An unusually low mass of some “neutron” stars?

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Received, Accepted

Abstract. The X-ray emission of RXJ1856.5-3754 has been found to coincide to unprecedented accuracy with that of a blackbody, of radius 5.8 ± 0.9 km for the measured parallax distance of 140 pc (Burwitz et al. 2001, Drake et al. 2002). If the emission is uniform over the whole surface of a non-rotating star, the mass of the star cannot exceed 0.75 ± 0.12M⊙ regardless of its composition. If the compact object is a quark star described by the MIT-bag equation of state (a “strange star”), the mass is no more than 0.3M⊙. Comparably small masses are also obtained for the X-ray bursters Aql X-1 and KS1731-260 for some fits to their spectra.

Key words. dense matter - equation of state - stars: neutron - stars: general - X-rays: stars

1. Introduction

As noted by several authors, conventional neutron stars always have a (circumferential) radius larger than 6 km. Recent reports of a rather small blackbody radius of a nearby neutron-star candidate have generated speculation that the compact object may not be a neutron star but a quark star instead. Here, we point out that although the actual composition of stars with a 6 km radius is not known, what would make such stars unusual is their low mass, posing a challenge to current theories of their formation. Detailed simulations of supernovae do not predict remnant masses less than 1.2M⊙ (Timmes et al. 1996).

2. Dense matter and compact objects

The properties of bulk matter at about nuclear density are not well understood. On one hypothesis, its stable form is composed of deconfined up, down and strange quarks in about equal numbers, and quark stars should exist (Itoh 1970, Bodmer 1971, Witten 1984). On another, the lowest energy state of matter at supranuclear density consists mainly of neutrons. Some observations of young pulsars, specifically of impulsive changes (glitches) in the radio period, seem to favor the latter hypothesis (Alpar 1987).

Much effort has been expended in trying to constrain the equation of state (e.o.s.) of very dense matter through the comparison of calculated and observed properties of neutron stars. Unfortunately, the density and angular momentum of the observed “neutron” stars are poorly constrained. The rotational periods of radio pulsars have been measured with exquisite accuracy, but the masses remain largely unknown. In the few cases where the masses have been measured, there is hardly any information on the radius. For the accreting “neutron” stars in persistent low mass X-ray binaries some idea about the radius can be gleaned from spectral data, but the masses are very uncertain (although said to be consistent with ~ 1.4M⊙), the rotational periods also remain largely unknown.

Once the e.o.s. is selected, calculating the structure and space-time metric of a compact object presents no fundamental difficulty. Detailed numerical models of neutron stars have been computed for a range of conventional e.o.s. of baryonic matter (Arnett and Bowers 1977, Cook et al. 1994, Lattimer & Prakash 2001). Ditto for quark stars (Alcock et al. 1986, Haensel et al. 1986, Gourgoulhon et al. 1999, Stergioulas et al. 1999, Gondek-Rosińska et al. 2000, 2001). One essential difference between conventional neutron stars and quark stars is that if quark matter is stable, there is no lower limit to the mass of quark stars. Fully relativistic numerical computations show that at masses below ~ 0.1M⊙ rotating quark stars are very well approximated by Maclaurin spheroids (Amsterdamski et al. 2002). The maximum mass of quark stars falls in the conventional range of maximum neutron star masses, it does not exceed ~ 2.6M⊙ for static models (Zdunik et al. 2000) and ~ 3.7M⊙ for rapidly rotating models (Stergioulas et al. 1999), at least in the MIT-bag model of quark matter.
An unconventional e.o.s. of baryonic matter has also been proposed, which could have densities below or above nuclear, depending on the choice of parameters—Bahcall, Lynn, and Selipisky (1989) show, using an effective field theory approach, that self-bound bulk baryonic matter is consistent with nuclear physics data and low-energy strong interaction data. For neutron stars modeled with this e.o.s. very low masses are allowed, as for quark stars, while the maximum mass depends on the choice of parameters and could be lower or much higher than that of the Hulse-Taylor binary pulsar (1.4\(M_{\odot}\)). These are the so-called Q-stars (Bahcall et al. 1990). We stress that Q-stars would be composed of hadronic matter, baryons and mesons. This matter differs from the one considered in conventional neutron star models only in the detailed description of nuclear interactions.

