between the ions and the strange matter.

This thin layer is identical to the "outer crust" of a neutron star. For this reason, a strange star with a crust is not different from a neutron star in its photon emissivity. Furthermore, since the crust is held onto the star by gravitation, this new surface is subject to the Eddington limit.

It seems likely that this latter view of the surface of a strange star is more realistic. The universe is a "dirty" environment, and certainly supernova remnants contain a lot of material that may accrete onto the surface of a newly formed strange star and make a crust. Hence, we are once again driven to conclude that a strange star is very similar to a neutron star in its observable properties.

4.2.3 Pulsar Glitches

Radio pulsars are observed to have periods that steadily increase. This is attributed to the loss of angular momentum by magnetic dipole radiation. In some pulsars small "glitches" in this smooth spin-down are occasionally observed. In a glitch the period abruptly (in less than a day) decreases; over the next 40–80 days most of this decrease is lost as the pulsar appears to "heal" back toward its original spin-down curve.

A model has been developed for this phenomenon involving the behavior of superfluid neutrons in the inner crust of a neutron star: see Pines & Alpar[28] for a review. There is no equivalent for this model involving strange stars. It is not clear how seriously the lack of a model for glitches should be taken; this may reflect only lack of imagination on our part. It is certainly disingenuous to claim that the success of the superfluid neutron model provides a model-independent argument against the strange matter hypothesis.[29]

4.2.4 Conversion of Neutron Matter to Strange Matter

A variety of "routes" from neutron matter to strange matter have been suggested.[5,30,31] These include conversion via two-flavor quark matter, clustering of lambda's, kaon condensates, direct "burning", and seeding from the outside. The uncertainties in each of these are so large that estimates of conversion rates cannot be made with confidence. It is possible, if unlikely, that neutron stars will not convert to strange stars, even if the strange matter hypothesis is correct.

However, once there is a seed of strange matter inside a neutron star it is possible to calculate the rate of growth.[31] The strange matter front absorbs neutrons, liberating u and d quarks into the strange matter. Weak equilibrium is then reestablished by the diffusion of strange quarks and by the weak interactions. The rate of progress of this front has a strong inverse temperature dependence.

If this conversion happens just after the supernova explosion one expects a neutrino signature of $10^{52} erg$ over a period between minutes and hours. Neutrino astronomy will be able to detect neutrinos from a nearby supernova and this signature can be tested.

This conversion can also happen in the later stages of neutron star evolution. If it happens in an active pulsar, a macroglitch will be observed because of the change in moment of inertia. An old defunct pulsar will convert even faster, and a gamma-ray burst will be its signature.

4.2.5 Cooling of Strange Stars

The cooling properties of neutron stars are very sensitive to their composition. Neutron stars cool primarily via neutrino emission, which is more effective than photon emission for about the first 10^4years. During this time a small amount of heat is lost by photon emission at the surface; this flux is determined entirely by the temperature of the core and by the transport properties of the crust of the star.

Since neutrinos do not interact with the crust, the thermal structure of the crust and the core evolve essentially independently. After a few hundred years the core becomes approximately isothermal, while the crust acts as a thin insulating envelope containing almost all of the temperature gradient. The temperature gradient occurs where electrons become nondegenerate, which corresponds to the outermost layer of a neutron star. The temperature drops between two and three orders of magnitude in this small region.

In the standard model the primary neutrino emission reactions are $n + n \rightarrow n + p + e^- + \bar{\nu}_e$ and $n + p + e^- \rightarrow n + n + \bar{\nu}_e$. The "spectator neutron" is necessary to satisfy four-momentum conservation at the top of the Fermi sea. The matrix elements for these processes are small; for a review see Shapiro & Teukolsky.[32]

Neutrino emission may be greatly enhanced by the presence of meson condensates. The possibility of pion condensation in sufficiently dense matter was first pointed out by Migdal[33] and, independently, by Sawyer[34] and Sawyer & Scalapino.[35] More recently Nelson & Kaplan[31] showed that kaons can also form a condensate. Meson condensates can be formed because as the density in nuclear matter increases the electron chemical potential increases, and may exceed the effective mass of pions or kaons. The effective mass of pions and kaons in dense matter can be significantly lower than their mass in vacuum because of attractive nuclear interactions. If the meson effective mass lies below the chemical potential, the meson field develops a classical expectation value and forms a condensate.

