Determining the Equation of State of Cold, Dense Matter with X-ray Timing Observations of Neutron Stars

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Neutron Star Structure and the Equation of State

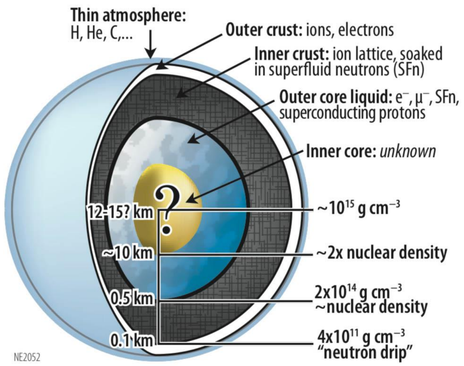

Figure 1. A depiction of the interior structure of a neutron star (not to scale). The crust and the outer core down to a depth of ~0.5 km, where densities are of the order of nuclear density, are well understood. Beyond that, our understanding of the structure relies on theoretical extrapolations. At the extreme densities found in the neutron star core (5-10 times the nuclear saturation density), we currently do not know how matter behaves, what the phase structure is or what the dynamical degrees of freedom are. Image credit: D. Page/NASA

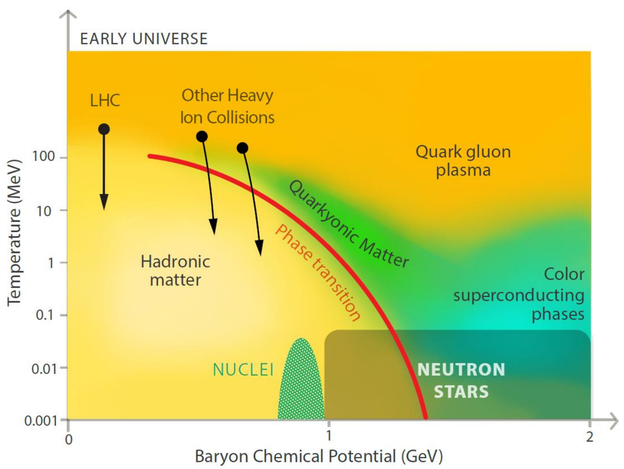

Figure 2. A schematic view of the quantum chromodynamics phase diagram. The stabilizing effect of gravitational confinement in neutron stars permits long-timescale weak interactions (such as electron captures) to reach equilibrium, generating matter that is neutron rich and may involve matter with strange quarks. This means that neutron stars access unique states of matter that cannot be replicated in terrestrial laboratories: nuclear superfluids, strange matter states with hyperons, deconfined quarks, and color superconducting phases. Image credit: A. L. Watts

Dense Matter Constraints with Thermal X-rays from Neutron Stars

Since we cannot directly sample the matter in the core of neutron stars, we must rely on indirect inference using sensitive observations of their exteriors. Because the mass-radius (M-R) relation of neutron stars is strongly dependent on the Equation of State (EoS) of the dense matter in their interior (**Fig. 3**), measurements of the masses and radii of several neutron stars to a precision of a few percent using astrophysical observations can provide insight into the state of matter in their interior. This has motivated the development of a host of observational and data modeling techniques for inferring the masses and radii of neutron stars. A large subset of such methods rely on observations of the surface thermal radiation from neutron stars, because the properties of the observed photons are greatly affected by the immense gravity in the vicinity of the star, which in turn, is determined by the stellar M and R. The X-ray portion of the electromagnetic spectrum is of particular interest in this regard, since it is where the bulk of the thermal radiation from neutron stars is observed.

By obtaining measurements for many neutron stars and delivering M-R measurements for a selected subset of targets at the >5% level, one can study the EoS across a wider range of central densities, mapping the EoS more fully and probing with finer resolution any potential phase transitions.

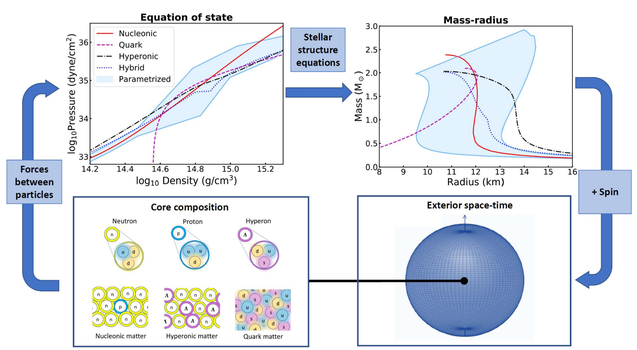

Figure 3. The nature of matter in the high density, low temperature environment of the neutron star core is highly uncertain: both the composition of the matter and the interactions between the particles are poorly constrained by theory. Our uncertainty about these microphysical aspects (lower left: uds = up/down/strange quarks) is encoded in the EoS (top left). The pale blue band shows the rough range covered by the full set of currently viable models, as computed from Chiral Effective Field Theory (CEFT). The different EoS then affect macroscopic properties of the star such as mass, radius, and oblateness for a given rotation rate, via their influence on stellar structure (top right). These determine the exterior space-time properties of the star, exerting measurable influences on radiation propagating from the stellar surface that we exploit to infer information about the EoS and the associated microphysics. Figure adapted from Ray et al. 2019, arXiv:1903.03035