Fig. 1 illustrates some models of compact stars computed by solving the TOV equation (Oppenheimer and Volkoff 1939) with the equation of state

\[ P = a(\rho - \rho_0)c^2. \]  

Here, \( P \) is the pressure, \( \rho \) the energy density, \( \rho_0 \) the density at zero pressure, and \( a \) a parameter. In the MIT-bag model of quark matter (Farhi and Jaffe 1984), quark confinement is modeled with a non-zero energy density of the vacuum, e.g., \( B = \rho_0 c^2/4 \) when the quarks are massless and \( a = 1/3 \) is also obtained. Zdunik (2000) gives expressions for \( a \) and \( \rho_0 \) as functions of the quark masses and the QCD coupling constant. With a different model of quark confinement, Dey et al. (1998) derive an e.o.s. which to a very good approximation is the same as eq. (1) (Gondek-Rosińska et al. 2000). For illustrative purposes we reproduce one of the Dey et al. (1998) sequences of models, the one with a maximum gravitational mass of 1.44\(M_{\odot}\), for which \( a = 0.463 \) and \( \rho_0 = 1.153 \times 10^{-13} \text{g cm}^{-3} \).

To compute sequences of mainstream (MIT-bag) models of quark stars, we have used \( m_s = 200 \text{MeV} \) for the mass of the strange quark, a value of \( \alpha = 0.2 \) for the QCD coupling constant and a bag constant \( B = 56 \text{MeV fm}^3 \), corresponding to \( \rho_0 = 4.50 \times 10^{14} \text{g cm}^{-3} \), and \( a = 0.301 \) in eq. (1), for the “MIT SS1” curve; and \( m_s = 100 \text{MeV} \), \( \alpha = 0.6 \), \( B = 40 \text{MeV fm}^3 \), corresponding to \( a = 0.324 \), \( \rho_0 = 3.056 \times 10^{14} \text{g cm}^{-3} \) for the “MIT SS2” curve. These sequences allow gravitational masses of quark stars to be as high as any value reported for the observed “neutron” stars (within error bars). The models were computed with and without a crust. For the crust we use the BPS e.o.s. (Baym et al. 1971). The maximum density of the crust is taken to be equal to the neutron-drip density \( \rho_{\text{drip}} = 4.3 \times 10^{11} \text{g cm}^{-3} \), but thinner crusts are not excluded.

For the Q-stars, we have chosen parameters in such a way that the e.o.s. formally coincides with that of eq. (1), and the maximum static mass is about 1.0\(M_{\odot}\). With this choice for the three sequences of stellar models, at any given stellar mass, the Q-star, which is a neutron star really (i.e., a star composed of baryonic matter), is the one with the smallest radius, and the MIT-bag quark star is the least compact. With another choice of parameters, the Q-star would have the largest radius. All three types of stars considered are typically more compact than conventional neutron stars.

### 3. The blackbody radius in the Schwarzschild metric

In this letter we neglect rotation of the star. The exterior of any spherically symmetric star is described by the Schwarzschild metric. We also assume that the stellar radius satisfies \( R > 3GM/c^2 \), this is true for all the models considered in Fig. 1.

If the stellar surface radiates as a blackbody, the spectrum and luminosity at infinity satisfy the Stefan-Boltzmann law with a blackbody radius

\[ R_{\text{bb}} = R/\sqrt{1 - 2GM/(Rc^2)}, \]  

where \( R \) is the circumferential radius of the star and \( M \) its mass. The same formula applies when \( R_{\text{bb}} \) is determined from an effective temperature derived by fitting the spectra to theoretical models of neutron-star atmospheres (e.g., Rutledge et al. 2001a). All recent conventional neutron-star models have the property that \( R_{\text{bb}} > 12 \text{km} \) (Lattimer & Prakash 2001, Haensel 2001). A star with a blackbody radius significantly smaller than 10 km probably cannot be described by a conventional e.o.s.