Whether or not pions condense at neutron star densities is still a controversial issue. Early calculations of the critical baryon number density for pion condensation indicated that it was higher than densities inside nuclei, but lower than densities reached inside the core of massive neutron stars. Negative results of experimental searches for evidence of pion condensation in atomic nuclei indicate that the critical density is higher than nuclear densities. More recent studies have pushed up the critical density, and made pion condensation in neutron stars less likely.

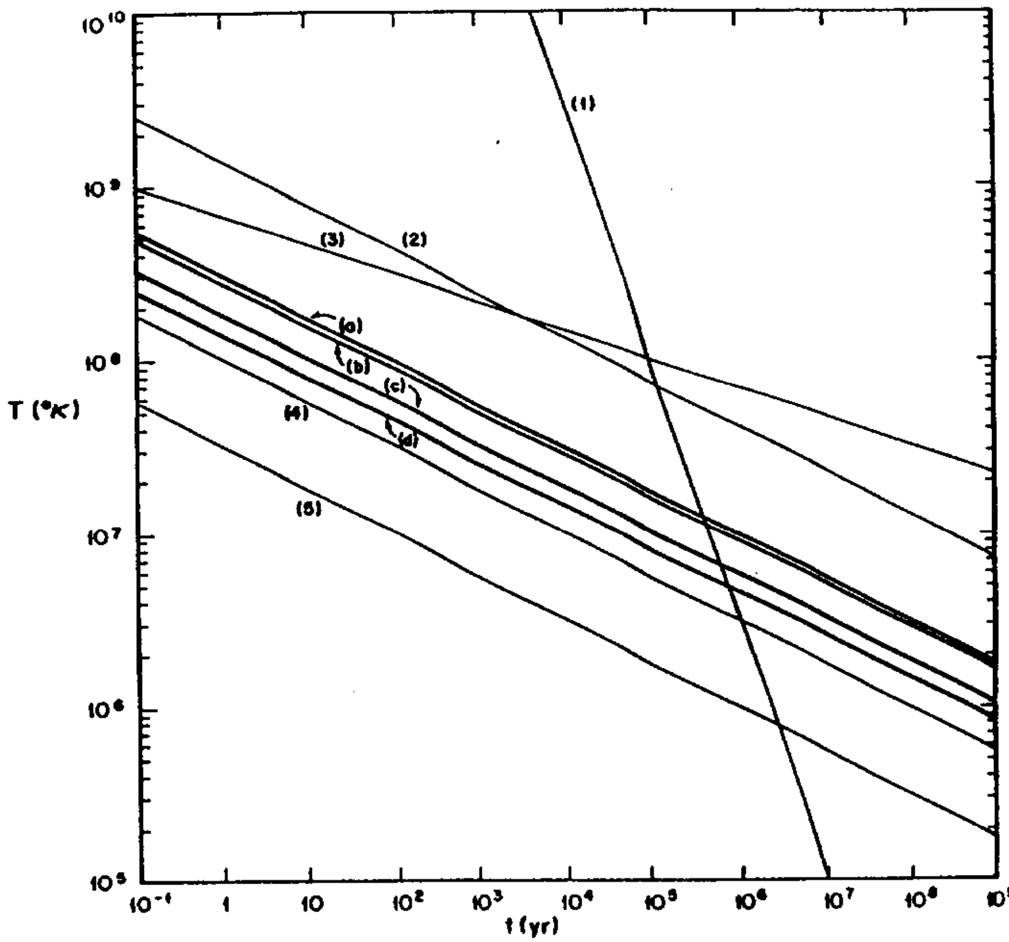
Nelson and Kaplan showed that it is possible for kaons to condense at lower densities than pions, in spite of the fact that kaons are so much heavier. Pions have attractive axial vector but repulsive vector interactions with nucleons, while kaons have attractive vector and axial vector interactions. The attractive nuclear interactions may compensate for the mass difference between pions and kaons and make kaon condensation possible at lower densities.

In either case, the condensate will soften substantially the equation of state of dense matter. Cooling rates for neutron stars are also strongly affected by the formation of a condensate. Pion condensates cool via $n + \text{“}\pi^-\text{”} \rightarrow n + e^- + \bar{\nu}_e$ (and its inverse reaction) where "π^-" represents the pion condensate built in the quasiparticle states of the neutron. Maxwell et al[36] showed that even a small amount of pion condensate will produce a dramatic enhancement of the neutrino emissivity. The condensate brings an additional four-momentum making it easier to satisfy energy-momentum conservation. Pion condensation is driven by derivative interactions, so it occurs for nonzero wave numbers (p wave). A neutron on the top of its Fermi sea does not have to change into a low-momentum neutron, which greatly enhances the rate for this reaction.

