Constraining the Bulk Properties of Dense Matter by Measuring Millisecond Pulsar Masses
A White Paper for the Astronomy and Astrophysics Decadal Survey, CFP Panel

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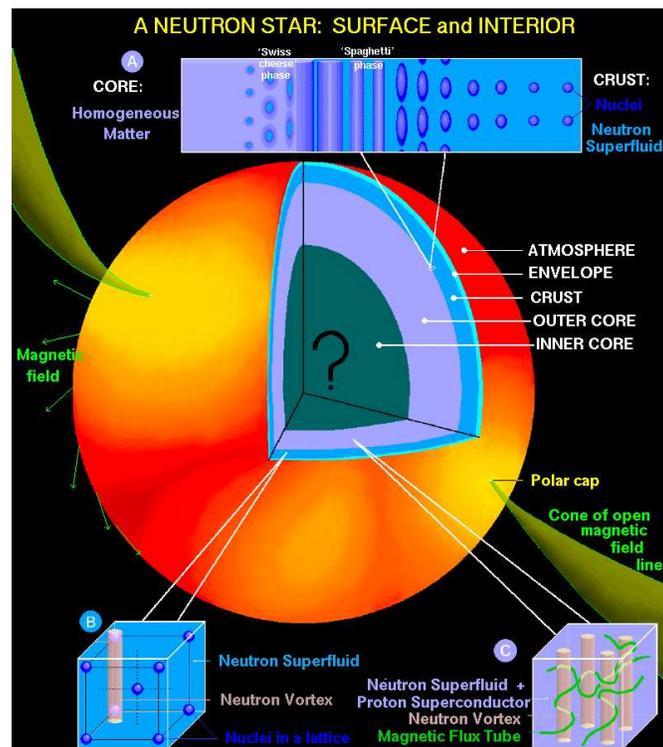
The big question mark: More than four decades after the discovery of pulsars, the composition of matter at their cores is still a mystery. This white paper summarizes how recent high-precision measurements of millisecond pulsar masses have introduced new experimental constraints on the properties of super-dense matter, and how continued timing of intriguing new objects, coupled with radio telescope surveys to discover more pulsars, might introduce significantly more stringent constraints. (Figure from Lattimer & Prakash 2004).

1   Central Questions

1. What is the nature of matter at supra-nuclear densities?

2. What is the equation of state for matter in the centers of neutron stars?

3. What are the upper mass limit, upper spin limit, and typical radii of neutron stars?

4. What is the distribution of masses for millisecond pulsars?

2   Studying the Properties of Dense Nuclear Matter

Given their small size ($R \sim 10\,\mathrm{km}$) and large mass ($M \sim 1.4 M_\odot$), neutron stars contain some of the densest matter in the Universe. They are unique astrophysical laboratories for testing theories of nuclear matter under high pressure. Neutron stars may exhibit conditions and phenomena not observed elsewhere, such as hyperon-dominated matter, deconfined quark matter, superfluidity and superconductivity with critical temperatures near 10^{10} kelvin, opaqueness to neutrinos, and magnetic fields in excess of 10^{13} Gauss.

The microscopic behavior of nuclear matter, encapsulated in the equation of state (EOS), must be inferred from potentially observable, macroscopic neutron star properties, such as their masses and radii. This connection can be made by numerically solving the relativistic equations of hydrostatic equilibrium (the Tolman-Oppenheimer-Volkov equations) to calculate mass-radius ($M-R$) relations for a given EOS. As Fig. 1 shows, there are large variations in predicted radii and maximum masses for different candidate EOSs. These reflect basic uncertainties about the behavior and composition of matter at and above nuclear density. Some EOSs, such as GS1, assume that large percentages of matter are in exotic states (hyperons, deconfined quark matter), any of which produces a decrease in the nucleonic (protonic and neutronic) degeneracy pressure at any given density, since a larger variety of particles are present. This means that matter is relatively more compressible; this produces smaller maximum stellar masses. Other EOSs, such as MS0, assume a larger fraction of nucleons and have higher pressures for any given density. This means that they predict matter to be relatively incompressible and result in larger neutron star mass limits.

