CONSTRAINTS ON SUPERDENSE MATTER FROM X-RAY BINARIES

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Abstract From the earliest measurements of the masses of binary pulsars, observations of neutron stars have placed interesting constraints on the properties of high-density matter. The last few years have seen a number of observational developments that could place strong new restrictions on the equilibrium state of cold matter at supranuclear densities. We review these astronomical constraints and their context, and speculate on future prospects.

1. Introduction and Overview

Neutron stars are important laboratories for the physics of high-density matter. Unlike particles in relativistic heavy-ion colliders, the matter in the cores of neutron stars has a thermal energy that is much less than its rest-mass energy. Various researchers have speculated whether neutron star cores contain primarily nucleons, or whether degrees of freedom such as hyperons, quark matter, or strange matter are prevalent (see Lattimer & Prakash 2001 for a recent review of high-density equations of state).

However, it is impossible to isolate the matter in the core of a neutron star for detailed study. It is thus necessary to identify observable aspects of neutron stars that can be, in some sense, mapped to the equation of state of high-density material. In this review we discuss various constraints on the equation of state from astronomical observations. We focus on observations of accreting binary systems.

We start by listing a few of the structural aspects of neutron stars that are affected by high-density microphysics and can be observed astronomically. We assume that the neutron star is in dynamical equilibrium. In this list, by "mass" we mean the gravitational mass, rather than the sum of the rest masses of the individual particles.

- Mass M, from binary orbits (extra information is available if the orbits are relativistic; see § 3).
- Radius R, from surface emission, linear surface velocity, or orbital constraints. Estimates of radius have historically been fraught with systematic uncertainties; see § 6.
- Compactness GM/Rc^2, from surface redshifts or general relativistic light deflection; see § 4 and § 5.
- Dimensionless angular momentum cJ/GM^2, which is potentially measurable by its effects on light deflection or characteristic particle frequencies in certain orbits; see § 4 and § 6.

In addition to these, there are some overall theoretical constraints. For example, neutron stars are believed to originate via the collapse of the core of a massive star. The rest mass of the core is close to the Chandrasekhar limit of $1.4\,M_\odot$ at which degeneracy pressure can no longer compete with gravity. Thus a neutron star is constrained by having a rest mass no less than about $1.4\,M_\odot$; for typical equations of state, this translates into a gravitational mass that is greater than about $1.2\,M_\odot$ (for a more detailed model of a protoneutron star, see, e.g., Goussard, Haensel, & Zdunik 1998).

The strength of a particular constraint depends on how precisely one can measure the associated quantity. Lattimer & Prakash (2001) show that if the radius is measured to within ~ 1 km this will distinguish between several competing EOS even if nothing else is known about the star. Mass measurements alone are only constraining if the masses are fairly high. For example, a neutron star with gravitational mass $M = 1.4\,M_\odot$ can be accommodated by any existing EOS, but if $M = 2.2\,M_\odot$ and the spin is less than a few hundred Hz then only the hardest of current EOS would survive. In addition, the indirect nature of most observations means that one must be cautious about interpretation. For example, the radius is not measured directly, but rather is inferred through the filter of some model.

In this review, after describing accreting neutron star binary systems in § 2, we discuss various proposed observational constraints from the least model-dependent to the most speculative. In § 3 we talk about the status of mass measurements from observations of radial velocity curves. In § 4 we discuss an exciting recent observation of a surface redshift as estimated from atomic resonance scattering features, and speculate on the prospects for future line observations and analysis. In § 5 we examine another new development: constraints on neutron star parameters by the detailed profiles of regular pulses from accreting neutron stars. In § 6 we evaluate current constraints on stellar radius, especially from orbital frequencies. We conclude in § 7 with the opinion that, although EOS with just nucleonic degrees of freedom are consistent with all current data, exotic components are not yet excluded.

2. Overview of Neutron Star X-ray Binaries

We now discuss the differences between neutron stars with a low-mass companion (usually $M < 1\,M_\odot$) and neutron stars with a high-mass companion (usually $M \gtrsim 3\,M_\odot$), then show that low-mass X-ray binaries (LMXBs) are likely to provide the most important future constraints on neutron star structure. We begin with an overview of accretion and magnetic fields, because both the field strength and type of accretion are thought to differ between LMXBs and high-mass X-ray binaries (HMXBs). For an excellent general discussion of accretion in binary systems, see Frank, King, & Raine (2002).

Basics of accretion and magnetic fields

Neutron stars in binaries can accrete significant amounts of mass from their companions. This happens primarily via Roche lobe overflow if the companion star is low-mass, but primarily via accretion from a wind if the companion star is high-mass. In either case, most of the energy release is due to accretion. This is because the accretion energy release per mass, which is $\sim GM/R \sim 0.2c^2$, is much larger than the energy release from any competing mechanism (e.g., fusion of hydrogen to helium releases $\sim 0.007c^2$ per mass). Characteristic luminosities of accreting neutron stars span the range of $< 10^{33}$ erg s^{-1} to $> 10^{38}$ erg s^{-1}. If the energy is thermal and emitted over most of the $4\pi R^2 \sim 1000$ km^2 area of a neutron star, then the characteristic energy is $kT \sim 100 - 2000$ eV, in the X-ray range. Various processes such as Compton upscattering in a hot corona can cause the spectrum to deviate from thermal (e.g., Psaltis & Lamb 1997), but nonetheless X-rays contain most of the luminosity of these systems. Given that these systems are primarily accretion-powered, if the accretion and emission are both roughly isotropic then their luminosities are limited by the Eddington luminosity $L_E \equiv 4\pi GMm_pc/\sigma_T \approx 1.3 \times 10^{38}(M/M_\odot)$ erg s^{-1}. Here G is Newton's constant, M is the stellar mass, m_p is the mass of the proton, c is the speed of light, and $\sigma_T = 6.65 \times 10^{-25}$ cm^2 is the Thomson cross section for electron scattering. Above this luminosity, the radial acceleration due to radiation is greater than the gravitational acceleration, halting accretion. This assumes a fully ionized plasma (a good approximation at these temperatures). Strong beaming could in principle violate this constraint (e.g., King et al. 2001).

