Is SAX J1808.4-3658 a Strange Star?

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The possibility of strange stars is one of the most important issues in the study of compact objects. Here we use the observations of the newly discovered millisecond x-ray pulsar SAX J1808.4-3658 to constrain the radius of the compact star. Comparing the mass-radius relation of SAX J1808.4-3658 with theoretical models for both neutron stars and strange stars, we argue that a strange star model could be more consistent with SAX J1808.4-3658, and suggest that it is a likely strange star candidate. Our results are useful in constraining microscopic chiral symmetry restoration parameters in the quantum chromodynamics (QCD) modeling of strange matter.

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Strange stars (SS) are astrophysical compact objects which are made entirely of deconfined *u,d,s* quark matter (*strange matter*). The possible existence of SS is a direct consequence of the conjecture [1] that strange matter may be the absolute ground state of strongly interacting matter. Detailed studies have shown that the existence of strange matter is allowable within uncertainties inherent in a strong interaction calculation [2]; thus SS may exist in the Universe. Recent studies have shown that the compact objects associated with the x-ray pulsar Her X-1 [3,4], and with the x-ray burster 4U 1820-30 [5], are good strange star candidates. Apart from the fact that SS may be relics from the cosmic separation of phases as suggested by Witten [1], a seed of strange matter may convert a neutron star to a strange one [6]. Conversion from protoneutron stars during the collapse of supernova cores is also possible [7].

The search for a deconfined phase of quark matter is one of the main goals in heavy ion physics. Experiments at Brookhaven National Lab's Relativistic Heavy Ion Collider and at CERN's Large Hadron Collider, will hopefully clarify this issue in the near future. The existence of SS could provide an alternative signature for this new phase of strong interacting matter.

In the present work we use the observations of the newly discovered millisecond x-ray pulsar SAX J1808.4-3658 to constrain the radius of the compact star. Then, comparing the mass-radius relation of SAX J1808.4-3658 with theoretical models for both neutron stars and SS, we show that a strange star model is more consistent with SAX J1808.4-3658, and suggest that it is a likely strange star candidate.

SAX J1808.4-3658 is by far the fastest-rotating, lowest-field accretion-driven pulsar known, and the first pulsar to show both coherent pulsations in its persistent emission and thermonuclear bursts. It was discovered in September 1996 with the Wide Field Camera on board BeppoSAX [8]. Two bright type-I x-ray bursts, which are thought to be unstable thermonuclear burning on the surface of a neutron star [9], were detected, each lasting less than 30 sec, suggesting that this source is a member of low-mass x-ray binaries (LMXBs), consisting of a low ($\lesssim 10^{10}$ G) magnetic field neutron star accreting from a companion star of less than one solar mass [10]. 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^{-1} in its bright state, and $<10^{35}$ erg s^{-1} in quiescence [8]. On the other hand, a transient x-ray source designated XTE J1808-369 was recently detected with the Proportional Counter Array on board the Rossi X-ray Timing Explorer (RXTE) [11]. The source is positionally coincident within a few arcminutes with SAX J1808.4-3658, implying that both sources are the same object. Coherent pulsations at a period of 2.49 msec were discovered [12]. The star's surface dipolar magnetic moment was derived to be $\lesssim 10^{26}$ G cm^3 from detection of x-ray pulsations at a luminosity of 10^{36} erg s^{-1} [12], consistent with the weak fields expected for type-I x-ray bursters [9] and millisecond radio pulsars (MS PSRs) [10]. The binary nature of SAX J1808.4-3658 was firmly established with the detection of a 2 h orbital period [13], as well as with the optical identification of the companion star [14].