3   Constraints on Pulsar Masses and Radii

There are several ways in which observations of radio pulsars constrain the properties of dense matter. (Considerable effort is also being put into observations of X-ray pulsars to determine neutron star radii and masses. This is the subject of a separate white paper. X-ray instrumentation can also study neutron star cooling, which is important to understand nuclear processes and the composition of dense neutron matter well within the stellar core.)

3.1   Constraints from pulsar spin rates

Pulsars must be compact so that they do not shed mass due to centrifugal forces. For a pulsar with given rotation period and mass, this puts an upper limit on the radius. The strictest

Figure 1: Mass-Radius relation for neutron stars. Each black curve represents a family of neutron stars masses and radii according to a given equation of state. The region bounded by the Schwarzschild condition $R < 2GM/c^2$ is excluded by general relativity, and that bounded by $R < 3GM/c^2$ (labeled "causality") is excluded by requiring the speed of sound inside the star to be smaller than the speed of light. The mass-shedding limit for the fastest spinning radio pulsar (PSR J1748−2446ad, with spin frequency 716 Hz) is labeled "rotation"; points in the green region below this line are not allowed for that particular pulsar. Stricter constraints may arise from X-ray sources like XTE J1739−285 (dashed curves calculated under different neutron star models) if their spin frequencies are confirmed to be higher than that of PSR J748−2446ad, potentially excluding some equations of state (such as GM3) which lie almost entirely below the rotation curve. A recent, precise millisecond pulsar (MSP) mass measurement (for PSR J1903+0327) excludes the "softest" EOSs (red horizontal line) (Adapted from Lattimer & Prakash 2007)].

constraint comes from the fastest-spinning pulsar. The present confirmed record holder is PSR J1748−2446ad, which rotates at 716 Hz Hessels et al. (2006). This star is tantalizingly close to the centrifugal disruption spin frequency for several EOSs (Fig. 1). Although this spin rate can't presently constrain the neutron star radius or the EOS, this situation could change in the near future, as more fast-spinning pulsars are discovered. Especially exciting would be the discovery of a pulsar near the centrifugal limit whose mass was measured through other means; this would lead to limits on the neutron star radius.

3.2   Mass limits from double-neutron-star systems

The best EOS constraints to date come from precise measurements of neutron star masses. Constraints on masses are obtained by measuring one or more post-Keplerian (PK) (relativistic) orbital elements in binary pulsars: advance of periastron, varying redshift and time dilation, orbital decay due to gravitational radiation emission, and range and shape of Shapiro delay (Taylor 1992). Measurement of two PK parameters uniquely determines the masses of the pulsar and companion star. (Measurement of more than two PK parameters overconstrains the system and can be used for tests of gravitation; this crucial application of binary pulsars is the subject of a separate white paper.) In some sources, most notably the double pulsar, additional constraints come from observations of the companion star.

The most precise mass limits come from double neutron star (DNS) systems, like the Hulse-Taylor binary, PSR B1913+16. The pulsar in this system has a mass of (1.4408 ± 0.0003) $M_\odot$ (Weisberg & Taylor 2003). This means that if a EOS predicts a maximum pulsar mass below 1.44 $M_\odot$, it is automatically excluded. The extremely soft EOS GS1 (see Fig. 1) is therefore not a realistic description of matter at supra-nuclear densities.

The most massive observed neutron star also sets a quantitative upper limit to its central density, which then cannot be exceeded in any neutron star. As successively more massive neutron stars are observed, the limiting central density gets smaller. Approximately, the limit is $\rho_{max} \leq 36\rho_s(M_\odot/M_{max})^2$ where $\rho_s = 2/7 \times 10^{14}$ g cm^{-3} is the nuclear saturation density. A large enough observed mass could rule out the appearance of exotic phases in neutron stars, such as deconfined quarks (Lattimer & Prakash 2005).

Since the discovery of PSR B1913+16 in 1974, at least eight other DNS systems have been discovered. The well-measured pulsar masses measured range between 1.24 and 1.44 $M_\odot$, a surprisingly narrow range, all near the Chandrasekhar limit.

3.3   Mass limits from other pulsar binaries

Pulsars in neutron star-neutron star binaries discussed in the previous section have been mildly spun up, achieving rotation periods of 10s of milliseconds. By contrast, pulsars in neutron star-white dwarf binaries undergo much longer episodes of accretion and are spun up to periods of a few milliseconds (hence the name "millisecond pulsar," or MSP). Their fast periods lead to superior timing precision. However, they provide difficult targets for PK parameter measurements because of very low eccentricities, wide orbits, and low companion masses.

