The Physics and Astrophysics of Strange Matter

1. INTRODUCTION

It is generally believed that if a nucleus or collection of nuclei is subjected to a high enough pressure, a transition to quark matter occurs.[1] Above a critical pressure, p_c, individual nucleon boundaries dissolve and a system with baryon number A is best described as $3A$ quarks and not as A nucleons. The quarks are still confined to the system as a whole but they are no longer parts of three quark units. In this quark matter phase, quarks have very different wave functions than they do in nuclei, and hadrons, as we know them, do not exist.

The scale of the strong interactions, Λ, is roughly $m_{\text{proton}}/3$ or 300 MeV. On this scale the up and down quark masses are negligible and it is reasonable to assume that the transition pressure, p_c, is characterized by Λ. If we think of a system under a pressure just above p_c as a Fermi gas of $3A$ quarks (assume A is large), then the chemical potentials of the quarks are of order Λ. The mass of the strange quark, m, is not well determined but is usually taken to be between 50 MeV and 300 MeV. I will assume that m is comfortably below the chemical potentials of the quarks just considered. In this case, weak interactions such as $u + d \leftrightarrow u + s$ or $u \leftrightarrow s + e^+ + \nu$ will convert up and down quarks to strange quarks. The system will lower its energy (more precisely its Gibbs potential) by distributing its quarks in three Fermi seas instead of

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two. Thus, quark matter will always contain a significant fraction of strange quarks. (The higher mass quarks, charm, etc., will not enter the discussion because their masses are much larger than any chemical potentials we ever consider.)

Suppose we keep a giant nucleus or collection of nuclei, with total baryon number A, at a pressure above p_c long enough for the weak interactions to establish the favored numbers of up, down and strange quarks. The conversion to strange quarks lowers the Gibbs potential by lowering the energies of individual quarks. The excess energy can be carried away by photon or neutrino emission without changing the baryon number. Now imagine slowly reducing the pressure to zero. If, as the pressure is lowered, the Gibbs potential of the quark matter with up, down and strange quarks rises above that of compressed nuclei, then weak interactions will eliminate the strange quarks and at zero pressure the system will be ordinary nuclei with a total baryon number A.

However, another outcome is possible. It is conceivable that the Gibbs potential of quark matter containing a large fraction of strange quarks is below that of compressed nuclei *for all pressures*. In this case, the system will not return to nuclei but will stay quark matter even after the external pressure has gone to zero. This possibility was first entertained by E. Witten who pointed out that we may have misidentified the true, *zero pressure*, ground state of the strong interactions which may be "strange matter" and not iron.[2]

Immediately an objection can be raised. If strange matter has a lower energy per baryon than ordinary nuclei, then why do ordinary nuclei exist? Why do they not convert to strange matter? The answer is that they are metastable and the rate to convert is essentially zero. For a nucleus to convert, it must change roughly one-third of its quarks to strange. If it tries to do this one quark at a time, it will convert protons and neutrons to lambdas which is energetically unfavorable. Strange matter is postulated to be stable in bulk but, as we will see, it is not stable for very low baryon number. (There are no known stable strange baryons.) For a large nucleus to become strange matter it needs to convert many quarks *simultaneously* to strange. This requires a high-order weak interaction and gives a negligible rate. Only under high pressure, where nucleon boundaries are dissolved, can a system convert one quark at a time. So, for example, the interiors of neutron stars may be stable strange matter.

At present, detailed calculations are incapable of deciding if strange matter is stable or not. No QCD based calculation schemes predict the energy per baryon number of strange matter to even 100 MeV accuracy. I will assume that strange matter is stable and explore the consequences of that assumption, relying as little as possible on detailed calculations. In the next section I will discuss the general properties of strange matter.

We will see that since strange matter has a low electric charge to baryon ratio, it is stable against fissioning and can, in principle, be found in lumps ranging from nuclear to stellar dimensions. I will explore the general properties of very large lumps which can be treated as bulk systems and very small lumps which must be viewed as consisting of distinct quarks. We will see that strange matter can be stable above a certain critical baryon number, of order 100, but unbound for lower baryon number.

