Athena’s Constraints on the Dense Matter Equation of State from Quiescent Low-Mass X-ray Binaries

Sebastien Guillot
Pontificia Universidad Católica de Chile
Athena shall constrain the equation of state of neutron stars by obtaining X-ray spectra of quiescent low-mass X-ray binaries with a good distance estimate.
The internal structure of neutron stars is still unknown and many theories are proposed.

Weber et al. 2007
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Lattimer and Prakash 2001

<table>
<thead>
<tr>
<th>Density (fm⁻³)</th>
<th>Pressure (MeV fm⁻³)</th>
<th>M₉₉ (M₆₉₃)</th>
<th>R₉₉ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear density</td>
<td>WFF1, MS3, PCL2</td>
<td>WFF1, MS3, PCL2</td>
<td>WFF1, MS3, PCL2</td>
</tr>
<tr>
<td>Pressure (MeV fm⁻³)</td>
<td>WFF2, GM3, SQM1</td>
<td>WFF2, GM3, SQM1</td>
<td>WFF2, GM3, SQM1</td>
</tr>
<tr>
<td>M₉₉ (M₆₉₃)</td>
<td>WFF3, ENG, SQM2</td>
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</tr>
<tr>
<td>R₉₉ (km)</td>
<td>AP4, PAL6, SQM3</td>
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</tr>
</tbody>
</table>
Low-mass X-ray binaries experience high- and low- accretion states.
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\[ F_X \sim 10^{-13} \text{ erg/sec/cm}^2 \]
Quiescent LMXBs inside globular clusters provide the observational solution.
Fitting the X-ray spectra of qLMXBs provides measurement of $R_{NS}$ and $M_{NS}$.

Assuming non-magnetic Hydrogen atmosphere NS with uniform surface emission

$$R_{\infty} = R_{NS} (1 + z) = R_{NS} \left(1 - \frac{2GM_{NS}}{R_{NS} c^2}\right)^{-1/2}$$

Photon energy (keV)

Bogdanov et al. 2016
Guillot et al. 2011, 2013
Heinke et al. 2006, 2014
Özel et al. 2016
Webb & Barret 2007
For observations of qLMXBs, ATHENA’s capabilities will be critical.

- High throughput at soft X-ray energies
- High time resolution
- Low background
- Good angular resolution

Barret et al. 2016
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Bogdanov et al. 2008

![Graph showing counts per bin vs rotational phase](image)
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Rau et al.
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Chandra  XMM  ATHENA
About 500 ks of qLMXBs observations with ATHENA will place constraints on the EoS.

<table>
<thead>
<tr>
<th>Host Globular Cluster</th>
<th>qLMXB Flux (erg/cm(^2)/sec)</th>
<th>Dist. (kpc)</th>
<th>Exposure time (ksec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 Tuc</td>
<td>(5 \times 10^{-13})</td>
<td>4.6</td>
<td>10</td>
</tr>
<tr>
<td>NGC 6397</td>
<td>(9 \times 10^{-14})</td>
<td>2.2</td>
<td>35</td>
</tr>
<tr>
<td>NGC 362</td>
<td>(8 \times 10^{-14})</td>
<td>8.6</td>
<td>50</td>
</tr>
<tr>
<td>M13</td>
<td>(5 \times 10^{-14})</td>
<td>7.1</td>
<td>65</td>
</tr>
<tr>
<td>OmCen</td>
<td>(5 \times 10^{-14})</td>
<td>4.6</td>
<td>75</td>
</tr>
<tr>
<td>M80</td>
<td>(3 \times 10^{-14})</td>
<td>10.0</td>
<td>95</td>
</tr>
<tr>
<td>NGC 6304</td>
<td>(5 \times 10^{-14})</td>
<td>6.2</td>
<td>115</td>
</tr>
</tbody>
</table>

Combined analysis of 7 qLMXBs with exposure times sufficient to get 50000 counts for each source

\[
\frac{\Delta R_{NS}}{R_{NS}} \bigg|_{1.4 \ M_\odot} = \pm 1.7\%
\]

Polytropic parameterization of the EOS

**TOTAL:** 450 ksec
Some current limitations will be resolved by X-ray and multi-wavelengths observations.

- **Neutron star atmosphere**  
  Identifying the lightest element in the system

- **$M_{NS} - R_{NS}$ degeneracy**  
  Measuring $M_{NS}$ independently

- **Distance precision**  
  Be patient and wait for GAIA’s results

- **Presence of a hot-spot**  
  Looking for pulsations, or evidence for two-Temperature spectrum
High Signal-to-Noise X-ray spectra can exclude the presence of a hot-spot.

Simulated neutron star surface with hot spot, but fitted with single temperature model

120 eV surface with 150 eV hot-spot

$T_{\text{surf}} = 120\text{ eV with } T_{\text{spot}} = 150\text{ eV}$

120 eV surface with 180 eV hot-spot

$T_{\text{surf}} = 120\text{ eV with } T_{\text{spot}} = 180\text{ eV}$

See Elshamouty et al. (2016) for bias on $R_{\text{NS}}$ caused by hot spots
Summary

• Quiescent LMXBs offer one of the robust method to constrain the equation of state

• ATHENA can provide high S/N observations of qLMXBs to constrain the equation of state with high precision

• Synergy with other observatories will limit the effect of systematic uncertainties.

• We could probably use more than 500 ks
Combining observations into a statistical analysis provides more useful constraints.

See also the works of:
Steiner et al. (2013)
Lattimer & Steiner (2014)
Baillot d’Etivaux et al. (in prep.)