Observations of neutron stars suggest that they have a wide range of magnetic field strengths, from surface fields of 10^{7-10} G for neutron stars in LMXBs (see below) to 10^{11-15} G for young neutron stars (e.g., Morris et al. 2002 for one recent survey) and 10^{11-13} G for neutron stars in HMXBs (see below). At the high temperatures of accretion disks surrounding the stars, the gas is mostly ionized and therefore couples strongly to the field. The details of this coupling are debated (e.g., Ghosh & Lamb 1979; Shu et al. 1994). However, one can make simple estimates to show that, generically, one expects that far from the star the stellar magnetic field has little effect on the flow, but near the star the field can be important.

To do this, consider the material stress and the magnetic stress. As an approximation, the magnetic stress in a region with total field strength B is $T_B \sim B^2$. The material stress in a region of matter density ρ and speed v is $T_M \sim \rho v^2$. How do these depend on radius? If the magnetic field is dipolar, then $B \sim r^{-3}$, hence $T_B \sim r^{-6}$. To estimate the material stresses, assume that the matter flows in an accretion disk with a disk half-thickness h that is a constant fraction of r. This implies that at radius r, the cross-sectional area of a cylindrical section of the disk scales as $A \sim r^2$. For a geometrically thin ($h \ll r$), optically thick disk, accretion disk theory (e.g., Shakura & Sunyaev 1973) indicates that in addition to the orbital speed $v_K \sim r^{-1/2}$, there is a sound speed $c_s \sim (h/r)v_K$ and an inward radial speed $v_r \sim \alpha(h/r)^2 v_K$, where $\alpha \sim 0.01 - 1$ is related to the mechanism for transport of angular momentum (Shakura & Sunyaev 1973). For a thin disk, the total velocity is therefore $v_{\rm tot} \approx v_K \sim r^{-1/2}$. In addition, if there is a constant mass flux rate through all radii, mass continuity implies $\rho v_r A = {\rm const}$, hence $\rho \propto r^{-3/2}$ and the material stress is $T_M \sim r^{-5/2}$.

Therefore, the radial dependence of the magnetic stress is much steeper than the radial dependence of the material stress. This implies that at large distances material stress dominates, but that close to the star the magnetic stress can be more important (indeed, it will be for $B \gtrsim 10^8$ G at the surface). In detail, one actually needs to compare specific components of the magnetic and material stresses (primarily the $r\phi$ component; e.g., Ghosh & Lamb 1979), but the large differences in radial dependences means that the overall picture is robust. One implication of this picture is that disks with higher accretion rates are able to push in closer to the star.

This comparison suggests that there will be a transition region between materially-dominated and magnetically-dominated flow. The region inside of which the stellar magnetic field controls the flow is called the *magnetosphere*. To within a factor of 2–3, the radius at which the transition occurs is (e.g., Ghosh & Lamb 1979)

$$r_M \approx 3 \times 10^8 (\dot{M}/10^{17}\ \mathrm{g\ s^{-1}})^{-2/7} (\mu/10^{30}\ \mathrm{G\ cm^3})^{4/7}\ \mathrm{cm}\ . \quad (1)$$

Here μ is the stellar dipole magnetic moment and $\dot{M}$ is the mass accretion rate through the disk. For this formula we assume a purely dipolar field; higher multipoles weaken the dependence on $\dot{M}$ because the field is effectively stiffer.

If one pictures the transition region as sharp, then in a rough sense one can imagine the ionized gas orbiting in a disk outside the magnetosphere, but flowing along field lines at the stellar angular velocity inside the magnetosphere. Let us denote r_M as the "magnetospheric radius" (understanding that there is no single such radius, but rather a transition zone). Suppose that the Keplerian orbital angular velocity at this radius is $\omega_K(r_M)$. Suppose also that the stellar angular velocity is ω_s. Consider a particle fixed to a field line at r_M, corotating with the star. If $\omega_s < \omega_K(r_M)$, then the particle falls towards the star and accretes. If instead $\omega_s > \omega_K(r_M)$, then the particle is flung outwards. Another way of phrasing this is that there is some radius $r_{\rm co}$ in the disk, the *corotation radius*, at which the Keplerian angular velocity equals the stellar angular velocity. If $r_M < r_{\rm co}$ then particles in the magnetosphere fall towards the star, and because the matter couples to the star with a higher angular velocity than the current stellar spin rate, the star is spun up over time. If instead $r_M > r_{\rm co}$ then particles tied to field lines that corotate with the star will be pushed outwards, and the stellar spin rate slows down. From equation (1) we see that if the average mass accretion rate is fixed, stars with weaker magnetic fields will be spun up to higher frequencies.

The magnetic torque picture therefore implies the possibility of a centrifugal barrier, or "propeller effect" (Illarionov & Sunyaev 1975). For example, imagine a source that undergoes a large range of mass accretion rates (as is true for transient sources). At a high accretion rate, r_M is small and all the matter accretes. However, at a low accretion rate, r_M is large (by equation [1]), so when the matter couples to the field it is flung out again, preventing accretion. This simple picture may not be correct. The disk-magnetosphere boundary is highly complex and many instabilities may be present (Stella, White, & Rosner 1986). In addition, because the coupling to the field is not perfectly abrupt, matter in the disk is more likely heated than flung out, and if cooling is efficient then there could be a buildup of matter that occasionally dumps onto the star (Maraschi, Traversini, & Treves 1983).

With this general introduction, we now discuss the specifics of systems with low-mass or high-mass companions.