Strange matter, produced in the early universe, was originally proposed as a dark matter candidate. Its virtue as a dark matter candidate is that, because of its extreme density, relatively few lumps are required to close the universe and these stable lumps would be very difficult to detect astronomically. However, in Section 3 I will show that any lump produced early in the history of the universe would have evaporated by the time the universe was one second old. It is still possible that strange matter exists in what are usually called neutron stars. In Section 4 I will discuss the properties of strange stars and contrast them with conventional neutron stars. The main differences lie in the mass radius relation for small mass and in the properties of the solid crust of the star which a strange star may not even possess. Finally, in Section 5 I will survey some techniques for searching for strange matter here on Earth today.

2. GENERAL PROPERTIES

A lump of strange matter can be modelled[2,3] as a Fermi gas of up, down and strange quarks, with total baryon number A, confined in a (nearly) spherical volume, V, proportional to A. By assumption, for large A, the energy per baryon, E/A, of strange matter is below 930 MeV *at zero pressure*. Thus, strange matter is absolutely stable, i.e., it can absorb nuclei. As we will see, lumps of strange matter can range in size from a few Fermis with $A \sim 100$ to 10 km with $A \sim 10^{57}$. This enormous range of sizes makes strange matter interesting to study in a wide variety of physical situations.

Weak interactions, such as $u + d \leftrightarrow u + s$ or $u \rightarrow s + e^+ + \nu$, allow the relative numbers of up, down and strange quarks to vary and energetic considerations determine the equilibrium composition. If the mass of the strange quark was as small as the up and down quark masses, then the equilibrium configuration would consist of equal numbers of up, down and strange quarks. This configuration is electrically neutral. Since the strange quark mass is actually not negligible, strange matter has fewer strange quarks than ups or downs and has a small positive charge carried by its quarks. This hadronic charge is neutralized by electrons. For very small lumps, the electrons surround the lump much like atomic electrons surround a nucleus. For larger lumps, the electrons form a Fermi sea on the inside of the lump.

To proceed further, it is helpful to introduce a phenomenological model of strange matter. We summarize the confining effects of the strong interaction by saying that the region the quarks live in is endowed with a constant energy per unit volume, B, which acts as a pressure holding the quarks in. B is characterized by the strong interaction scale, Λ, and plays the same role as the bag constant in bag models of the hadrons. (Its value can be taken from the hadronic fits but the significance of this identification is certainly questionable.) This inward pressure is balanced by the Fermi pressure of the A quarks. The size of the system is adjusted to minimize the total energy.

For very large lumps, $A \gtrsim 10^6$, it is reasonable to neglect surface effects and to include electrons inside the lumps. Each of the three quark flavors and the electrons have their own chemical potentials which are constrained by the weak interactions to obey:

$$\begin{aligned} \mu_d &= \mu_s \equiv \mu \\ \mu_u + \mu_e &= \mu \end{aligned} \tag{1}$$

so only two are independent. Each of these chemical potentials is related to a thermodynamic potential:

$$\Omega_u = -\frac{\mu_u^4}{4\pi^2}$$

$$\Omega_d = -\frac{\mu_d^4}{4\pi^2}$$

$$\Omega_e = -\frac{\mu_e^4}{12\pi^2} \tag{2}$$

$$\Omega_s = -\frac{1}{4\pi^2}\left\{\mu_s(\mu_s^2 - m^2)^{1/2}\left(\mu_s^2 - \frac{5}{2}m^2\right) + \frac{3}{2}m^4 \ln\frac{\mu_s + (\mu_s^2 - m^2)^{1/2}}{m}\right\}$$

where only the strange quark's mass, m, is included. Here we have assumed that the only effect of the strong interactions is seen in B and that the quarks can be treated as free inside the lump. First-order QCD corrections can be included and are discussed in Ref. 2. The number density of each species is

$$n_a = -\frac{\partial\Omega_a}{\partial\mu_a}. \tag{3}$$

Since any bulk system must be electrically neutral,

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0, \tag{4}$$

which tells us that only one chemical potential, say μ, is independent.