Nevertheless, some measurements have been made in these systems. See, for example, figure 3 of Lattimer & Prakash (2007) and figure 3 of Nice et al. (2008). In most cases, the

uncertainties on the mass measurements are frustratingly large. In cases with unusually high eccentricity or high timing precision, more precise measurements can be made. In the case of PSR J0024−7204H, an MSP in a mildly eccentric ($e = 0.07$) binary system in globular cluster (GC) 47 Tucanae, measurement of periastron advance, together with the mass function of the system, yields $M_p < 1.5$ M$_\odot$ (Freire et al. 2003). In the case of PSR J1909−3744, a bright MSP with a fortuitously "edge-on" geometry, measurement of Shapiro delay yields $M_p = 1.47^{+0.03}_{-0.02} M_\odot$ (Hotan et al. 2006). These results established that at least some MSPs can be recycled with relatively small amounts of mass, but introduced no significantly new EOS constraints.

The situation has now changed dramatically. The most important event has been the discovery of PSR J1903+0327 (Champion et al. 2008). This extraordinary binary pulsar has a period similar to NS-WD systems ($P =$2.15 ms), but is in a wide ($P_b = 95$d), eccentric orbit. It was the first MSP discovered in the ongoing ALFA pulsar survey. It is unique among fast MSPs in having a fairly massive companion (either a massive white dwarf or possibly a main-sequence star, as suggested by the spatial coincidence of a Sun-like star with the astrometric position of the pulsar) and absolutely extraordinary in having an orbital eccentricity of 0.44. These properties are completely at odds with all expectations based on our present understanding of the stellar evolution in binary systems.

In addition to being an intriguing system from a binary evolution point of view, the unusual orbital characteristics are extremely useful for measuring the pulsar mass. By combining a precise measurement of the apsidal motion of this system ($\dot\omega = 86.58 \pm 0.25$ arcseconds per century) with Shapiro delay measurements, the mass has been determined to be 1.671 ± 0.008M$_\odot$ (the 4σ uncertainty is only 0.032M$_\odot$). Shapiro delay measurements are beginning to over-constrain the system and confirm the unusually high mass of this neutron star. The precision of this measurement is unprecedented for any MSP, and the mass is significantly higher than any previous precise neutron star mass measurement. If these results stand under further scrutiny, we can exclude several soft EOSs (see red line in Fig. 1).

3.4   Millisecond Pulsars in Globular Clusters

There has been a wealth of MSP discoveries in globular clusters in recent years, thanks to deep observations with the Green Bank Telescope and elsewhere; about 2/3 of the MSPs now known are located in GCs[1]. Because of perturbations from passing stars, or in some cases exchange encounters, these systems can be considerably more eccentric than MSPs in the Galactic disk, as in the case of PSR J0024−7204H mentioned above. In fact in some cases these MSP binaries are more eccentric than any system in the Galactic disk Freire et al. (2004, 2007). The number of highly eccentric ($e > 0.3$) MSP binaries increased from 1 known before 2004 to 14 at present. Follow-up observations of these pulsars over the coming years promise to yield a wealth of PK parameters and, therefore, measurements and constraints on neutron star masses.

Even now, a statistical analysis of these measurements strongly suggests that some of these pulsars are massive. By considering the likelihood of different orientations of PSRs J1747−2446I and J in Terzan 5, it has been found that there is a 95% probability

