What can the redshift observed in EXO 0748-676 tell us?

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ABSTRACT

The mass-radius relations for bare and crusted strange stars are calculated with the bag model. Comparing these relations with the observed one derived from the redshift, we address that the conclusion, that EXO 0748-676 can not be a strange star, is incorrect. Various strange star models can show that EXO 0748-676 could have a mass of $\left(1.3 \sim 1.7\right)M_\odot$ and a radius of $\left(8.4 \sim 11.4\right)$ km. It is proposed that part of nascent strange stars could be bare and have mass $\sim 0.1M_\odot$, whereas their masses increase during a long accretion history.

Subject headings: stars: fundamental parameters — dense matter — stars: neutron

1. Introduction

On one hand, identifying strange stars is among the most important problems in the new millennium astrophysics. Strange stars are hypothetical compact objects that consists of roughly equal numbers of deconfined up, down and strange quarks, to affirm or negate the existence of which should have great implications in the study of the elemental strong interaction (see, e.g., Xu 2002a, for a review). Some compact objects, previously known as neutron stars, may actually be strange stars. Whatever they are, the most essential and important thing is to find clear observational signatures of strange stars.

However, on the other hand, how to identify a neutron star? If a neutron star is found with certain, we are very probably to obtain a negative conclusion of strange stars eventually. A neutron star, as its name implies, is made mainly of neutrons, the outmost part of which is an atmosphere of normal ions. Recently, it is a central goal and a real competition among the observers to find line emission from the atmosphere, since the stellar mass $M$ and radius $R$ may be derived by obtaining its gravitational redshift (as $M/R$) and the pressure broadening (as $M/R^2$) of the lines. Still almost no line is observed (Xu 2002b) except for those two sources 1E 1207.4-5209 and SGR 1806-20 (Xu et al. 2002).
It is possible that strong magnetic field, $\gtrsim 10^{12}$ G, around a neutron star may greatly modify the thermal spectrum, making lines difficult to identify (Pons et al. 2002). A recent research of studying EXO0 748-676, a compact star that has much weaker field ($\sim 10^8$ G), shows significant absorption lines, the Fe XXVI and XXV $n = 2 \rightarrow 3$ and the O VIII $n = 1 \rightarrow 2$, in the spectra of 28 bursts\(^1\). All of these lines are redshifted, with an unique value of 0.35 (Cottam et al. 2002). The authors concluded then, according to the redshift, that their results are expected for neutron star models, but do not agree with a strange star model based on the equation of state proposed by Dey et al. (1998) if the mass of EXO 0748-676 is greater than $1.1M_\odot$.

It will be addressed in this paper that strange star models for EXO 0748-676 can not be excluded. According to a simplified version of the MIT bag model, we calculate the mass-radius relations of strange stars and compare them with observations, and find that it is very reasonable to assume that EXO 0748-676 is a strange star.

### 2. The mass-radius relations

In the outer vacuum of a spherically symmetric object with mass $M$, due to the general relativity effects, a photon with wavelength $\lambda_0$, radiated at radius $r$, should be red-shifted. The received wavelength at infinity is $\lambda = \lambda_0/\chi$, where $\chi = \sqrt{1-2GM/(c^2r)}$ is called as the redshift factor ($c$ is the speed of light). The redshift is defined as $z = (\lambda - \lambda_0)/\lambda_0$, and one thus have a relation,

$$M_1 = 3.37[1 - (1 + z)^{-2}]r_6 = 1.52r_6 \quad \text{(for } z = 0.35),$$

(1)

where $M_1 = M/M_\odot$, and $r_6 = r/(10^6\text{cm})$. The second equation above is for $z = 0.35$ observed in EXO 0748-676. If photons are emitted at stellar surface, $r = R$ ($R$ is the stellar radius), Eq.(1) is actually the mass-radius relation of a central object, which is a beeline the M-R diagram.

Can strange star models satisfy this relation? Actually strange star structures with crusts were discussed previously (e.g., Kettner et al. 1995, Huang & Lu 1998, Madsen 1999). We need an equation of state of strange matter in order to model a strange star. In a simplified version of the bag model, assuming quarks are massless, we then have quark pressure $P_q = \rho_q/3$ ($\rho_q$ is the quark energy density); the total energy density is $\rho = \rho_q + B$.

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\(^1\)EX 00748-676 is an X-ray burster; the mechanism responsible for the bursts is attributed to the nuclear fusion on the surface due to enough accretion from its low mass company.
but the total pressure is \( P = P_q - B \). One therefore have the equation of state for strange matter (Alcock et al. 1986),

\[
P = (\rho - 4B)/3.
\]  

(2)

Although the equation is simple, the crucial parameter, the so called bag constant \( B \), can hardly be given. Nevertheless, the preferred value for \( B \) is in the range of \( 60\text{MeV}/\text{fm}^3 \lesssim B \lesssim 110\text{MeV}/\text{fm}^3 \), according to the studies of the hadronic spectrum, the hadronic structure functions, and the comparison of bag model with lattice quantum chromodynamics (Drago 2000). We will thus calculate with \( B = 60\text{MeV}/\text{fm}^3 \) and \( 110\text{MeV}/\text{fm}^3 \) for indication.