The energy density is

$$\epsilon = \sum_a (\Omega_a + \mu_a n_a) + B \tag{5}$$

where the first contribution comes from the fermions and the second is the vacuum energy associated with confinement. The equilibrium configuration is found by minimizing the total energy ϵV, by varying μ, subject to the constraint that the total baryon number $A = (1/3)(n_u + n_d + n_s)V$ is held fixed. Once this is done the energy per baryon E/A, the density and the relative numbers of up, down, strange quarks and electrons are all determined by B and m.

In Fig. 1, contours of fixed E/A are plotted in the $B^{1/4}$–m plane for strange matter. The vertical line on the left, independent of m, gives the value of $B^{1/4}$ for which quark matter without strange quarks has an energy per baryon of 930 MeV. IF $B^{1/4}$ were below

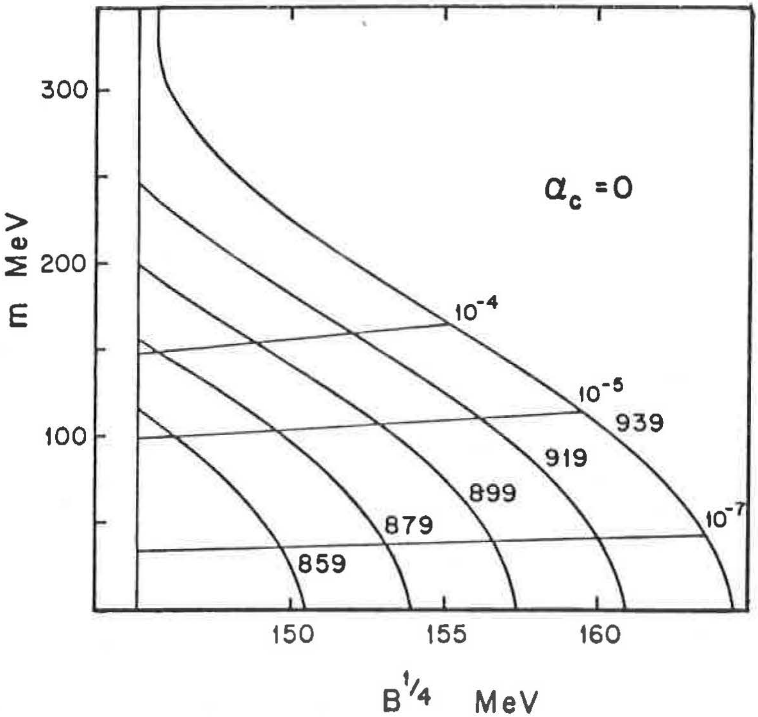

FIGURE 1 Contours of fixed E/A in the $B^{1/4}$–m plane for E/A = 859, 879, 899, 919, and 939 MeV. The vertical line on the left gives the minimum value of B for which two-flavor quark matter is unbound. The nearly horizontal lines give the electron to baryon ratio.

this value, then quark matter consisting of only up and down quarks would be more stable than ordinary nuclei and ordinary nuclei would readily convert to strange matter. Thus, this value of $B^{1/4}$ is a lower bound on $B^{1/4}$ in our phenomenological model. The nearly horizontal lines are contours of fixed hadronic electric charge per baryon which you can see is very small and approaches zero as m approaches zero.

Once values of B and m have been chosen to guarantee that strange matter is stable, the other properties of strange matter, such as its strangeness per baryon and density, can be determined. Again, a typical density is comparable to nuclear densities, (110 MeV)$^3 \approx (6\ \mathrm{fm}^3)^{-1}$, and if m were zero the strangeness per baryon would be unity while more typically it is a fraction like one-half. Again, see Ref. 3 for elaboration and a discussion of order α_c effects.