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[1]see http://www.naic.edu/∼pfreire/GCpsr.html
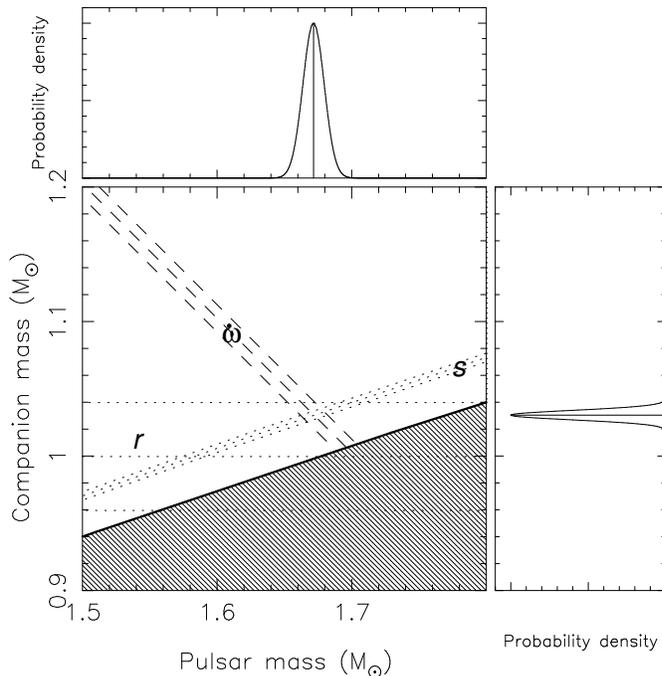
Figure 2: Constraints on the masses of PSR J1903+0327 and its companion, based on Green Bank and Arecibo timing. The hashed area is excluded by knowledge of the mass function and by $|\sin i| \leq 1$, where i is the orbital inclination. The remaining constraints are derived from the rate of advance of periastron ($\dot\omega$) and the "range" and "shape" (r, s) of the Shapiro delay, *assuming* they are of general-relativistic origin. The different constraints give a consistent measurement of the components masses, i.e., GR passes this test. The companion is significantly lighter than any NS measured to date, it is likely to be a massive WD or a MS star. The pulsar is significantly more massive than any other NS with a precise mass determination. Marginal panels, *top*: probability distribution function for the mass of the pulsar, the median is indicated with a vertical line, *right:* probability distribution function for the mass of the companion. From Freire et al. (2009).

that at least one of these objects is more massive than $1.68\,M_\odot$ (Ransom et al. 2005). For PSR B1516+02B, in M5, there is a 95% chance that $M_p > 1.72\,M_\odot$ (Freire et al. 2008b). Finally, for PSR J1748−2021B in NGC 6440 there is a 99% probability of $M_p > 2.0\,M_\odot$ Freire et al. (2008a). These probabilities are all calculated assuming that the apsidal motion is purely relativistic. In the case of M5B the non-identification of the companion in HST images guarantees that the apsidal motion is relativistic; this is not guaranteed in the case of NGC 6440B. A deep HST observation of the environs of NGC 6440B is planned in order to investigate the nature of its companion.

The apsidal motions are now being measured for four more systems in Terzan 5 and two others in M28, and it is likely that measurements will be extended to more than a dozen GC binaries in the very near future. This, coupled with more multi-wavelength observations and improved statistical methods will allow more detailed knowledge of the underlying distribution of MSP masses. Further, we are now reaching the stage at which other PK parameters, particularly γ, the time dilation and gravitational redshift parameter, may be measurable in some sources, particularly Terzan 5 I.

3.5 Moment of Inertia of PSR J0737−3039A

Continued timing of the double pulsar system, J0737−3039, will greatly improve the precision of its PK parameters, in particular the measurement of the orbital decay due to the emission of gravitational waves. Eventually, the precision of this measurement is limited by

uncertainties in the kinetic contribution to the orbital decay. Present (Deller, Bailes and Tingay, arXiv:0902.0996) and future interferometric studies will allow a very precise estimate of the contribution of kinetic effects to its orbital decay. By doing this we might be able to measure the expected spin-orbit contribution to the $\dot{\omega}$ (Damour & Schäfer 1988) of PSR J0737−3039A, allowing an estimate of this pulsar's moment of inertia (Kramer & Wex 2009). This, together with its well-determined mass, will introduce unique and fundamental constraints on the equation of state for dense matter (Lattimer & Schutz 2005). These would complement the constraints derived from the measurement of MSP masses.

4   Key Requirements

High Sensitivity Facilities Pulsars are low luminosity sources, and most of the objects that are providing the new mass limits, the GC pulsars, are exceptionally faint. Detection of PK parameters typically requires consistent observation of a pulsar over a period of years. Obtaining any new results on these sources absolutely requires the world's most sensitive radio telescopes, particularly the GBT and Arecibo Observatory. These are the only instruments capable of even detecting the vast majority of the GC pulsars—and the only ones capable of detecting PSR J1903+0327 with the S/N required to measured the three PK parameters we now measure for that system.

