Nuclear Physics B (Proc. Suppl.) 24B (1991) 93–102
North-Holland

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

STRANGE STARS

Charles ALCOCK

Institute of Geophysics and Planetary Physics, Lawrence Livermore National Lab., Livermore, CA 94550, U.S.A.

The general structure of strange stars is reviewed, paying particular attention to their similarities to and differences from neutron stars.

1. INTRODUCTION

The advent of theoretical discussion of stable three flavor quark matter, now known as strange matter, that came with Witton's seminal paper[1], has proved very interesting for the discussion of compact stars in astrophysics. This review discusses the properties of strange stars that have made them so interesting, and pays particular attention to the possibility of distinguishing neutron and strange stars observationally.

2. STRUCTURE - A CRUDE APPROACH

Much can be learned about the structure of a strange star using an extremely simple model for the equation of state. This simplified approach will be described here; the extra information that is gained by taking a more rigorous approach is summarized in Section 3. The basic results described here were obtained in the early papers on strange stars[1, 2, 3].

The equation of state for quark matter in a simplified version of the MIT bag model[4] may be thought of as a degenerate Fermi sea of massless quarks which exist only in a region of space endowed with a vacuum energy density B. The equation of state for massless particles is:

$$P_q = \frac{1}{3}\rho_q, \qquad (2.1)$$

where P_q is the pressure due to the quarks, and ρ_q is the density of mass-energy. The total pressure $P = P_q - B$, and the total density $\rho = \rho_q + B$, whence the model equation of state becomes:

$$P = \frac{1}{3}(\rho - 4B), \qquad (2.2)$$

(Note that we have not yet specified the number of quark flavors, or for that matter any of the statistics of the Fermions. This will be discussed further in Section 3.)

A "typical" value of the bag constant $B = (145\ \text{MeV})^4 = 57\ \text{MeV fm}^{-3}$. Looking at equation (2) we see that there is a minimum density $4B$ at which $P = 0$: in conventional units $4B \approx 4 \times 10^{14}$ g cm^{-3} for $B = (145\ \text{MeV})^4$.

To obtain a model of a strange star one must integrate the Tolman-Oppenheimer-Volkoff equations[5]:

$$\frac{dp}{dr} = -\frac{G\left[(M(r) + 4\pi r^3 P)[\rho + P]\right]}{r\left[r - 2GM(r)\right]} \qquad (2.3)$$

$$\frac{dM}{dr} = 4\pi r^2 \rho, \qquad (2.4)$$

where $M(r)$ is the mass interior to radius r, and G is Newton's constant. The boundary conditions are that $M \to 0$ as $r \to 0$ and $P \to 0$ at the surface. Sequences of models are constructed

Elsevier Science Publishers B.V.

by choosing central pressures (or equivalently, central densities) and integrating outwards until $P \rightarrow 0$.

The radial variation of density is shown for four different models in Figure 1. Those familiar with neutron stars will notice one important distinguishing feature: there is only modest variation of density with radius. In particular, the density variation from center to edge for the astrophysically relevant 1.4 $M_\odot$ model is less than a factor of two! This is markedly different from the situation that is normally encountered in stars, and results from the very high minimum density.

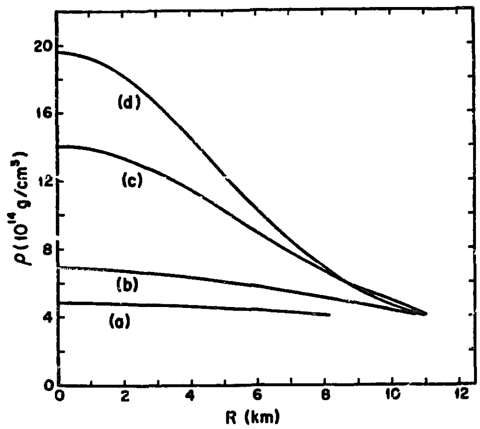

FIGURE 1

Density versus radius for strange stars of mass: (a) 0.53 $M_\odot$; (b) 1.4 $M_\odot$; (c) 1.95 $M_\odot$; (d) 1.99 $M_\odot$.