Given the density of strange matter we see that lumps with baryon number $\sim 10^6$ are $\sim$100 Fermis in radius and are too small to contain most of their neutralizing electrons on the inside. Thus, Coulomb effects should be included in calculating the energy of these smaller lumps and Eq. (4) does not hold. Coulomb effects favor fission and potentially could destabilize these charged lumps. However, the hadronic charge per baryon is rather small and the Coulomb effects are small. In fact, a small surface tension is enough to stabilize charged lumps. By small, I mean, for example, that adding a surface energy $\sigma(4\pi r^2)$ with $\sigma \simeq (40\ \mathrm{MeV})^3$ will prevent all charged lumps from fissioning for most of the values of the parameters considered in the model calculations of Ref. 3.

Surface effects make the energy per baryon of strange matter decrease with increasing baryon number. Thus, strange matter can be bound for very large A, i.e., $E/A < 930$ MeV, but is likely to be unbound for small A. For very small A, the Fermi gas model can be replaced by a hadronic bag model in which levels are explicitly filled. This model also shows the decrease in E/A with A and can be used to estimate the size of the surface effects.

This model starts with fixed values of B, m and A. Quarks fill orbitals in a spherical cavity of radius R. The number of up, down and strange quarks and the radius are adjusted to minimize the energy. In this way the strangeness, S, and E/A are determined as functions of A. In Fig. 2, a sample calculation is displayed. The

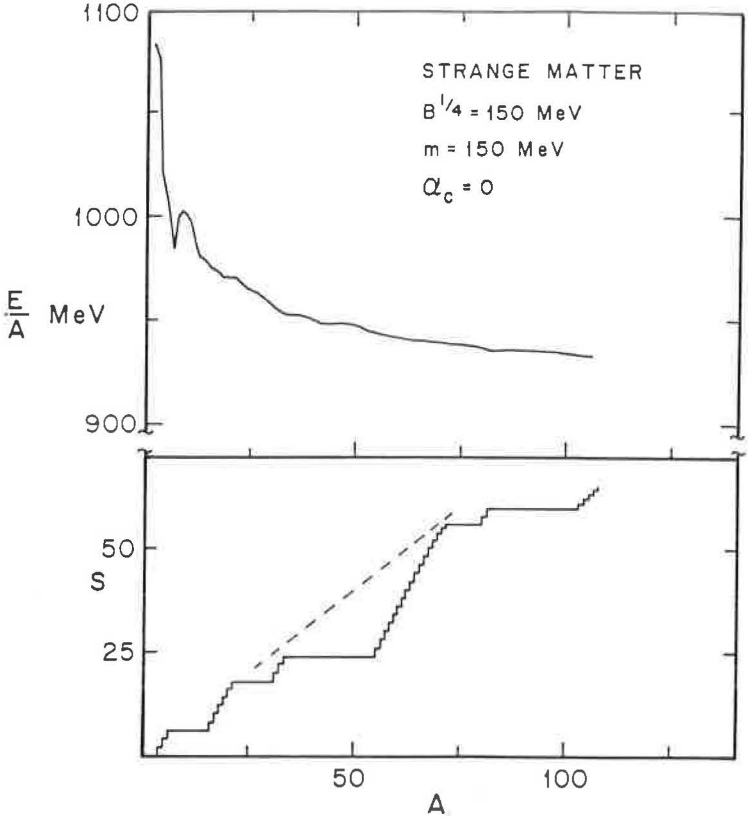

FIGURE 2 E/A and S versus A for strange matter in the hadronic bag model. Parameters are such that E/A is 930 MeV in the bulk limit.

shell effects are evident and the decrease in E/A makes it plausible that strange matter is stable only for baryon numbers above some critical value of order 100. The critical baryon number is rather uncertain and could be closer to 10.

