Part 6

Neutron Stars and Strange Stars

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Structure of Strange Quark Matter and Neutron Stars

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Abstract. The properties of neutron and strange matter stars are discussed from global and observational perspectives. The global features, i.e., the mass-radius relation, the moment of inertia, and the binding energy, of these objects can be understood by examination of the few known relevant analytic solutions to Einstein's equations. A close connection exists between neutron star radii and the density dependence of the isospin dependence of strong interactions, i.e., the nuclear symmetry energy. Interestingly, a similar relation has been found to exist between the symmetry energy and the neutron skin thickness of neutron-rich nuclei, the object of a new generation of laboratory experiments, although these are 10^{18} times smaller. Recent observations of neutron star masses and radiation radii are summarized. The status of these observations as predictors of nuclear force properties is examined. The combination of observations, laboratory experiments, and theory is an extremely powerful tool for both nuclear physics and nuclear astrophysics.

1. Introduction

Neutron stars are born in the aftermath of supernova explosions, with interior temperatures approaching 10^{11} K. Neutrino emission rapidly cools the star's interior, and within a few hundred years the interior becomes nearly isothermal. A steep temperature gradient remains in the star's crust, however, and the surface from which photons emerge (densities of order $10^0 - 10^3$ g cm^{-3}) is about 30–100 times cooler than the interior. Neutron stars younger than about one million years are expected to have surface temperatures in the range of 30–100 eV, for which the dominant emission will be in X-rays. Current X-ray space-based telescopes are capable of observing such emission, even from objects with emitting areas as small as 1500 km^2, to distances of thousands of light years. However, neutron stars older than about one million years cool more efficiently via photon cooling from the surface than by neutrino emission from the interior, and they will disappear rapidly from view.

Until recently, almost all known neutron stars were pulsars, in which an intense magnetic field couples with rapid rotation to produce beams of radiation. Even if such objects were relatively young, less than about one million years, the radiation produced by the magnetosphere completely swamps the star's thermal radiation. Recently, however, a new class of objects has been found in which thermal radiation is clearly observed, and magnetospheric emission is unimpor-

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tant either because the magnetic field of the star is small and there is no extensive pulsing, or the beam of the pulsar (estimated to have an opening angle of tens of degrees) never crosses our line of sight. With the detection of thermally emitting neutron stars, astrophysicists have entered a new realm that promises valuable constraints on the composition and equation of state of dense matter.

The chief observables that are most important to determining the structure of neutron stars include the mass, the radius and the temperature-age (cooling) correlation. Large observed masses will limit the softening that could occur from exotic components, such as hyperons, Bose condensates and quarks. They also limit the maximum density that can exist in the present-day universe. Accurate radius measurements will limit the isospin dependence of nuclear interactions, and in conjunction with laboratory results for the neutron skin thickness of lead, will severely constrain the magnitude and density dependence of the isospin interactions. The suite of temperature-age measurements can be a possible indicator for the existence of 'exotic' interior compositions.

2. Thermal Emission From Neutron Stars

To a zeroth approximation, thermal emission from a neutron star resembles blackbody emission. However, the star's atmosphere and magnetic field redistributes the energy, and absorption by interstellar hydrogen nearly obliterates radiation in the ultraviolet region. Observations of thermal emission, coupled with suitable atmosphere models, allow estimates of the surface temperature (T_∞), observed at infinity, and the effective angular size R_∞/d, where:

$$T_\infty = T_*/\sqrt{1-2GM/Rc^2}, \qquad R_\infty = R/\sqrt{1-2GM/Rc^2}, \tag{1}$$

and d is the distance to the star. Note that both the temperature and radiation radius are both corrected by redshift factors. An observed value of the radiation radius implies an upper limit to the star's mass:

$$M < 3^{-3/2}c^2 R_\infty/G \simeq (R_\infty/7.68 \text{ km}) \text{ M}_\odot. \tag{2}$$

If spectral lines can be identified, the redshift $z = (1-2GM/Rc^2)^{-1/2} - 1$ can be found, and both the mass and the radius can be determined. It has been a major disappointment that spectral lines have proven difficult to identify in thermally emitting neutron stars, and in the few cases in which they are seen, their interpretation remains highly controversial.

