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ABSTRACT

Part one of this paper deals with the recent finding of the possible existence of a mixed phase of baryon matter and quark matter inside neutron stars. In part two we review the theoretically determined minimum rotational periods of neutron stars, which serve to distinguish between pulsars that can be understood as rotating neutron stars and those that can not. Likely candidates for the latter are hypothetical strange stars. Their mass-radius relationship is discussed in the last part. It is pointed out that strange stars with a nuclear crust can give rise to the observed phenomena of pulsar glitches, thus passing the only astrophysical test of the strange-matter hypothesis existing to date.

1 Introduction

The investigation of matter under extreme conditions of density and/or temperature is the central topic of this conference. Neutron stars, which are associated with two classes of astrophysical objects, i.e. Pulsars and compact X-ray sources, contain matter in one of the densest forms found in the universe. Matter in their cores is compressed to densities ranging from a few times the density of normal nuclear matter (2.5×10^{14} g/cm^3) to an order of magnitude higher. The physical behavior of matter under such extreme densities is rather uncertain. In what follows, we (1) outline recently made progress concerning the transition of dense hadronic matter to quark matter in neutron stars, (2) point out the difference between the minimum possible rotational periods of neutron and strange quark stars, and (3) investigate the properties of the latter objects with respect to the observed glitch behavior of pulsars, which serves as a "test" of the strange-matter hypothesis.

2 Possibility of a Mixed Phase of Quarks and Baryons in the Cores of Neutron Stars

To date the only existing, consistent investigation of the transition of confined hadronic matter into quark matter in the cores of neutron stars has been performed only recently by Glendenning [1, 2];[1] it accounts for the fact that the transition between confined hadronic matter and quark matter takes place subject to the conservation of baryon and electric charge. Correspondingly, there are *two* chemical potentials, and the transition of baryon matter to quark matter is to be determined in three-space spanned by pressure and the chemical potentials of the electrons *and* neutrons. This circumstance has not been considered in the numerous investigations published on this topic earlier. As shown by Glendenning, it turns out that there exists a *mixed* phase of baryons and quarks in neutron stars, which already begins at densities slightly larger than two-times nuclear matter density (denoted ϵ_0) and ends (i.e. the pure quark phase begins) at $\sim 15\,\epsilon_0$. Of course, the existence of a mixed phase in a neutron star is of decisive importance for its possible conversion to a strange quark matter star. (Such objects will be discussed in Sect. 4.) Furthermore we stress the expectation of a Coulomb lattice of the mixed phase, and the existence of lumps of nuclear matter in quark matter and vice versa, depending on the properties of the two phases [2]. This will have very important consequences for the transport properties of the matter and also for star glitches, because the whole mixed phase (extending from near the edge somewhat above twice nuclear density to the star's center) would be a Coulomb lattice.

The main difference between strange and neutron stars regards their different minimum rotational periods, which can be smaller for strange stars and thus serve as a *signature* of such objects. We will turn to this in the next section.

3 Minimum Rotational Periods of Neutron Stars

From our extensive investigations of the minimum possible rotational periods of rotating neutron stars presented elsewhere [7, 8] it is known that the gravitational radiation-reaction instability sets a lower limit on stable rotation for massive stars of $\sim$ 0.8 msec. Lighter ones possessing typical pulsar masses of $1.45\,M_\odot$ were found to have rotational periods *larger than roughly 1 msec.* From this it follows that the nature of any pulsar that is found to have a shorter period, say 0.5 msec, must be different from the one of a neutron star. Natural candidates for such objects are rapidly rotating strange quark stars [9].[2]

4 Strange Stars

The typical mass-radius relationship for strange stars with a nuclear crust, whose maximum density is the neutron drip density, is shown in Fig. 1. Here a value for the bag constant of $B^{1/4} = 145$ MeV for which 3-flavor strange matter is stable has been chosen. This choice

[1] An investigation of the structure of the mixed phase of baryons and quarks has recently been performed by Heiselberg, Pethick, and Staubo [3].