Stability against gravitational collapse plays a significant role in the theory of compact stars[5]. This complex theory will not be discussed here; instead we will abstract from the theory only a necessary condition for stability against gravitational collapse:

$$\frac{dM}{d\rho_c} > 0, \qquad (2.5)$$

where M here refers to the total mass of the star and ρ_c is the central density. Figure 2 shows M versus ρ_c, for the case $4B = 4\times10^{14}$ g cm^{-3}. Only the stable models are plotted; unstable equilibria may be found for higher central densities, but for lower total masses than the peak at $2M_\odot$. Note the vertical asymptote at the minimum density $4B = 4\times10^{14}$ g cm^{-3} ; for this equation of state there is no minimum mass. (Of course, for extremely low masses the effects described by Jaffe in this volume begin to play an important role.)

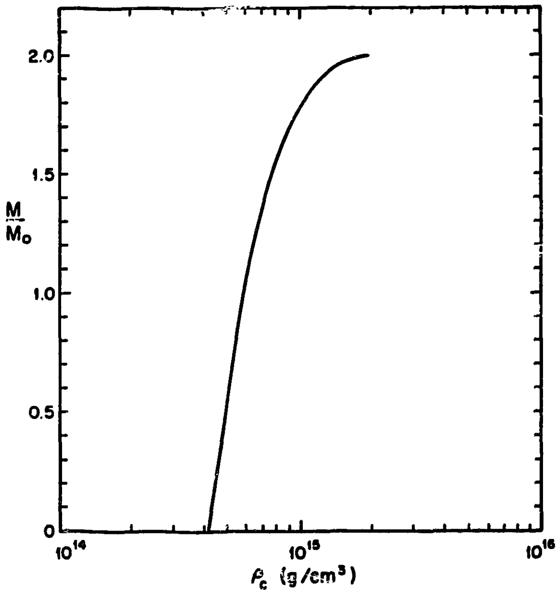

FIGURE 2

Total mass versus central density for stable strange stars.

The total mass is plotted versus the total radius for the same sequence of models in Figure 3. Also plotted are mass radius curves for neutron stars computed with a variety of model equations of state[6]. The difference between the two types of models are striking. The mass of a strange star is, except near the maximum, an increasing function of radius; the reverse is the

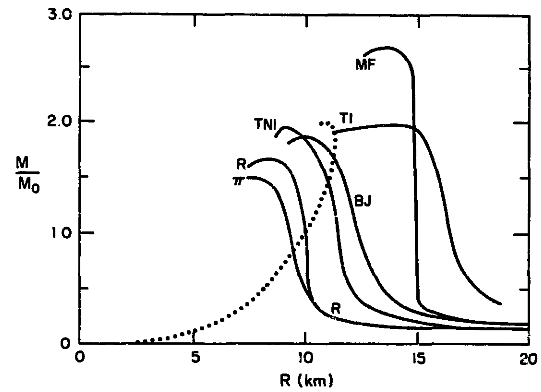

FIGURE 3

Mass versus radius for strange stars (dots) and neutron stars (adapted from Alcock and Olinto).

case for neutron stars. There is no minimum mass for the strange star, while neutron stars have clearly a minimum mass (for dynamical stability). In general the radius of a neutron star is larger than that of a strange star of the same mass, if the mass is $\leq 1 M_\odot$.

The substantial differences between the global properties of the strange stars and the neutron stars might lead one to suppose that straight forward observable distinctions between the two pictures might emerge. This has not proved to be the case, however, because all estimates of the masses of candidate objects have been $\sim 1.4 M_\odot$. The list of candidates includes the famous binary radio pulsar PSR 1913 + 16[7], for which careful analysis yields masses of the two objects of $1.4\ M_\odot$ for the emitting pulsar and for the unseen companion. A survey of mass determinations for other candidates shows that all masses are close to $1.4\ M_\odot$. It is clear from Figure 3 that for a mass of this magnitude, the overall structures of strange stars and neutron stars are indistinguishable.

