Observational evidence for strange matter in compact objects from the x-ray burster 4U 1820-30

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We present systematic calculations of the mass-radius (MR) relation of a neutron star (NS) using a large variety of modern equations of state (EOS) of dense matter. The role of strangeness on the EOS and on the MR relation is particularly emphasized. Theoretical results are then compared with the semiempirical MR relation recently extracted for the x-ray burst source 4U 1820-30. Based on this comparison, we propose that the compact object in 4U 1820-30 is a kaon-condensed nucleon star or a strange star. [S0556-2813(97)03303-7]

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The presence of strange bearing matter (hyperons, K^- condensate), the possibility for a deconfined phase of strange quark matter in the core of neutron stars, or the existence of strange stars has been investigated by many authors. However, up to now, no clear evidence for the existence of such an ''exotic'' phase of dense matter in astrophysical compact objects has been found.

The issue of whether or not ''exotic'' components are present in dense matter has dramatic consequences for the terminal stages of stellar evolution [1–4]. In fact, it has been recently pointed out [1] that when the very early evolution of a newborn neutron star is considered, two different scenarios for the latest stages of stellar evolution (neutron stars and black holes formation) are possible, according to the composition of dense hadronic matter.

The equation of state (EOS) of dense matter is also a topic of remarkable interest in heavy ion physics. The search for a signature for a deconfined phase of quark matter is the subject of a great experimental effort. Future experiments at Brookhaven's Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC) will hopefully clarify our understanding of dense matter. Neutron stars offer a unique opportunity to investigate dense matter in alternative to relativistic heavy ion collisions.

The mass-radius (MR) relation is one of the neutron star properties which is more sensitive to the composition of the stellar material. It could be used to distinguish observationally a ''conventional'' neutron star from an ''exotic'' strangeness rich compact object. Using recent observational data on the x-ray burst source 4U 1820-30 in the globular cluster NGC 6624, Haberl and Titarchuk [5] were able to extract a semiempirical MR relation for the underlying compact object that, according to the current theories [6–8], should be responsible for the observed bursts. In this work, we present systematic theoretical calculations of the MR relation of neutron stars, based on a great variety of recent and sophisticated models for the EOS of dense hadronic matter, and compare them with the semiempirical MR relation for 4U 1820-30. Based on this comparison, we suggest that the compact object in 4U 1820-30 could be a kaon-condensed nucleon star or a strange star.

The MR relation for nonrotating neutron stars has been calculated solving the Tolman-Oppenheimer-Volkoff (TOV) equations [9]. Using a terminology employed in a previous paper [1], we denote two different classes of EOS, according to the constituents of neutron star material. We call ''conventional'' an EOS in which hadronic components of stellar matter are neutrons and protons. We call ''exotic'' an EOS in which, in addition to nucleons, other hadronic constituents like hyperons or a condensate of K^-, or a deconfined phase of strange quark matter, are present in the neutron star material.

We employed, for both classes, a wide collection of distinct EOS models. Such a systematic study has been undertaken, to achieve a grasp of the possible dependence of MR relation on different techniques to derive the EOS (nonrelativistic vs relativistic and/or phenomenological vs microscopic EOS), and to highlight the physical role of the nature of different constituents.

The semiempirical MR relation for 4U 1820-30, is shown in Figs. 1–4 by the closed region in the MR plane labeled with 4U 1820-30. In Figs. 1 and 2, we show the MR relation as calculated for ''conventional'' EOS. Results in Fig. 1 are relative to phenomenological models for the EOS. The two continuous curves in Fig. 1, express the MR relation calcu-

