Snowmass2021 - Letter of Interest

Probing Nuclear Astrophysics and Gravitation with Neutron Stars

Thematic Areas:

■ (CF7) Cosmic Probes of Fundamental Physics

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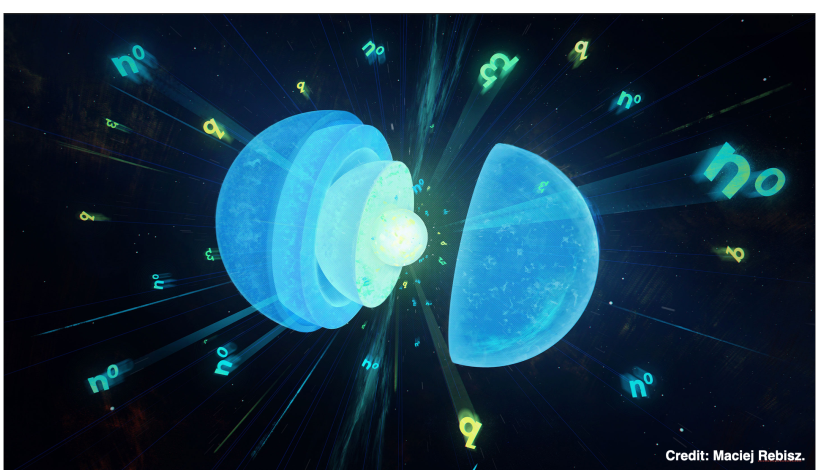
Abstract:

Neutron stars are among the Universe's most extreme exotic objects. The physics at play in their supranuclear-density cores remains poorly understood, but pulsar timing — the process of accounting for every rotation from rapidly rotating neutron stars — is a remarkably effective way to study these mysterious stellar remnants. In this Letter of Interest, we discuss the use of pulsar timing to constrain the neutron star interior equation of state and the particle physics at play, test theories of gravitation, and eventually measure the neutron star moment of inertia in an effort to probe the radius and core properties of these objects.



Artistic rendition of the neutron star interior with matter under extreme conditions. (Credit: Maciej Rebisz.)

Motivation: Neutron stars (NSs) are stellar remnants that represent an endpoint of a massive star's life. Though partially supported by quantum-mechanical degeneracy pressure between neutrons, the details of the repulsive forces from the unknown particle makeup within the core are poorly understood. While most viable models predict NS masses of $0.5 - 3$ $M_\odot$ and radii of ∼10 km [1], the diverse landscape of proposed interior nuclear microphysics – namely the energy density and phase transitions of nuclear material throughout the star, and particularly in the core – leads to important questions regarding the nature of matter at supranuclear densities. Moreover, and regardless of the interior composition and particle physics, NSs exhibit immensely strong gravitational fields that impact both their internal structure and their external environments, making NSs a highly sought-after probe of fundamental physics [2].

Many of the decisive measurements in experimental gravity and nuclear astrophysics have come from studying the timing properties of *pulsars*, rotating NSs that emit beamed radiation along their magnetic poles. An early example is the discovery and analysis of the "Hulse-Taylor" pulsar-binary system that (indirectly) confirmed of the existence of gravitational radiation [3,4]. The recent discoveries of additional relativistic pulsar orbits and massive NSs, as well as the eventual detection of nanohertz-frequency gravitational radiation through pulsar timing, show that pulsars continue to serve as ideal laboratories for fundamental physics. In this Letter of Interest, we highlight key opportunities made possible through pulsar timing, and encourage readers to also read the related Letter regarding "pulsar timing array" experiments (PTAs) and their use in constraining beyond-Standard-Model physics (X. Siemens et al).

Constraining Equation-of-State Physics by measuring Neutron-Star Masses: Precisely measuring macroscopic NS parameters, such as their masses and radii, can constrain the NS equation of state (EoS) and the particle and nuclear physics that determines it. As shown in Figure 1, the discovery of high-mass NSs can rule out softer EoSs that predict stellar collapse at a lower maximum mass due to, for example, phase transitions and/or additional degrees of freedom in the core of the NS. An effective way of obtaining NS mass measurements through pulsar timing is by observing the relativistic Shapiro delay [5] in binary orbits containing a pulsar. The Shapiro delay manifests as a small delay in pulse arrival times (of order $\sim 10\,\mu$s) induced by the spacetime curvature near a radio pulsar's companion star. Measurement of the Shapiro delay directly determines the masses of the NS and its companion, as well as the geometry of the system.

Pulsar-timing observations that measure the relativistic Shapiro delay alone have provided some of the best measurements of high-mass NSs [6, 7]. While rare, observations of $>2\,M_\odot$ NSs have greatly impacted our understanding of the NS interior EoS; for example, the initial measurement of the mass of PSR J1614−2230 effectively ruled out most non-baryonic EoS models (i.e., hyperons, kaons, Bose-Einstein condensates, free-quark stars, etc.), though recent work argues that the cores of maximally-massive NSs can be composed of quark-gluon matter under certain conditions (e.g., see [8]). Large NS masses also constrain the interaction between hadronic and strange-quark matter, and particular in phase transitions between the two states [9]. On the other hand, measuring masses and radii of the lowest-mass NSs can constrain nuclear symmetry-energy parameters, at mean central densities close to the nuclear-saturation limit, that have strong implications for unknown aspects of supernova physics and other astrophysical phenomena [10].

