

## DIFFERENCES IN THE COOLING BEHAVIOR OF STRANGE QUARK MATTER STARS AND NEUTRON STARS

CHRISTOPH SCHAAB, BERND HERMANN, FRIDOLIN WEBER, AND MANFRED K. WEIGEL

Institut für theoretische Physik, Ludwig-Maximilians Universität München, Theresienstrasse 37, D-80333 München, Germany;  
 schaab@gsm.sue.physik.uni-muenchen.de

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### ABSTRACT

The general statement that hypothetical strange quark matter stars cool more rapidly than neutron stars is investigated in greater detail. It is found that the direct Urca process can be forbidden not only in neutron stars, but also in strange-matter stars. In this case, strange-matter stars cool slowly and their surface temperatures are more or less indistinguishable from those of slowly cooling neutron stars. We investigate the case of enhanced cooling again. We find that strange-matter stars cool significantly more rapidly than neutron stars within the first  $\sim 30$  yr after birth. This result may become particularly interesting if continued observation of SN 1987A reveals the temperature of the pulsar that may reside at its center.

*Subject headings:* stars: evolution – stars: neutron

### 1. INTRODUCTION

The theoretical possibility that strange quark matter, matter made up of roughly equal numbers of up, down, and strange quarks, may be more stable than atomic nuclei (specifically iron, which is the most stable atomic nucleus) constitutes one of the most startling predictions of modern physics (see Bodmer 1971; Witten 1984; Terazawa 1989a, 1989b, 1989c), which, if true, would have implications of the greatest importance for laboratory physics, cosmology, the early universe and its evolution to the present day, and massive astrophysical objects (e.g., Madsen & Haensel 1991). Unfortunately, it seems unlikely that lattice QCD calculations will be accurate enough in the foreseeable future to give a definitive prediction of the absolute stability of strange matter, so that one must currently use experiments and astrophysical studies (Glendenning & Weber 1992; Glendenning, Kettner, & Weber 1995) to confirm or reject the absolute stability of strange matter. Using astrophysics to study this question, this Letter compares the cooling behavior of neutron stars with that of their hypothetical strange counterparts, strange-matter stars (see Witten 1984; Haensel, Zdunik, & Schaeffer 1986; Alcock, Farhi, & Olinto 1986; Glendenning 1990). The theoretical predictions are compared with the body of experimental data taken by *ROSAT* and *ASCA*. There have been investigations of this topic prior to ours (e.g., Alcock & Olinto 1988; Pizzochero 1991; Page 1992; Schaab et al. 1996b). These studies, however, did not incorporate the so-called standard cooling scenario, which turns out to be possible not only in neutron star matter but in strange quark matter as well, altering some of the conclusions made in the earlier investigations significantly.

### 2. DESCRIPTION OF STRANGE MATTER

We use the MIT bag model, including  $O(\alpha_c)$  corrections (Chodos et al. 1974; Farhi & Jaffe 1984), to model the properties of absolutely stable strange matter. Its equation of state and quark-lepton composition, which are governed by the conditions of chemical equilibrium and electric charge neutrality, is derived for that range of model parameters (bag constant  $B^{1/4}$ , strange quark mass  $m_s$ , and strong coupling constant  $\alpha_c$ ) for which strange matter is absolutely stable (energy per baryon  $E/A$  less than that for iron, i.e., 930 MeV).

In the limiting case of vanishing quark mass, the electrons need not be present to maintain charge neutrality. In the realistic case of finite strange quark mass  $m_s$ , the electrons still need only be present below some density that depends on  $\alpha_c$ . It was pointed out by Duncan, Shapiro, & Wassermann (1983) (see also Alcock et al. 1986; Pethick 1992) that the neutrino emissivity of strange matter depends strongly on its electron fraction  $Y_e$ . For this reason we introduce two different, complementary parameter sets denoted SM-1 and SM-2 (see Table 1) that correspond to the case of strange matter that contains a relatively high electron fraction (SM-1) and the case of  $Y_e = 0$  (SM-2) for the density range of interest here.

### 3. NEUTRINO EMISSIVITY

The quark *direct* Urca processes

$$d \rightarrow u + e^- + \bar{\nu}_e \quad (1)$$

and

$$s \rightarrow u + e^- + \bar{\nu}_e, \quad (2)$$

as well as their inverse processes, are only possible if the Fermi momenta of the quarks and electrons ( $p_F^i$ ,  $i = u, d, s, e^-$ ) fulfill the so-called triangle inequality (e.g.,  $p_F^d < p_F^u + p_F^e$  for process [1]). This relation is the analog of the triangle inequality established for nucleons and electrons in the nuclear matter case for the direct Urca process (Boguta 1981; Lattimer et al. 1991).