Low-mass X-ray binaries

Consider a neutron star in a binary with a $1\,M_\odot$ companion. The companion star loses very little mass to winds; for example, solar-type stars typically lose only few$\times 10^{-14}\,M_\odot$ yr^{-1} (e.g., Wood et al. 2002), so there is negligible mass transfer via this channel. The only way that significant mass can be transferred to the neutron star is if the separation between the two is small enough that gas on the near side of the companion is more attracted gravitationally to the neutron star than to the companion itself. That is, mass transfer only occurs if the companion fills its Roche lobe. If the companion and neutron star were initially not in Roche contact, then evolutionary processes can drive them into contact. For example, the companion could evolve into a red giant, or orbital angular momentum could be lost (shrinking the orbit). Loss of angular momentum is thought to occur in two main ways (see Frank et al. 2002). For well-separated systems, the primary mechanism is magnetic braking. A star with a wind of charged particles loses angular momentum to the wind because the particles are forced by the magnetic field of the star to rotate at the stellar angular velocity, hence as they move away they increase their angular momentum per mass. If the companion star is tidally locked to the neutron star, then as the companion slows down in its rotation it extracts angular momentum from the orbit. If the companion gets close enough to the neutron star, then angular momentum can instead be lost to gravitational radiation.

The companions are made primarily of hydrogen (or helium in some cases, if the outer hydrogen envelope has been stripped). As hydrogen and helium flow onto the surface of the neutron star, some of it undergoes thermonuclear fusion. In some cases, however, hydrogen or helium can build up on the surface without being burned completely. As investigated by many researchers, this can lead to an ignition of the layer of fuel under certain circumstances (see Woosley & Taam 1976; Joss 1977, 1978; Lamb & Lamb 1977, 1978; Woosley & Wallace 1982). This ignition is unstable, so once the layer starts burning it is completely consumed within seconds to hours, depending on the details of the burning (see Cumming 2003 for a recent overview including the hours-long "superbursts"). In a number of these so-called thermonuclear bursts, or type 1 bursts, nearly coherent oscillations in the brightness are observed (for a review in the overall context of bursts see, e.g., Strohmayer & Bildsten 2003). These are thought to be caused by rotational modulation of the flux we receive from a "hot spot" on the surface, and imply spin frequencies as seen at infinity of several hundred Hertz. The high spin frequencies are consistent with these objects being the progenitors of millisecond-period rotation-powered pulsars, suggesting that neutron stars are spun up by the accretion.

One would also expect that fast pulsations would be observed during the persistent accretion-powered emission, and this is indeed seen in five transient LMXBs. For a review, see Wijnands (2003). In order of their discovery, the five sources are SAX J1808–3658 (401 Hz; Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998), XTE J1751–305 (435 Hz; Markwardt et al. 2002), XTE J0929–314 (185 Hz; Galloway et al. 2002), XTE J1807–294 (191 Hz; Markwardt, Smith, & Swank 2003b; Markwardt, Juda, & Swank 2003a); and XTE J1814–338 (314 Hz; Markwardt et al. 2003c; Strohmayer et al. 2003). However, the majority of LMXBs do not have detectable pulsations in their persistent emission. The reason for this is debated, but one possibility is that most LMXBs are shrouded by a corona of hot electrons with a large enough optical depth to smear out the beamed pulsations (e.g., Titarchuk, Cui, & Wood 2003). The lack of pulsations in most sources does suggest that their magnetic fields are comparatively weak ($B \lesssim 10^{10}$ G), otherwise the flow would be channeled relatively far from the star and pulsations would be strong. The weak-field hypothesis is also supported by the high spin frequencies of these sources; from equation (1), if these sources are in magnetic spin equilibrium then their surface magnetic field strengths are $B \sim 10^8$ G (Chakrabarty et al. 2003).

The thermonuclear X-ray bursts observed from LMXBs argue strongly that their crusts down to a density of at least $\sim 10^8$ g cm^{-3} are composed of normal nuclei. The relevant properties are (1) the time-averaged energy released in persistent emission divided by the time-averaged energy released in bursts is typically 20–200, consistent with the ratio of gravitational binding energy per mass to nuclear binding energy per mass; (2) the recurrence time of $\sim$hours to weeks, which is consistent with the time to build up a new fuel layer that becomes unstable to nuclear burning; and (3) the durations of seconds to hours seen in different types of bursts, which fits well with the expected time to burn the layer and transport the energy from the instability region. For recent detailed reviews, see Cumming (2003) and Strohmayer & Bildsten (2003). The data are well-fit quantitatively in this model. Of course, this does not rigorously exclude any other possible explanations, but it does suggest that a model in which the compact objects are truly bare strange stars (down to zero density) will have a very difficult time explaining these phenomena. Models in which there is a normal crust to densities

$\rho \gg 10^8$ g cm^{-3}, then an abrupt transition to strange matter at much higher densities, could be consistent with the data.

High-mass X-ray binaries

Now consider a companion star of mass $10\,M_\odot$. Such a star is more massive than a neutron star, and angular momentum conservation implies that Roche lobe mass transfer is usually unstable in these systems (see Frank et al. 2002). However, even if the companion is out of Roche contact, it can still transfer significant mass via a wind. High-mass main-sequence stars can have winds that lose more than $10^{-6}\,M_\odot$ per year, or $\sim 10^{20}$ g s^{-1}. If just 1% of this falls on the neutron star, the luminosity can be close to the Eddington luminosity. Indeed this happens in many systems, with the key being that gravitational focusing and self-interaction of the plasma give the neutron star an effective cross section to the wind that is many orders of magnitude greater than its geometric cross section.

The short lifetimes of high-mass stars means that HMXBs are not thought to be long-lived, typically only a few million years. As a result, even at an Eddington accretion rate of $\dot{M} = 10^{18}$ g s^{-1}, only a few hundredths of a solar mass is transferred to the neutron star. Therefore, the mass of a neutron star in an HMXB is expected to be close to its birth mass. In contrast, LMXBs can last for tens of millions of years and in principle accrete tenths of a solar mass.