A few thermally emitting stars have the great advantage that they have been observed both in the X-ray range as well as in optical radiation (Table 1). Thus, one is better able to model the thermal emission, which is tricky if information in only a narrow spectral region is available. A particular difficulty with X-ray emitting stars is that interstellar hydrogen absorbs much or most of the radiation (primarily in the ultraviolet and low-energy X-ray regions). It is necessary to account for this absorption when modelling the spectrum.

The quantity $T_{\infty,BB}$ is the temperature obtained by fitting the X-ray emission to a blackbody, with fitting parameters interstellar absorption and the star's angular size $R_{\infty,BB}$, assuming a distance d in parsecs given by the subscript.

Table 1. Neutron stars with X-ray and optical thermal emissions.

Source	Period (s)	$kT_{\infty,BB}$ (eV)	$R_{\infty,BB}$ (km)	m_V (mag)	Optical Excess	Reference
RX J1856.5–3754		61	$4.4d_{130}$	25.8	6	Burwitz et al. 2003
RX J0720.4–3125	8.39	81	$6.1d_{300}$	26.8	6	Pavlov et al. 2002
RX J1308.6+2127	10.3	91	$6.5d_{700}$	28.7	5	Kaplan et al. 2002
RX J1605.3+3249		92	$3.3d_{300}$	27.1	14	Kaplan et al. 2003

Thus, for RX J1856.5–3754, the angular size has the best-fit value of 4.4/130 km pc^{-1}. If one extrapolates the X-ray blackbody spectrum into the optical region, it is generally found that the star's observed optical brightness m_V is several times brighter than the prediction. This optical excess (f) is included in the table, and indicates the extent to which the star's spectrum deviates from a blackbody. A proper atmospheric model should account for the optical excess, and usually results in a larger predicted radius. One way to see the effect is to consider blackbody emission from a non-uniformly heated surface.

In a simple model with two components, labelled by subscripts h and c, the hot component determines the X-ray spectrum ($\propto T^4$) while the Rayleigh-Jeans tail ($\propto T$) from both components forms the optical emission. The optical excess measures $f = (R^2_{\infty,h}/R^2_{\infty,c})(T_{\infty,h}/T_{\infty,c})$, so

$$R_\infty/R_{\infty,h} = \sqrt{1 + fT_{\infty,h}/T_{\infty,c}}\,. \tag{3}$$

The inferred radius can be substantially larger than that determined from the X-rays alone ($R_{\infty,BB}$), but is in practice limited by the shape of the optical spectrum. In the case of RX J1856.5–3754, the linear optical flux – frequency behavior observed would break down if $T_{\infty,c} < 15$ eV. Spectral fitting generally results in a ratio $T_{\infty,h}/T_{\infty,c} \approx 2-3$. If f is in the range of $3-5$, then $R_\infty/R_{\infty,h} \simeq 3-4$. For the case of RX J1856.5–3754, the resulting value of R_∞ lies in the range 13–16 km, and for $M = 1.4$ M$_\odot$, $R \simeq 11.9 - 14.9$ km (see Fig. 1).

The X-ray data alone implies rather small values for the radius, which has prompted a flurry of suggestions that quark matter stars are being observed. These conclusions are premature. Nevertheless, it is instructive to examine the relative structures of strange quark matter and normal neutron stars to illustrate how observations might be able to distinguish these possibilities.

3. Structure of Compact Objects

The significant difference between the $M - R$ trajectories of quark and normal stars (viz. Fig. 1) arises from the nearly incompressible nature of the former: $M \propto R^3$. On the other hand, low-mass (intermediate-mass) normal matter neutron stars behave like $\gamma = 5/3$ (2) polytropes, for which $R \propto M^{-1/3}$ ($\propto M^0$). Both high-mass pure quark and normal matter stars are significantly affected by general relativity, which imposes a maximum stable mass and maximum central density for a given equation of state.

