Strange star candidates

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1 Introduction

One of the most exciting aspects of modern astrophysics is the possible existence of a new family of compact stars, which are made entirely of deconfined *u,d,s* quark matter (*strange quark matter* (SQM)). These strange quark matter stars are called in the scientific literature *strange stars* (SS). They differ from neutron stars, where quarks are confined within neutrons, protons, and eventually within other hadrons (hadronic matter stars). The possible existence of SS is a direct consequence of the so called *strange matter hypothesis* [1]. According to this hypothesis, SQM (in equilibrium with respect to the weak interactions) could be the true ground state of matter. In other words, one assumes the energy per baryon of SQM (at the baryon density where the pressure is equal to zero) to be less than the lowest energy per baryon found in nuclei, which is about 930 MeV for ^{56}Fe. According to the strange matter hypothesis, the ordinary state of matter, in which quarks are confined within hadrons, is a metastable state [1, 2]. The strange matter hypothesis does not conflict with the existence of atomic nuclei as conglomerates of nucleons, or with the stability of ordinary matter [2, 3, 4].

From a basic point of view the equation of state for SQM should be calculated solving QCD at finite density. As we know, such a fundamental approach is presently not doable. Therefore one has to rely on phenomenological models. In this work, we use two simple phenomenological models for the equation of state (EOS) of strange quark matter. One is a model [2] which is related to the MIT bag model for hadrons. The other is a model proposed by Dey *et al.* [20].

2 The mass–radius relation for compact stars

To distinguish whether a compact star is a neutron star or a strange star, one has to find a clear observational signature. There is a striking qualitative difference in the mass–radius (MR) relation of SS with respect to that of neutron stars (see Fig. 1).

For SS with "small" ($M << M_{max}$) gravitational mass, M is proportional to R^3. In contrast, neutron stars have radii that decrease with increasing mass. This is a consequence of the underlying interaction between the stellar constituents which makes "low" mass SS self-bound objects (see *e.g.* ref.[6]) contrary to the case of neutron stars which are bound by gravity. As we know, there is a minimum mass for a neutron star ($M_{min} \sim 0.1\ M_\odot$). In the case of a strange star, there is essentially no minimum mass. As the central density $\rho_c \to \rho_s$ (surface density), a strange star (or better a strangelet for very low baryon number) is a self–bound system, until the baryon number becomes so low that finite size effects destabilize it.

The transient X-ray burst source SAX J1808.4-3658 was discovered in September 1996 by the BeppoSAX satellite. Two bright type-I X-ray bursts were detected, each lasting less than 30 seconds. Analysis of the bursts in SAX J1808.4-3658 indicates that it is 4 kpc distant and has a peak X-ray luminosity of 6×10^{36} erg/s in its bright state, and a X-ray luminosity lower than 10^{35} erg/s in quiescence [7]. Coherent pulsations at a period of 2.49 milliseconds were discovered [8]. The binary nature of SAX J1808.4-3658 was firmly established with the detection of a 2 hour orbital period [9] as well as with the optical identification of the companion star. SAX J1808.4-3658 is the first pulsar to show both coherent pulsations in its persistent emission and X-ray bursts.

A mass–radius (MR) relation for the compact star in SAX J1808.4-3658 has been obtained by Li *et al.* [10] using the following two requirements. (*i*) Detection of X-ray pulsations requires that the inner radius R_0 of the accretion flow should be larger than the stellar radius R. In other words, the stellar magnetic field must be strong enough to disrupt the disk flow above the stellar surface. (*ii*) The radius R_0 must be less than the so-called co-rotation radius $R_{\rm c}$, *i.e.* the stellar magnetic field must be weak enough that accretion is not centrifugally inhibited: $R_0 \lesssim R_{\rm c} = [GMP^2/(4\pi^2)]^{1/3}$. Here G is the gravitation constant, M is the mass of the star, and P is the pulse period. The inner disk radius R_0 is generally evaluated in terms of the Alfvén radius $R_{\rm A}$, at which the magnetic and material stresses balance [11]: $R_0 = \xi R_{\rm A} = \xi[B^2R^6/\dot{M}(2GM)^{1/2}]^{2/7}$, where B and $\dot{M}$ are respectively the surface magnetic field and the mass accretion rate of the pulsar, and ξ is a parameter of order of unity almost independent [12] of $\dot{M}$. Since X-ray pulsations in SAX J1808.4-3658 were detected over a wide range of mass accretion rate (say, from $\dot{M}_{\rm min}$ to $\dot{M}_{\rm max}$), the two conditions (*i*) and (*ii*) give $R \lesssim R_0(\dot{M}_{\rm max}) < R_0(\dot{M}_{\rm min}) \lesssim R_{\rm c}$. Next, we assume that the mass accretion rate $\dot{M}$ is proportional to the X-ray flux F observed with RXTE. This is guaranteed by the fact that the X-ray spectrum of SAX J1808.4-3658 was remarkably stable and there was only slight increase in the pulse amplitude when the X-ray luminosity varied by a factor of ~ 100 during the 1998 April/May outburst [13, 14, 15]. Therefore, Li *et al.* [10] get the following upper limit of the stellar radius:

