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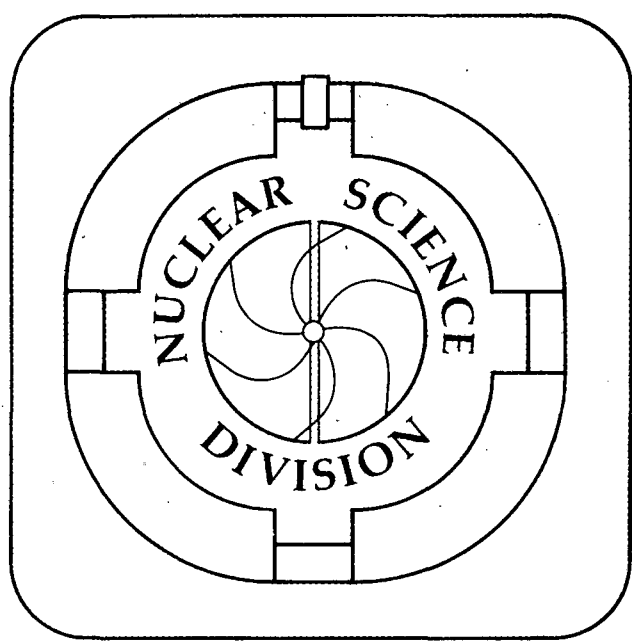
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**PSR1987A: The Case for Strange Quark Stars**

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July 1989

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PSR1987A:  
The Case for Strange Quark Stars<sup>†</sup>

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# PSR1987A: The Case for Strange Quark Stars<sup>†</sup>

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## Abstract

The new fast pulsar observed in the remnant of SN1987A together with other considerations provide evidence that there are two types of collapsed stars, neutron stars, having moderate central densities and subject to the usual mass constraint, and strange quark matter stars. We show that (1) all known pulsar masses and frequencies with the exception of the new one can be accounted for by *plausible* neutron star models; (2) no known neutron star model can withstand the fast rotation of the new pulsar unless the central energy density is  $\sim 15$  that of normal nuclei at which densities hadrons cannot plausibly exist as constituents; (3) if strange quark matter is the true ground state of the strong interactions, strange quark stars can sustain the high rotation imputed to the new pulsar. In the absence of another plausible structure that can withstand the fast rotation, we provisionally infer that the new pulsar is such a star.

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# PSR1987A: The Case for Strange Quark Stars

Norman K. Glendenning

July 17, 1989

Strange quark stars have been hypothesized by several authors and are said, if they exist, to be virtually indistinguishable from neutron stars [1,2]. However the recent discovery of the fastest known pulsar [3], with period  $\sim \frac{1}{2}$  millisecond, if it signifies rotation, appears to have changed that. It was born in the supernova SN1987A. We show that: (1) All known masses and rotation frequencies of pulsars can be accounted for by plausible neutron star models with the exception of the new pulsar. (2) To withstand the very high rotational frequency of the new pulsar, collapsed stars consisting of hadrons would have to be so dense that hadrons could not possibly exist as separate entities. (3) Quark matter, which is the subject of intense laboratory searches [4,5], is the expected state of very dense matter and we show that a strange quark matter star can sustain the observed fast rotation. It appears to us [6] that there are two types of collapsed stars, neutron stars, which are metastable but possibly long lived, and strange quark matter stars. We now fill in the details of the above three points and then discuss some consequences.

(1) The next highest angular velocity observed for a pulsar is  $\Omega = 0.4033$  in units of  $10^4 \text{ s}^{-1}$  for PSR1937+214, which compares with  $\Omega = 1.237$  in the same units for the new pulsar. The factor three is a crucial difference as it turns out, and interestingly is about the amount by which a typical neutron star would spin up if it converted to a strange quark matter star. The largest known masses of neutron stars are about  $1.4$  to  $1.8M_{\odot}$ . The pulsar PSR1913+16 has a mass  $1.442 \pm .003M_{\odot}$  [7] and 4U0900-40 has a mass  $1.85 \pm 0.3M_{\odot}$ . In Fig. 1 we show two neutron star models [6,8] for two assumptions about the compression modulus,  $K_{n.m.}$  of the corresponding symmetric nuclear matter [9,10]. One sees that the masses can be accommodated easily, and most importantly, *at densities that are plausible*. In particular the central baryon density is  $7.29\rho_0$  in the  $K_{n.m.} = 300 \text{ MeV}$  model for the star at the limit, where  $\rho_0 = 0.153 \text{ fm}^{-3}$  is nuclear saturation density. The maximum (Keplèrian) angular velocity at which a star can rotate without mass loss

