Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 1, 33–37
(http://www.chjaa.org or http://chjaa.bao.ac.cn)

Chinese Journal of
Astronomy and
Astrophysics

LETTERS

What Can the Redshift Observed in EXO 0748–676 Tell Us? *

Ren-Xin Xu

Department of Astronomy, School of Physics, Peking University, Beijing 100871;
rxxu@bac.pku.edu.cn

Received 2002 November 12; accepted 2002 December 23

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 of EXO 0748–676, we come to the conclusion that it is incorrect to say that EXO 0748–676 cannot be a strange star. Various strange star models can show that EXO 0748–676 could have a mass of $(1.3 \sim 1.7)M_\odot$ and a radius of $(8.4 \sim 11.4)$ km. It is proposed that a proportion of nascent strange stars could be bare and have masses $\sim 0.1\,M_\odot$, and their masses increased over a long period of accretion.

Key words: 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 are composed of roughly equal numbers of deconfined up, down and strange quarks; to affirm or negate whether such stars exist 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. In fact, there are some astrophysical events (e.g. cosmic γ-ray burst, see Cheng & Lu 2001) which may be relevant to strange stars. Whatever they are, the most essential and important thing is to find *clear* observational signatures of such objects.

However, on the other hand, *how to identify a neutron star?* If a neutron star is found with certainty, then, very probably we shall arrive eventually at a negative conclusion on strange stars. A neutron star, as the name implies, is made mainly of neutrons, with as its outermost part, an atmosphere of normal ions. Recently, it has been a central goal and a real competition among observers to find line emission from this atmosphere, since the star's mass M and radius R may be obtained from the lines' gravitational redshift (varying as M/R) and pressure broadening (as M/R^2). So far, the lines have only been observed in two sources, 1E 1207.4–5209 and SGR 1806–20 (Xu 2002b; Xu et al. 2003).

* Supported by the National Natural Science Foundation of China.

Now, it is possible that a strong magnetic field, $\gtrsim 10^{12}$ G, around a neutron star may greatly modify the thermal spectrum, making the lines difficult to identify (Pons et al. 2002). A recent study of EXO 0748–676, a compact star that has a much weaker field ($\sim 10^8$ G), showed 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 at the same value of 0.35 (Cottam et al. 2002). The authors then concluded that, according to the redshift, their results are as expected for neutron star models, but do not agree with the strange star model based on the equation of state proposed by Dey et al. (1998) if the mass of EXO 0748–676 is assumed to be greater than $1.1\,M_\odot$.

It will be argued in this paper, however, that a strange star model for EXO 0748–676 cannot 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 the observations, and find that it would be very reasonable to suggest that EXO 0748–676 is a strange star.

2 THE MASS-RADIUS RELATIONS

According to general relativity, in the outer vacuum of a spherically symmetric object of mass M, a photon (wavelength λ_0, radiating at radius r) should be red-shifted. The received wavelength at infinity is $\lambda = \lambda_0/\chi$, where $\chi = \sqrt{1 - 2GM/(c^2 r)}$ is the redshift factor (c is the speed of light). The redshift is defined as $z = (\lambda - \lambda_0)/\lambda_0$, and so we have,

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

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 the star's surface, $r = R$ (R is the stellar radius), Eq. (1) is actually the mass-radius relation for the central object, and is a straight line in the M-R diagram.

Can strange star models satisfy this relation? Actually, strange star structures with crusts have been 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, if we assume quarks to be massless, then we have the quark pressure $P_\text{q} = \rho_\text{q}/3$ (ρ_q is the quark energy density); the total energy density is $\rho = \rho_\text{q} + B$ but the total pressure is $P = P_\text{q} - B$. We therefore have the equation of state for strange matter (Alcock et al. 1986),

$$P = (\rho - 4B)/3. \tag{2}$$

Although the equation is simple, the crucial parameter, the so called the bag constant B, can not be easily specified. The preferred value for B is in the range of $60\text{MeV/fm}^3 \lesssim B \lesssim 110\text{MeV/fm}^3$, according to the studies of the hadronic spectrum and the hadronic structure functions, and a comparison of the bag model with lattice quantum chromodynamics (Drago 2000). We will therefore use $B = 60\text{MeV/fm}^3$ and 110MeV/fm^3 in our indicative calculation.