There is a simple scaling law governing the simple models of strange stars that are described here. This scaling law can be used to estimate the range of uncertainty within the sequence of models shown in Figures 1, 2, and 3. The equation of state given in equation (2.2) depends on only one parameter, B. The magnitude of B is quite uncertain. Suppose that instead a different value $B' = aB$ were of interest. One may obtain the new sequence of models by taking each model from the original sequence and applying the homology transformation:

$$\rho' = a^p \rho$$

$$P' = a^q P$$

$$r' = a^s r \qquad (2.6)$$

$$M' = a^t M$$

The transformed model will still satisfy equations (2.2), (2.3) and (2.4) if $p = q = 1$, and $s = t = -1/2$. The new models resemble the original models in all respects except that, if B is increased (decreased) they are more (less) compact. Taking the limiting (i.e. marginally stable) model, one can write:

$$M_{max} = 2\ M_\odot\ (B/[145\ MeV]^4)^{-1/2} \qquad (2.7)$$

$$R_{max} = 11\ km\ (B/[145\ MeV]^4)^{-1/2} \qquad (2.8)$$

Taking the strong evidence cited above that the mass of the compact stars in PSR 1913 + 16 is $1.4 M_\odot$, we may derive an upper limit to the magnitude of B (in this model) of $B < (173\ MeV)^4$.

3. A MORE RIGOROUS APPROACH

The elementary model for a strange star that was described above contains much of the physics of these objects. It turns out that the more rigorous approach described here does not lead to any significant (quantitative or qualitative) modification. What is added by the more rigorous approach is some understanding of the microscopic constituents of the star, and one new (and important) global parameter, the binding energy of the whole star.

The model equation of state described here is not fully rigorous (i.e. derived from QCD). Fully rigorous calculations of the kind one needs are not available. Rather, in the spirit of Farhi and Jaffe[4], the model takes into account what is known about the microscopic constituents of strongly interacting matter and their known interactions, but retains the Bag Model for its description of confinement. The description given here is adapted from Farhi and Jaffe, together with the straight forward extension to finite pressure given in Alcock, Farhi and Olinto[3].

The first, and most obvious, gain from this more rigorous approach is that the relationship of the macroscopic physics to the microscopic physics becomes apparent. The equation of state given by equation (2.2) makes no reference to the number of distinguishable Fermions, their statistics, or any other property other than their low (or zero) mass.

Specifically, strange matter is modelled as a Fermi gas of up, down and strange quarks, with overall charge neutrality preserved by a small number of electrons. The quarks exist only in an extended MIT "bag". The important physical parameters describing the equation of state are B, the mass of the strange quark, m_s, and the strong interaction coupling constant α_c. In addition, some derived properties depend upon the adopted value of the renormalization point.

The calculations described here are carried out at zero temperature. This is a good approximation for most purposes, since the temperatures of the stars are likely to be small compared to the chemical potentials of the quarks and electrons. The impact of finite temperature has been discussed by Heiselberg, Madsen, and Riisager[9] and Chmaj and Slominski[10].

The equation of state is determined by the thermodynamic potentials of the quarks and electrons, and by chemical equilibrium reactions. These reactions are:

$$d \to u+e+\bar{\nu}_e, \tag{3.1}$$

$$u+e \to d+\nu_e, \tag{3.2}$$

$$s \to u+e+\bar{\nu}_e, \tag{3.3}$$

$$u+e \to s+\nu_e, \tag{3.4}$$

and

$$s+\leftrightarrow d+u. \tag{3.5}$$

The neutrinos which appear in reactions (3.1) - (3.4) do not appear in the thermodynamic description of the equation of state because they are lost by the star (i.e. their chemical potential is zero). These are the reactions which lead to the cooling of strange matter at finite temperature.