is given approximately by [11],

$$\Omega_K = 24 \sqrt{\frac{M/M_\odot}{(R/\text{km})^3}} \quad (10^4 \text{ s}^{-1}) \quad (1)$$

where  $M$  and  $R$  are the mass and radius of the non-rotating star. From this we find that the limiting frequency at the termination of this sequence of stars is  $\Omega = 0.87$  in the above units or twice that of the next fastest pulsar, but too small to account for the new one. Thus this standard neutron star model (and possibly others), computed in nuclear field theory, and consisting of an equilibrium mixture of nucleons and hyperons at plausible densities for hadronic matter, is shown to be compatible with all measured pulsar masses and rotation frequencies, with the exception of the new pulsar.

(2) Now we argue that standard neutron star models *cannot* withstand the fast rotation of the new pulsar except at such high central densities that the constituents cannot be hadrons. The way in which matter is distributed in a star is prescribed by Einstein's equations and the equation of state of the matter out of which the star is made. From the study of Friedman, Ipser and Parker [12] we can learn that the central density of matter in the fast pulsar must be very high. We exhibit in Table 1 the central densities and frequencies at the termination of sequences of those neutron star models, from a broad selection, that can sustain the fast rotation [12]. We tabulate the central energy densities in terms of that of normal nuclear matter,  $\epsilon_0 \approx 2.48 \times 10^{14} \text{ g/cm}^3$ , and they are typically  $\sim 15\epsilon_0$ . To appreciate how high this is we note that the baryon density corresponding to cubic packing of classical spheres of radius equal to the proton charge radius, 0.8 fm, is  $1.6\rho_0$  or if packed to the hard core radius taken as 0.5 fm, the density is  $6.7\rho_0$ . Therefore it is implausible that matter can consist of hadrons at the central energy densities,  $\sim 15\epsilon_0$ , that appear to be required of the mass energy distribution in a star that can withstand the high rotation of the new pulsar. For more slowly rotating stars based on the same equations of state, the central densities are even higher by about 20 % than those quoted in the table! *We conclude that the central density of a collapsed star has to be so high to withstand the high angular velocity of the new pulsar that the constituents cannot be hadrons.* It is worth noting that many neutron star models have unrealistic central densities near the limiting mass.

Table 1: Central energy density,  $\epsilon_c$ , and angular velocity,  $\Omega_K$ , of several neutron star models that sustain fast rotation. (Data adapted from ref. [12]. Key to models cited therein.)

	G	B	F	A	$\pi$
$\epsilon_c/\epsilon_0$	20	21	17	13	18
$\Omega_K(10^4 \text{ s}^{-1})$	1.54	1.57	1.24	1.28	1.74

(3) The expected state of very dense matter is quark matter, of which an approximately equal mixture of u,d,s quarks is the lowest energy state. (For massless or equal mass quarks the mixture is equal, and charge neutral.) We postulate, following Witten [13], that such matter is the true ground state of the strong interactions and refer to this as *strong* confinement. This hypothesis is controversial with opinions in favor [13,14] and against [15]. It really cannot be settled by recourse to models of confinement with their unsatisfactory convergence, and the problem is so far intractable for lattice QCD. The position we take in this note is that the new pulsar together with our other considerations may provide the answer. For if the hypothesis is true, the mass-radius relation for quark stars is remarkably different than for neutron stars [1,2] and its generic form is *independent* of any particular confinement model. Because of the generic character of the results there is no point in adopting anything but the simplest of models so we adopt the MIT bag model in its simplest form, massless quarks and  $\alpha_s = 0$  [16].

$$\rho = \frac{\mu^3}{\pi^2}, \quad p = \frac{3}{4\pi^2}\mu^4 - B, \quad \epsilon = 3p + 4B, \quad Q = 0 \quad (2)$$

where  $\rho, p, \epsilon, \mu, B$  and  $Q$  are the baryon number density, the pressure, energy density, chemical potential (fermi energy), bag pressure and electric charge density. We show three star sequences obtained by solving the Oppenheimer-Volkoff equations in Fig.1, marked according to the value of the bag constant,  $B^{1/4}$ , and list properties at the limit in Table 2. The *qualitatively* different behavior compared to neutron stars is not model dependent but rather is a consequence of the postulate. Under the postulate, the quark stars are bound by confinement and gravity, whereas all other stars are bound by gravity alone. The solid line is the trajectory of eq.(1) at the frequency of the new pulsar. (Eq.(1) is good to 2 % as confirmed for us in ref. [11] for  $B^{1/4} = 170$  MeV.) Stars in sequences or parts thereof that lie below this line are stable against mass loss above the frequency of the new pulsar. Therefore strong confinement of strange quark matter stars can account for the high frequency, depending, in this model, on  $B^{1/4}$ , or generally on the *degree* of confinement strength. We place no interpretation on the value of the  $B^{1/4}$  however because it is a model dependant quantity, and we do not expect the bag model

Table 2: Strange quark star properties at the limit; gravitational mass,  $M$ , radius,  $R$ , and central energy density,  $\epsilon_c$ , for non-rotating, and angular velocity,  $\Omega_K$  of rotating star.