$R < (F_{min}/F_{max})^{2/7} R_c$, or

$$R < 27.5\left(\frac{F_{min}}{F_{max}}\right)^{2/7}\left(\frac{P}{2.49\ \mathrm{ms}}\right)^{2/3}\left(\frac{M}{M_\odot}\right)^{1/3}\ \mathrm{km}, \tag{1}$$

where $F_{\rm max}$ and $F_{\rm min}$ denote the X-ray fluxes measured during X-ray high- and low-state, respectively, $M_\odot$ is the solar mass. Note that in writing inequality (1) it is assumed that the pulsar's magnetic field is basically dipolar [1].

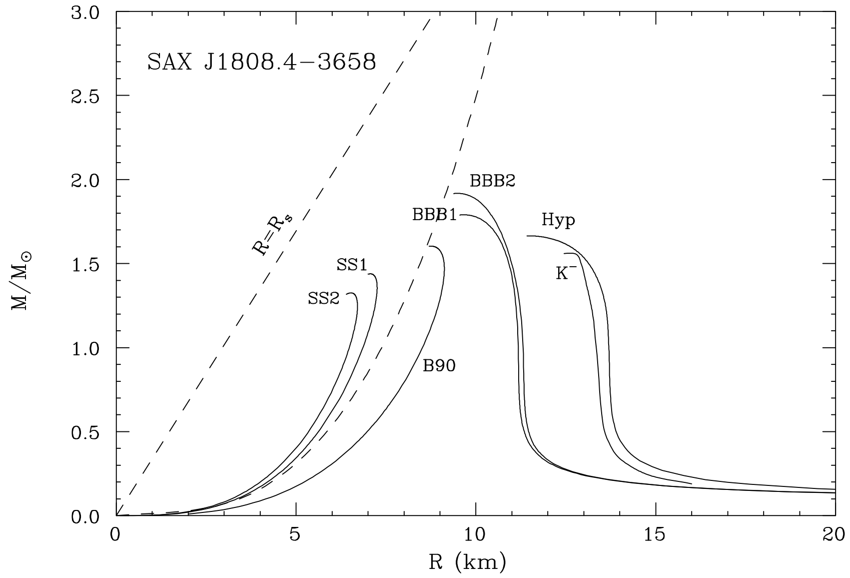

Figure 1: Comparison of the MR relation of SAX J1808.4 -3658 determined from RXTE observations with theoretical models of neutron stars and of SS. The solid curves represents theoretical MR relations for neutron stars and strange stars.

Given the range of X-ray flux at which coherent pulsations were detected, inequality (1) defines a limiting curve in the MR plane for SAX J1808.4-3658, as plotted in the dashed curve in Fig. 1. The authors of ref.[10] adopted the flux ratio $F_{\rm max}/F_{\rm min} \simeq 100$ from the measured X-ray fluxes with the RXTE during the 1998 April/May outburst [14, 15]. The dashed line $R = R_{\rm s} \equiv 2GM/c^2$ represents the Schwartzschild radius - the lower limit of the stellar radius to prevent the star collapsing into a black hole. Thus the allowed range of the mass and radius of SAX J1808.4-3658 is the region confined by these two dashed curves in Fig. 1.

[1] see ref.[10] for arguments to support this hypothesis. See also ref.[15] for a study of the influence on the MR relation for SAX J1808.4-3658 of a quadrupole magnetic moment, and of a *non-standard* disk–magnetosphere interaction model.