The question of the stability of strange matter appears impossible to decide based on our present understanding of QCD. Our simple model of strange matter, which assumes its stability, serves as a useful guide to its properties. Lumps of strange matter may be absolutely stable, against nucleon emission or fissioning, for baryon numbers above roughly 100 all the way up to the maximum size which is unstable due to gravitational collapse, $A \sim 10^{57}$.

What happens when strange matter comes in contact with ordinary matter? A neutron which enters strange matter will lower its energy by falling apart and releasing its quarks to the quark phase. If many neutrons enter, eventually the relative numbers of up and down quarks will become higher than the most favored equilibrium configuration. However, weak interactions can change up and down quarks to strange and reestablish the favored distributions. A lump of strange matter has an insatiable appetite for neutrons and grows fat by eating them.

Strange matter carries a small positive hadronic charge and is neutralized by electrons. Even for very large lumps, the electrons extend beyond the edge of the strange matter because the electrons are only electromagnetically bound while the hadronic surface of strange matter falls off in a few Fermis. A proton or positive ion approaching a lump first passes through a film of electrons. In this region there is an outward electric force repelling the projectile. For a positively charged particle to enter strange matter it must overcome a Coulomb barrier which may be tens of MeV. A lump of strange matter moving at galactic velocities would not have strong interactions with material which it bumps into. A small lump of strange matter could be found resting in some material on the earth without interacting with the material.

3. STRANGE MATTER IN THE EARLY UNIVERSE

If strange matter is the true ground state of the strong interactions, then a natural place to look for the production of strange matter is in the early universe when temperatures and densities were of order of the QCD scale. In fact, the original suggestion[2] that strange matter could be stable was made in the context of a scenario for the production of large amounts of strange matter when the universe cooled though the QCD phase transition at a temperature of roughly 200 MeV. However, I will now show[4] that any strange matter produced during this epoch would have evaporated before the universe cooled to 1 MeV. Thus, any strange matter around today must have been produced more recently.

To begin, I will use detailed balance to get the evaporation rate of a lump of strange matter at a temperature T. Consider a neutron incident on a lump. The neutron lowers its energy by entering the strange matter and falling apart. The excess binding energy, I, is typically tens of MeV and in no case do we expect I to exceed 100 MeV (see Fig. 1). The neutron absorption cross section is

$$\sigma = f_N(4\pi r^2) = f_N\sigma_0 A^{2/3} \tag{6}$$

where f_N is the absorption efficiency with $f_N \lesssim 1$, r is the radius of the lump and σ_0 depends on the density chosen.

Consider an equilibrium situation where lumps of various A are in equilibrium with neutrons at a temperature T. The reaction $(A + 1) \leftrightarrow (A) + n$ implies for the chemical potentials:

$$\mu(A + 1) = \mu(A) + \mu(n) + I. \tag{7}$$

At the temperatures of interest, all particles are nonrelativistic and obey

$$\mu = T \ln \left\{ \left(\frac{2\pi}{mT}\right)^{3/2} \frac{N}{g} \right\} \tag{8}$$

where m is the mass of the particle, N is the number per unit volume and g is the degeneracy. Equations (7) and (8) combine to give:

$$\frac{N(n)N(A)}{N(A + 1)} = 2 \left(\frac{m_N T}{2\pi}\right)^{3/2} e^{-I/T} \tag{9}$$

which is known as the law of mass action or the Saha equation.

In equilibrium, lumps with baryon number $A + 1$ are being created at the same rate as they decay. The creation rate per unit volume is

$$R[A + n \rightarrow (A + 1)] = N(A)N(n)f_N\sigma_0 A^{2/3} \left(\frac{T}{2\pi m_N}\right)^{1/2} \tag{10}$$

where the last factor is the mean thermal velocity of the neutrons. The rate at which the lumps disappear is

$$R[(A + 1) \rightarrow A + n] = N(A + 1)r \tag{11}$$

where r is the evaporation rate of a lump at temperature T. In equilibrium we can equate (10) and (11) and using (9) obtain