$B^{1/4}$ MeV	$M/M_\odot$	$R$ km	$\epsilon_c/\epsilon_0$	$\Omega_K$ $10^4\text{s}^{-1}$
200	1.08	5.91	27.3	1.74
170	1.50	8.17	14.3	1.26
145	2.00	10.9	7.74	0.943



to be more than a caricature of confinement. Rather it is the generic form of the mass-radius relation that we rely on to show that for suitable *degree* of confinement, the fast rotation of the new pulsar can be sustained.

If confinement of quarks is not *strong* in the sense described above, then there might exist hybrid stars that are bound perforce by gravity alone and that have quark cores in the dense interior in chemical equilibrium at their interface with a neutron star exterior [18,19]. This type of star does not have a mass-radius relation of the generic form characteristic of those that are bound by both confinement and gravity. Rather it belongs to the neutron star family, its lighter members being purely hadronic in composition, and its heavier members having an increasing quark core with increasing mass. This type of star has to satisfy both the mass and frequency constraint, since in this scenario there is only one family of collapsed stars. The systematics of our search for a successful model of this type suggests that that is not possible.

We now discuss the above results. From the structure of the mass-radius relation for neutron stars shown in Fig.1, notice that if a neutron star model can sustain fast rotation it will be near its termination point, for which the window in mass is extremely small. This contrasts with quark stars, where, depending on the degree of strong confinement, the whole sequence can sustain very high rotation. A neutron star will generally spin up to conserve angular momentum if it converts to a quark star, because the latter is more compact for the same baryon number ( $A \sim M/m$ ) as seen in Fig.1. A mass  $M = M_{\odot}$  neutron star in both models of Fig.1 have stability against mass loss up to  $\Omega \approx 0.48 \times 10^4 \text{ s}^{-1}$  (which is about the frequency of PSR1937+214). From the moments of inertia, we calculate that such a star will spin up by a factor about 3.9 in converting to a quark star on the most compact of the sequences of Fig.1. Therefore the angular velocity of the new pulsar may be the result of the conversion of a fast neutron star with angular velocity about equal to that of PSR1937+214. High angular velocity like that of the new pulsar appears to be the most conspicuous way in which a quark star can differ in observable properties from a neutron star. It could be that some other pulsars are also quark stars, but at frequencies that do not distinguish them from neutron stars. Indeed most pulsar periods are in the 0.2 to 2 second range rather than near the millisecond range. However, if a pulsar were observed to spin up by a significant amount, especially a factor two or more on the time scale for conversion, it would be a candidate for a strange quark star. (Pulsar glitches are small spin ups of the order of  $\sim 10^{-4} \%$ , thought to be caused by crust readjustments.) Conditions under which a neutron star might convert to a quark star have been discussed in the literature [2,17]. It is of course particularly advantageous if the hyperon population is already high, which is likely to be the case for the heavier neutron stars where we calculate a preponderance of hyperons in the core [8].

It appears from all the foregoing that there are two types of collapsed stars, neutron stars and quark matter stars, most of which are indistinguishable. The equation of state of neutron stars would have to obey the usual mass constraint

and that of strange quark matter stars would have to satisfy the angular velocity constraint of the new pulsar. In Fig.2 we show one possible family of each which satisfy the above constraints, respectively.

The spin up of a neutron star that accompanies a conversion to a quark star has interesting ramifications. Using Fig.2 as an illustration, we see that more massive neutron stars will have to spin off considerable material, else the quark matter star will exceed its mass limit and subside into a black hole. Depending on the time scale, a secondary shock may also accompany the collapse during conversion, which may eject mass, mostly hadronic matter but possibly some quark matter "strangelets" [14]. Hadronic material, if below the neutron star mass limit ( $\approx 0.05M_{\odot}$ ) will explode. Otherwise it will be disbursed into dust by the strong tidal forces of the quark star and create a very dirty environment about it. But the high density of the strangelets may allow them to survive and serve as seeds for the conversion of other stars, or possibly as companions of PSR1987A, in this instance. Such a mini strange quark star may be the small mass object ( $M \sim \frac{1}{20}M_{Jupiter}$ ) that we have conjectured in a recent paper [6,20] and for which some evidence appears in the the reanalysis of the data on the new pulsar [21].

