CONSTRAINTS ON DENSE MATTER FROM X-RAY OBSERVATIONS OF NEUTRON STARS

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X-RAY BINARIES

- Neutron star (NS) accretes mass from companion
- Incoming matter produces accretion disk
- Roughly 100 NSs accreting at high rates in Galaxy

Low-mass X-ray binary (LMXB)
X-RAY BINARY TRANSIENTS

- Brief outbursts, most of disk falls onto neutron star
- Disk builds up during long quiescent periods
- Quiescent X-ray flux $10^3$-$10^5$ times fainter than outburst; little or no accretion
X-ray spectrum shows: blackbody-like emission from surface; high-energy emission (nature unknown); photoelectric absorption at low energy

Blackbody-like emission modeled as radiation of whole surface through hydrogen atmosphere

X-ray spectrum of Cen X-4 in quiescence, Rutledge 01
**H-atmosphere Models**

- Assume pure ionized H, B<10⁹ G: adequate for kT~100 eV quiescent NS. Atmosphere fractionates within seconds.

- Models computed by Zavlin & Pavlov, Rybicki in very close agreement. Well-understood case.

- Possible uncertainties:
  - Low-level accretion (alter opacity with traces C,O,N; e.g. Rutledge 02a)
  - White dwarf companion-> He atmosphere
  - Temperature inhomogeneities?
A: RADIUS CONSTRAINTS

- Can constrain radius of blackbody if know flux, temperature, distance (Brown 98)

- Flux=$\sigma(R/D)^2 T_{\text{eff}}^4$

- Must correct for redshift of light from neutron star surface, giving constraint on mass and radius. Surface gravity effects on spectrum mean confidence contours don’t perfectly track $R_\infty$.

- Distance rarely known accurately in galaxy, except in globular clusters--Rutledge 02b for $\omega$ Cen.
GLOBULAR CLUSTERS

- Dense clusters of $10^4$-7 stars of same age, composition
- Distance can be well constrained (currently to ~10%)
- Extremely dense core, leading to stellar interactions
- Stellar collisions or exchanges, putting many neutron stars into close binaries

R. Gilliland, Hubble on 47 Tuc
Chandra X-ray studies find dozens of X-ray binaries in quiescence, 5 in this deep image of 47 Tuc.

- Brightest (X7) shows blackbody-like spectrum without second component.

- Second brightest also blackbody-like spectrum, eclipses at 8.7 hours, binary optical counterpart detected.

Chandra on 47 Tuc, Heinke 05
- Excellent fit to H-atmosphere
- No evidence for lines, edges
- No variability (hours to decades), no evidence for accretion
- Temp. inhomogeneities testable with long Chandra HRC dataset
- Perfect test object!!
Spectral fit to X7 places constraints on $M$, radius

Indicates moderately large radius, excluding several NS structures

XMM measurements of other NSs find slightly smaller radii (Gendre 03)

90%, $2\sigma$, $3\sigma$ contours; Heinke 06
During accretion, outer crust heated, quickly radiates heat (see Ed Cackett’s talk).

Deep crust under pressure fuses nuclei, heats core (Brown 98).

Heat from core emitted from surface in quiescence, on timescale of $10^4$ years, at rate $\sim 1/130$ of time-averaged flux from accretion under minimal cooling (see K. Levenfish’s talk for details).

Well-studied transient LMXBs provide constraints on cooling rate, neutrino emission, NS interior structure.
“Standard” neutrino cooling in low-mass neutron stars through neutron-neutron bremsstrahlung

Higher mass neutron stars can reach higher neutrino emissivity

E.g., direct URCA process: \( \text{n} \rightarrow \text{p} + \text{e} + \nu \), \( \text{p} + \text{e} \rightarrow \text{n} + \nu \), if protons >10%

Proton superconductivity prevents direct URCA processes, decays with increasing density, allowing range of cooling rates for range of NS masses

\( T = 10^9 \text{ K} \)

\( \log(\text{Q} \text{ (erg cm}^{-3} \text{ s}^{-1})) \)

\( \log(\rho \text{ (g cm}^{-3}) \)

Yakovlev & Pethick 04
COOLING THRU EXOTICA

- Compare young cooling NSs with cooling predictions
- Hottest NS agree with standard cooling
- Coolest NSs consistent with any enhanced cooling mechanism

Yakovlev & Pethick 2004
SAX J1808.4-3658

- Equivalent measurement for transient LMXBs, IF mass transfer rate and quiescent temperature measured.

