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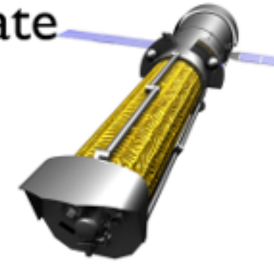
Constraining the dense matter equation of state with ATHENA–WFI observations of neutron stars in quiescent LMXBs



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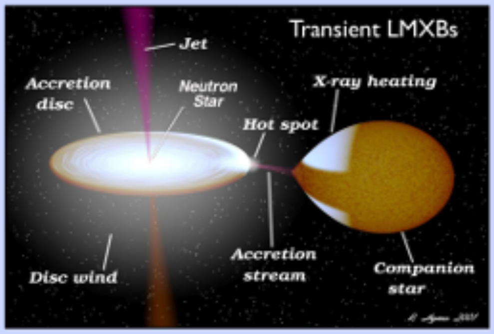
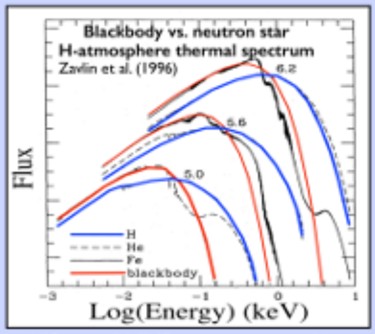
The X-ray thermal emission from neutron stars (NSs) in quiescent low-mass x-ray binaries (qLMXBs) allows us to place constraints on the dense matter equation of state (dEoS). This science goal of ATHENA requires combining the M_{NS}–R_{NS} measurements from qLMXBs. I present simulated observations of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

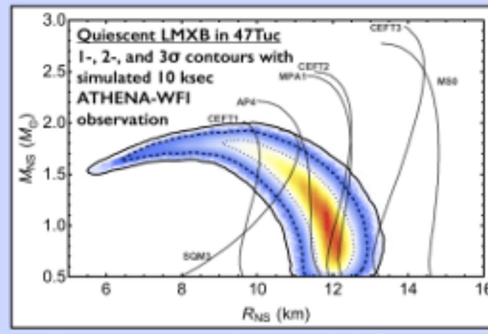
Quiescent Low-Mass X-ray Binaries



The thermal emission from the NS surface dominates the X-ray emission of qLMXBs.

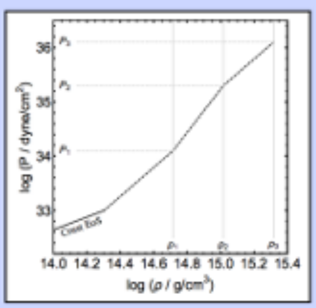


NSs in qLMXBs are powered by deep crustal heating, radiating energy through an **H-atmosphere.**



X-ray spectral analyses of qLMXBs inside globular clusters provide **R_∞ measurements** to constrain the dEoS.

From M_{NS}-R_{NS} Measurements to Dense Matter Equation of State



Solving the equations of stellar structure in a relativistic regime:

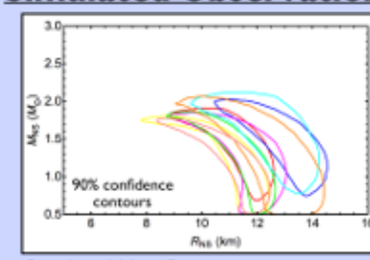
$$\frac{dP}{dr} = -G\frac{\rho(r)M(r)}{r^2}\left(1+\frac{P(r)}{\rho(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)}\right)\left(1-\frac{2GM(r)}{r}\right)^{-1}$$

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

Using a Bayesian approach, we solve for $P(\rho)$ by finding P_1, P_2, P_3 at three fiducial densities ρ_1, ρ_2, ρ_3, given the measured $M_{NS}(R_{NS})$:

$$\mathcal{P}(P_1, P_2, P_3) \propto \prod_{i=1}^{N} \int_{M_{min}}^{M_{max}} \mathcal{P}_i(M, R|P_1, P_2, P_3)\,\mathcal{P}_{prior}(M)dM$$

Simulated Observations



Simulated M_{NS}–R_{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 = 550 ksec.

Analysis Assumptions

Slowly-rotating neutron stars:
Emission spectrum possibly distorted for $P_{spin} < 3$ ms.

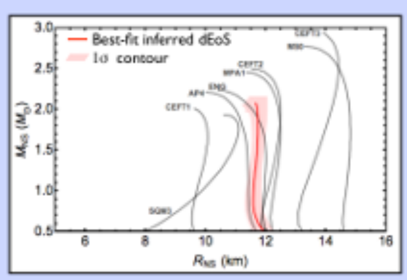
Low magnetic field neutron stars ($B \sim 10^8$ G):
No evidence of high magnetic field (X-ray pulsations, etc…).

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_{NS}–R_{NS} contours.

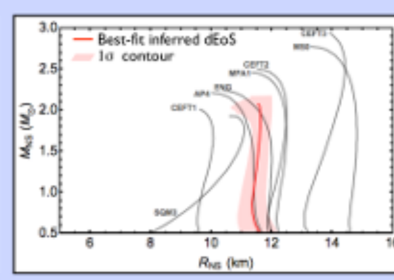
Pure hydrogen atmosphere:
H-rich matter transferred from main-sequence companion.
Heavier elements stratify within 10 sec.

Results



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

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



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

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

Selection of references on the subjects related to this work:

- *Deep crustal heating*: Brown et al. 1998;
- *Neutron star atmosphere models*: Zavlin et. al 1996; Heinke et al. 2006; Haakonsen et al. 2012.
- *R_∞ measurements*: Heinke et al. 2006; Webb & Barret 2007; Guillot et al. 2011; Servillat et al. 2012; Guillot et al. 2013, Heinke et al. 2014.
- *Equation of state inversion*: Read et al. 2009; Özel et al. 2009, 2010; Steiner et al. 2010, 2013; Özel et al. 2015.