In this note we have inferred that if the high frequency of the signals from the new pulsar is due to rotation, it cannot be a neutron star but it can be a strange quark matter star, if the postulate of strong confinement holds, and with suitable degree, as discussed above. If no other plausible explanation of the new pulsar can be found, then it appears that this pulsar is evidence for the hypothesis of strong confinement. The outlook for laboratory and terrestrial searches for quark matter, that are underway by many groups working at CERN and Brookhaven [5], would be much improved if this is the case, because a very promising signature would be strangelet production [22].

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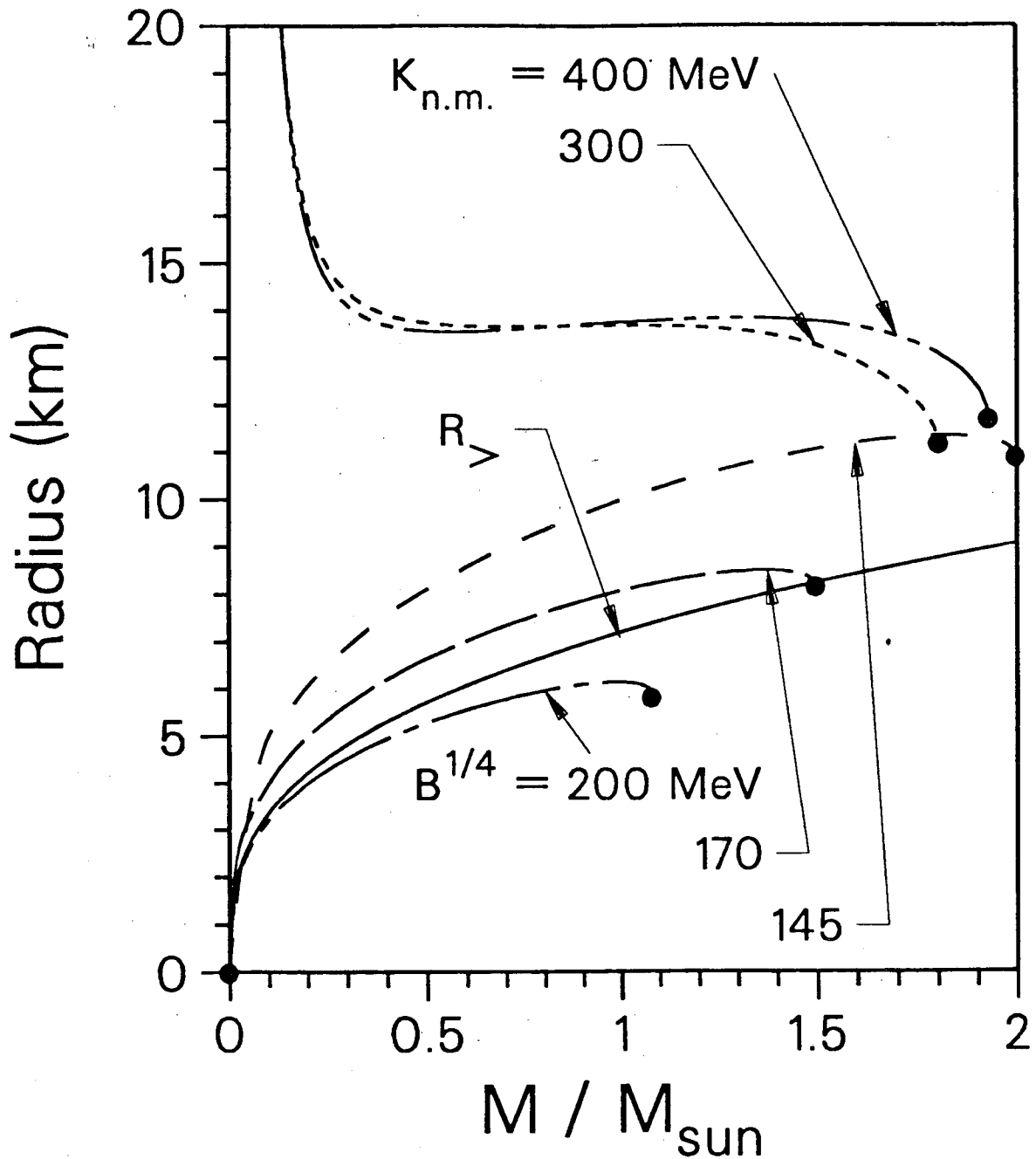


FIG. 1 Radius vs. mass for neutron stars (top two) and strange quark matter stars labeled by compression,  $K_{n.m.}$ , of the equation of state and bag constant,  $B^{1/4}$ , respectively [6]. Solid line is the upper limit on radius of stars that can sustain the high angular velocity of the new pulsar, ( $\Omega = 1.237 \times 10^4 \text{ s}^{-1}$ ).