Kaon condensates cool via the analogous reaction $n +$ "K^-" $\to n + e^- + \bar{\nu}_e$. Kaon interactions do not involve derivatives, and the condensate occurs for zero wave number (s wave). The additional four-momentum is not as large as in the pion case, hence kaon condensates are not as effective in speeding the neutrino emissivity. Brown et al[37] find that the cooling of a neutron star with a kaon condensate in the core is the same as the strange matter cooling curves.

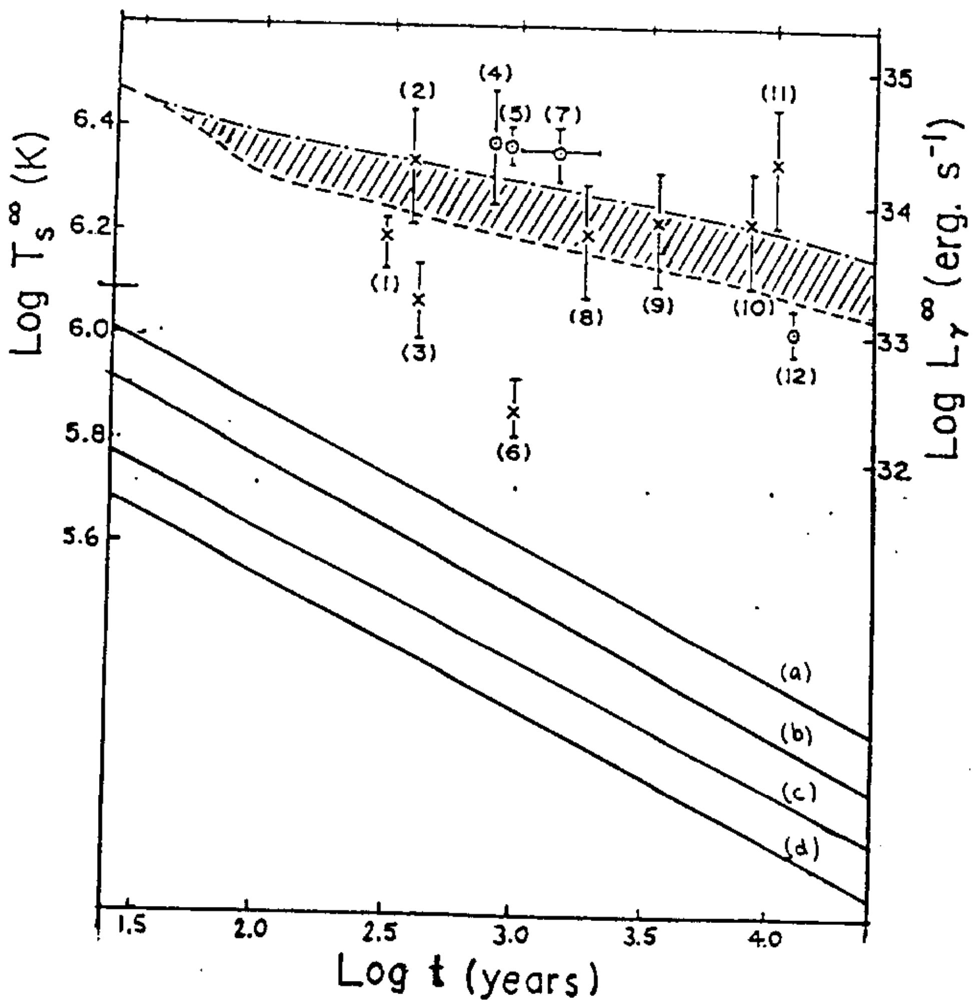
Strange stars cool via neutrino emission as a result of the following reactions: $u + e^- \to d + \nu_e + e^-$, $u + e^- \to s + \nu_e$, $d \to u + e^- + \bar{\nu}_e$, and $s \to u + e^- + \bar{\nu}_e$. The emissivity for these processes is proportional to the electron fraction in strange matter. In turn, the density of electrons depends on the density of up and down quarks being higher than that of strange quarks. The emissivity is, therefore, sensitive to the choices of m_s and α_c. Fig.5 shows how this dependence affects the cooling curves for some typical choices of these parameters.

Figure 5. Cooling curves for strange matter with different parameters (a), (b), (c), (d) and standard cooling curves : (1) photon emission; (2) crust bremstrahlung; (3) Modified Urca; (4) quark matter; (5) pion condensate.