[2] For details about strange matter, see Jes Madsen's conference contribution.

represents strongly bound strange matter with an energy per baryon $\sim$ 830 MeV, and thus corresponds to strange quark matter being absolutely bound with respect to ^{56}Fe. Since

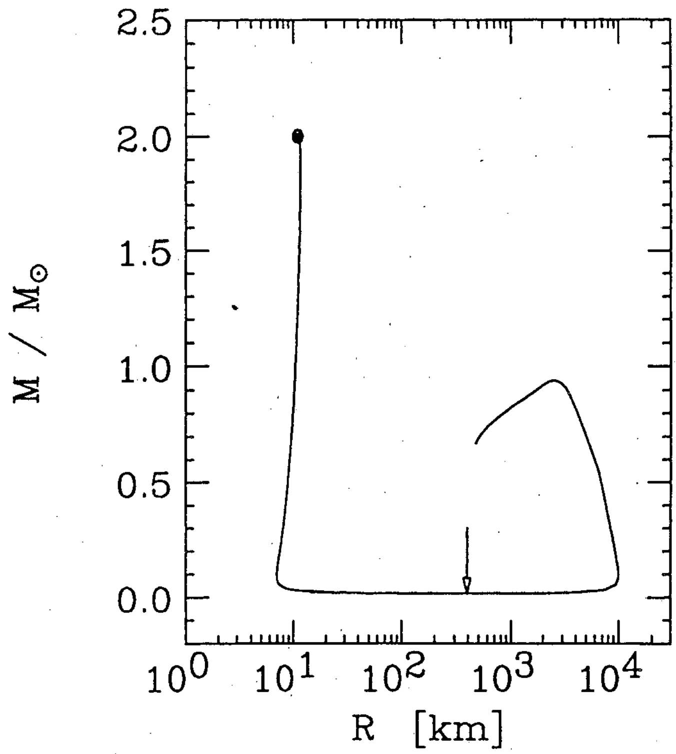

Figure 1: Radius as a function of mass of a strange star with crust. Two segments of the curve represent stable stars, the compact stars with radii $\sim$ 10 km and white dwarf-like stars with strange quark matter cores at radii $\sim$ 7000 km. The solid dot refers to the maximum-mass compact star and the vertical arrow to the minimum-mass star of the compact sequence. The stable "white dwarfs" terminate at the maximum near one solar mass and radius 2000 km.

the crust is bound by the gravitational interaction (and not by confinement, which is the case for the strange matter core), stars possessing masses that are larger than the minimum mass of the sequence have a mass-radius relation that is qualitatively similar to the one for neutron stars: the radius is small for the heavier stars in the sequence, behaves not necessarily monotonic at intermediate masses ($0.1 \lesssim M/M_\odot \lesssim 1.8$), and is the larger the closer the mass to its minimum value. The sequence of strange stars has a minimum-mass of $\sim 0.015\, M_\odot$ (radius of $\sim$ 400 km), or about 15 Jupiter masses, which is smaller than that of neutron star sequences, about 0.1 $M_\odot$ (radius $\sim$ 200 km) [10]. The low-mass strange stars may be of considerable importance since they may be difficult to detect and therefore may effectively *hide baryonic matter*. Furthermore, of interest to the subject of cooling of strange stars is the crust thickness of strange stars [11]. It ranges from $\sim$ 400 km for stars at the lower mass limit to $\sim$ 12 km for stars of mass $\sim 0.02\, M_\odot$, and is a fraction of a kilometer for the star at the maximum mass [12]. Those strange stars which result from solving the Oppenheimer-Volkoff equations for central star densities that are smaller than the corresponding central density of the minimum-mass star, but larger than the smallest possible one (determined by $\epsilon = 3\, P_{\rm drip} + 4\, B$, $P_{\rm drip}$ denotes the drip pressure [12]) are shown in Fig. 1 too. The cross refers to that star whose strange-matter core radius has shrunken to zero, thus possessing mass and radius values of a white dwarf star [13]. (Details will be given in Ref. [14].) Finally we note the dependence of the minimum-mass of a strange star on its inner crust density, ϵ_{cr}. As an example, for $\epsilon_{cr} = 10^{-4}\,\epsilon_{drip}$ one obtains a minimum-mass star of $4 \times 10^{-4}\,M_\odot$ (0.4 Jupiter masses) and radius $\sim$ 820 km [14].

At the present time there appears to be only one crucial *astrophysical test* of the strange-quark-matter hypothesis, and that is whether strange quark stars can give rise to the observed phenomena of pulsar glitches. In the crust quake model an oblate solid nuclear crust in its present shape slowly comes out of equilibrium with the forces acting on it as the rotational period changes, and fractures when the built up stress exceeds the sheer strength of the crust material. The only existing investigation which deals with the calculation of the thickness, mass and moment of inertia of the nuclear crust that can exist on the surface of a rotating, general relativistic strange quark star has only recently been performed by Glendenning and Weber [12]. It was found that the data on relative frequency changes $\Delta\Omega/\Omega$ of observed glitches (Ω denotes the star's rotational frequency) and the measured values of the ratio $(\Delta\Omega/\Omega)/(\Delta\dot{\Omega}/\dot{\Omega})$ for the Crab and Vela pulsars can be understood from the computed crustal moment of inertia of strange stars.

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