If the electron Fermi momentum is too small (i.e.,  $Y_e$  is too small), then the triangle inequality for the above processes (1) and (2) cannot be fulfilled, and a bystander quark is needed to ensure energy and momentum conservation in the scattering process. The latter process is known as the quark *modified* Urca process, whose emissivity is considerably smaller than the emissivity of the direct Urca process. If the electron fraction vanishes entirely, as is the case for SM-2, both the quark direct and the quark modified Urca processes become unimportant. The neutrino emission is then dominated by bremsstrahlung processes only,

$$Q_1 + Q_2 \rightarrow Q_1 + Q_2 + \nu + \bar{\nu}, \quad (3)$$

TABLE 1  
MODEL PARAMETERS FOR SM-1 AND SM-2

Parameter	SM-1	SM-2
$B^{1/4}$ .....	140	140
$m_s$ .....	150	150
$\alpha_c$ .....	0.10	0.15
$E/A$ (two quark flavors) .....	959	987
$E/A$ (three quark flavors) .....	878	892

<sup>a</sup> All in units of MeV, except  $\alpha_c$ , which is dimensionless.

where  $Q_1, Q_2$  denote any pair of quark flavors. For the emissivities associated with the quark direct Urca, quark modified Urca, and quark bremsstrahlung processes, we refer to Price (1980), Iwamoto (1982), and Duncan et al. (1983).

It has been suggested (see Bailin & Love 1979, 1984) that the quarks may eventually form Cooper pairs. This process would suppress, as in the nuclear matter case, the neutrino emissivities by a factor of  $\exp(-\Delta/k_B T)$  for  $\Delta$  the gap energy,  $k_B$  Boltzmann's constant, and  $T$  the temperature. Unfortunately, at present there exists no precise experimental or theoretical value of the gap energy. To provide a feeling for the influence of possible superfluid behavior of the quarks in strange matter, we choose  $\Delta = 0.4$  MeV, as estimated in the work of Bailin & Love (1979). (Such a value for  $\Delta$  is not too different from that for the nuclear-matter case, for which the proton  $^1S_0$  gap, for instance, amounts to  $\sim 0.2$ – $1.0$  MeV [Wambach, Ainsworth, & Pines 1991; Elgaroy et al. 1996], depending on the nucleon-nucleon interaction and the microscopic model.) The outcomes of our superfluid strange matter calculations will be labeled SM-1<sup>sf</sup> and SM-2<sup>sf</sup>, where electron fractions for the two cases are taken as for the nonsuperfluid calculations.

#### 4. OBSERVED DATA

Among the X-ray observations of the 14 sources identified as pulsars, the *ROSAT* and *ASCA* observations of PSRs 0833–45 (Vela), 0656+14, 0630+18 (Geminga), and 1055–52 (see Table 2) had a sufficiently high photon flux that the effective surface temperatures of these pulsars could be extracted by two- or three-component spectral fits (Ögelman 1995). The effective surface temperatures obtained, shown in Figures 1 and 2, depend crucially on whether a hydrogen atmosphere is used or not. Since the photon flux measured

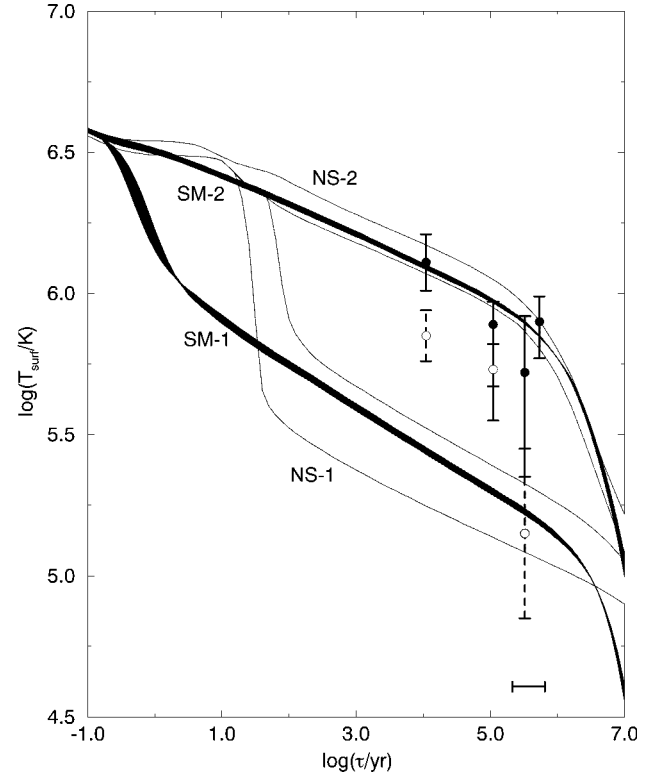


FIG. 1.—Cooling of nonsuperfluid strange-matter star models SM-1 (lower solid band) and SM-2 (upper solid band) and neutron star models NS-1 (lower dotted band) and NS-2 (upper dotted band). The surface temperatures obtained with a blackbody or magnetic hydrogen atmosphere are marked with solid and dashed error bars, respectively (see Table 2). The uncertainty in the pulsar's age is shown by the error bar at the bottom.