Many neutron stars in HMXBs are pulsars, with periods ranging from seconds to minutes. The slow rotation periods suggest strong magnetic fields, typically $B \sim 10^{12}$ G, from the arguments presented earlier, and this is corroborated by the detection of features identified with electron cyclotron resonance scattering (the first being in Her X-1; Trümper et al. 1978). The strong fields are consistent with spindown measurements of young isolated pulsars. The puzzle, therefore, is why LMXBs have much weaker fields. Various explanations have been suggested. For example, it could be that there is a characteristic rate of decay of neutron star magnetic fields that is independent of external factors such as accretion, and that LMXBs simply live long enough for this decay to be significant (this would suggest that old enough isolated pulsars also experience field decay; see Geppert & Rheinhardt 2002). Alternately, accretion could speed the decay of the field (Ruderman 1995; Konar & Bhattacharya 1999) or even bury the field (for a recent study see Cumming, Zweibel, & Bildsten 2001), although magnetic instabilities may make it difficult to start the burial process.

Unlike neutron stars in LMXBs, neutron stars in HMXBs do not display thermonuclear bursts. This is understood in terms of stable versus unstable burning (see Cumming 2003 for a review). If a neutron star has a strong magnetic field, accreting matter is funneled into a small patch of the star's surface. The effective accretion rate per area is therefore high, and hence so is the temperature. At high temperatures, nuclear fusion proceeds steadily as the matter accretes, not allowing buildup of nuclear fuel for a later flash. The lower accretion rates per area in low-field neutron stars, however, can allow such buildup.

Magnetic fields revisited

For the purposes of constraining neutron star structure and gaining insight into high-density matter, strong magnetic fields complicate analysis. The accretion flow is controlled by the field out to large radii, so emission from the flow does not contain information about orbits near the star, and hence does not inform us about strong gravity effects or constraints on the stellar radius. In addition, for the field strengths inferred from neutron stars in HMXBs, even atomic physics is influenced considerably. This can be seen by comparing the electron cyclotron energy $\hbar\omega_c = \hbar eB/m_e c = 11.6(B/10^{12}\ \mathrm{G})$ keV to atomic binding energies, which are at most a few keV even for heavy elements such as iron. This adds another unknown to the identification of spectral lines and their interpretation. In contrast, $\sim 10^8$ G fields such as those inferred for neutron stars in LMXBs have negligible impact on atomic lines from iron or other heavy elements, so more confident inferences may be made (Cottam et al. 2002; Loeb 2003).

Even for estimates of mass from radial velocities (see § 3), for which magnetic fields are irrelevant, LMXBs have advantages over HMXBs. One important advantage is that because the active lifetimes of LMXBs are larger than those of HMXBs, more mass can be transferred, meaning that the masses of neutron stars in LMXBs could well be larger on average than those in HMXBs by a few tenths of a solar mass. These higher masses are important because many theories predict transitions to new forms of matter in the cores of neutron stars when the mass gets high enough. For all of these reasons, LMXBs are more promising than HMXBs for a variety of constraints on neutron star structure and high density matter.

3. Radial Velocity Measurements

The most rigorous constraints on neutron star structure are derived from mass measurements using binary orbits. Ideally, one would like to measure the full three-dimensional velocity, but this is not possible because accreting binaries are so small that they cannot be spatially resolved, hence motions transverse to the line of sight are undetectable. For example, an LMXB with a few hour orbit has a semimajor axis of $\lesssim 0.01$ AU, meaning that even for a relatively nearby source at 1 kpc the angular separation is $\lesssim 10^{-5}$ arcseconds, far below current instrumental capability. Only the line of sight component of the motion can be observed, using Doppler shifts. These can be measured by periodic shifts of atomic lines (if the star observed is a white dwarf or main sequence star) or of pulse frequency (if the star observed is a pulsar).

To understand this effect more quantitatively, consider an idealized measurement of Doppler shifts from one member of a binary, call it star 1. Assume that both objects are effectively point masses. One can measure the period P of the orbit and the velocity semiamplitude v_1 of star 1 in the direction of the line of sight. If the two stars have masses m_1 and m_2 and are orbiting in a circle with a semimajor axis a and an inclination i (such that $i = 90^\circ$ means an orbit edge-on to our line of sight), then

$$\begin{aligned} P &= 2\pi\sqrt{a^3/G(m_1+m_2)} \\ v_1/\sin i &= [m_2/(m_1+m_2)]\sqrt{G(m_1+m_2)/a}\ . \end{aligned} \tag{2}$$

Combining these, we can define the *mass function* f

$$f \equiv P v_1^3/(2\pi G) = (m_2 \sin i)^3/(m_1+m_2)^2\ . \tag{3}$$

The mass function, which is a pure combination of observables, is a lower limit to the possible mass of star 2; if the orbit is other than edge-on (that is, if $i < 90^\circ$) or the observed star has $m_1 > 0$, then $m_2 > f$. Thus, observation of one star constrains the mass of the other star. Note, incidentally, that in a neutron star binary system with a high-mass companion ($m_1 \gg m_2$), f is low and it is difficult to constrain the neutron star mass strongly. If the companion is instead low-mass ($m_1 \ll m_2$), then $f \approx m_2 \sin^3 i$ and the only significant uncertainty is in the inclination. Regardless of the mass of the companion, if Doppler shifts from both stars can be observed then an measurement of the inclination would solve the system completely.

Various methods of estimating the inclination have been suggested in the literature. By far the most robust are applicable when the system contains two neutron stars, one of which is a rotation-powered pulsar. Such systems involve no mass transfer and no tidal effects, and are therefore a perfect theorist's problem with two point masses. The extraordinary intrinsic stability of rotation-powered pulsars means that a number of subtle post-Newtonian effects can be measured (for a review see Taylor 1994), such as orbital decay, precession of the pericenter, and Shapiro delay (the delay in propagation caused by passage through the warped spacetime near a massive object). These effects involve different combinations of the masses and semimajor axis; for example, the angle of precession of the pericenter per orbit is $\Delta\phi \propto G(m_1 + m_2)/a$, and the orbital decay time due to gravitational radiation is $T_{\rm decay} \propto a^4/[m_1 m_2(m_1 + m_2)](1 - e^2)^{7/2}$ for eccentricity e. These effects therefore break the degeneracies of the system and allow the measurement of the masses of both components to high precision as well as sensitive tests of the predictions of general relativity (see Taylor 1994).