$$r = \frac{1}{2\pi^2} m_N T^2 e^{-I/T} f_N \sigma_0 A^{2/3}. \tag{12}$$

This is the evaporation rate into neutrons of a lump with baryon number A, assuming that the lump is maintained at a temperature T. This rate has been calculated in the context of an equilibrium situation but can be used in other contexts. In particular, if an isolated lump is maintained at a temperature T it will evaporate entirely in a time

$$\tau(A) = \frac{6\pi^2 e^{I/T} A^{1/3}}{m_N T^2 f_N \sigma_0}. \tag{13}$$

I will now apply this result to the early universe. Imagining that lumps of strange matter are produced when the universe has a temperature of 100–200 MeV. For the lump to survive through the epoch when the universe has a temperature T_u, the lifetime (13) should be greater than the age of the universe at this temperature. There is a well-known relation between the age of the universe and its temperature during the radiation dominated era:

$$\tau_u = \left[\frac{45}{172\pi^3 G}\right]^{1/2} \frac{1}{T_u^2} \tag{14}$$

where I have assumed that the energy density is mostly in photons, electrons and three types of neutrinos. (G is Newton's constant.) By comparing (13) and (14) with $\sigma_0 = 3 \times 10^{-4}\ \text{MeV}^{-2}$ we see that for a lump to survive until $T_u \sim I$, the lump must have a baryon number, A, greater than $10^{55} f_N^3$. Since we expect $f_N \lesssim 1$, the minimum baryon number which can survive is clearly very large.

The analysis just presented leaves out many important effects which lower the minimum baryon number required to survive. For example, evaporating lumps cool rapidly and will cease evaporating unless energy is continuously supplied. The source of this energy is incoming neutrinos which have energies of order T_u.

Also, neutrons near the surface can be reabsorbed and reduce the net evaporation rate. These neutrons form a blanket around the lump and shield it from incoming neutrinos which cuts off the energy supply and the evaporation. All of these effects have been taken into account in a detailed calculation[4] which shows that even with a very high binding energy of 100 MeV and an absorption efficiency of 10% the minimum baryon number required to survive is 10^{52}.

This analysis of evaporation is based on thermodynamics, the conditions of the early universe, and model independent properties of strange matter such as its binding energy. The analysis shows that no matter what mechanism is used to produce strange matter during the QCD phase transition at 100–200 MeV, all lumps with $A \lesssim 10^{52}$ subsequently evaporate. A baryon number of 10^{52} is very large by cosmological standards during this epoch. At $T_u = 100$ MeV, the baryon number within a horizon is 10^{49}. Thus, any production mechanism which results in lumps that survive must involve large perturbations in the baryon number on the horizon scale. Also, since there is so much evaporation below 100 MeV, it is difficult to imagine any scenario which succeeds in producing much strange matter above 100 MeV. We can safely conclude that no strange matter existed by the time the universe cooled down to roughly 100 MeV, one second after the big bang.

4. STRANGE STARS

If strange matter is stable it is likely that what were previously thought of as neutron stars are in fact strange stars.[2] Imagine that the central density of an ordinary neutron star is high enough so that a conversion to two-flavor quark matter occurs. Two-flavor quark matter readily converts to strange matter so that the star would have a strange central core. This core would be in contact with neutrons, but strange matter readily absorbs neutrons, so the core would grow, consuming the entire star, except for a possible thin crust which I will describe later.