Tests of Gravitation from Pulsars in Two/Three-Body Systems: The small physical scales of neutron stars (with radii ∼ 10 km) allow them to be considered as point masses in binary orbits. Relativistic pulsar-binary systems, with orbital periods ∼ hours, are generally regarded as idealized astrophysical environments for testing viable theories of strong-field gravitation due to the point-like nature leading to "clean" interactions. The discovery and long-term radio timing of relativistic double-neutron-star (DNS) systems, such as the Hulse-Taylor system, yield a variety of "post-Keplerian" (PK) parameters – the parameters of the Shapiro delay being examples of PK effects – that quantify $O(|v|^2/c^2)$ corrections to purely Newtonian motion, where $|v|$ represents the NS's orbital speed. An ensemble of PK parameters can be used to test general relativity and directly estimate the binary-component masses [13–16]. With sufficiently long timing baselines it will be possible to resolve $O(|v|^4/c^4)$ PK effects in DNS systems, such as temporal shifts

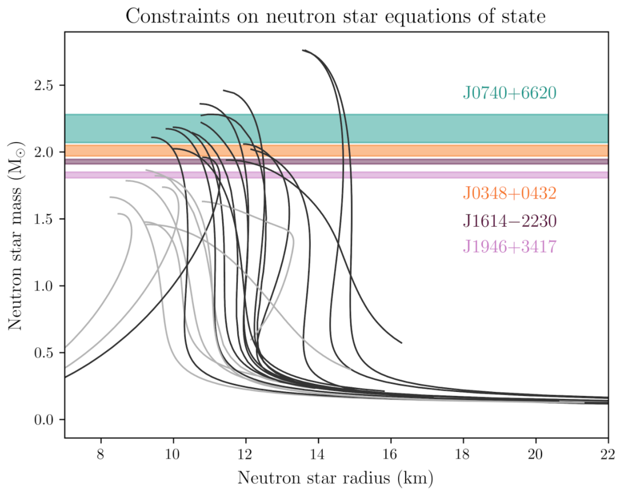


Figure 1: NS mass-radius relations obtained by solving the Tolman-Oppenheimer-Volkoff equations [11, 12] for different nuclear EoSs. Data shown as lines are taken from [1]. The discovery of a $2.14M_{\odot}$ NS, shown in teal [7], calls several EoSs into question; EoS models consistent with this measurement are represented by black lines, while grayed lines (largely composed of EoS models that assume significant amounts of hyperons, kaon condensates, or bosons) denote models that cannot predict NS masses consistent with radio timing observations.

in the periastron argument due to spin-orbit interaction [17]; this particular effect directly depend on the NS moment of inertia and is thus of considerable interest for ongoing timing-based experiments in nuclear astrophysics (see the next section for additional discussion).

A diverse set of tests for the presence of scalar fields as gravity mediators [18,19] are accessible when examining two/three-body systems contain pulsars with white-dwarf companions and of various sizes [20,21]. These particular tests place stringent limits on tensor-scalar gravity theories, where notable effects include temporal variation of Newton's gravitational constant, violation of Lorentz invariance through excess acceleration of spinning, self-gravitating bodies within a preferred reference frame, and violations of equivalence principles through differing accelerations felt by bodies of different internal compositions and binding energies [22]. The recent discovery and analysis of a pulsar in a three-body system with two white dwarfs [23] have provided the strongest constraints of equivalence-violation principles to date [24,25]. Future discoveries and refined measurements will continue to provide exceptional strong-field tests of gravity.

Constraining the Neutron-Star Moment of Inertia: The first radio-timing measurement of the NS moment of inertia from DNS systems (e.g., [26]) will provide another independent test for nuclear theory [27–30] and for gravity theories [31]. Assuming general relativity is the correct theory of gravity, a NS moment-of-inertia measurement can constrain the NS radius as well as nuclear-physics parameters at nuclear saturation density [32–34]. Such constraints may also be able to probe the possible existence of a hadron-quark phase transition at supranuclear densities, i.e., whether or not NSs may have a quark core [35].

NS interiors are in both the strong-field and high spacetime curvature regime where gravity modifications may appear in alternative theories and alter the interior structure. NS interiors thus provide both a strong-field and high-curvature test of gravity complementary to binary-pulsar tests. Given that the nuclear EoS is itself uncertain, this presents a possible observational degeneracy when one allows gravity to deviate from General Relativity. A number of observable macroscopic NS properties, however, may obey quasi-universal relations that are practically insensitive to the EoS [36]. Such quasi-universal relations allow for testing gravity with NSs in an EoS-independent manner, regardless of nuclear-physics uncertainties [37]. For example, combining independent measurements of the moment of inertia (from radio timing) and the tidal deformability (from gravitational waves) can rule out alternative gravity theories [38] as well as test quasi-universality [39].

Conclusions: The timing of pulsars provides key opportunities to extensively probe various aspects of fundamental physics, including the NS interior EoS and tests of gravity. Additional discoveries of new pulsars in relativistic orbits, as well as refined PK measurements and the eventual measurement of moments of inertia, will continue to unveil lingering mysteries in NS interior physics at supranuclear densities.

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