If one of the stars in the binary is not a neutron star, then the tests become less precise. Suppose that one observes the optical light from the companion to a neutron star. In addition to the spectral information that allows measurement of P and v_1, one also has photometric information (e.g., the total optical flux from the companion). The companion is distorted into a pear shape by the gravity of the neutron star, with the point towards the neutron star. Therefore, from the side there is more projected area and hence greater flux than from either end. If the orbit is edge-on ($i = 90°$) then the flux varies maximally; if the orbit is face-on ($i = 0°$) then there is no variation. Therefore, by modeling the system one can estimate the inclination from the flux variations. This is called the method of *ellipsoidal light curves* (Avni & Bahcall 1975).

However, one must be careful because in an LMXB the optical emission from the accretion disk (whether in the outer, cool regions or as reprocessed X-ray emission) can outshine the companion by a large factor. This makes spectral lines difficult to measure and also complicates the ellipsoidal light curve technique. The ideal systems to study are therefore transient systems, which undergo periods of active mass transfer (often for a few weeks to a few months) before lapsing into quiescence, where there is little to no mass transfer. During quiescence, the companion is still distorted by the gravity of the neutron star, hence the flux variations still occur, but without any contamination by the accretion disk. There is a relatively new approach similar to this that uses flux variations from the disk itself that has good promise for constraining the inclination in many neutron star systems (Juett, Galloway, & Chakrabarty 2003).

Results: neutron star and white dwarf companions

As just described, the most precise measurements of masses come from double neutron star systems. There are currently five such systems known, three of which will coalesce due to gravitational radiation in less than the age of the universe, $\sim 10^{10}$ yr (Taylor 1994). These three systems in particular allow very precise measurements of the masses of the components, which are between $1.33\,M_\odot$ and $1.45\,M_\odot$ (Thorsett & Chakrabarty 1999). The other two double neutron star systems also have component masses consistent with a canonical $\sim 1.4\,M_\odot$. It has been suggested that the tight grouping of masses implies that the maximum mass of a neutron star is $\sim 1.5\,M_\odot$ (Bethe & Brown 1995). However, it is important to remember that double neutron star systems all have the same evolutionary pathway and thus the similar masses may simply be the result of a narrow selection of systems.

Pulsars with white dwarf companions produce the next most robust constraints on mass, because white dwarfs are small enough ($\sim 10^{8-9}$ cm radius compared to 10^{10-12} cm for a main sequence star) that tidal effects are relatively unimportant. Timing of such systems yields masses that are typically consistent with $1.4\,M_\odot$, within broad error bars (Thorsett & Chakrabarty 1999). However, Nice, Splaver, & Stairs (2003) recently reported that the 22 ms pulsar in the 0.26 day binary J0751+1807 may be well above this mass. The mass function is only $10^{-3}\,M_\odot$, suggesting a low-mass white dwarf companion. This system likely underwent significant mass transfer, as its eccentricity is $e = 3 \times 10^{-6}$, which is consistent with circularization due to tidal interactions and accretion. Orbital decay is detected, as is Shapiro delay (marginally), which suggest that $M > 1.6\,M_\odot$ at better than 95% confidence. Further observations have the potential to refine this considerably. If so, this could be the first indisputable case of a mass well above the usual $1.4\,M_\odot$ quoted for neutron stars. A high mass would be consistent with the idea that a few tenths of a solar mass are transferred to a neutron star during the lifetime of an LMXB. If the mass turns out to be large enough, this would place tight constraints on the state of matter at high densities.

Results: Vela X–1

Even stronger constraints are potentially available from the high-mass X-ray binary Vela X–1. This source contains a $\sim 20\,M_\odot$ star, and radial velocity variations from the star have been measured as well as periodic timing variations from X-ray pulses. The orbital period is 8.96 days and the eccentricity of the orbit is $e \sim 0.1$. From the radial velocities measured in the lines and pulses by Quaintrell et al. (2003), the mass ratio is $M_{\rm comp}/M_{\rm NS} = 12.3$. The minimum mass of the neutron star (for an edge-on orbit) is $M_{\rm NS} = 1.88 \pm 0.13$. This is a rather high mass, and is surprising because this is precisely the type of system that could