The weak interactions yield the following relations between the chemical potentials for the up, down, and strange quarks (μ_u, μ_d, μ_s) and the electrons (μ_e):

$$\mu_d = \mu_s = \mu_u + \mu_e. \tag{3.6}$$

In addition, electric charge neutrality requires:

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0, \tag{3.7}$$

where n_u is the number density of up quarks, and so on. Equations (3.6) to (3.7) show that there is only one independent chemical potential.

The physics of strange matter is determined by equations (3.1) to (3.7) together with the thermodynamic potentials Ω_i ($i = u, d, s, e$) for the elementary particles. These potentials are given by Farhi and Jaffe, and will not be written out here.

Armed with this formalism, we may calculate number densities using:

$$n_i = -\frac{\partial \Omega_i}{\partial \mu_i}, \qquad (3.8)$$

whence the baryon number density is:

$$n_B = \frac{1}{3}\left(n_u + n_d + n_s\right). \qquad (3.9)$$

The total energy density is given by:

$$\rho = \sum_i (\Omega_i + \mu_i n_i) + B, \qquad (3.10)$$

and the pressure by:

$$P = n_B \frac{\partial \rho}{\partial n_B} - \rho. \qquad (3.11)$$

The Gibbs potential per baryon, $\Gamma = (P + \rho)/n_B$ is:

$$\Gamma = \frac{\partial \rho}{\partial n_B} = \mu_u + \mu_d + \mu_s \qquad (3.12)$$

In the limit $m_s \to 0$ and $\alpha_c \to 0$, equation (2.2) is recovered. This also happens for $m_s \to \infty$, $\alpha_c \to 0$, since equation (2.2) depends only upon the assumption that the Fermions are massless. It turns out that for intermediate values of m_s, the deviation from equation (2.2) is less than 4%[3]. This is because, as the strange quark mass increases from zero, the abundance of strange quarks decreases, and they play a smaller role in determining the equation of state.

Thus, it turns out that the new physical realism added by equations (3.1) through 3.12) modify the results given in Section 2 by a very small amount! One might ask, then, what has been gained by this extra work? As we will now see, one important piece of global information is obtained, and many interesting local properties may be discerned.

Whereas the relationship between pressure and density is nearly independent of the model equation of state, the relationship between energy density and baryon number density is sensitively dependent on the details. In particular, the defining requirement for strange matter, that it be stable at zero pressure, requires that the strange quark mass be comfortably less than the typical values of the chemical potentials (~300 MeV). In our notation, this is expressed as Γ<930 MeV at $P = 0$, where 930 MeV is the mass per baryon of ^{56}Fe at zero pressure. It is only meaningful to discuss models of strange stars which are derived from equations of state which have this property.

It is now possible to compute a meaningful binding energy for the model strange star. A reasonable definition is the difference between the mass of the star and the mass of a widely dispersed cloud of hydrogen which has the same total baryon number. Example curves of binding energy versus baryon number are shown by Alcock, Farhi and Olinto[3].

4. SURFACE OF A STRANGE STAR

4.1. The Emission of Photons

The most remarkable property of strange matter is that it is stable at zero pressure. This means that the "surface" of a strange star is very different from the surface of a neutron star, or any other type of star. At the surface of a strange star the density changes abruptly from zero to $\sim 4 \times 10^{14}$ g cm^{-3}! This abrupt change occurs because the material at the surface is bound to the star by the strong interaction, not by gravity.

An immediate consequence of this strongly bound surface is that the conventional upper limit to the luminosity of a star, the Eddington limit [3], does not apply. The Eddington limit is reached when the outgoing radiation exerts an outward directed force on the surface material that exceeds the attraction due to gravity. For objects of mass $\sim 1.4 M_{\odot}$ this limit is $\sim 10^{38}$ erg s^{-1}, the precise value depending on the opacity of the matter. Since the surface of a strange star is bound by the strong force, it can support outgoing radiant fluxes greatly in excess of the Eddington limit. This may play a role in the physics of energetic gamma ray events (discussed below).

