Constraining the Dense Matter Equation of State with Lynx Observations of Globular Cluster X-ray Binaries

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The interior structure of neutron stars is unknown.

- **Atmosphere**
- **Outer crust**
- **Inner crust**
- **Outer core**
- **Inner core**

- 0.5 km ($2 \times 10^{14}$ g cm$^{-3}$) - nuclear density
- 0.1 km ($4 \times 10^{11}$ g cm$^{-3}$) - “neutron drip”
- ~11 km ($4 \times 10^{14}$ g cm$^{-3}$)
- 12-15 km ($\sim 10^{15}$ g cm$^{-3}$)
The state of cold, supranuclear matter is unknown

The neutron star mass-radius relation

Graph showing the relationship between neutron star mass and radius, with various models and observational data points plotted. The graph includes a distinction between black holes and the causality limit, with data points labeled for different neutron stars and models such as PSR J0348+0432, PSR J1614−2230, and PSR J1903+0327.
Mapping between $P-\rho$ and M-R
Observational methods for dense matter equation of state constraints using neutron stars

- Mass measurements from radio pulsar timing
  - e.g. ~2M\textsubscript{$\odot$} NSs; Demorest et al. *Nature*, 467, 1081 (2010); Antoniadis et al. *Science*, 340, 448 (2013)

- Maximum spin rate of neutron stars
  - e.g. 716 Hz pulsar; Hessels et al. *Science*, 311, 1901 (2006)

- kiloHertz quasi-periodic oscillations (QPOs)

- Cooling rates of neutron stars
  - e.g. Page et al. *NuPhA*, 777, 497 (2006)

- Photospheric radius expansion in thermonuclear bursts
  - Joss *Nature*, 270, 310 (1977); Özel et al. (2009); Steiner et al. (2010); etc...

- Pulse profile/waveform/light curve modeling of accreting and “recycled” MSPs
  - e.g., Pechenick et al. (1983); Poutanen & Gierlinski (2003); Bhattacharyya et al. (2005); Morsink & Leahy (2011); Bogdanov (2013); Lo et al. (2013); etc...

- Radius measurements via X-ray spectroscopy of quiescent LMXBs
  - e.g., Rutledge et al. (2001); Heinke et al. (2006,2014); Guillot et al. (2013); etc...
Neutron Star Radius Measurements from Spectroscopy
Quiescent Low-Mass X-ray Binaries

\[ R_\infty \equiv (1+z) R_{NS} \quad T_\infty = \frac{T_{\text{eff}}}{1+z} \quad 1+z = (1 - R_S/r)^{-1/2} \quad R_S = 2GM/c^2 \]

- Flux measured by a distant observer:

\[ F(r_{\text{obs}}, \nu_{\text{obs}}) = (1+z)^{-1} \frac{r^2}{r_{\text{obs}}^2} F[r, (1+z)\nu_{\text{obs}}] \]

- Measurement relies on correct emission model and precise distance to source

![Diagram showing flat and Schwarzschild geometries with flux vs. \( \log(\nu/T) \)]
47 Tucanae (NGC 104)

Chandra ACIS-S 0.3–8 keV

Terzan 5

*Chandra* ACIS–S

0.5–6 keV

710 ks

Bahramian et al. in prep.
Bogdanov et al. in prep.
Spectroscopy of quiescent low-mass X-ray binaries

- NS M-R estimates from an ensemble of systems can provide stringent constraints on the dense matter EoS

Neutron Star Mass-Radius Constraints with Lynx

Chandra ACIS-S
1/8 subarray (200 ks)

Lynx micro-calorimeter (200 ks)
A complete census of rotation-powered MSPs in globular clusters

Blind X-ray timing searches could discover all MSPs in nearby clusters


Transitional Pulsars

Rotation-powered (radio) MSPs  □  Accretion-powered (X-ray) MSPs

Chandra HRC  IGR J18245–2452


47 Tucanae (NGC 104)

Chandra ACIS-S
0.3–8 keV
47 Tuc X9: An Ultracompact Black Hole X-ray Binary

- A 28 minute binary with a C-O WD donor and BH accretor!

contemporaneous $Chandra + NuSTAR + ATCA$ observations

Bahramian et al. MNRAS, 467, 2199 (2017)
Conclusions

• Lynx observations of NS qLMXBs in globular clusters can produce stringent dense matter EoS constraints

• Bonus science from the same observations: cataclysmic variables, chromospherically active binaries, radio millisecond pulsars, transitional pulsars, black hole LMXBs, etc.

• Sub-arcsecond angular resolution is essential!

Pooley, PNAS, 107, 7164 (2010)