The discovery of SAX J1808.4-3658 allows the study of the compactness of pulsars. Detection of x-ray pulsations requires that the inner radius R_0 of the accretion flow (generally in the form of a Keplerian accretion disk in LMXBs) should be larger than the stellar radius R (viz. the stellar magnetic field must be strong enough to disrupt the disk flow above the stellar surface), and less than the so-called corotation radius $R_{\rm c} = [GM/(4\pi^2)P^2]^{1/3}$ (viz. the stellar magnetic field must be weak enough that accretion is not centrifugally inhibited) [15,16]. Here G

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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_A, at which the magnetic and material stresses balance [10], $R_0 = \xi R_A = \xi[B^2R^6/\dot{M}(2GM)^{1/2}]^{2/7}$, 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 the order of unity almost independent of $\dot{M}$ [15,17]. 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 condition $R \lesssim R_0(\dot{M}_{\rm max}) < R_0(\dot{M}_{\rm min}) \lesssim R_c$ suggests an upper limit of the stellar radius,

$$R \lesssim 28\left(\frac{F_{\rm max}}{F_{\rm min}}\right)^{-2/7}\left(\frac{P}{2.49\ {\rm ms}}\right)^{2/3}\left(\frac{M}{M_\odot}\right)^{1/3}\ {\rm km}, \qquad (1)$$

where $F_{\rm max}$ and $F_{\rm min}$ denote the x-ray fluxes measured during x-ray high- and low-states, respectively, and $M_\odot$ is the solar mass. Here we have assumed that the mass accretion rate $\dot{M}$ is proportional to the x-ray flux 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 a slight increase in the pulse amplitude when the x-ray luminosity varied by a factor of $\sim$100 during the 1998 April–May outburst [16,18,19]. One should also be cautioned that inequality (1) was derived under the assumption that the pulsar's magnetic field remains a central dipole even when the accretion flow extends close to the stellar surface (see discussion below).

Given the range of x-ray flux at which coherent pulsations were detected, inequality (1) defines a limiting curve in the mass-radius (M-R) parameter space for SAX J1808.4-3658, as plotted in the dashed curve in Fig. 1. Here we have adopted the flux ratio $F_{\rm max}/F_{\rm min} \simeq 100$ from the observations that during the 1998 April–May outburst, the maximum 2–30 keV flux of SAX J1808.4-3658 at the peak of the outburst was $F_{\rm max} \simeq 3 \times 10^{-9}$ erg cm^{-2} s^{-1}, while the pulse signal became barely detectable when the flux dropped below $F_{\rm min} \simeq 2 \times 10^{-11}$ erg cm^{-2} s^{-1} [16,19]. The dotted curve represents the Schwarzschild radius $R = 2GM/c^2$ (where c is the speed of light)—the lower limit of the stellar radius to prevent the star collapsing into a black hole [20]. Thus the allowed range of the mass and radius of SAX J1808.4-3658 is the region confined by the dashed and dotted curves in Fig. 1.

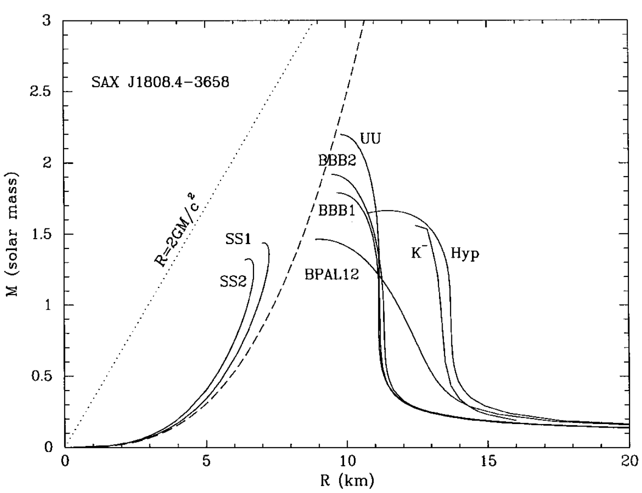

FIG. 1. The M-R relation of SAX J1808.4-3658 determined from RXTE observations (region outlined by the dashed and dotted curves) is compared with the theoretical M-R relations for neutron stars (curves labeled UU, BBB1, BBB2, BPAL12, Hyp, and K^-) and for strange stars (curves labeled ss1 and ss2). See text for details and references to the EOS models.