A strict lower limit to the radius for a given mass, from general relativity and causality is approximately $R_{causality} \simeq 3.0\ GM/c^2$ (Lattimer et al. 1990),

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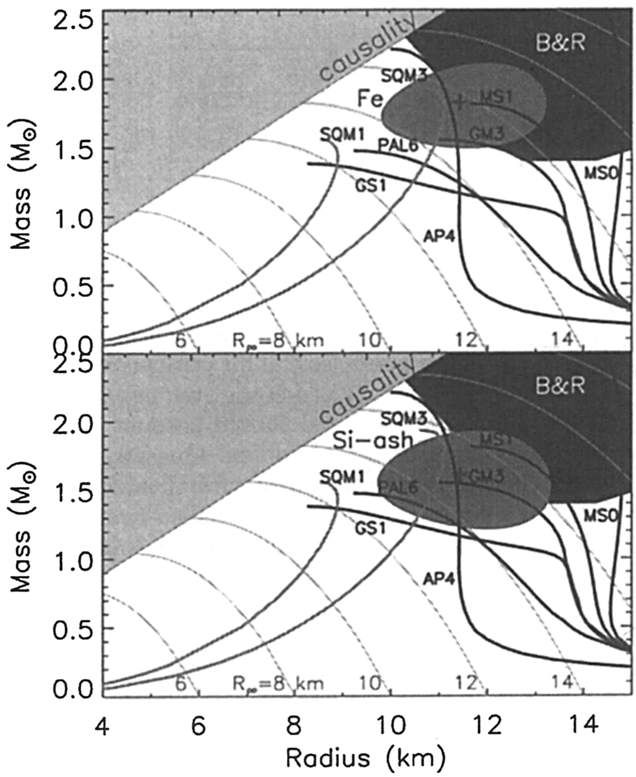

Figure 1. Allowed regions of mass and radius for Fe and Si-ash atmospheric models of RX J1856.5–3754 (light grey ellipses: Pons et al. 2002; dark ellipses: Braje & Romani 2002). Grey region at upper left is causally forbidden. Black (thick grey) curves are for typical neutron (pure quark) stars; thin grey curves are contours of R_∞. A distance of 130 pc is assumed.

about 50% larger than the Schwarzschild limit. From Fig. 1 note that normal matter stars tend to have a significant range of masses with relatively fixed radii. For a polytropic equation of state, $P = K\rho^\gamma$, Newtonian gravity predicts $R \propto K^{1/(3\gamma-4)} M^{(\gamma-2)/(3\gamma-4)}$. Since most equations of state have $\gamma \approx 2$ near nuclear saturation density, radii tend to be insensitive to mass. In addition, it seems that a radius measurement yields specific information about the constant K even if the neutron star mass is not well-determined. Lattimer & Prakash (2001) found, in fact, a general relation between the pressure of matter in the range 1–2 times nuclear saturation density and the radius:

$$R(M) \simeq C(M, n_o) P(n_o)^{1/4}. \qquad (4)$$

The quantity $C(M, n_o)$ is weakly dependent upon M and is roughly proportional to $1/\sqrt{n_o}$, a fiducial baryon number density n_o (in this density range, n_o could

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be replaced by the energy density ρ_o). Equation (4) can be justified using an analytic solution to Einstein's equations (viz. Eq. [5]). In consequence, an accurate determination of a neutron star radius permits evaluation of the pressure of neutron star matter just above nuclear density. In essence, this provides a direct probe of the nuclear symmetry energy function $S_v(\rho)$ at these densities, since $P \sim \rho^2 \partial S_v / \partial \rho$ (see, e.g., Lattimer & Prakash 2001).

Further insight into the structure of strange quark matter and neutron stars can be obtained by reference to the few known analytic solutions of the relativistic stellar structure equations. Out of the more than one hundred known analytical solutions, only a few are relevant to compact objects (Neary, Lattimer & Lake 2004). For normal matter neutron stars, for which it is required that the pressure monotonically decrease with increasing radius and that the pressure energy density vanish at the surface, these include

1) Tolman VII (Tolman 1939), in which the energy density is quadratic: $\rho = \rho_c[1 - (r/R)^2]$;

2) Buchdahl (1967), which has the ansatz that the equation of state is $\rho = 12\sqrt{P_* P} - 5P$, where P_* is a constant. In the low-density limit, this reduces to a $\gamma = 2$ polytrope. It predicts, using $\beta = GM/Rc^2$, that:

$$R = (1 - \beta)\sqrt{\frac{\pi c^4}{288 P_* G(1 - 2\beta)}}. \tag{5}$$

For strange quark matter stars, the energy density does not vanish at the star's surface. Known applicable analytic solutions include:

1) The incompressible fluid, $\rho =$ constant.