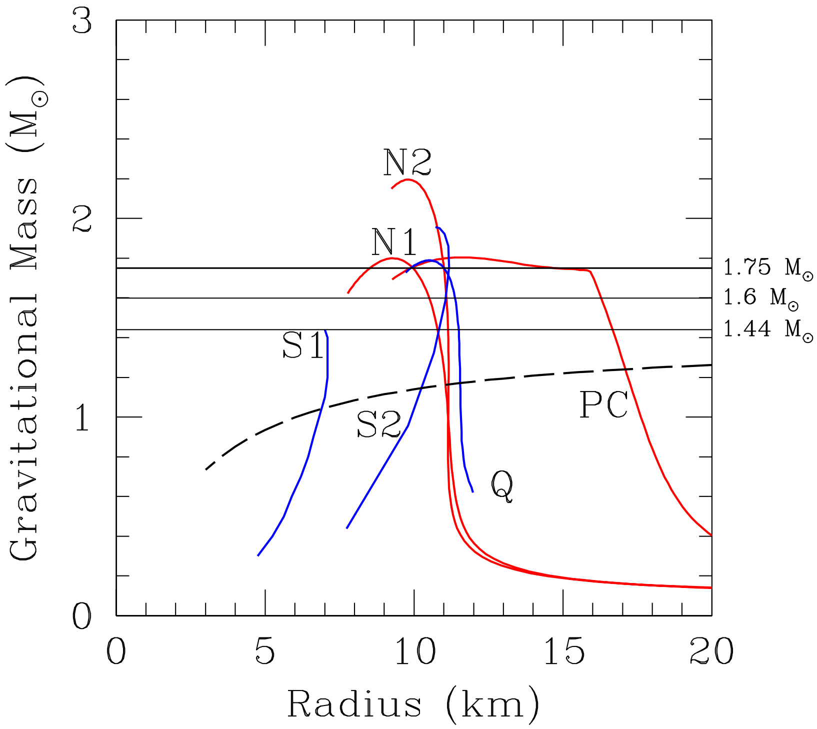

Figure 1. Mass-radius curves for different representative high-density equations of state, compared with gravitational mass estimates for neutron stars in different binary systems. The mass-radius curves are all for equilibrium nonrotating stars; note that rotation only affects these curves to second order and higher. Curves N1 and N2 are for nucleonic equations of state; N1 is relatively soft (Friedman & Pandharipande 1981), whereas N2 includes significant three-body repulsion (Wiringa, Fiks, & Fabrocini 1988). PC has a sharp change to a Bose-Einstein condensate of pions in the core when the mass reaches $\approx 1.8\,M_\odot$ (Pandharipande & Smith 1975). Equations of state N1, N2, and PC are not modern (i.e., not fitted to the most current nuclear scattering data), but are included for easy comparison to previous work on equation of state constraints. Curve S1 is for a compact strange star (Dey et al. 1998), whereas curve S2 is for a more standard strange star equation of state (Zdunik 2000). Curve Q is a quark matter equation of state with a Gaussian form factor and a diquark condensate (kindly provided by David Blaschke and Hovik Gregorian). The horizontal lines are mass constraints from different binaries, ranging from most certain to least certain going upwards. PSR 1913+16 has a measured mass of $1.44\,M_\odot$ (e.g., Taylor 1994), PSR J0751+1807 has a 95% lower limit of $1.6\,M_\odot$ (Nice et al. 2003), and Vela X-1 has a 90% lower limit of $1.75\,M_\odot$ if the measured radial velocities are purely orbital (Quaintrell et al. 2003). The dashed line shows the gravitational mass corresponding to a rest mass of $1.4\,M_\odot$ if the binding energy per mass is uniform throughout a star and equal to its surface value. In practice, this provides a strong lower limit to the gravitational mass (see, e.g., the numerical calculations of Cook, Shapiro, & Teukolsky 1994).

end up as a double neutron star binary, where measured masses are all consistent with $M \sim 1.4\,M_\odot$.

However, Quaintrell et al. (2003) point out a potential complication. The radial velocity measurements of the optical companion show puzzling residuals after the orbital motion is subtracted. Quaintrell et al. (2003) suggest that these could be caused by non-radial oscillations in the companion star induced by tidal forces from the neutron star. If such oscillations are in phase with the orbit then some of the observed radial velocity might not be from the orbit at all. This would decrease the required mass of the neutron star, potentially to the usual $1.4\,M_\odot$. Such high amplitudes of oscillation seem a priori implausible because they would require very high-order modes, but at the moment one cannot rule them out rigorously (C. Hansen, personal communication). A thorough theoretical study of non-radial oscillations in this system would go a long way towards resolving these issues, and if such a study showed that tidally induced oscillations are negligible then the Vela X–1 observations would place the strongest existing constraints on high-density matter.

4. Spectral Line Profiles

Atomic line spectroscopy has provided quantitative insight into countless astronomical objects. However, until recently, such information was unavailable for neutron stars. This could be because in an isolated neutron star the heavy elements (which produce strong lines) settle out quickly, leaving behind only fully ionized light elements. There was hope that accreting neutron stars, which receive continuing supplies of heavy elements, might have observable atomic lines. This hope was realized with the report (Cottam, Paerels, & Méndez 2002) that the LMXB EXO 0748–676 displays iron resonance scattering lines in the summed spectra of 28 thermonuclear X-ray bursts. These lines imply a redshift $z = 0.35$, consistent with an origin at the surface of a nucleonic neutron star in this system but not excluding more exotic components (Miller 2002).

These results have motivated researchers to determine theoretically what information could be extracted from a future high spectral resolution X-ray satellite. For example, Özel & Psaltis (2003) show that if the redshift is estimated from the energy of minimum flux in the line (assuming the line is absorption-like), then substantial systematic errors are possible in the resulting inference of the compactness GM/Rc^2 if the star rotates rapidly. Bhattacharyya, Miller, & Lamb (2003, in preparation) have begun a systematic study of spectral line profiles as

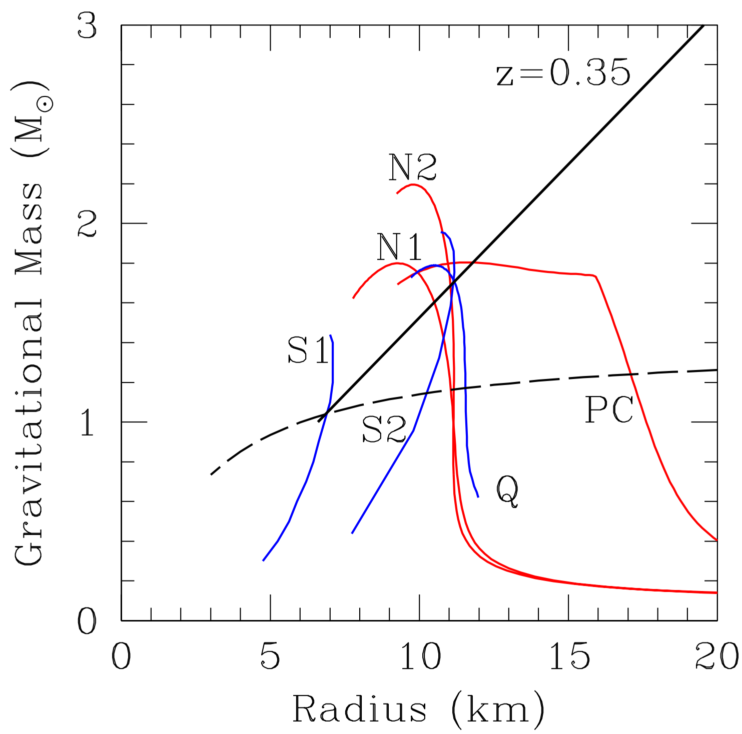

Figure 2. Equation of state constraints based on the surface redshift of $z = 0.35$ measured for EXO 0748–676 by Cottam et al. (1998). Other lines are as in Figure 1.