In an accreting binary system, it is possible that a strange star is crusted. The mass and the height of the crust can be calculated from 1) the density at the base of the crust ρ_b, and 2) gravitational equilibrium with a suitable equation of state for the matter of the crust. The

[1] EXO 0748–676 is an X-ray burster; the mechanism responsible for the bursts is attributed to nuclear fusion on the surface following sufficient accretion from its low mass companion.

density $\rho_{\rm b}$ cannot be higher than the neutron drip density, $\rho_{\rm d} = 4 \times 10^{11}$ g cm^{-3}, because free neutrons, which do not feel the Coulomb force and should melt in the strange quark matter, appear at any higher density. The crust height computed with $\rho_{\rm b} = \rho_{\rm d}$ is an upper limit, and the stellar radius (or mass) is thus between that of a bare strange star and that of a crusted strange star with $\rho_{\rm b} = \rho_{\rm d}$. The standard equation of state of cold, fully catalyzed matter below neuron drip is given by Baym, Pethick & Sutherland (1971), and is known as the BPS equation of state.

With Eq. (2) for the strange quark matter core and the BPS equation of state for the crust (we choose $\rho_{\rm b} = \rho_{\rm d}$), we calculated the mass-radius relations for bare and crusted strange stars shown in Fig. 1. Figure 1 also shows that the redshift of $z = 0.35$ is easily compatible with a strange star model, at least for the regime of strange quark matter described by the MIT bag model. For $B = 110$ MeV/fm^3, EXO 0748–676 could have a mass of $\sim 1.3\,M_\odot$ and a radius of ~ 8.4 km, whereas for $B = 60$ MeV/fm^3, it could have $M \sim 1.7\,M_\odot$ and $R \sim 11.4$ km. Therefore it is possible that the mass of EXO 0748–676, if it is a strange star, can be greater than $1.1\,M_\odot$, which is certainly comfortable on astrophysical grounds.

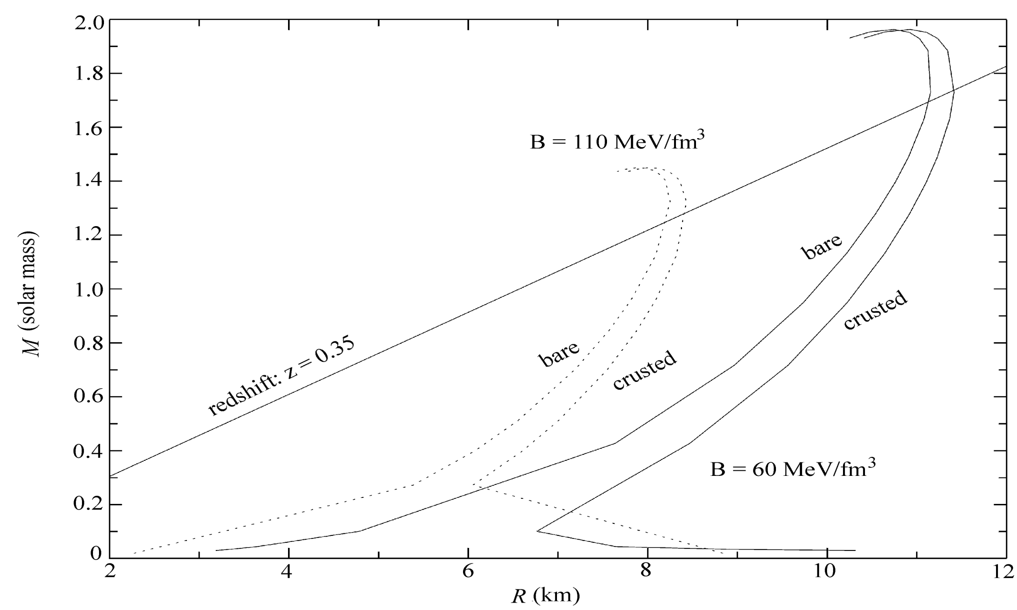

Fig. 1 Mass-radius relations for strange stars, both bare and crusted, based on a simplified version of the MIT bag models. Solid and dotted lines are for the bag constant $B = 60\,{\rm MeV/fm}^3$ and $110\,{\rm MeV/fm}^3$, respectively. The mass-radius relation derived from the redshift $z = 0.35$ is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

3 CONCLUSIONS AND DISCUSSION

Using the MIT bag model and the 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 redshift. It is found that we still cannot rule out a strange star model 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 $(8.4 \sim 11.4)$ km.