There is another important effect on the photon emissivity of strange matter. The density of electric charge in strange matter is high, and the propagation of electromagnetic waves is modified as in any other plasma[3]. The dispersion relation for photons in strange matter is the familiar plasma dispersion relation:

$$w^2 = w_p^2 + k^2, \tag{4.1}$$

where k is the wavenumber and w the angular frequency, and w_p is the "plasma frequency", which turns out to be ~20MeV[3, 11].

The conventional interpretation of equation (4.1) applies to this situation. Propagating modes exist only for $w > w_p$. In the limit $w \to \infty$ the dispersion relation for photons propagating in a vacuum is recovered. For intermediate cases there is substantial dispersion, the group velocity increasing with frequency.

A surface of strange matter has the following interesting property. An incoming photon with $w < w_p$ cannot penetrate the surface; instead the photon is reflected. The reflectivity of strange matter is very close to unity for photons of energy much less than 20 MeV (i.e. the star is like a "silver sphere" in the x-ray). Correspondingly, the emissivity of the surface is very low for photons of energy much less than 20 MeV. This emissivity has been estimated by Chmaj, Haensel, and Slominski[11].

There is a related consequence of the sturdiness of the strange matter surface that has implications for models of the magnetospheres of radio pulsars. A rotating, magnetized neutron star generates electric fields at its surface that are strong enough to draw ions or electrons out from the surface. These charges can have very serious consequences for the electromagnetic structure of the region immediately outside the star[12, 13]. The same process will not occur around a strange star, because the electrostatic forces are not able to remove particles from the surface. For this reason, the magnetosphere surrounding a bare strange star might be very different from that surrounding a neutron star.

4.2. Crusts of Normal Matter

The dramatic, unusual surface properties described above result from the exposure of a bare surface of strange matter. It is far from clear that such a surface can be realized in a real astrophysical environment, for reasons now discussed. It turns out that a strange star is likely to be covered by a thin crust of "normal" material.

This crust of normal material can exist in close proximity to the strange matter, even though the total energy of the star would be reduced if the crust were converted to strange matter, because a coulomb barrier develops between the strange matter and the ions in the crust. (It is for this reason that small lumps of strange matter can co-exist with normal matter, without reacting strongly.) The origin of the coulomb barrier is interesting.

As described in Section 3, the bulk strange matter contains a small number of electrons. These electrons are needed to ensure bulk charge neutrality. Bulk charge neutrality does not naturally occur among the quarks by themselves, because the strange quark mass slightly suppresses the number of strange quarks below the number of up and down quarks. Typically, the chemical potential of the electrons is ~20MeV.

The electrons are bound electrostatically to the quarks. This means that, deep inside the strange matter, there is an electrostatic potential of ~20MV. The behavior of the electrostatic potential at the surface is very interesting. The surface of the quark matter is of order 1 Fermi (a strong interaction length scale); the electrons are able to move freely across this surface, but clearly cannot move to infinity because of the bulk electrostatic attraction of the quarks; the "electron surface" is much thicker than the quark surface.

A model of the electron surface can be made using a simple Thomas-Fermi approximation[3]. It is found that the electron distribution extends up to 10^3 Fermi above the quark surface. The electrostatic potential falls to 3/4 of the deep interior value at the quark surface. The typical magnitude of the electric field in this region is ~5 x 10^{17} V cm^{-1}, directed outward. The run of electrostatic potential with height above the surface is shown in Figure 4.

The very large electric field is clearly capable of supporting an ion against the gravitational attraction to the underlying star. It turns out that this electric field can support a crust of material that is identical to the "outer crust" of a neutron star. There is a gap of a few hundred Fermi between the surface of the strange matter and the base of the crust. The structure of this gap is shown in Figure 4.