Modeling the Surface X-ray Emission from Neutron Stars

A future X-ray mission with a combination of soft and hard X-ray band coverage (from ≈0.1 keV up to at least 30 keV), large collecting area (>10× NICER, >5× RXTE), and high time resolution would be able to target three different types of neutron stars with surface hotspots: not only the *rotation-powered pulsars* studied by NICER, but also *accretion-powered pulsars* and *thermonuclear burst oscillation sources*. This would enable deployment of several techniques to study the EoS of ultra-dense matter. One of these is the Pulse Profile Modelling (PPM) technique that has been successfully demonstrated by NICER. PPM exploits the effects of General and Special Relativity on rotationally-modulated emission from surface hot spots to infer M and R (see **Fig. 4**).

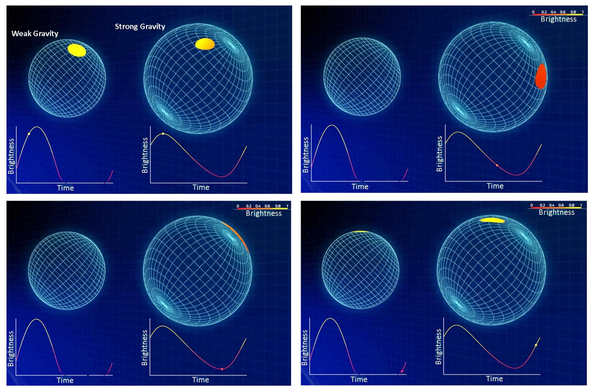

Figure 4. A schematic illustration of a rapidly rotating R = 12 km, M = 1.4 $M_\odot$ neutron star with an X-ray emitting "hot spot" of angular radius 0.5 radians at a colatitude $\pi/4$. Show are snapshots at four different rotational phases. In Newtonian (Weak) Gravity, the hotspot is occulted. In the Strong Gravity case, where relativistic effects are included, the bending of photon trajectories due to the immense gravitational field causes most of the star to be visible to an observer at any given time. This is why the Strong Gravity star appears larger and ensures that for this particular configuration the hot spot is visible at all times. Doppler boosting and aberration due to rapid stellar rotation cause the peak intensity to occur before the closest approach of the spot to the observer. Since the severity of the light bending and Doppler effects depend on the neutron star M and R, these effects encode information about M and R in the observed energy-resolved pulse profile, which can be extracted via careful modeling. Image credit: Morsink/Moir/Arzoumanian/NASA

Expected Constraints with Future X-ray Timing Missions

A next generation large-area X-ray timing mission would bring us into the data-dominated regime where EoS model priors are no longer playing a role and will let us probe for the first time the composition of the matter in the neutron star core. The results it will deliver will also be extremely robust. The ability to target multiple source classes and a wide range of neutron star masses, especially those not accessible by other methods (e.g., gravitational waves), allows us to cross-check techniques, compare the source populations, and hence identify and combat model systematics.

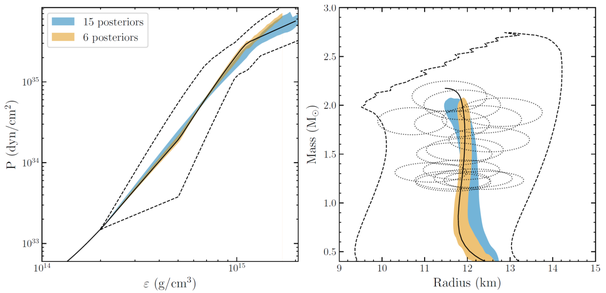

Figure 5. Constraints on the EoS and associated M-R relation representative of those expected from future measurements. The waveform modelling technique delivers M-R posteriors: here simple simulated posteriors are used modelled as bivariate Gaussians. We assume an initial set of 15 posteriors at ±5% accuracy (dashed ellipses) scattered around an underlying M-R (solid black line). The associated EoS is shown on the left, with the dashed lines indicating the range permitted by current models. We consider a piecewise-polytropic parameterization for the EoS with fixed transition densities. The 1σ constraints resulting from these 15 measurements is shown in blue. The orange band shows the results if we select 6 of these stars, based on ensuring an even spread over the mass range 1.2–2.0 $M_\odot$, for deeper observations that result in ±2% accuracy posteriors (not shown).

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SUMMARY: A future large area timing mission with soft and hard X-ray band coverage would enable mass-radius measurements for many more neutron stars and at much higher accuracy than previously possible. The resulting EoS measurements, when combined with gravitational wave and terrestrial laboratory measurements, hold the promise to deliver definitive empirical constraints on the true nature of the densest matter in the Universe and the high-density, low-temperature region of the quantum chromodynamics phase space.