There might be some observational indications of very-low-mass compact stars, with mass $\sim 0.1 M_\odot$, 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 Planck 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_∞ (the value observed at infinity), is not that which is calculated in Eq. (1). For a compact star with mass M and radius R, the relation is (e.g., Haensel 2001)

$$R_\infty = R/\sqrt{1 - (R_{\rm s}/R)}, \qquad (3)$$

where $R_{\rm s} = 2GM/c^2$ 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 its radio pulse beam and polarizations, it was suggested that the fastest rotating pulsar, PSR 1937+21, could be a strange star, with mass $M < 0.2 M_\odot$ 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 $P_{\rm min} \sim 0.1$ ms (or angular frequency $\Omega \sim 6 \times 10^6\,{\rm s}^{-1}$) for $M = 0.2\, M_\odot$, $R = 1$ km, and a nascent strange temperature $T = 10^9$ K. Therefore PSR 1937+21 may not have an accretion history since $P_0 \gg P_{\rm min}$.

3. Also, a mass $\sim 0.5 M_\odot$ towards LMC was reported in a gravitational microlensing study (Alcock et al. 2000), and masses of $M = 0.13\, M_\odot$ and possible $M = 0.25\, M_{\rm Jupiter}$ were reported in the globular cluster M22 (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 some of bare strange stars may have low masses, $\sim 0.1\, M_\odot$, while strange stars with a much higher accretion rate history could have high masses, $\sim 1.5\, M_\odot$. A natural explanation for this is that a long history of accretion increases the mass of the strange star. Therefore, it is possible that some of the newborn strange stars, which should be bare (Xu 2002b), could have much smaller masses and radii. What is the critical physical factor 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 cannot 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 $\gtrsim 1.1\, M_\odot$. The star can accrete much matter up to a mass $\sim 1\, M_\odot$ over a long period of accretion if its initial mass was very low.

Acknowledgements This work is supported by National Nature Sciences Foundation of China (10273001, 10173002) and the Special Funds for Major State Basic Research Projects of China (G2000077602). I would like to thank Mr. Yi Liu for technical help in preparing the figure.

References

Alcock C., Allsman R. A., Alves D. R. et al., 2000, ApJ, 542, 281
Alcock C., Farhi E., Olinto A., 1986, ApJ, 310, 261
Baym G., Pethick C. J., Sutherland P., 1971, ApJ, 170, 299
Cheng K. S., Lu T., 2001, Chin. J. Astron. Astrophys. (ChJAA), 1, 1
Cottam J., Paerels F., Mendez M., 2002, Nature, 420, 51 (astro-ph/0211126)
Dey M., Bombaci I., Dey J. et al., 1998, Phys. Lett. B438, 123 (erratum 467, 303)
Drago A., 2000, Nucl. Phys., A663, 749
Drake J. J., Marshall H. L., Dreizler S. et al., 2002, ApJ, 572, 996
Haensel P., 2001, A&A, 380, 186
Huang Y. F., Lu T., 1997, A&A, 325, 189
Kettner Ch., Weber F., Weigel M. K., Glendenning N. K., 1995, Phys. Rev., D51, 1440
Madsen J., 1999, In: Hadrons in Dense Matter and Hadrosynthesis, Proceedings of the Eleventh Chris Engelbrecht Summer School, 1998, Springer, 1999, p.162
Madsen J., 2000, Phys. Rev. Lett., 85, 10
Pons J. A., Walter F. M., Lattimer J. M. et al., 2002, ApJ, 564, 981
Sahu K. C., Casertano S., Livio M. et al., 2001, Nature, 411, 1022
Walter F. M., Lattimer J. M., 2002, ApJ, 576, L145
Xu R. X., 2002a, In: X. D. Li, Z. R. Wang, V. Trimble, eds., High Energy Processes, Phenomena in Astrophysics, Proceedings of IAU Symposium No. 214, (astro-ph/0211348)
Xu R. X., 2002b, ApJ, 570, L65
Xu R. X., Wang H. G., Qiao G. J., 2003, Chin. Phys. Lett., 20, 314
Xu R. X., Xu X. B., Wu X. J., 2001, Chin. Phys. Lett., 18, 837 (astro-ph/0101013)