A requirement for the survival of this crust is that it not react with the underlying strange matter. This requirement is met if two conditions are satisfied. First, the gap described above must not close because of the weight of the crust. Second, the density at the base of the crust must not grow so large that neutron drip occurs; free neutrons readily react with the strange matter. In practice, it appears that the second requirement is the more stringent, and hence the density at the base of the crust may not exceed 4 x 10^{11} g cm^{-3}.

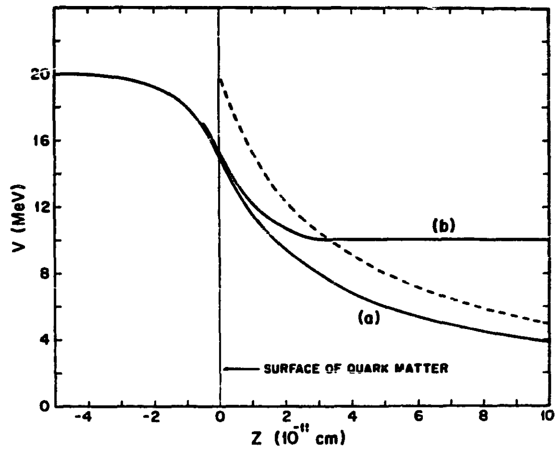

FIGURE 4

Electrostatic potential versus height above the surface of a strange star: (a) no crust; (b) crust with V = 10 MeV at base of crust.

Note that the discontinuity in density across the gap is >10^3.

The existence of this crust modifies the conclusions of Section 4.1. This new surface is subject to the Eddington limit; it can emit soft photons (as though the silver sphere were painted black). However, the existence of the crust is not a fundamental attribute of the star; whether or not the crust exits, and how thick it is (up to the limit set by neutron drip) depends upon the history of the object. It would seem likely that at least some sort of crust would form, given the large amount of ambient material surrounding a newly made strange star following a supernova explosion.

5. STRANGE OR NEUTRON STARS ?

Perhaps the most exciting possibility in this field of endeavor is that we might be able to use astrophysical inferences to determine whether very compact stars are strange stars or neutron stars. A definitive answer in either direction would tell us something fundamental about QCD which may not be learned using direct techniques in the foreseeable future. The remarkable similarity, however, between strange stars and neutron stars of 1.4 $M_\odot$ has made this hope difficult to achieve.

5.1. Rapid Pulsars

Rotating stars cannot have arbitrarily high angular rotation; at some point material will be ejected from the equator of a rapidly rotating object. For compact stars such as strange or neutron stars, there is an upper limit to the angular rotation velocity set by the onset of bar like dynamical instability. If the star is set into rotation at a higher angular frequency, the star evolves rapidly into a rotating bar, which then radiates away the excess angular momentum in gravitational waves.

The limiting angular frequency is[14]:

$$\Omega \leq \alpha \sqrt{GM / R^3} \qquad (5.1)$$

where $\alpha \approx 0.65$. The important feature of equation (5.1) is that the limiting angular frequency depends only upon the mean density of the star.

Referring back to Figure 3 we see that, for the most part, the strange stars have higher mean density than the neutron stars. Recalling the homology transformation at the end of Section 2, we see that it is possible that (for a reasonable, if large, choice of B) to make models of strange stars which can rotate faster than any model neutron star.

This last observation caused a brief flurry of intense excitement with the announcement of the discovery of an optical pulsar with period 0.5 mSec in Sn1987A[15]. A number of papers pointed out the near impossibility of reconciling this datum with the neutron star picture[16, 17]. The discoverers later retracted, and the brief time during which strange stars were "looking like winners" was over.

A number of papers[18, 19, 20, 21] concluded that even strange stars could not rotate so fast. The argument was made that if the choice of physical parameters was restricted to values which kept the energy per baryon of zero pressure strange matter below 939 MeV, then the stellar structure equations described in Section 2 did not admit model stars of high enough mean density to rotate with period 0.5 mSec. While this argument is both formally sound and highly suggestive, it is not rigorous; recall that the models of the equation of state are only approximate[4]. A more definitive treatment will be possible only when precise, QCD based calculations become possible!