solely in the X-ray energy band does not allow one to determine what kind of atmosphere one should use, we consider both the blackbody model and the hydrogen-atmosphere model, represented in Figures 1 and 2 by solid and dashed error bars, respectively. The kind of atmosphere possessed by a specific pulsar can be determined by multiwavelength observations (see Pavlov et al. 1996). All error bars represent the  $3\sigma$  error range due to the small photon fluxes. The pulsars' ages are determined by their spin-down times, assuming a canonical value of 3 for the braking index. In

TABLE 2  
PROPERTIES OF OBSERVED PULSARS

PSR Designation	Spin-down Age (yr)	Model Atmosphere	Surface Temperature (K)	Reference
0833–45 (Vela) .....	$1.1 \times 10^4$	Blackbody	$1.3 \times 10^6$	1
		Hydrogen	$7.0^{+1.6}_{-1.3} \times 10^5$	2
0656+14 .....	$1.1 \times 10^5$	Blackbody	$7.8^{+1.5}_{-4.2} \times 10^5$	3
		Hydrogen	$5.3^{+1.2}_{-0.9} \times 10^5$	4
0630+18 (Geminga) .....	$3.2 \times 10^5$	Blackbody	$5.2 \pm 3.0 \times 10^5$	5
		Hydrogen	$1.7 \pm 1.0 \times 10^5$	6
1055–52 .....	$5.4 \times 10^5$	Blackbody	$7.9^{+1.8}_{-3.0} \times 10^5$	3

References.— (1) Ögelman, Finley, & Zimmermann 1993. (2) Page, Shibano, & Zavlin 1996. (3) Greiveldinger et al. 1996. (4) Anderson et al. 1993. (5) Halpern & Ruderman 1993. (6) Meyer, Parlov, & Mészáros 1994.

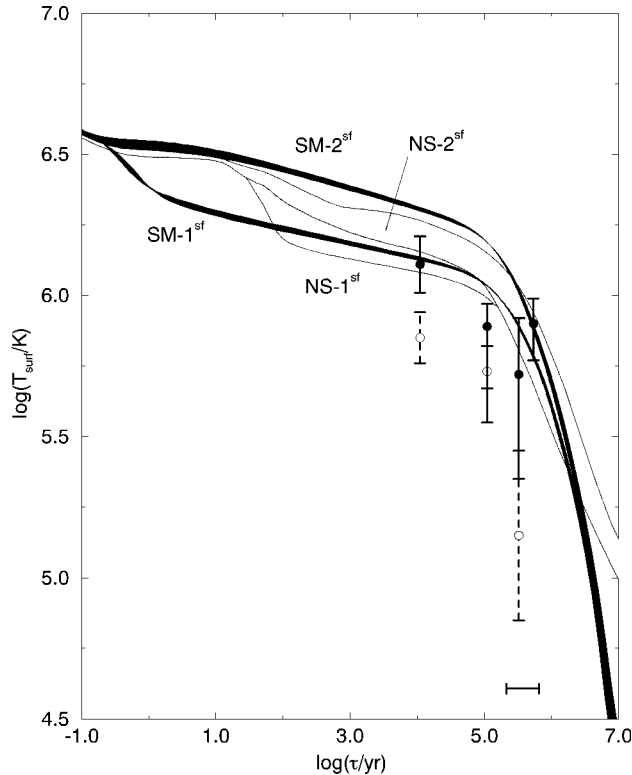


FIG. 2.—Same as Fig. 1, but for superfluid models.

reality, the braking index may be quite different from 3. Varying it between 2 and 4, for instance, changes the age of Geminga as indicated by the horizontal error bar shown at the bottom of Figures 1 and 2.

