Constraining the dense matter equation of state with ATHENA–WFI observations of neutron stars in quiescent LMXBs

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The X-ray thermal emission from neutron stars (NSs) in quiescent low-mass x-ray binaries (qLMXBs) allows us to place constraints on the dense matter equation of state (dEoS). This science goal of ATHENA requires combining the $M_{\text{NS}}$–$R_{\text{NS}}$ measurements from qLMXBs. I present simulated observations of known qLMXBs, and how well the dEoS can be reconstructed from ATHENA observations of these qLMXBs.

Quiescent Low-Mass X-ray Binaries

- The thermal emission from the NS surface dominates the X-ray emission of qLMXBs.
- NSs in qLMXBs are powered by deep crustal heating, radiating energy through an H-atmosphere.
- X-ray spectral analyses of qLMXBs inside globular clusters provide $R_{\text{NS}}$ measurements to constrain the dEoS.

From $M_{\text{NS}}$–$R_{\text{NS}}$ Measurements to Dense Matter Equation of State

Solving the equations of stellar structure in a relativistic regime:

\[
\frac{dP}{dr} = -G \frac{P(r)M(r)}{r^2} \left( 1 + \frac{P(r)}{\rho(r)} \right) \left( 1 + 4 \pi r^2 \rho(r) \right) \left( 1 - \frac{2GM(r)}{r} \right)^{-1}
\]

\[
\frac{dM}{dr} = 4\pi r^2 \rho(r)
\]

Using a Bayesian approach, we solve for $P(\rho)$ by finding $P_1, P_2, P_3$ at three fiducial densities $\rho_1, \rho_2, \rho_3$, given the measured $M_{\text{NS}}(R_{\text{NS}})$:

\[
\mathcal{P}(P_1, P_2, P_3) \propto \prod_{i=1}^{\text{Max}} \int_{M_{\text{Min}}}^{M_{\text{Max}}} P_i(M, R|P_1, P_2, P_3) \mathcal{P}_{\text{prior}}(M) dM
\]

Analysis Assumptions

- Slowly-rotating neutron stars: Emission spectrum possibly distorted for $P_{\text{sins}} < 3$ ms.
- Low magnetic field neutron stars ($B \sim 10^8$ G): No evidence of high magnetic field (X-ray pulsations, etc…).
- Isotropic surface emission: Source of heat deep inside NS creates isotropic emission.
- Globular cluster distance measurements: Expected Gaia precision on GC distance: ~2%.
- 2% uncertainties included in the $M_{\text{NS}}$–$R_{\text{NS}}$ contours.
- Pure hydrogen atmosphere: H-rich matter transferred from main-sequence companion. Heavier elements stratify within 10 sec.

Simulated Observations

Simulated $M_{\text{NS}}$–$R_{\text{NS}}$ contours measured from ATHENA observations of 8 known NSs with known properties.

Exposure time necessary for at least ~50,000 counts. Total exposure needed = 350 ksec.

Results

Best-fit inferred dEoS from 8 NS contours without calibration flux uncertainties.

\[
\frac{\Delta R_{\text{NS}}}{R_{\text{NS}}} = \pm 1.7\% \quad \text{at} \quad 1.4 \, M_\odot
\]

Best-fit inferred dEoS from 8 NS contours with 10% systematicatics added on the $M_{\text{NS}}$–$R_{\text{NS}}$ contours.

\[
\frac{\Delta R_{\text{NS}}}{R_{\text{NS}}} = \pm 3\% \quad \text{at} \quad 1.4 \, M_\odot
\]

Selection of references on the subjects related to this work:

- Deep crustal heating: Brown et al. 1998;