- NSs in X-ray binaries can accrete substantial mass. Greater range in masses, greater range in cooling rates?

- SAX J1808.4-3658: Regular outbursts (every ~2 years), known distance (3.4-3.6 kpc; Galloway 06) -> known mass transfer rate

- Perfect agreement with predictions of mass transfer rate from gravitational radiation.

- Allows accurate quiescent flux prediction!
- X-ray spectrum well-fit with power-law, with no blackbody component
- Constrains neutron star temperature < 34 eV (<$4 \times 10^5$ K), $L_{\text{bol,NS}} < 10^{31}$ erg/s
- Most restrictive constraint on neutron star cooling
  New 2007 observation: $kT < 30$ eV, $L_{\text{bol,NS}} < 5 \times 10^{30}$ erg/s

X-ray spectra and residuals, Heinke et al. 2007
SAX J1808-36 cools quickly, likely has large mass

1H 1905+000 (Jonker 07) also cold ($kT<39$ eV, $L_{\text{bol,NS}}<10^{31}$ erg/s)

Suggests direct URCA, by nucleons or hyperons; may reject minimal cooling

Luminosity vs. mass transfer rate, Heinke et al. 2007 (updated)
CONCLUSIONS

- X-ray observations of LMXBs in quiescence provide constraints on behavior of dense matter
- Radius measurements of NS in 47 Tuc suggests moderately large radius or high mass
- SAX J1808.4-3658 and 1H 1905+000 require very fast cooling, disagree with minimal cooling
More globular cluster quiescent LMXBs available: Webb re-analysis of XMM observations in revision, deep NGC 6397 Chandra observations occurring this week. Constellation-X will give spectacular results!

Many more transient NSs available for study; distance measurements crucial (need Type 1 bursts--RXTE critical!)

Would LOVE to have a cooling rate measurement AND a mass for several (even one) NSs!
To tell physicists (and other astronomers):

- Zero-B hydrogen-atmosphere models are **trustworthy**!

- M,R constraints from NSs in globular clusters are **sound**, beginning to reach interesting constraints.

- Cooling constraints from some transient LMXBs are strictest test of core cooling, and **disallow minimal cooling**.
To ask nuclear theorists:

What range of nuclear EOSs are considered reasonable? For a measured NS mass and radius, what is really ruled out?

What are the real ranges of cooling rates for different NS interior properties; i.e. can pion condensates explain the coldest NSs?
EQUATIONS OF STATE

- Proton-rich nucleus gives large maximum mass, radius (MS0)
- Kaons, pions etc. can reduce P, give small radius (GS1, PAL6)
- Shaded regions excluded
- Constraining mass and radius important