It is worth noting that the potential for finding a pulsar of very short period still exits, and that such an object could determine whether or not strange stars exist. Furthermore, as Glendenning points out[22], present search strategies include a bias against the detection of very short period radio pulsars; hence, the absence of such objects in the catalogs does not mean they do not exist. Current searches, which are focussing increasingly on globular clusters, might yet discover a very rapid pulsar.

5.2. Pulsar Glitches

An increasing number of radio pulsars have exhibited the glitch phenomenon. In a glitch, the pulsar period abruptly decreases by a small fractional amount (in the range 10^{-6} to 10^{-8}), then, remarkably, over a period of 40 - 100 days there is a relaxation back toward the pre-glitch period versus time curve, with substantial fractions of the change being lost.

A good model has been devised for this phenomenon which involves the interaction between superfluid neutrons and a crystal lattice of ions in the inner crust of a neutron star[23]. No equivalent model has been devised for the strange stars. Reactions to this situation have ranged from "this might be a failure of imagination"[3] to "this means that at least the glitching pulsars must be neutron stars"[23].

One very interesting development in this area is that, if the glitching pulsars must be neutron stars, very significant limits may be placed on the abundance of small lumps of strange matter in the universe. The argument here is that if one such lump were to get into a neutron star, either by direct capture or by capture in the pre-supernova star, it would certainly convert it to strange matter[24] (Madsen, elsewhere in this volume).

6. HIGH ENERGY ASTROPHYSICS

There are a number of distinguishing physical properties of strange matter that make possible models of high energy phenomena that are qualitatively different from models that may be constructed using neutron stars. These properties include the high density at zero pressure, the ability to circumvent the Eddington limit, the low photon emissivity of strange matter, and the reactivity of normal matter with strange matter. Some of these features apply to gamma ray bursts.

Gamma ray bursts are truly mysterious events. They are brief (typical durations 1 - 10 seconds) bursts of gamma rays that came from sources isotropically distributed over the sky. No convincing counterparts have been identified in any other spectral range, which has largely confounded their interpretation. (One controversial optical identification will be discussed below.) This fascinating field has been reviewed by several authors[25, 26].

The most remarkable of the gamma ray bursts occurred on 5 March 1979. This burst had the highest peak intensity recorded before or since, the shortest rise time ($< 250\ \mu s$), a brief (0.15 sec.) "high intensity phase", followed by a much longer "low intensity phase". During the low intensity phase the flux was modulated at a period of 8 seconds; 22 periods are discernable in the data[27, 28]. The error box on the sky included a young supernova remnant in the Large Magellanic Cloud[29]. At that distance, the peak luminosity of the burst was six orders of magnitude greater than the Eddington limit for a neutron star.

Alcock, Farhi and Olinto[30] proposed a model for this event in which a small ($10^{-8}\ M_\odot$) projectile of strange matter impacts a strange star. The short rise time is easily accommodated in the model because of the high density of the projectile. The high luminosity is not a problem for a strange star. The 8 second modulation is attributed to rotation. This model is still viable in broad outline, but should be revised in light of some new physics (discussed below). The key difficulty is verification, the observational interpretation remains vague.

Haensel, Paczynski and Amsterdamski[31] have proposed a more ambitious model in which some gamma ray bursts have an extragalactic origin. In their model two $1.4\ M_\odot$ strange stars collide and merge as a result of gravitational radiation driving a binary together. In their model, approximately 10^{50} ergs is released in gamma rays over a period just less than a second. With this enormous energy release, the typical gamma ray burster is at a cosmic distance; in contrast, models involving neutron stars require that the bursters be members of our own galaxy.