Figure 1 compares the theoretical M-R relations (solid curves) for nonrotating neutron stars given by six recent realistic models for the equation of state (EOS) of dense matter (see also [16]). In models UU [21], BBB1, and BBB2 [22] the neutron star core is assumed to be composed by an uncharged mixture of neutrons, protons, electrons, and muons in equilibrium with respect to the weak interaction (β-stable nuclear matter). Equations of state UU, BBB1, and BBB2 are based on microscopic calculations of asymmetric nuclear matter by use of realistic nuclear forces which fit experimental nucleon-nucleon scattering data and deuteron properties. In model Hyp [23], hyperons are considered in addition to nucleons as hadronic constituents of the neutron star core. Next, we consider, as a limiting case, a very *soft* EOS for β-stable nuclear matter, namely, the BPAL12 model [23], which is still able to sustain the measured mass $1.442M_\odot$ of the pulsar PSR 1913+16. In general, a *soft* EOS is expected to give a lower limiting mass and a smaller radius with respect to a *stiff* EOS [20]. Finally, we consider the possibility that neutron stars may possess a core with a Bose-Einstein condensate of negative kaons [24–26]. The main physical effect of the onset of K^- condensation is a softening of the EOS with a consequent lowering of the neutron star maximum mass and possibly of the radius. Actually, neutron stars with $R \sim 7$–9 km were obtained [25,26], for some EOS with K^- condensation. However, in those models [25,26] the kaon condensation phase transition was implemented using the Maxwell construction, which is inadequate in stellar matter, where one has two conserved charges: baryon number and electric charge [27]. When the kaon condensation phase transition is implemented properly [27], one obtains neutron stars with "large" radii, as shown by the curve labeled K^- in Fig. 1. Moreover, the presence of hyperons [28] and/or the inclusion of kaon-nucleon and nucleon-nucleon correlations [29] raise the threshold density for the onset of kaon condensation, possibly to densities higher than those found in the center of stable neutron stars.

It is clearly seen in Fig. 1 that none of the neutron star M-R curves is consistent with SAX J1808.4-3658 (including rotational effects will shift the M-R curves to upright in Fig. 1 [30], and does not help improve the consistency between the theoretical neutron star models and observations of SAX J1808.4-3658). Additionally, it is unlikely that the actual mass and radius of SAX J1808.4-3658 lie very close to the dashed curve, since the minimum flux $F_{\min}$ at which x-ray pulsations were detected by RXTE was determined by the instrumental sensitivity, and the actual value could be even lower [16]. Therefore it seems that SAX J1808.4-3658 is not well described by a neutron star model. As shown below, a strange star model seems to be more compatible with SAX J1808.4-3658.

Most of the previous calculations [31] of strange star properties used an EOS for strange matter based on the phenomenological nucleonic bag model, in which the basic features of QCD, such as quark confinement and asymptotic freedom are postulated from the beginning. The deconfinement of quarks at high density is, however, not obvious in the bag model. To find a star of small mass and radius, one has to postulate a large bag constant, whereas one would imagine in a high density system the bag constant should be lower.

Recently, Dey *et al.* [4] derived an EOS for strange matter, which has asymptotic freedom built in, shows confinement at zero baryon density, deconfinement at high density, and gives a stable configuration for chargeless, β-stable strange matter. In this model the quark interaction is described by an interquark vector potential originating from gluon exchange, and by a density dependent scalar potential which restores the chiral symmetry at high density. This EOS was then used [4] to calculate the structure of strange stars. Using the same model (but different values of the parameters with respect to those employed in Ref. [4]) we calculated the M-R relations, which are also shown in solid curves labeled ss1 and ss2 in Fig. 1, corresponding to SS with maximum masses of $1.44M_{\odot}$ and $1.32M_{\odot}$ [32] and radii of 7.07 km and 6.53 km, respectively. It is seen that the region confined by the dashed and dotted curves in Fig. 1 is in remarkable accord with the strange star models. Figure 1 clearly demonstrates that a strange star model is more compatible with SAX J1808.4-3658 than a neutron star one.