In an accreting binary system, it is possible that a strange star could be crusted. The mass and the height of the crust can be calculated by 1, the density, \( \rho_b \), at the base of the crust, and 2, the gravitational equilibrium with suitable equation of state of matter in the crust. The density \( \rho_b \) can not be higher than the density of neutron drip \( \rho_d = 4 \times 10^{11} \text{g/cm}^3 \), because free neutrons, which will not fell Coulomb force and should melt in the strange quark matter, appear at higher density. The crust height computed with \( \rho_b = \rho_d \) is an upper limit, and the stellar radius (or mass) is thus between that of bare strange star and that of crusted strange star with \( \rho_b = \rho_d \). The standard equation of state of cold, fully catalyzed matter below neutron drip is given by Baym, Pethick & Sutherland (1971), which is called as BPS equation of state.

The mass-radius relations of strange stars are calculated with Eq.(2) for the strange quark matter core and with BPS equation of state for the crust (we choose \( \rho_b = \rho_d \)), which are shown in Fig.1. It is found from Fig.1 that the redshift of \( z = 0.35 \) can easily be consistent with strange star models, at least in the regime of strange quark matter described by MIT bag model. For \( B = 110 \text{MeV}/\text{fm}^3 \), EXO 0748-676 could have a mass of \( \sim 1.3M_\odot \) and a radius of \( \sim 8.4 \text{ km} \), whereas for \( B = 60 \text{MeV}/\text{fm}^3 \), it could have \( M \sim 1.7M_\odot \) and \( R \sim 11.4 \text{ km} \). Therefore it is possible that the mass of EXO 0748-676, if being a strange star, can be larger than \( 1.1M_\odot \), which is certainly comfortable from astrophysical arguments.

3. Conclusions and Discussions

Using MIT bag model and BPS equation of state, we calculate the mass-radius relations for both bare and crusted strange stars, and compare them with the observed one derived from the redshift. It is found that we still can not rule out strange star models for the X-ray burster EXO 0748-676. According to the calculations presented, EXO 0748-676 could have a mass of \( (1.3 \sim 1.7)M_\odot \) and a radius of \( (8.4 \sim 11.4) \text{ km} \).

There might be some observational indications of very-low-mass compact stars, with
mass \sim 0.1M_\odot, which could be representative of strange stars. 1. From the 500 Ksec Chanrda record of thermal spectrum of the nearest and brightest isolated neutron star RX J1856-3754, fitted with a single temperature Plank spectrum, one can deduce a radius \( R_\infty = 3.8 \sim 8.2 \) km (Pons et al 2002, Drake et al. 2002), although these results were soon criticized by Walter & Lattimer (2002). It is worth noting that the apparent radius \( R_\infty \), i.e., the values observed at infinity, is not that calculated in Eq.(1). For a compact star with mass \( M \) and radius \( R \), the relation is (e.g., Haensel 2001)

\[
R_\infty = R/\sqrt{1 - (R_s/R)},
\]

where \( R_s = 2GM/c^2 \) is the Schwartzschild radius. According to Haensel’s (2001) results for bare strange stars [RX J1856-3754 could be a bare strange star because of its featureless spectrum, see Xu (2002b) for details], RX J1856-3754 may therefore have a mass of (0.06 \sim 0.4)M_\odot. 2. Based on the study of radio pulse beam and its polarizations, it is suggested that the fastest rotating pulsar, PSR 1937+21, could be a strange star, with mass \( M < 0.2M_\odot \) and radius \( R < 1 \) km (Xu et al. 1999). If this very-low-mass strange star was born with a period \( P_0 \lesssim 1.56 \) ms, in order to prevent it from developing the rotation-mode instability (e.g., Madsen 1998), the star can have a minimum period \( P_{\text{min}} \sim 0.1 \) ms (or angular frequency \( \Omega \sim 6 \times 10^6/s \)) in case of \( M = 0.2M_\odot, R = 1 \) km, and the temperature of a nascent strange \( T = 10^9 \) K. Therefore PSR 1937+21 may not have an accretion history since \( P_0 \gg P_{\text{min}} \).

3. Also the gravitational microlensing study reports events with a mass \( \sim 0.5M_\odot \) towards LMC (Alcock et al. 2000), and with \( M = 0.13M_\odot \) and \( M = 0.25M_{\text{Jupiter}} \) at the globular cluster M33 (Sahu et al. 2001).

Combining the results of masses and radii of very-low-mass compact stars and of EXO 0748-676, we may conjecture, that part of bare strange stars may have low masses, \( \sim 0.1M_\odot \), while strange stars with much high accretion rate history could have high masses, \( \sim 1.5M_\odot \). A natural explanation for this is that long historical accretion increases the masses of strange stars. Therefore, it is possible that some of the newborn strange stars, which should be bare (Xu 2002b), could have much small masses and radii. What is the critical physical reason which determines the initial mass of a strange star? This is one of the interesting topics in the study of supernova explosion.

The strange star model can not be excluded even for the equation of state of Dey et al. (1998). No solid evidence to show that EXO 0748-676 has a mass \( \gtrsim 1.1M_\odot \). The star can accrete much to a mass \( \sim 1M_\odot \) during a long accretion history if its initial mass is very low.

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Fig. 1.— The mass-radius relations for strange stars, both bare and crusted, based upon a simplified version of MIT bag models. Solid and dotted lines are for bag constant $B = 60$ MeV/fm$^3$ and 110 MeV/fm$^3$, respectively. The mass-radius relation derived from the redshift $z = 0.35$ is also shown.