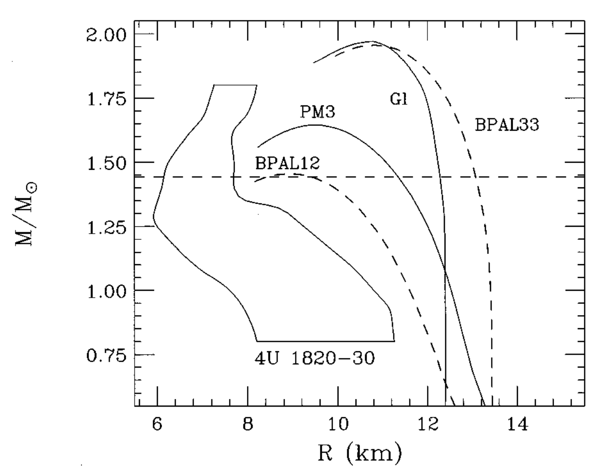

FIG. 1. Theoretical mass-radius relations (curves) for different equations of state (EOS) are compared with the semiempirical MR relation extracted in [5] from the x-ray burster 4U 1820-30 (closed region of the MR plane labeled 4U 1820-30). Calculations are relative to ''conventional'' (neutrons, protons, leptons) relativistic and nonrelativistic phenomenological EOS. The dashed horizontal line represents the gravitational mass $1.44M_\odot$ of the pulsar PSR1916 +13, in unit of the solar mass $M_\odot$.

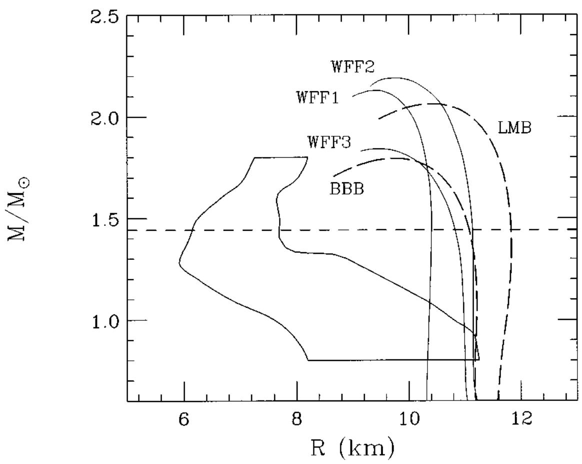

FIG. 2. Same as in Fig. 1, but for ''conventional'' microscopic EOS.

lated from phenomenological relativistic EOS. The curve labeled with Gl has been obtained using a nuclear EOS developed by Glendenning [10]. The MR curve labeled PM3 has been calculated using an EOS developed by the Kyoto group [11]. The dashed curves show the MR relation for the nonrelativistic EOS termed BPAL ([12]). BPAL33 is a moderately *stiff* EOS characterized by a nuclear incompressibility $K_0=240$ MeV and a potential part of the nuclear symmetry energy which increases quadratically with the number density ($V_{\rm sym}^{\rm pot}\sim n^2$). In general, for a fixed value of the NS mass, a soft EOS is expected to give a smaller radius with respect to a stiff EOS [9]. Therefore, we consider a *very soft* EOS (BPAL12) characterized by $K_0=120$ MeV and $V_{\rm sym}^{\rm pot}\sim n$. The value 120 MeV for the incompressibility is unrealistically small when compared with the value (180–240 MeV) extracted from monopole nuclear oscillations [13,14], however, BPAL12 EOS is still able to sustain the measured mass 1.44 $M_\odot$ of the pulsar PSR1916+13 (dashed horizontal line in Fig. 1).

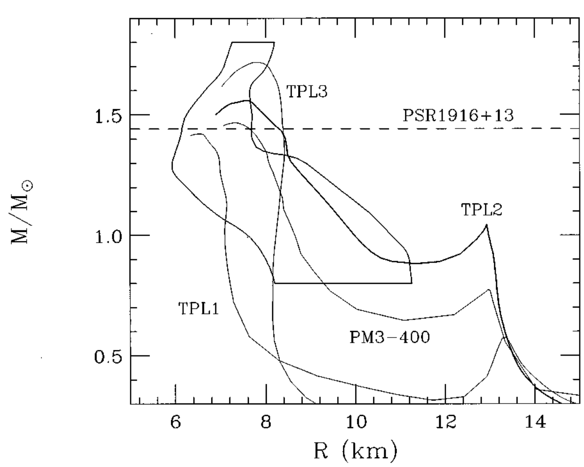

FIG. 3. Same as in Fig. 1, but for ''exotic'' EOS with K^- condensation. Note that the increasing portion of the MR curve, between the minimum and the second maximum (sharp peak), represents unstable stellar configurations.