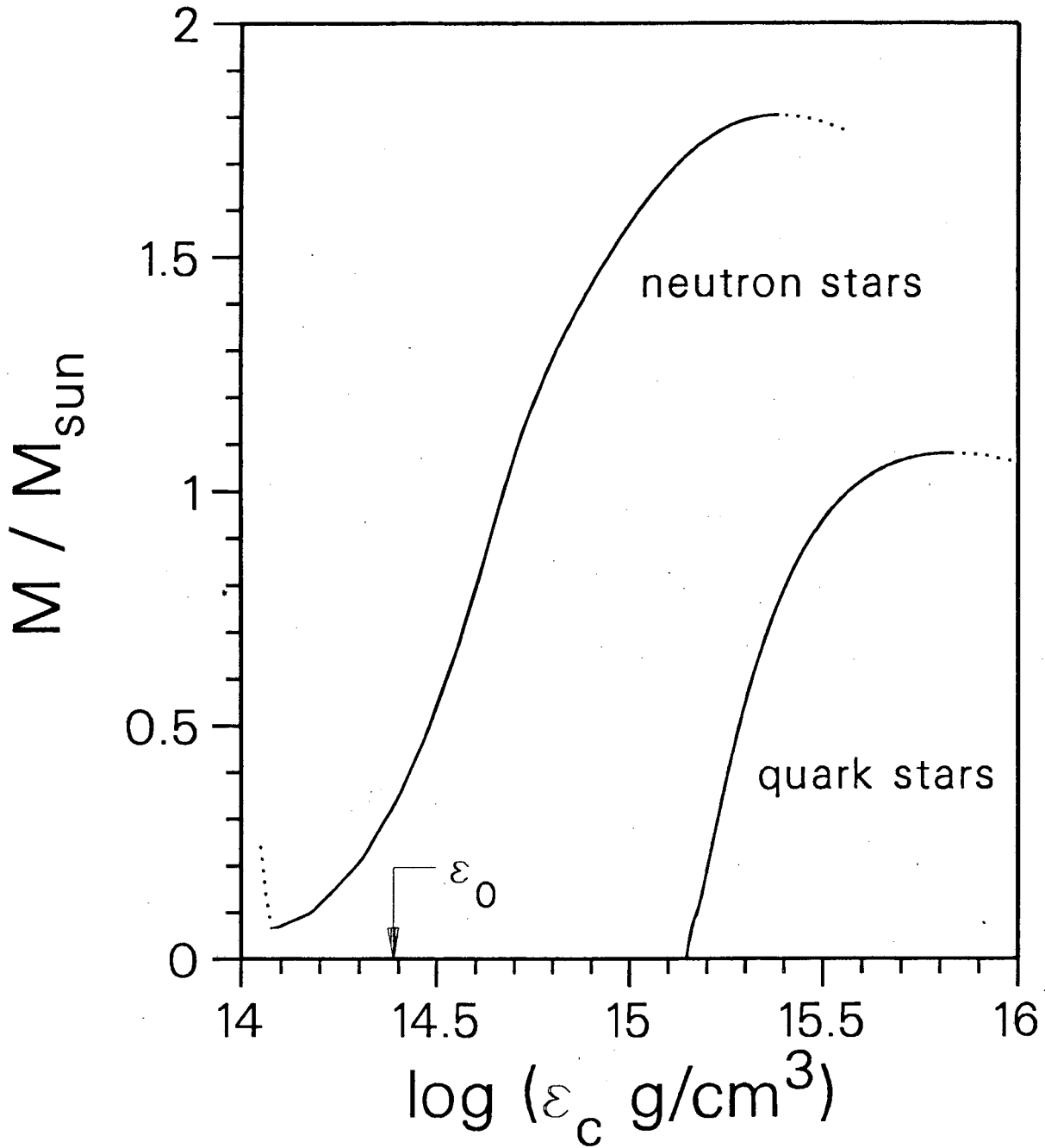


FIG. 2 Two families of collapsed stars, neutron stars ( $K_{n.m.} = 300 \text{ MeV}$ ,  $m^*/m = 0.75$ , see [8]) and strange quark matter stars (with  $B^{1/4} = 200 \text{ MeV}$ ). Solid lines denote hydrostatically stable stars.

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