## 5. RESULTS AND DISCUSSION

The thermal evolution of strange-matter stars and neutron stars was simulated using the evolutionary numerical code described in Schaab et al. (1996b) (see also Tsuruta 1966; Richardson, Van Horn, & Malone 1982; Van Riper 1991; Page 1995; Schaab et al. 1996a). The neutron star models are based on a broad collection of equations of state (EOSs) that includes both relativistic, field theoretical EOSs and nonrelativistic ones based on Schrödinger's equation (see Schaab et al. 1996b for details). A specific feature of the relativistic models is that they account for all baryon states that become populated in dense neutron star matter up to the highest densities reached in the cores of the heaviest neutron stars constructed from this collection of equations of state. Neutron stars are known to lose energy via either standard cooling or enhanced cooling. Both processes may be delayed by superfluidity. Consequently all four cases have been taken into account here. These are labeled in Figures 1 and 2 as NS-1 (enhanced cooling) and NS-2 (standard cooling) for normal neutron star matter and NS-1<sup>sf</sup> and NS-2<sup>sf</sup> (both delayed cooling) for superfluid neutron star matter. The parameters of NS-1<sup>sf</sup> and NS-2<sup>sf</sup> are listed in Table 4 of Schaab et al. (1996b). The corresponding strange-star cooling curves are SM-1 (enhanced cooling) and SM-2 (standard cooling) for normal strange quark matter and SM-1<sup>sf</sup> and SM-2<sup>sf</sup> (delayed cooling) for superfluid quark matter.

All calculations are performed for a star mass of  $M =$

$1.4 M_{\odot}$ , the approximate mean of the observed pulsar masses. The depiction of the cooling curves as bands rather than single lines reflects the uncertainties inherent in the EOSs of neutron-star matter and strange matter. These uncertainties have their origin, in the case of neutron stars (Figs. 1 and 2, *dotted bands*), in the various many-body techniques used to solve the nuclear many-body problem and the star's baryon-lepton composition. In the case of strange-matter stars (Figs. 1 and 2, *solid bands*) the error comes from the uncertainty in bag value,  $B^{1/4}$ , which varies from 137 to 148 MeV for SM-1 and from 133 to 146 MeV for SM-2. All values correspond to absolutely stable strange matter. One might suspect that the large gap between the cooling tracks of the SM-1 and SM-2 models in Figure 1 can be bridged smoothly by varying the strong coupling constant  $\alpha_c$  in the range 0.1–0.15. However, it turns out that the gap can be filled only for  $\alpha_c$  values within an extremely small range. This effect is caused by the sensitive functional dependence of the neutrino luminosity  $L_{\nu}$  on  $\alpha_c$  near the value of  $\alpha_c$  for which the electrons vanish from the quark core of the star. All other values of  $\alpha_c$  give cooling tracks that are close to the upper or lower bands. This behavior might be compared with the case of neutron stars, where the neutrino luminosity depends sensitively on the star's mass.

One sees from Figures 1 and 2 that, except for the first  $\sim 30$  yr of the lifetime of a newly born pulsar, both a neutron star and a strange-matter star may show more or less the *same* cooling behavior, provided both stars are made up either of normal matter or of superfluid matter. (We will return to this issue below.) This result occurs because standard cooling (NS-2) and enhanced cooling (NS-1) in neutron stars both have counterparts in strange-matter stars (SM-2 and SM-1, respectively). The time at which the surface temperature drop of a strange-matter star occurs depends on the thickness of the nuclear crust that may envelop the strange-matter core (Schaab et al. 1996b). In the present calculation, we suppose that strange-matter stars possess the densest possible nuclear crust, which is about 0.2 km thick. Thinner crusts would lead to temperature drops at even earlier times and thus to an earlier onset of the photon-cooling era. Figures 1 and 2 indicate that cooling data of observed pulsars do not allow us to determine the true nature of the underlying collapsed star, that is, whether it is a strange-matter star or a conventional neutron star. On the other hand, we can make this determination by observations of a very young pulsar shortly after its formation in a supernova explosion. In this case a prompt drop of the pulsar's temperature, say within the first 30 yr after its formation, could offer a good signature of a strange-matter star (see Alcock & Olinto 1988; Pizzochero 1991). This feature, provided it withstands a rigorous future analysis of the microscopic properties of strange matter, could become particularly interesting if continued observation of SN 1987A reveals the temperature of the pulsar that may exist at its center.

Finally, we add some comments about the possibility that neutron stars are made up of superfluid matter but that strange-matter stars are not. In this case one must compare models SM-1 and SM-2 (see Fig. 1) with models NS-1<sup>sf</sup> and NS-2<sup>sf</sup> (see Fig. 2), yielding different cooling histories for neutron stars and enhanced-cooling strange-matter stars (SM-1). The standard argument pointed out quite frequently in the literature that strange-matter stars cool much more rapidly than neutron stars applies only to this special case.

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