When eq. (2) is inverted at any value of the blackbody radius, \( M \) reaches a maximum at the photon orbit \( R = 3GM/c^2 \). Accordingly (Lattimer & Prakash 2001),

\[ M < 0.13M_{\odot} \frac{R_{\text{bb}}}{1.0 \text{km}}. \]  

Thus, a non-rotating star radiating as a blackbody cannot have a mass greater than 1\(M_{\odot}\) if the blackbody radius is \( R_{\text{bb}} < 7 \text{km} \). This value is much less than the 1.44\(M_{\odot}\) masses measured for the binary pulsars, assumed to be representative of the neutron star mass at its birth in a supernova collapse.

The limit of eq. (3) is shown in Fig. 1 as the dashed line. There are no solutions to the redshift eq. (2) for any value of \( R_{\text{bb}} \) above this line—the excluded area is shown in gray. Also shown are some representative models of ultracompact stars (Section 2), as well as best-fit values of \( R_{\text{bb}} \), reported in the literature under certain assumptions as to the spectrum, for three actually observed compact objects (Sections 4, 5).

### 4. RXJ1856.5-3754

Shortly after its discovery with ROSAT, Walter et al. (1996) and Neuhauser et al. (1997) suggested that the steady, dim \((\sim 1.5 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2})\) X-ray source RXJ1856.5-3754 is a nearby neutron star. Pavlov et al. (1996) performed the first spectral fits to the ROSAT data, and found strong dependence of the results on chemical composition.
Fig. 1. The upper limit to mass allowed by eq. (2), and the masses of theoretical models of compact objects, plotted as a function of the blackbody radius in Schwarzschild geometry. The excluded area is shown in grey. The best fit values of the blackbody radius of RXJ 1856.5-3754 (Drake et al. 2002) are shown as vertical lines for two values of the distance to the source, \( d = 117 \) pc and 140 pc; the quoted 1σ error on \( R_{bb} \) is 0.68 km/100 pc. Also shown are the best fit radii for “hydrogen” atmospheric models of well-known X-ray bursters KS1731-260 and Aql X-1 (Rutledge et al. 2001a,b). The thin continuous lines are the mass-radius relationship for three sequences of quark star models with the thickest possible crust of normal atomic matter, the dotted lines are the same models without the crust (“bare quark stars”), models with intermediate thickness of the crust would fall in between these limiting lines. The thick continuous line is a sequence of neutron star models (Q-stars) based on an unconventional equation of state of baryonic matter (Bahcall et al. 1990). See text for details.

The X-ray spectrum of the source observed with Chandra is inconsistent with that expected from a hydrogen, helium or iron rich neutron star atmosphere, solar composition is also excluded (Burwitz et al. 2001). The spectrum is fit to an extraordinary accuracy by a blackbody, and the best fit blackbody radius is \( R_{bb} = (4.12 \pm 0.68) \) km \( \times d/(100 \) pc (Burwitz et al. 2001, Drake et al. 2002); \( d \) is the distance to the source.

Drake et al. 2002 come to the conclusion that the new distance determinations, especially the optical parallax determination of Kaplan et al. (2002), firmly place RXJ1856.5-3754 at less than 140 pc distance. On the tacit assumption that the whole surface of the star is emitting uniformly, and that the star is not rotating rapidly, Drake et al. further suggest that the inferred radius is too small for the star to be a neutron star, and the star may be a quark star instead. The upper limit to the pulsed fraction in the frequency range \( 10^{-4} \) Hz to 100 Hz is less than 2.7%. The possibility that RXJ1856.5-3754 is a millisecond pulsar still remains.

A bare quark surface is a very weak photon emitter (Chmaj et al. 1991, Usov 2001), and normal matter is usually expected to have an atmosphere, so the observed spectrum is a major puzzle in itself. In this letter we focus on the radius alone. Small blackbody radii have been found for the polar caps of active pulsars, but in those cases a power-law component of the X-ray spectrum and pulsations have also been detected.

If the X-ray source is indeed a star of blackbody radius of about 6 km, or less, it must be of unusually low mass for a compact stellar remnant, less than \( 0.8 M_{\odot} \) by eq. (3). If it is a quark star of the usually considered properties, its mass must be extremely small, \( 0.1 M_{\odot} \) to within a factor of two (as seen in Fig. 1 for the MIT-bag models).
5. Are low mass “neutron” stars common?