Whether the central densities of neutron stars are high enough to guarantee a conversion to quark matter is controversial, so this route to strange stars is not guaranteed. At above roughly five times nuclear density, nuclear matter contains a large fraction of lambdas and it is certainly conceivable that somewhere in the star a group of lambdas will convert to a lump of strange matter. Any seed of strange matter would eventually convert the whole star. However, since strange matter is only favored above a certain critical baryon number of order 10 or 100, it is difficult to find a naturally occurring fluctuation which must result in a stable seed in all neutron stars. It is possible that the conditions at the time of supernovae explosions favor the creation of strange matter and neutron stars are born as strange stars. However, we can not conclude decisively. For this discussion, I will assume strange stars exist and analyze their properties.[5,6]

Strange stars have very different equations of state than ordinary neutron stars and, consequently, they have different mass–radius relations. An ordinary neutron star is held together gravitationally and the material obeys an equation of state with the density going to zero as the pressure goes to zero. A very low mass neutron star is very large. Strange matter has a nonvanishing density at zero pressure and small lumps, which are not gravitationally bound, are self-bound and have $M \propto R^3$. In Fig. 3, the mass–radius relation for strange stars and ordinary neutron stars is displayed and the low mass differences are obvious. However, most neutron stars are thought to have masses close to 1.4 $M_\odot$ where the difference between strange stars and neutron stars is much less apparent. The maximum mass of a strange star, above which it collapses into a black hole, is not appreciably different than that of a conventional neutron star.

Since strange matter is stable at zero pressure, a strange star could be strange matter all the way to the surface. Such an exposed quark matter surface could radiate in excess of the Eddington limit since this limit is determined by the luminosity at which the radiation pressure exceeds the gravitational binding, but this surface is bound strongly, not gravitationally. However, such a surface would not radiate photons of all energies. Photons propagating in strange matter have a "plasma frequency" of roughly 20 MeV. A photon with less energy will typically be reflected from the surface and correspondingly the surface is a poor radiator of photons with energy below 20 MeV. Thus, strange stars may not radiate in the x ray.

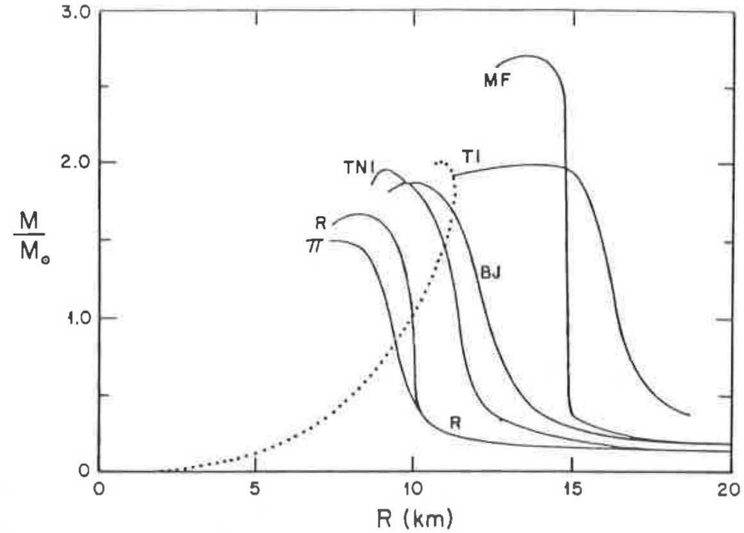

FIGURE 3 The dashed line is the strange star mass versus radius relation. The solid lines represent mass versus radius relations for conventional neutron stars assuming different equations of state. These curves are discussed in *Black Holes, White Dwarfs and Neutron Stars* by S. L. Shapiro and S. A. Teukolsky (Wiley, 1983).

A strange star may be coated by a thin crust of ordinary matter. Recall that strange matter carries a positive charge and is neutralized by electrons which extend beyond the hadronic material. There is an outward electric field in this region which can support positive ions but, of course, does not support neutrons. Ordinary atoms can float on the surface of strange matter and make up the crust.