Detection of type-I x-ray bursts is usually regarded as a strong indicator for a neutron star [9]. However, the complexity of the observed x-ray bursts and of theoretical shell flashes on accreting compact stars would make it difficult to eliminate the possibility that some type-I x-ray bursters are actually SS [33,34].

Note that in writing inequality (1) we have implicitly assumed that the pulsar's magnetic field is basically dipolar (i.e., $B \propto r^{-3}$, where r is the radial distance). This is supported by the agreement between the dipolar spin-up line and the location of MS PSRs in the spin period—spin period derivative diagram, implying that the multipole moments in LMXBs are no more than ~40% of the dipole moments if the quadrupole component is comparable to or larger than higher order anomalies [35], although it does not exclude the possibility that, in case of SAX J1808.4-3658, the pulsar may have unusual field structure, either intrinsically or induced by the current flow in the boundary layer which terminates the star's corotating magnetosphere. Compared to a central dipole, more complicated field configurations with steeper (weaker) r dependence will result in weaker (steeper) $\dot{M}$ dependence of R_0, and the dashed curve will shift to right (left) in Fig. 1, influencing the constraints on the stellar compactness. The considerable uncertainties in the nature of the stellar magnetic field-disk interaction do not allow a definite conclusion, since (1) the dependence of B on r is related to the field topologies; (2) while the multipolar toroidal field component induced when the disk approaches the star tends to weaken the $\dot{M}$ dependence of R_0 (e.g., [16]), a steeper $\dot{M}$-dependence of R_0 would appear when field lines become open because of differential shearing between the disk and the star [36]. However, pulse shape phenomenology may serve as a probe to the field geometry. The presence of higher multipole moments tends to increase the number of visible hot spots (but not in a well-determined way), leading to complicated pulse structure (as seen in some of the x-ray pulsars). The pulse profiles of SAX J1808.4-3658, instead, can be modeled adequately by a single sine function with little dependence on energy and luminosity [12,19].

There is an important and unsettled issue related to SAX J1808.4-3658, if it is a neutron star, that is, why it is the only known LMXB with an MS PSR? While the similarities in outburst histories, x-ray spectral properties, and broadband noise features between SAX J1808.4-3658 and other LMXBs [12,37] suggest that they have similar structures of the inner accretion disk flow and of the magnetic fields, the nondetection of pulsations in the latter cannot be simply attributed to photon scattering around the neutron stars or geometric effect [16]. The most straightforward explanation seems to be that the surface magnetic field of SAX J1808.4-3658 is considerably stronger than those of other systems of similar x-ray luminosity [12]. We point out that a strange star is more liable to radiate pulsed emission than a neutron star because of its compactness. As seen in Fig. 1, the radius of a $\sim(1-1.4)M_{\odot}$ strange star is about 50%–70% of the radius of a neutron star of similar mass, implying that, for instance, with the same magnetic moment (the observable quantity), the surface field strength of the strange star is 3–8 (or 8–30) times as high as that of the neutron star if the stellar fields are purely dipolar (or quadrupolar), and that the size of the polar caps in the strange star for field-aligned flow, $\sim 4\pi R^2[1-(1-R/R_0)^{1/2}]$, is up to 10 times smaller than in the neutron star. The more efficient magnetic channeling of the accreting matter close to the strange star surface could then lead to higher pulsation amplitudes, making it easier to detect.

Strange stars have been speculated to model γ-ray bursters [38], soft γ-ray repeaters [39], and the bursting x-ray pulsar GRO J1744-28 [34]. In this work, we suggest that SAX J1808.4-3658 is a likely strange star candidate, by comparing its M-R relation determined from x-ray observations with the theoretical models of a neutron star and of a strange star. If so, there will be very deep consequences for both the physics of strong interactions and astrophysics. It has been suggested that SS could become unstable to the $m = 2$ bar mode [40]. Further observations of this signature in case of SAX J1808.4-3658 will be of great interest.

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