influenced by various physical effects. These include Doppler boosts, special relativistic beaming, gravitational redshifts, light-bending, and frame-dragging. They find a robust estimator of the compactness, using the following procedure. Suppose that the energies E_1 and E_2 of the red and blue limits of the line feature are identified. Calculate their geometric mean $E_{\rm gm} = \sqrt{E_1 E_2}$ and use it to define an effective redshift $z_{\rm eff} \equiv (E_{\rm rest}/E_{\rm gm}) - 1$, where $E_{\rm rest}$ is the rest energy of the line. Estimate the compactness using the Schwarzschild formula

$$GM/Rc^2 = \frac{1}{2}\left[1 - 1/(1+z_{\rm eff})^2\right] . \tag{4}$$

The error in this estimate compared to the equatorial value of GM/Rc^2 is always less than 4% for a spin frequency $\nu_* < 600$ Hz (Bhattacharyya et al. 2003). Bhattacharyya et al. (2003) also find that future high-precision measurements could detect a signature of frame-dragging if there are two horns in the line profile. The ratio of the depth of the low energy (red) horn to the depth of the high energy (blue) horn increases quickly with the increase of a/M, but it either decreases or slowly increases with the increase of other parameters. Hence a precise measurement of a line profile could demonstrate the existence of frame-dragging.

5. Light Curve Profiles

Both thermonuclear burst brightness oscillations and pulsations from the persistent accretion-powered emission in LMXBs are caused by rotational modulation of the flux from a hot spot on the star. The light curve produced by this rotation is influenced by effects such as special relativistic aberration and general relativistic light deflection, hence detailed observation of light curves can produce constraints on neutron star structure. However, these effects are imprinted primarily in harmonic ratios, so if only the fundamental of the oscillation is detected (as it is in most burst oscillations), then the information content is minimal (Pechenick, Ftaclas, & Cohen 1983; Strohmayer 1992; Miller & Lamb 1998; Braje, Romani, & Rauch 2000; Psaltis, Özel, & DeDeo 2000; Weinberg, Miller, & Lamb 2001; Muno, Özel, & Chakrabarty 2002; Nath, Strohmayer, & Swank 2002). Therefore, the recent report of significant harmonic content in the millisecond pulsar XTE J1814–338 (Strohmayer et al. 2003) opens up exciting new ways to constrain neutron star structure.

Analysis of the bursts from this source is ongoing (Bhattacharyya, Strohmayer, & Miller 2003, in preparation). As with spectral line analyses (e.g., Bhattacharyya, Miller, & Lamb 2003, in preparation), one calculates model light curves as a function of parameters such as the compactness, stellar spin frequency, and emission parameters related to the hot spot and compares those model curves with the data. Initial analysis of the bolometric light curves of 22 bursts from XTE J1814–338 indicates that, at the 90% confidence level, the compactness GM/Rc^2 is between 0.21 and 0.27. Further analysis, including the energy-dependent light curves, will tighten these constraints.

6. Orbital Frequencies

A more model-dependent way to constrain neutron star structure has to do with measurements of orbital frequencies in the accretion disk near the neutron star. Suppose that the frequency of some observed phenomenon could be identified with an orbital frequency $\nu_{\rm orb}$, and that this phenomenon lasted many cycles. The orbital radius $R_{\rm orb}$ is clearly greater than the stellar radius R. In addition, the relative stability of the orbit requires that it be outside the region of unstable circular orbits predicted by general relativity. For a nonrotating star, for which the exterior spacetime is described by the Schwarzschild geometry, the radius of the innermost stable circular orbit (ISCO) is $R_{\rm ISCO} = 6GM/c^2$. The constraint $R_{\rm orb} > R$ places a mass-dependent limit on the radius; for example, for a nonrotating star $R < (GM/4\pi^2\nu_{\rm orb}^2)^{1/3}$ (Miller, Lamb, & Psaltis 1998). The additional constraint $R_{\rm orb} > R_{\rm ISCO}$ places a absolute upper limit on the mass and hence on the radius. When one considers frame-dragging effects, then the upper limits on the mass and radius are (Miller, Lamb, & Psaltis 1998)

$$\begin{aligned} M &< 2.2\ M_\odot(1000\ {\rm Hz}/\nu_{\rm orb})(1+0.75j) \\ R &< 19.5\ {\rm km}(1000\ {\rm Hz}/\nu_{\rm orb})(1+0.2j)\ . \end{aligned} \tag{5}$$

Here $j \equiv cJ/GM^2$ is a dimensionless spin parameter, where J is the stellar angular momentum. If in a particular case one believes that the observed frequency is in fact the orbital frequency at the ISCO, then the mass is equal to the upper limit given above.

A strong candidate for the orbital frequency has in fact been observed from more than twenty neutron star LMXBs, using the *Rossi* X-ray Timing Explorer (RXTE). This is the phenomenon of kilohertz quasi-periodic brightness oscillations. The basic phenomenon is that power density spectra of the X-ray countrates from these systems show peaks with frequencies of hundreds of Hertz, often in a pair (for a detailed review, see van der Klis 2000). In the most widely developed models, the higher frequency of the two peaks is identified with the orbital frequency or close to it (e.g., Miller, Lamb, & Psaltis 1998; see van der Klis 2000 for a more general discussion of proposed models). The highest frequency QPO so far detected with confidence has a frequency $\nu_{\rm QPO} = 1330$ Hz (van Straaten et al. 2000), which would imply $M \lesssim 1.8\,M_\odot$ and $R \lesssim 15$ km for a system with spin parameter $j = 0.1$. These constraints essentially rule out the hardest equations of state proposed. Observations of higher frequencies would be more constraining. Projection of the amplitudes of QPOs versus their countrate suggest that a future timing mission with a $\sim 10\ {\rm m}^2$ area could detect QPOs to a frequency of ~ 1500 Hz or higher (M. van der Klis, personal communication). This would reduce the allowed region in the $M - R$ diagram significantly. It would also have strong prospects for the detection of the signature of the ISCO if $M > 1.6\,M_\odot$ for some of these systems (as suggested by the timing measurements of J0751–1807; Nice et al. 2003).