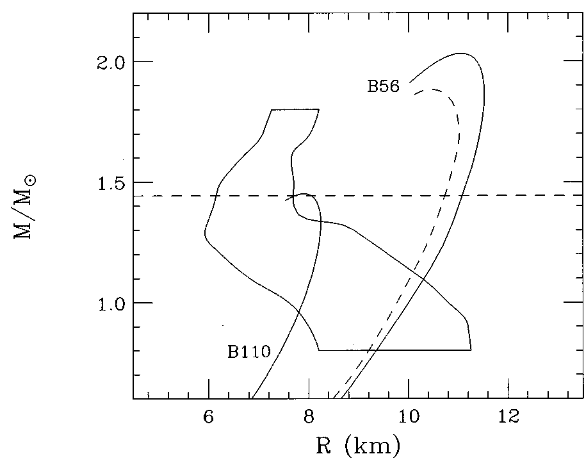

FIG. 4. Same as in Fig. 1, but for u,d,s quark matter stars (strange stars) within the MIT bag model EOS. Continuous curves refer to massless free quarks. Dashed curve refers to $m_s=175$ MeV, $\alpha_c=0.06$, $B=56$ MeV fm^{-3}.

Results in Fig. 2 are relative to microscopic models for the EOS. The dashed curve labeled by LMB has been calculated fitting the EOS to microscopic Dirac-Brueckner calculations [15] for the Bonn-A *NN* potential; the other dashed MR curve is relative to an EOS calculated [16] in the Brueckner-Hartree-Fock approximation using the Argonne v14 (Av14) potential implemented by a three-body force (TBF), included to reproduce the empirical saturation point of symmetric nuclear matter. The remaining curves in Fig. 2 exhibit the MR relation obtained solving the TOV equations with the Wiringa-Ficks-Fabrocini (WFF) EOS [17]. This EOS is based on a nonrelativistic variational many-body approach. EOS WFF1 and WFF2 have been obtained, respectively, using the Av14 and Urbana v14 (Uv14) *NN* potential, and adding a three-nucleon interaction (UVII), which in both cases has been adjusted to reproduce the binding energies and radii of light nuclei (^{3}H, ^{4}He). In the case of the WFF3, the Uv14 *NN* interaction has been implemented by a phenomenological two-body density dependent interaction (TNI), which on average simulate a TBF. Parameters in the TNI model are then adjusted to reproduce the empirical saturation point of symmetric nuclear matter.

Neutron star configurations with masses $M\sim 1M_\odot$ calculated from WFF EOS's lie inside the semiempirical MR region for 4U 1820-30. As we now discuss, this marginal agreement with observational data is partially misleading and fortuitous. In fact, results in the present work are relative to nonrotating configurations. We know that neutron stars rotate, and they may have periods as low as a few milliseconds [18]. Rotation is, in general, expected to increase the limiting mass and to shift the MR curve to higher radii. Rotating neutron star configurations have recently been computed by Cook *et al.* [19]. In particular, for the WFF1 EOS, the radius of a $1.0M_\odot$ neutron star, which rotates at the limiting mass-shed frequency Ω_K, has been calculated [19] to be $\sim$14.6 km, far away the observational data for 4U 1820-30. Moreover, WFF1 and WFF2 models do not reproduce the empirical saturation point of nuclear matter, having minima, respectively, at $n_0=0.194$ fm^{-3} and $n_0=0.175$ fm^{-3} (see

Table I of [17]). Correct saturation of nuclear matter is a fundamental requisite to demand to any realistic EOS [16]. Therefore, WFF1 and WFF2 EOS underestimate pressure in the low density ($n \sim n_0$) region. To check the sensitivity of neutron star radius to the low density EOS, we rescaled the WFF1 EOS in such a way to saturate at $n_0 = 0.16$ fm^{-3}. As expected, we found an average increase of the radius of about 10%, and a global shift of the MR curve to the right part of the MR plane outside the semiempirical region for 4U 1820-30.