2) Tolman IV (Tolman 1939), in which

$$\rho = \frac{3M}{8\pi R^3} \frac{(1 - 3\beta)(2 - 3\beta) + \beta(r/R)^2(3 - 7\beta + 2\beta(r/R)^2)}{(1 - 3\beta + 2\beta(r/R)^2)^2}. \tag{6}$$

3) A case only recently worked out (Neary et al. 2004):

$$\rho = \frac{3M}{4\pi R^3} \frac{(1 - 5\beta/2 + 5\beta(r/R)^2/6)(1 - \beta)^{2/3}}{(1 - 5\beta/2 + 3\beta(r/R)^2/2)^{5/3}}. \tag{7}$$

Figures in Lattimer & Prakash (2001) show how well these analytic solutions track moments of inertia and binding energies for realistic equations of state.

4. Neutron Star Maximum Mass and Density

The primary source of information regarding neutron star masses has been from pulsar timing in binaries (Fig. 2). The data is divided into four groups: X-ray binaries, neutron star-pulsar binaries, white dwarf-pulsar binaries, and a main sequence-pulsar binary. The best-measured values are from double neutron star binaries, and they cluster closely around the value of 1.35 ± 0.06 M$_\odot$. However, it is premature to conclude from this that the neutron star maximum mass is near this value, since evolutionary considerations may be responsible for this clustering. Indeed, there is mounting evidence that neutron star masses can be considerably larger. Recent measurements of pulsar masses in systems containing white dwarfs indicate an average mass of over 1.6 $M_\odot$. The case of PSR J0751+1807 is especially interesting: the favored mass value is 2.2 ± 0.3 $M_\odot$ within 1 σ. X-ray binaries also appear to contain larger neutron stars, and Vela X-1 has a relatively firm lower limit, due to geometrical considerations, of about 1.7 $M_\odot$. The neutron star in 4U 1700–37 might be even more massive.

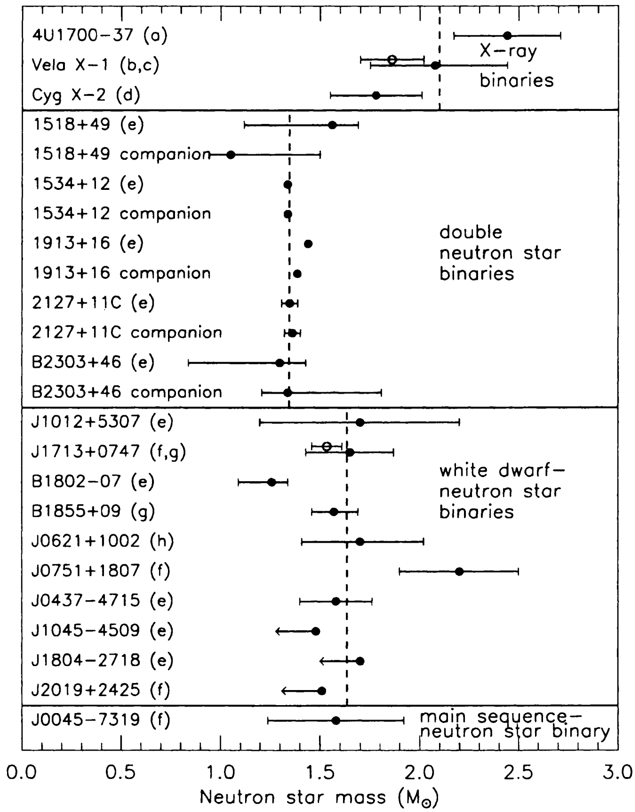

Figure 2. Radio pulsar and X-ray binary neutron star mass measurements. Letters following source names indicate references. Error bars are 1 σ. Dashed lines represent group average masses. The open circle data for J1713+0747 arises from employing the additional binary period-white dwarf mass constraint from Rappaport et al. (1995).

