Measuring the Radius of a Neutron Star Using NICER Pulse Profile Modeling

Abstract

Neutron stars represent some of the densest matter in the universe, offering a unique opportunity to probe the behavior of matter under extreme conditions. One of the most effective methods for constraining the equation of state (EoS) of such dense matter is through precise measurements of a neutron star's radius. This proposal outlines a plan to model the thermal X-ray pulse profile of PSR J1614–2230 using observations from NASA's Neutron Star Interior Composition Explorer (NICER). By analyzing phase-resolved spectroscopy and applying relativistic pulse profile modeling techniques, the objective is to constrain the radius of PSR J1614–2230 to within ±1 km. These results will contribute to a better understanding of the EoS, improving our knowledge of the internal composition of neutron stars. NICER's advanced timing capabilities and soft X-ray sensitivity make it an optimal instrument for this investigation.

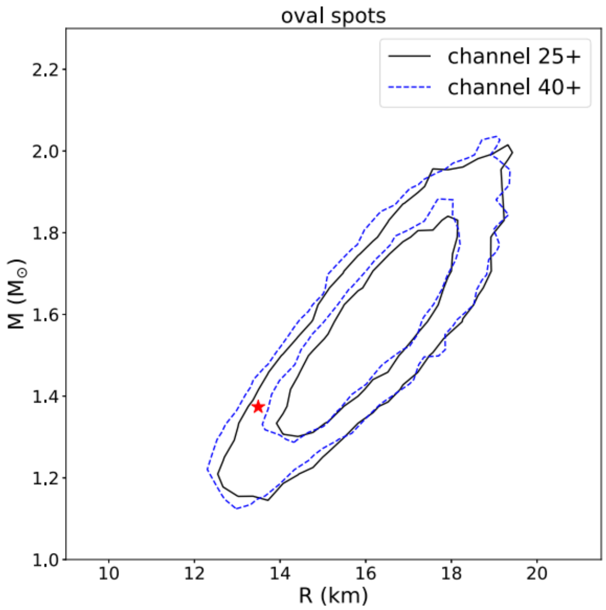
Introduction

Main sequence stars eventually run out of hydrogen and begin fusing other lighter elements into heavier ones until they exhaust each fuel source. Once only iron remains, fusing it into heavier elements requires more energy than it yields, causing the core to collapse and explode into a supernova. The remaining super-dense core becomes a neutron star, which is second only to black holes in density. These stars are primarily observed in X-ray and radio bands (NASA, n.d.).

The equation of state (EoS) defines how pressure, density, and temperature of a substance are related. Currently, the EoS for neutron stars remains unclear, as they are difficult to study due to their extreme density—far beyond what we can replicate—and the unknown nature of the matter within them. Neutron stars are also small and not very luminous, making them difficult to detect (Riley et al., 2022). However, observing neutron stars offers a unique opportunity to advance our understanding of nuclear physics since we cannot recreate certain environments on Earth (Raaijmakers et al., 2021). For instance, nuclear physicists are particularly interested in neutron stars' dense cores as they allow us to investigate properties of cold, catalyzed matter at densities exceeding nuclear saturation density (Miller et al., 2019). Better understanding the EoS of neutron stars would help explain the nature of the matter present, and how matter behaves in these unique environments.

Figure 1

Confidence contours for mass and radius of J0030



Note: This figure shows the 68% and 95% confidence contours for mass M and equatorial radius R obtained from waveform modeling. Two sets of synthetic data were analyzed—one using NICER energy channels 25–299 (solid black) and the other using 40–299 (dashed blue). Both sets yield consistent results with the true M and R (marked by a star), demonstrating that excluding the lower energy channels does not bias the estimates or significantly reduce their precision (Miller et al., 2019).

One of the best methods to constrain the EoS of a neutron star is by measuring its radius (Miller et al., 2019). Depending on the radius, we can infer whether the star has a stiff or soft EoS. A stiff EoS indicates larger radii as it resists compression, whereas a soft EoS produces smaller radii due to higher compressibility. Since pressure is constrained by radius, accurate radius measurements are key to understanding matter behavior.

Radius estimates from X-ray emission models yield values between ~10–14 km, which are in line with theoretical predictions (Miller et al., 2019). Past research on neutron stars like PSR J0030+0451 and PSR J0740+6620—located over 1000 light years away—found J0030 has a radius of about 12.7 km, while J0740 ranges between 13–15.1 km. Refining such values for multiple neutron stars will improve the precision of the EoS. I propose the study of PSR J1614-2230 through observations obtained by NICER to enrich the available data for determining the EoS of a neutron star.

Objectives

The overarching goal of this project is to obtain precise constraints on the radius of PSR J1614−2230 using NICER observations. I aim to constrain the radius to within ±1 km by modeling the thermal X-ray pulse profile, thereby extracting physical parameters that inform the dense matter EoS above nuclear saturation density.