In the same figure, we report the theoretical MR relations (solid curves) for neutron stars given by some recent realistic models for the EOS of dense matter (see ref.[10] for references to the EOS models). Models BBB1 and BBB2 are relative to "conventional" neutron stars (*i.e.* the core of the star is assumed to be composed by an uncharged mixture of neutrons, protons, electrons and muons in equilibrium with respect to the weak interaction). The curve labeled Hyp depicts the MR relation for a neutron star in which hyperons are considered in addition to nucleons as hadronic constituents. The MR curve labeled K^- is relative to neutron stars with a Bose-Einstein condensate of negative kaons in their cores. It is clearly seen in Fig. 1 that none of the neutron star MR curves is consistent with SAX J1808.4-3658. Including rotational effects will shift the MR curves to up-right in Fig. 1 [16], and does not help improve the consistency between the theoretical neutron star models and observations of SAX J1808.4-3658. Therefore SAX J1808.4-3658 is not well described by a neutron star model. The curve B90 in Fig. 1 gives the MR relation for SS described by the schematic EOS of ref. [2] for massless non-interacting quarks with B = 90 MeV/fm^3. The two curves SS1 and SS2 give the MR relation for SS calculated with the EOS of Dey *et al.*[20] for two parameterizations which give absolutely stable SQM according to the strange matter hypothesis. Clearly a strange star model is more compatible with SAX J1808.4-3658 than a neutron star one.

Stringent constraints on the MR relation have been also obtained for the compact star in the X-ray source 4U 1728-34 ($M < 1.0\ M_\odot$ and $R < 9$ km) [17], for the isolated compact star RX J1856-37 ($M = 0.9 \pm 0.2\ M_\odot$ and $R = 6^{+2}_{-1}$ km) [18] (see also [19]) and for the X-ray pulsar Her X-1 ($M = 1.1 - 1.8\ M_\odot$ and $R = 6.0 - 7.7$ km) [20]. Clearly it is very difficult to model the MR relation for these compact objects (see *e.g.* Fig. 1) using any realistic EOS for neutron star matter.

3 Astrophysical implications and final remarks

If the strange matter hypothesis is true, then a neutron star could "decay" to a strange star (NS$\to$SS conversion) once a "seed" of SQM forms in the neutron star's core or it comes from the galactic space [20]. The conversion of the whole star occurs in a very short time [21], in the range 1 ms – 1 s, and liberates a total energy [22] of a few 10^{53} erg. The NS$\to$SS conversion has been proposed [22] as a possible energy source to power γ-ray bursts at cosmological (redshift $z \sim 1 - 3$) distances [23].

Strange stars are the natural site for a color superconducting state of quark matter [24, 25]. Particularly, there could be a region inside a strange star where quark matter is in a crystalline ("LOFF"[4]) superconducting phase [24, 25]. This raises the possibility to successfully model pulsar glitches with strange stars [25].

A very unpleasant consequence of the strange matter hypothesis could be the possible formation of stable negatively charged strangelets during heavy ion collisions at RHIC or at LHC. In fact, it has been pointed out [27] that these "dangerous" negatively charged strangelets may trigger the disruption of our planet. Luckily, there are various theoretical as well as experimental arguments [27] to rule out this "Disaster Scenario".

The main result of the present work (*i.e.* the likely existence of strange stars) is based on the analysis of observational data for the X-ray sources SAX J1808.4-3658. The interpretation of these data is done using *standard* models for the accretion mechanism, which is responsible for the observed phenomena. The present uncertainties in our knowledge of the accretion mechanism, and the disk–magnetosphere interaction, do not allow us to definitely rule out the possibility of a neutron star for this X-ray source. For example, making *a priori* the *conservative* assumption that the compact object in SAX J1808.4-3658 is a neutron star, and using a MR relation similar to our eq.(1), Psaltis and Chakrabarty [15] try to constrain disk–magnetosphere interaction models or to infer the presence of a quadrupole magnetic moment in the compact star.

SAX J1808.4-3658, 4U 1728-34, RX J1856-37, and Her X-1 are not the only X-ray sources which could harbour a strange star. Recent studies have shown that the compact objects associated with the X-ray burster 4U 1820-30 [28] and the bursting X-ray pulsar GRO J1744-28 [10] are likely strange star candidates. For each of these X-ray sources (strange star candidates) the conservative assumption of a neutron star as the central accretor would require some particular (possibly *ad hoc*) assumption about the nature of the plasma accretion flow and/or the structure of the stellar magnetic field. On the other hand, the possibility of a strange star gives a simple and unifying picture for all the systems mentioned above.

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