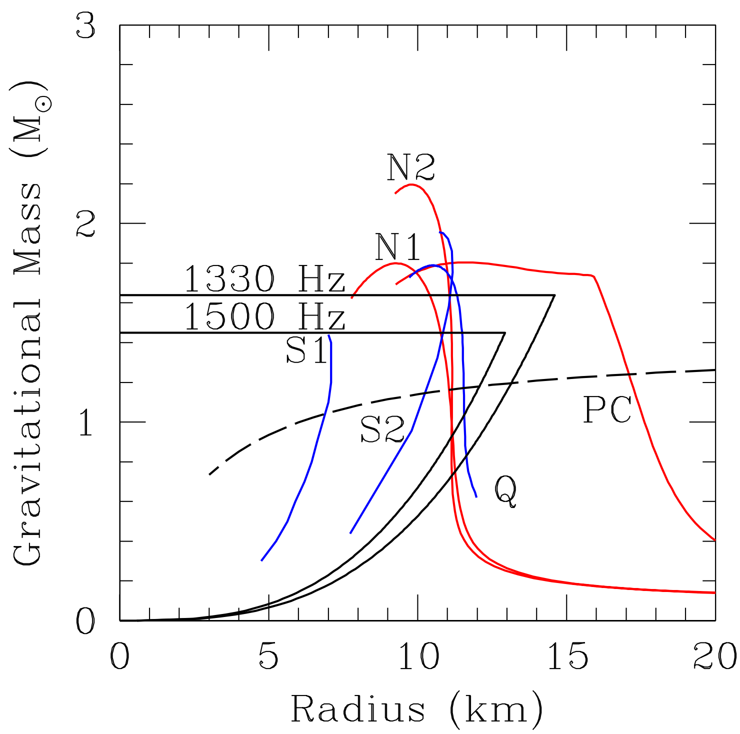

Figure 3. Constraints from orbital frequencies. The 1330 Hz curve is for the highest kilohertz quasi-periodic oscillation frequency yet measured (for 4U 0614+091, by van Straaten et al. 2000). The 1500 Hz curve shows a hypothetical constraint for a higher-frequency source. Other lines are as in Figure 1. All curves are drawn for nonrotating stars; the constraint wedges would be enlarged slightly for a rotating star (see Miller, Lamb, & Psaltis 1998).

Such a detection would confirm the presence of unstable orbits, a key prediction of strong-gravity general relativity, and allow a direct mass measurement. It is possible that the system 4U 1820–30 has already shown such a signal (Zhang et al. 1998), but there are complications in the spectral behavior that make this uncertain (Méndez et al. 1999).

More speculative constraints on the radius have been proposed by Li et al. (1999). Observations in 1998 of the accreting millisecond X-ray pulsar SAX J1808–3658 show pulsations at 401 Hz with a relatively steady pulse fraction and energy spectrum even as the flux from this source changed by a factor of ~ 100. Li et al. (1999) then argue as follows. From the spin frequency we know the corotation radius $R_{\rm co}$ for a given mass. If the radius of the magnetosphere R_M is governed by equation (1), then if the mass accretion rate $\dot{M}$ is proportional to the flux and the field is primarily dipolar we know that $R_M \propto F^{-2/7}$, where F is the observed flux. If we assume further that $R_M > R$ (to allow funneling and pulsations), and $R_M < R_{\rm co}$ (to allow accretion and keep the energy spectrum relatively constant), then we find $R < (F_{\rm min}/F_{\rm max})^{2/7} R_{\rm co}$. The data would then imply $R < 7.5$ km with a very weak dependence on stellar mass (Li et al. 1999).

If the radius is indeed this small then this result is of profound importance because it conflicts with all standard nucleonic or hyperonic equations of state. However, caution is necessary. The constraint $R_M < R_{\rm co}$ comes from the assumption that matter that couples to the magnetic field outside of corotation will be flung away from the star. But as discussed in § 2, this is not necessarily true. Instabilities at the magnetospheric interface, or cooling of matter there, could allow accretion even if $R_M > R_{\rm co}$. Li et al. (1999) argue that this is implausible because of the steadiness of the energy spectrum, but the spectral formation mechanism is not well-established; for example, if it only requires matter to get to the stellar surface, then perhaps it is irrelevant whether all the matter flows to the surface or only a small fraction. In that case, $\dot{M} \not\propto F$ and rigorous constraints on the radius are no longer possible. In particular, when $R_M \gtrsim R_{\rm co}$, the accretion rate on the stellar surface may decrease rapidly as the accretion rate at R_M decreases slightly, hence the flux could change by a large factor even if R_M itself changes little. It may be that as numerical magnetohydrodynamical codes become faster and more efficient, simulations of this system from first principles will eventually become possible and this issue can be resolved.

7. Summary

Equations of state involving only nucleonic matter are consistent with all available data. Some hints of evidence for very compact stars have been proposed (Li et al. 1999), which could indicate strange matter, but these are very model-dependent at the present. Even so, exotic states such as quark matter or strange matter are not excluded.

In just the last year, several observations have allowed new constraints on neutron star structure: (1) a mass of $M > 1.6\,M_\odot$ (at >95% confidence) has been measured for a neutron star (Nice et al. 2003); (2) the first surface redshift, $z = 0.35$, has been detected from a neutron star (Cottam et al. 2002), and (3) the first non-sinusoidal light curve has been measured from an accreting millisecond neutron star (Strohmayer et al 2003). These observations, along with many previously available data, hold out good hope for strong constraints on high-density matter in the next few years.

Acknowledgments

I appreciate many productive discussions with my collaborators Sudip Bhattacharyya, Fred Lamb, and Tod Strohmayer, and with the participants at the NATO ASW meeting in Yerevan. I also am grateful to David Blaschke and David Sedrakian for their superb organization of the conference. This work was supported in part by NSF grant AST 0098436.

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