RXJ1856.5-3754 is only $10^2$ pc away. On statistical grounds, it cannot be an uncommon object. There should be about $10^5 \cdot \left(10^5 \frac{\gamma}{\tau}\right)$ such objects in the Galactic disk (assuming a half-thickness of 1 kpc), where $\tau$ is the (cooling) time for the RXJ source to become undetectable at 140 pc. Are the inferred mass and radius of RXJ1856.5-3754 unique in the observed “neutron” star population?

There are hints in the literature that other stars of mass clearly less than the canonical 1.4 $M_\odot$ may have been observed. Steeghs and Casares (2002) have measured the mass function of Sco X-1. A mass of 1.4 $M_\odot$ is consistent with the observed light curve, but a somewhat lower value $\sim 0.9 M_\odot$ is more likely a priori.

Spectral fits to some X-ray bursters are especially interesting in this regard. The derived mass and radius strongly depend on the atmospheric model. Whether the blackbody emission of RXJ 1856.5-3754 originates from the whole surface of the compact stellar source, or only a part of it, spectral fits exclude conventional neutron-star atmospheres. Is there a compelling reason in other sources to prefer atmospheric models not required by the data?

Aquila X-1 is a case in point. A hydrogen atmosphere without a power law component fits the data for a radius of $R_{bb} = 9.4^{+2.7}_{-2.4}$ km, and with a power-law for a larger radius of about 14 ± 4 km (Rutledge et al. 2001a). It is the latter value which is usually adopted, but in Fig. 1 we plot the former. A blackbody fit yields the even smaller radius of $R_{bb} = 1.9 \pm 0.3$ km.

A hydrogen atmosphere fit to another X-ray burster, KS1731-260, yields a comparable radius $R_\infty = 6.5^{+6}_{-6}$ km (Rutledge et al. 2001b). We plot the central value in Fig. 1. A blackbody fit gives $R_{bb} = 1.3^{+0.6}_{-0.3}$ km. The point we are making here is that for some X-ray bursters observations do not exclude low radii and low masses.

6. Is RXJ1856.5-3754 a binary system?

There is an excess optical emission (over the extrapolated X-ray blackbody) of RXJ1856.5-3754, and it can also be fit by a blackbody, with a lower limit to the blackbody radius of 17 km (Burwitz et al. 2002). The optical source is constrained to be within 2” of the X-ray source.

If so, we would like to suggest that a binary system is being observed, one component being a larger (in radius) and cooler object, while the other significantly smaller and hotter, but both at about nuclear density (few times $10^{14}$ g cm$^{-3}$). It is reasonable to assume that both members of the putative pair have the same composition. The MIT-bag e.o.s. of quark matter can accommodate these two disparate radii (less than 6 km and more than 17 km) in two ways. The binary could be a massive ($\sim 2 M_\odot$) star with a low mass satellite. Alternatively, both stars could be of very low mass, and differ in the thickness of the crust. As is clear from Fig. 1, the maximal thickness of the crust increases with decreasing mass, the “larger” optical source could then be of even lower mass than the X-ray source.

Extremely low mass quark stars with a thick crust are stable (Glendenning 1995, Gondek 1998). Whether the two objects have been formed at the same time, perhaps as a result of fragmentation of a rapidly rotating collapsing core, or whether one is older and the other younger is at present a matter of speculation, as no evolutionary calculations producing such a pair have been performed. However, we note that Newtonian simulations indicate that under violent circumstances quark stars are subject to fragmentation, in which low mass ($\sim 0.1 M_\odot$) quark “starlets” may be formed (Lee and Kluźniak 2001).

Acknowledgements. It is a pleasure to thank Dr. J. Trümper for valuable discussion. This work has been funded by the KBN grant 5P03D01721, the Greek-Polish Joint Research and Technology Program (EPP-M.43/2013555), the EU Program “Improving the Human Research Potential and the Socio-Economic Knowledge Base” (Research Training Network Contract HPRN-CT-2000-00137), and by CNRS.

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