Discovered in 2006, PSR J1614−2230 is a pulsar in the Scorpius constellation located about 1200 pc away at a right ascension of 16h 14m 36.5051s and declination of −22° 30′ 31.081″ (Gaia Archive, n.d.). It was identified using the Parkes radio telescope through a survey of unidentified sources. The pulsar has a spin period of 3.15 ms and orbits a white dwarf of about 0.4 solar masses every 8.7 days (Demorest et al., 2010). J1614 has a mass of 1.908 solar masses and an estimated age of 5.91×10^5 years. Its current measured radius is 13 ± 2 km, but this uncertainty is too large to contribute meaningfully to EoS models.

In 2010, Demorest et al. measured the Shapiro delay in the PSR J1614−2230 system, determining its mass to be approximately 1.97 solar masses—the highest known at that time. More recent measurements have refined this to 1.908 ± 0.016 solar masses (Lattimer, 2012). Several other studies have also explored the evolution and characteristics of this pulsar (Tauris et al., 2011).

To enable high-precision modeling, I propose a total exposure of 1 Ms using NICER's X-ray Timing Instrument (XTI). Given the pulsar's brightness and count rate (~1–2 counts per second), this exposure should yield sufficient photons for detailed spectroscopy. NICER's sensitivity in the 0.2–12 keV band matches the expected thermal emission. Observations will be conducted in standard event mode. Because J1614 has a relatively low X-ray flux and limited NICER coverage, a longer exposure time is justified despite its potential modeling limitations.

I will use similar methods to those used in Miller et al. (2019) to conduct the analysis on the obtained observations as it yielded a radius estimate close to ±1 km. In the analysis of PSR J0030+0451 they used pulse profile modeling, phase-resolved spectroscopy, and bayesian inference approach to estimate distributions of the star's mass and radius.

Pulse profile modeling analyzes the shape of the light curve over time to infer stellar radius. Surface hotspots emit thermal X-rays, and relativistic effects—such as gravitational light bending, Doppler boosting, aberration, and time delays—modulate the observed signal. This modeling helps constrain the mass, radius, and compactness of neutron stars (Riley et al., 2019).

Phase-resolved spectroscopy examines the different stages of a pulsar's rotation by observing radiation from surface hotspots. By dividing the spin cycle into phase bins and extracting spectra, researchers can trace flux and spectral changes over time to model surface emission geometry, hotspot locations, and thus constrain mass, radius, and compactness (Miller et al., 2019).

In the context of neutron star modeling, Bayesian inference allows researchers to estimate parameters like mass and radius by comparing theoretical models of X-ray pulse profiles to observed data. The result is a posterior probability distribution that reflects both the prior knowledge and the likelihood of the observed data under different model assumptions.

Technical Justification

The Neutron Star Interior Composition Explorer (NICER) is an X-ray observatory launched in 2017 by NASA. Mounted on the International Space Station, it observes thermal and non-thermal emissions in the 0.2–12 keV band. Designed specifically for neutron star observations, NICER enables precise timing and spectroscopy with low background and high throughput (NASA HEASARC, n.d.-a).

NICER's X-ray Timing Instrument (XTI) includes 56 X-ray concentrator optics and silicon drift detectors. It collects X-rays over an area >2000 cm^2 at 1.5 keV and provides energy resolution of 85 eV at 1 keV and 137 eV at 6 keV (NASA HEASARC, n.d.-b). Its timing resolution is accurate to 100 nanoseconds, offering high signal-to-noise for studies of neutron stars and other sources.

Compared to five other observatories, NICER offers unmatched timing precision and minimal dead time, making it optimal for this study. While Chandra, Swift, and XMM–Newton have excellent spectroscopy, they lack the necessary timing resolution (Chandra X-ray Center, n.d.; XMM-Newton UHB, n.d.). NuSTAR focuses on hard X-rays (3–79 keV), which are not ideal for this study (NASA HEASARC, n.d.-c). XRISM, though capable of high-resolution spectroscopy, lacks sufficient timing resolution (NASA HEASARC, n.d.-d; NASA HEASARC, n.d.-e).

Conclusion

The measurement of neutron star radii is central to constraining the equation of state of ultra-dense matter, a fundamental open question in nuclear and high-energy astrophysics. This proposal presents a feasible and well-supported strategy to constrain the radius of PSR J1614–2230 using high-precision NICER observations and pulse profile modeling. By leveraging NICER's sensitivity and timing resolution, and employing established Bayesian inference techniques, it is possible to extract meaningful constraints on the star's mass and radius. These measurements will not only refine our understanding of PSR J1614–2230 but also contribute to the broader effort of mapping the EoS for neutron stars. Continued observations and improvements in modeling will enhance the precision of these constraints, bringing us closer to unraveling the nature of matter at supranuclear densities.

Citations

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