Even Higher Sensitivity Facilities The additional sensitivity of an instrument like the Square Kilometer Array (SKA) would revolutionize this field, by vastly increasing the sample of MSPs with measurable masses and greatly increasing the number of measurable PK parameters in all sorts of systems. It will also be able to determine the distance to PSR J0737−3039 with enough precision to allow a precise measurement of the moment of inertia of PSR J0737−3039A.

Improved Radio Instrumentation Precision pulsar timing requires observing the pulsar signal with high time resolution over large radio bandwidths ($\sim$1 GHz). The development of the GBT and upgrades to Arecibo, have made such wide bandwidths available for the first time, and back-end instrumentation is continually evolving toward taking full advantage of these bandwidths. This increase in bandwidth and time resolution is essential to fully resolve the radio pulses' fine structure and increase the sensitivity to these faint sources.

Continuous Long-term Observations For all GC pulsars, only continued, long-term timing will allow measurement of the relativistic γ, which is vital for precise measurements of pulsar masses. In some important cases, like NGC 6440B, this will require a couple of decades. Improvements in sensitivity and timing precision will be important to reduce these time horizons, but the long-term nature of these projects is essentially inevitable.

New MSPs Progress in using pulsar mass measurements to constrain the EOS of neutron star matter has only been possible because of the discovery of new objects, like PSR J1903+0327 or the GC pulsars. This is driven by continual improvement in telescope sensitivity, available bandwidth, computing capabilities, and pulsar search algorithms.

Continued searches, like the ALFA pulsar survey, the 350-MHz drift-scan survey with the GBT, the 327-MHz drift-scan survey with Arecibo and others might discover new binary MSPs with orbital characteristics that make their masses easy to measure. Some of them might have masses that happen to constrain the EOS. Whatever their masses, the more we increase the sample of MSPs with measurable masses, the better will be our understanding of their mass distribution.

The improvements in time resolution that allow better timing precision also allow much higher search sensitivity to fast-spinning pulsars. The present pulsar surveys can detect sub-millisecond pulsars in Galactic volumes that are hundreds of times larger than any previous pulsar surveys. As discussed above, the discovery of such systems also has the potential to fundamentally constrain the EOS.

References

Champion, D. J. et al., 2008, Science, 320, 1390

Damour, T. & Schäfer, G. 1988, Nuovo Cim., 101, 127

Freire, P. C. et al. 2003, MNRAS, 340, 1359

Freire, P. C., Gupta, Y., Ransom, S. M., & Ishwara-Chandra, C. H. 2004, ApJ, 606, L53

Freire, P. C. C., Ransom et al. 2008a, ApJ, 675, 670

Freire, P. C. C., Ransom, S. M., & Gupta, Y. 2007, ApJ, 662, 1177

Freire, P. C. C., Wolszczan, A., van den Berg, M., & Hessels, J. W. T. 2008b, ApJ, 679, 1433

Hessels, J. W. T. et al. 2006, Science, 311, 1901

Hotan, A. W., Bailes, M., & Ord, S. M. 2006, MNRAS, 369, 1502

Kramer, M. & Wex, N. 2009, Class. Quant. Grav., in press

Lattimer, J. H. & Prakash, M. 2004, Science, 304, 536

Lattimer, J. M. & Prakash, M. 2005, Phys. Rev. Lett., 94, 111101

—. 2007, Physics Reports, 442, 109

Lattimer, J. M. & Schutz, B. F. 2005, ApJ, 629, 979

Nice, D. J., Stairs, I. H., & Kasian, L. E. 2008, in AIP Conf. Proc. 983: 40 Years of Pulsrs, ed. C. Bassa, Z. Wang, A. Cumming, & V. Kaspi (Springer), 453–458

Ransom, S. M. et al. 2005, Science, 307, 892

Taylor, J. H. 1992, Philos. Trans. Roy. Soc. London A, 341, 117

Weisberg, J. M. & Taylor, J. H. 2003, in Radio Pulsars, ed. M. Bailes, D. J. Nice, & S. Thorsett (San Francisco: Astronomical Society of the Pacific), 93–98