If only the core of a neutron star is made of strange quark matter (in which case it is stable only at high pressure), it has the same neutrino emissivity calculated for strange stars. The luminosity will be somewhat smaller since only a fraction of the total volume of the star has this higher emissivity. The cooling curves $(a), (b), (c)$, and (d) should be shifted to the right accordingly.

Figure 6. Surface Temperature for strange stars (a)-(d) compared to upper limits from x-ray observations (1)-(12), and the standard cooling curves (shaded area).



Observation of x-ray thermal emission from known supernovae remnants places upper limits on the surface temperatures of the inferred neutron stars as in Fig.6. Standard nuclear matter cooling curves lie above a few of these upper limits, making the more exotic alternatives somewhat appealing.

While the core cooling for strange stars and neutron stars with quark matter or kaon condensate cores are very similar, the surface temperature evolves very differently. Neutron stars have layers of normal matter separating the exotic inner core from the surface. The signature of faster cooling will take some thermal diffusion time scale to affect the surface. Brown et al[37] et al. estimated that it would take between 50 and 100 yrs for kaon condensation to manifest itself at the surface. The same time scale is appropriate for quark matter cores. Strange stars have strange matter almost up to the surface. The diffusion time scale is much shorter for strange stars, and the faster cooling should be promptly manifest. The very large range for strange stars occurs because the mass of the outer crust may vary from zero to the full neutron star outer crust. These possibilities may be explored by observing the young neutron star that may exist in SNR1987A.

6. CONCLUSION

It is certainly an extremely unsatisfactory state of affairs that the ground state for the strong interaction remains unknown. Low-energy QCD remains a fertile area of research for particle physics and astrophysics, in part due to the difficulty of performing accurate calculations.

Given the state of the theory, one should turn to experiment. There are some tantalizing possibilities of experimental verification of the strange matter hypothesis. Unfortunately, none of the experiments described above contain a clear possibility of contradicting the hypothesis.

The astrophysical consequences of strange matter are very interesting and will remain a most active area of research. There is in the astrophysics of neutron stars and strange stars the possibility of distinguishing the two models observationally. A convincing distinction will require a deeper understanding of the dynamics of strange stars (and of neutron stars).

In summary, more work is needed in order to answer the central question: What is the ground state in QCD?

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QUESTIONS AND ANSWERS

Question from U. Ornick: Are there any predictions about the lifetime of strange matter metastable objects produced in heavy ion collisions?

Answer:There are some, but are highly model dependent (see ref.8).

Question from T. Kodama: Are there any error bars in the estimates of lifetimes of neutron stars? Are they model independent?

Answer: Lifetimes could be as long as the age of the Universe. But, ages in the cooling curves are determined either by known observations (hystorical supernovae) or are estimated by the behaviour of the supernova remnant (size and expansion rate of the remnant).

Question from Y. Hama: Is your strange matter of small radius (nuclear radius) stable against weak interactions? Is it possible to avoid neutrino evaporation in a finite system?

Answer:It depends on the baryon number of the strangelet. Strangelets of low baryon number can have β decays and emit α's or nucleons. Neutrino evaporation can be avoided in very hot and very dense environments like in a newly born neutron star.

Question from W. Bauer: Let me start my question with a little story which may be true: When the BEVALAC accelerator was proposed in Berkeley, the creation of Lee-Wick matter was the big excitement. But some citizens were concerned that the creation of a new ground state of nuclear matter in the accelerator might suck the whole Earth into it. Their worries was put to rest by the observation that the moon exists. Since it is continuously bombarded by very high energy cosmic rays, the above danger can be ruled out. In the same spirit, then, isn't the fact that everything around us is non-strange proof that strange matter cannot be the true ground state of matter, because our planet and the stars should then have settled into the strange "ground state" and not into our nuclear matter "meta-stable state"?

Answer: Most of our planet and surely most of the stars are not made of the ordinary ground state, ^{56}Fe.

Question from J. Hill: The big bang scenario you described follows a low density path and thus excludes a high density strange-matter ground state for the universe. Would not it be possible for the big bang to follow a high density path thus producing a "strange universe"? Does this argument thus exclude heavy strange matter?

Answer: No and no. From Big Bang nucleosynthesis and the cosmic microwave background, we can be pretty sure the universe had a high temperature low baryon number density path. For example, at times $\sim 10^{-6} sec$ the baryon asymmetry $(n_B - n_{\bar{B}})/n_B \sim 10^{-8}$, even though n_B was very high. This argument does not exclude strange matter, just like ^{56}Fe is not excluded as the ground state of hadronic matter even though it wasn't produced in the early universe.