There is a limit to how much ordinary material can be supported by a strange star.[6] Imagine adding material to a strange star's crust. The pressure at the base of the crust, just where it interfaces the strange matter, will increase. If this pressure is too great, the material will be pushed into the strange matter. The maximum pressure which can be tolerated depends on the hadronic charge density of the strange matter and is rather model dependent. However, there is another limit which is model independent. Again, imagine adding material to the crust which increases the pressure and density of the material at the base of the crust. For ordinary material at a density of 4×10^{11} g/cm^3 neutron drip occurs. This means that the material does not just consist of concentrated nuclei neutralized by electrons, but there is also a component of free neutrons. This material is not safe in contact with strange matter because the neutrons are absorbed. There is a natural limit of 4×10^{11} g/cm^3 to the density at the base of the crust which corresponds to a maximum total mass of the crust of 5×10^{28} g. This is a factor of 1000 less massive than a typical neutron star crust.

Strange stars may support a thin crust or no crust at all. Whether a star has a crust depends on its history. Gently accreting material can accumulate to form a crust whereas particles on ballistic trajectories have more than enough kinetic energy at the surface of the star to penetrate the Coulomb barrier and be absorbed. It is difficult to say whether a strange star born in a supernovae explosion would come with a crust or not.

Crusts play an important role in models of pulsar glitches. Some pulsars are observed to have sudden decreases in the period between pulse emission. This has been associated with a cracking of the crust (star quake) which results in a slight inward movement of material and subsequent spin up of the star. Strange stars without crusts or with thin crusts would not exhibit this behavior. Other models of glitches involve neutron superfluidity, but strange stars have no neutrons in their interiors or crusts. There does not yet exist a model of strange star pulsar glitches.

For more complete discussion of strange star properties, please see Refs. 5 and 6.

5. SEARCHING FOR STRANGE MATTER

I have argued that any strange matter produced very early in the history of the universe would have evaporated before the universe was one second old but that strange matter may exist in stars today. Collision of such stars or other astrophysical events may have produced small lumps of strange matter which permeate the galaxy. Regardless of any astrophysical or cosmological considerations, if strange matter is more stable than iron, it is worthwhile considering ways to search for strange matter. Perhaps some lumps are to be found on Earth today. Any lump found on Earth could not have a baryon number much above 10^{16} corresponding to a radius of a few hundred Fermis. Larger lumps are too heavy; they could not be supported by ordinary materials and would sink to the center of the earth.

One proposal[7] is to use heavy ion activation to search for small impurities of strange matter in laboratory samples of ordinary matter. Lumps of strange matter carry a positive hadronic charge and are neutralized by electrons which extend beyond the hadronic material. Like an ordinary nucleus, a lump of strange matter presents a Coulomb barrier to an incoming positive ion. However, strange matter has a much lower charge to baryon ratio than nuclei and, for typical values of the parameters in model calculations, it presents a lower Coulomb barrier than nuclei. An ion whose energy is just below the Coulomb barrier for ordinary nuclei may have enough energy to enter a lump of strange matter. An ion which does enter a lump will fall apart and release its excess binding energy to the lump. If the lump is large it will not fission and it will radiate away the excess binding energy as well as the kinetic energy of the projectile.

To find an impurity of strange matter in a sample, you could use the sample as a target of a heavy ion beam whose energy is just below the Coulomb barrier for ordinary nuclear reactions. If a beam nucleus enters a lump, a striking signal would appear in an otherwise quiet system. For example, if the binding energy of strange matter relative to gold is 20 MeV, then a single gold nucleus, just below the Coulomb barrier, would release 5 GeV after entering a lump of strange matter. This energy would show up as an isotropic photon burst which would be hard to miss. A discussion of sensitivities and of a preliminary experiment carried out at the Super HILAC can be found in Ref. 7.

Small lumps of strange matter whizzing around in our galaxy may occasionally pass through the Earth. DeRujula and Glashow[8] have analyzed a variety of detection methods sensitive to different mass ranges and fluxes. For example, underground proton decay detectors are sensitive to the light produced by strange lumps passing directly through them. They estimate that a lump whose radius is larger than 10^{-10} cm could produce a detectable signal in the IMB detector. Lumps larger than 10^{-2} cm passing through Earth would deposit so much energy that they may be detected as "epilinear earthquakes." They analyze this and other possible means of detection of strange lumps passing through Earth.

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