Haensel et al's model differs in a number of interesting respects from the model of Alcock et al. First, the calculation by Sawyer[32] of the damping rate for oscillations of a strange star yield a damping time of less than a second; all of the energy of impact is dissipated rapidly into heat. Further, an interesting physical model of the radiation process is employed: most of the thermal energy is emitted into neutrinos. Pair processes above the surface produce an expanding cloud of electrons and positrons. These charged particles produce the gamma rays. This model serves to illustrate how the strange matter picture can radically alter our notions about high energy phenomena.

7. CONCLUSION

To summarize, strange stars differ in many interesting ways from the more conventional neutron stars. These differences have not resulted in a definitive answer to the most important question in this field: "Are compact stars made of strange matter or neutron matter?" There is more work to be done!

REFERENCES

1. E. Witten, Phys. Rev. D30 (1984) 272.
2. P. Haensel, J. L. Zdunik, and R. Schaeffer, Astron. Astrophys. 160 (1986) 121.
3. C. Alcock, C. E. Farhi and A. Olinto, Ap. J. 310 (1986) 261.
4. E. Farhi and R. L. Jaffe, Phys. Rev. D30 (1984) 2379.
5. S. Weinberg, "Gravitation and Cosmology" (Wiley: New York, 1972).
6. C. Alcock and A. Olinto, Ann. Rev. Nucl. Part. Sci. 38 (1988) 161.
7. J. M. Weisberg and J. H. Taylor, Phys. Rev. Letters 52 (1984) 1348.
8. P. C. Joss and S. A. Rappaport, Ann. Rev. Astr. Ap. 22 (1984) 537.
9. H. Heiselberg, J. Madsen and K. Riisager, Physica Scripta 34 (1986) 556.
10. T. Chmaj and W. Slominski, Phys. Rev. D40 (1989) 165.
11. T. Chmaj, P. Haensel and W. Slominski, elsewhere in this volume.
12. P. Goldreich and W. H. Julian, Ap. J. 157 (1969) 869.
13. F. C. Michel, "Theory of Neutron Star Magnetospheres", (University of Chicago Press: Chicago, 1991).
14. N. K. Glendenning, Proc. 1989 International Nuclear Physics Conference Sao Paulo, eds. M. S. Hussein et al., World Scientific (1990) 711.
15. J. Kristian et al, Nature 338 (1989) 234.
16. J. A. Frieman and A. V. Olinto, Nature 341 (1989) 633.
17. N. K. Glendenning, Phys. Rev. Lett. 63 (1989) 2629.
18. P. Haensel and J. L. Zdunik, Nature 340 (1990) 241.
19. J. L. Zdunik and P. Haensel, Phys. Rev. D 42 (1990) 710.
20. J. M. Lattimer, M. Prakash, D. Masak and A. Yahil, Ap.J. 355 (1990) 241.
21. M. Prakash, E. Baron and M. Prakash, Phys. Lett. B 243 (1990) 175.
22. N. K. Glendenning, Mod. Phys. Lett. A5 (1990) 2197.
23. M. A. Alpar, Phys. Rev. Lett. 58 (1987) 2152.
24. J. Madsen, Phys. Rev. Lett. 61 (1988) 2909.
25. W. D. Evans and J. G. Laros, in "The Origin and Evolution of Neutron Stars", ed. D. J. Helfand and J. -H Huang (Reidel: Dordrecht, 1987).
26. P. V. Ramana Murthy and A. W. Wolfendale, "Gamma Ray Astronomy", (Cambrige University Press: Cambridge, 1986).
27. E. P. Mazets, et al., Nature 282 (1979) 587.
28. T. L. Cline, et al., Ap. J. (Letters) 237 (1980) L1.
29. W. D. Evans, et al., Ap. J. (Letters) 237 (1980) L7.
30. C. Alcock, E. Farhi and A. V. Olinto, Phys. Rev. Lett. 57 (1986) 2088.
31. P. Haensel, B. Paczynski and P. Amsterdamski, Ap. J. 375 (1991) 209.
32. R. F. Sawyer, Phys. Lett. 233B (1989) 412.