Lattimer & Prakash 2004
## Table 2. Luminosities and Mass Transfer Rates

<table>
<thead>
<tr>
<th>Source</th>
<th>( N_H ) (10^{22} \text{ cm}^{-2})</th>
<th>( kT ) (eV)</th>
<th>D (kpc)</th>
<th>Outbursts</th>
<th>Years</th>
<th>( \dot{M} ) (( M_\odot \text{ yr}^{-1}))</th>
<th>( L_{NS} ) (erg s(^{-1}))</th>
<th>Refs</th>
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<tbody>
<tr>
<td>Aql X-1</td>
<td>( 4.2 \times 10^{21} )</td>
<td>( \sim 94 )</td>
<td>5</td>
<td>8</td>
<td>10.7</td>
<td>( 4 \times 10^{-10} )</td>
<td>( 5.3 \times 10^{33} )</td>
<td>1,2,3,4</td>
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<tr>
<td>Cen X-4</td>
<td>( 5.5 \times 10^{20} )</td>
<td>76</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>(&lt; 3.3 \times 10^{-11} )</td>
<td>( 4.8 \times 10^{32} )</td>
<td>5,3</td>
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<tr>
<td>4U1608–522</td>
<td>( 8 \times 10^{21} )</td>
<td>170</td>
<td>3.6</td>
<td>4</td>
<td>10.7</td>
<td>( 3.6 \times 10^{-10} )</td>
<td>( 5.3 \times 10^{33} )</td>
<td>6,3,4</td>
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<tr>
<td>KS 1731–260</td>
<td>( 1.3 \times 10^{22} )</td>
<td>70</td>
<td>7</td>
<td>1</td>
<td>30</td>
<td>(&lt; 1.5 \times 10^{-9} )</td>
<td>( 5 \times 10^{32} )</td>
<td>7,4</td>
</tr>
<tr>
<td>MXB 1659–29</td>
<td>( 2.0 \times 10^{21} )</td>
<td>55</td>
<td>( \sim 10? )</td>
<td>2</td>
<td>10.7</td>
<td>( 1.7 \times 10^{-10} )</td>
<td>( 2.0 \times 10^{32} )</td>
<td>7,4</td>
</tr>
<tr>
<td>EXO 1747–214</td>
<td>( 4 \times 10^{21} )</td>
<td>(&lt; 63 )</td>
<td>(&lt; 11 )</td>
<td>-</td>
<td>-</td>
<td>(&lt; 3 \times 10^{-11} )</td>
<td>(&lt; 7 \times 10^{31} )</td>
<td>8</td>
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<tr>
<td>Terzan 5</td>
<td>( 1.2 \times 10^{22} )</td>
<td>(&lt; 131 )</td>
<td>8.7</td>
<td>2</td>
<td>10.7</td>
<td>( 3 \times 10^{-10} )</td>
<td>(&lt; 2.1 \times 10^{33} )</td>
<td>9,10,4</td>
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<tr>
<td>NGC 6440</td>
<td>( 7 \times 10^{21} )</td>
<td>87</td>
<td>8.5</td>
<td>3</td>
<td>35</td>
<td>( 1.8 \times 10^{-10} )</td>
<td>( 3.4 \times 10^{32} )</td>
<td>11,4</td>
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<tr>
<td>Terzan 1</td>
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<td>74</td>
<td>5.2</td>
<td>-</td>
<td>-</td>
<td>(&lt; 1.5 \times 10^{-10} )</td>
<td>(&lt; 1.1 \times 10^{33} )</td>
<td>12</td>
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<tr>
<td>XTE2123–058</td>
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<td>(&lt; 66 )</td>
<td>8.5</td>
<td>1</td>
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<td>(&lt; 2.3 \times 10^{-11} )</td>
<td>(&lt; 1.4 \times 10^{32} )</td>
<td>3,4</td>
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<tr>
<td>SAXJ1810.8–2609</td>
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<td>1</td>
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<td>(&lt; 1.5 \times 10^{-11} )</td>
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<td>13,3,4</td>
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<tr>
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<td>122</td>
<td>8.8</td>
<td>2</td>
<td>10.7</td>
<td>( 1.8 \times 10^{-10} )</td>
<td>( 2.2 \times 10^{33} )</td>
<td>14,15,4</td>
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<tr>
<td>1H1905+000</td>
<td>( 1.9 \times 10^{21} )</td>
<td>(&lt; 50 )</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>(&lt; 1.1 \times 10^{-10} )</td>
<td>(&lt; 4.8 \times 10^{31} )</td>
<td>16,15</td>
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<tr>
<td>SAXJ1808.4–3658</td>
<td>( 1.3 \times 10^{21} )</td>
<td>(&lt; 34 )</td>
<td>3.5</td>
<td>5</td>
<td>10.7</td>
<td>(&lt; 1.0 \times 10^{-11} )</td>
<td>(&lt; 1.1 \times 10^{31} )</td>
<td>17,4,15</td>
</tr>
</tbody>
</table>

**Note.** — Estimates of quiescent thermal luminosities from neutron star transients, and mass transfer rates (inferred from RXTE ASM observations for systems with RXTE-era outbursts). Quiescent thermal luminosities are computed for the unabsorbed NS component in the 0.01-10 keV range. Outbursts and years columns give