In Figs. 3 and 4, we show the MR relation as calculated for ''exotic'' EOS. Bose-Einstein (BE) condensation of negative kaons in neutrons stars has been recently a subject of increasing interest [11,12,20,21], and intriguing implications for the terminal stages of stellar evolution have been proposed [1,2]. In Fig. 3 we show the MR relation calculated using an EOS with K^- condensation developed by Thorsson, Prakash, and Lattimer (TPL) [20], in which the NN interaction is described by a nonrelativistic phenomenological model and the KN interaction by a chiral model. Neutron star properties are very sensitive to the critical density $\rho_{\rm cr}$ for the onset of the K^- condensate. $\rho_{\rm cr}$ depends crucially upon the poorly known strangeness content of the proton and on the kaon-nucleon self-energy, which in the TPL model are described by a phenomenological parameter $a_3 m_s$. With an appropriate choice of the EOS parameters, the MR relation for neutron stars with kaon-condensed core falls well inside the semiempirical box for 4U 1820-30. TPL1 EOS has $K_0 = 180$ MeV, $a_3 m_s = -222$ MeV. For TPL2 and TPL3 EOS's one has, respectively, $K_0 = 240$ MeV, $a_3 m_s = -222$ MeV, and $K_0 = 240$ MeV, $a_3 m_s = -310$ MeV. The curve labeled PM3-400 refers to the MR relation we obtained using an EOS with K^- condensation developed by the Kyoto group [11], in which the nucleons are described in a relativistic mean field approach. Note that from a theoretical point of view, the occurrence of a K^- condensate in dense stellar matter is a controversial subject. Recent work indicates that the presence of hyperons [22,23] or the effects of KN and NN correlations [24] make the onset of K^- condensation less favorable. A peculiarity of kaon-condensed compact objects is that they are made of almost symmetric nuclear matter rather than (almost pure) neutron matter; therefore, following Brown and Bethe [2] we call them *nucleon stars*. Rotating kaon condensed nucleon stars have been recently calculated by Nozawa *et al.* [25] for the PM3-400 EOS. Configurations up to the limiting rotational frequency Ω_K are still compatible with the observational data for 4U 1820-30; for example [25], the radius of a $1.0 M_\odot$ star, which rotates at $\omega = \Omega_K$, is $\sim$9.4 km. EOS's with π^- condensation developed in the 70s (see e.g., [26]) may give theoretical configurations compatible with the MR for 4U 1820-30. However, recent theoretical progress, on the study of BE condensation in dense matter, shows that K^- condensation prevents the condensation of pions [27].

Strange stars, i.e., compact objects made of deconfined u,d,s quark matter, have been studied by numerous researchers [12,28,29]. We employ an EOS from QCD in the context of the MIT bag model, as described in [30]. First, we consider the simple case of massless free quarks. The calculated MR relation for two different values of the bag constant ($B = 56$ MeV fm^{-3} and $B = 110$ MeV fm^{-3}) is shown in Fig. 4 (continuous curves). The value $B = 56$ MeV fm^{-3} is a standard value which is able to reproduce the mass spectrum of light hadrons and heavy mesons [31]. However, in general, the bag constant may be regarded as a phenomenological parameter. $B = 110$ MeV fm^{-3} is the higher value which in this context gives stellar configurations compatible with the measured mass of the pulsar PSR1916+13. We next consider nonzero strange quark mass m_s and contributions to the EOS up to first order in the strong interaction coupling constant α_c [30]. The corresponding MR relation (for a particular set of B, m_s, α_c) is shown by the dashed curve in Fig. 4. The inclusion of quark interaction ($\alpha_c \neq 0$), and finite m_s, produces only small changes in the MR relation, with respect to the massless free gas. The agreement with the MR relation for 4U 1820-30 is striking.

In conclusion, we found that neutron star models based on ''conventional'' EOS can hardly reproduce the semiempirical MR relation for 4U 1820-30. We showed that, with a suitable choice of the parameters which control the onset of the phase transition to a K^- condensate, theoretical models of neutron stars structure are consistent with the semiempirical MR relation for 4U 1820-30. We showed that strange star models are compatible with observational data too. Our analysis strongly suggests that the compact object in 4U 1820-30 could be a kaon-condensed nucleon star or a strange star. Our conclusions become more robust when effects due to rotation are included [19,25]. If confirmed by further observations and theoretical studies, the Haberl-Titarchuk MR relation could provide the first observational evidence for the presence of strange matter in collapsed compact objects.

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