The phenomenon of quasi-periodic oscillations (QPOs), which originate in accreting low-mass X-ray binaries, also suggests large neutron star masses. The standard interpretation is that the highest observed QPO frequency is the orbital frequency of the inner edge of the accretion disc (Lamb & Miller 2004). The minimum stable circular orbit in general relativity, $r = 6GM/c^2$ for non-rotating stars, implies the maximum frequency is limited to $\Omega = \sqrt{GM/r^3} < c^3/(6^{3/2}GM)$. This translates into a mass limit $M \lesssim (2200\ \mathrm{Hz}/\nu)\ M_\odot$, using $\nu = \Omega/2\pi$. The largestest observed frequencies are of order of $\nu = 1$ kHz implying $M \approx 2$ $M_\odot$. Correcting for stellar spin lowers this value by about 10%.

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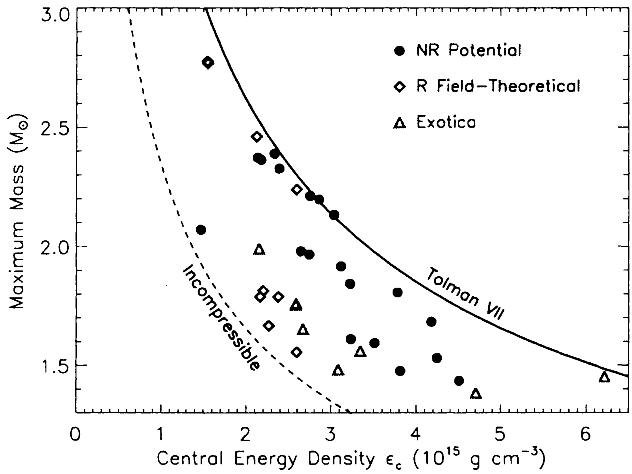

Figure 3. Central density versus maximum mass for equations of state modeled with non-relativistic potential or field-theoretical interactions. Cases in which substantial softening occur are shown as "Exotica". The analytic incompressible fluid and Tolman VII solutions, coupled with $R \gtrsim 3GM/c^2$, are displayed and bracket all results.

It is now shown that measurements of neutron star masses set an upper limit to the maximum possible energy density in *any* compact object! If a neutron or strange quark matter star were incompressible, the causality constraint $R \gtrsim 3GM/c^2$ would imply that its central density would be

$$\rho_{c,Inc} = \frac{3}{4\pi}\left(\frac{c^2}{3G}\right)^3 \frac{1}{M^2} = 5.5 \times 10^{15}\left(\frac{\mathrm{M}_\odot}{M}\right)^2 \text{ g cm}^{-3}. \quad (8)$$

The maximum mass star must have the highest possible central density. However, the above limit is not realistic because an incompressible fluid violates causality: $\partial P/\partial\rho = \infty$. Phenomologically, however, I have found that no causal equation of state has a central density greater than that given by employing the Tolman VII result, $\rho_{c,T\ VII} = 2.5\rho_{c,Inc}$, as is demonstrated in Figure 3 for a wide wariety of neutron star equations of state, including models containing significant softening due to "exotica", such as strange quark matter.

The maximum mass of neutron stars has the traditional limit that Rhoades & Ruffini (1974) discovered utilizing the condition $\partial P/\partial\rho \leq c^2$ for $\rho > \rho_f$, $M_{max} \lesssim 4.1\sqrt{\rho_s/\rho_f}$ $\mathrm{M}_\odot$, where $\rho_s = 2.7 \times 10^{14}$ g cm^{-3} is the nuclear saturation density. In practice, the causality constraint might be too restrictrive. At sufficiently high densities, in which quark asymptotic freedom is realized, the sound speed approaches $v_s^2/c^2 = \partial P/\partial\rho \simeq 1/3$. If this is a strict limit at all densities, the maximum mass is reduced from the Rhoades-Ruffini value by the factor $3^{-1/2}$ to $2.4\sqrt{\rho_s/\rho_f}$ $\mathrm{M}_\odot$, and that the compactness limit

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becomes $\beta = GM/Rc^2 \lesssim 3^{-5/4}$ (Lattimer et al. 1990). One then obtains $\rho_c \simeq (5/2)3^{-3/4}\rho_{c,Inc} \simeq 1.1\rho_{c,Inc}$. If masses near 2.2–2.3 $M_\odot$ are confirmed, the maximum possible density would be about $10\rho_s$, possibly limiting the onset of strange quark matter.

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