The X-ray Universe
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NEUTRON STAR
STRUCTURE CONSTRAINTS
FROM LOW-RESOLUTION
X-RAY SPECTROSCOPY

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X-RAY BINARIES

- I focus on NSs in quiescence, between outbursts
- See NS surface directly, understand spectrum
- Two complementary methods to constrain NS interiors (see Mendez’s talk)

Low-mass X-ray binary (LMXB)
Quiescence

- 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 NS surface through hydrogen atmosphere
- Blackbody-like radiation from either release of internal heat, or continued low-level accretion

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

- Assume pure ionized H, B<10^9 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)
  - Temperature inhomogeneities?
A: RADIUS CONSTRAINTS

- Can constrain radius of blackbody (or NS) if know flux, temperature, distance.

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

- Hydrogen atmosphere must be considered when computing \( T_{\text{eff}} \). Must correct for redshift of light from neutron star surface, giving constraint on mass and radius.

- Distance rarely known accurately in galaxy, except in globular clusters (Brown+98, Rutledge+02, Heinke+03, Gendre+03).
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

HST image of 47 Tuc

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.
- 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 cluster NSs find slightly smaller radii (Gendre 03, Webb 07)

90%, $2\sigma$, $3\sigma$ contours; Heinke 06
During accretion, outer crust heated, quickly radiates heat.

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.

Well-studied transient LMXBs provide constraints on cooling rate, neutrino emission, NS interior structure.
Cooling Neutron Stars

- “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: $n \rightarrow p + e + \nu$, $p + e \rightarrow n + \nu$, if protons >10%
- Proton superconductivity prevents direct URCA processes, decays with increasing density, allowing range of cooling rates for range of NS masses

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, for $\dot{M}=1\times10^{-11}$ $M_{\odot}$/yr

- Allows accurate quiescent flux prediction!
- X-ray spectrum well-fit with power-law, with no blackbody component
- Constrains neutron star temperature $< 40$ eV ($< 4.6 \times 10^5$ K), $L_{\text{bol,NS}} < 1.9 \times 10^{31}$ erg/s
- One of most restrictive constraints on neutron star cooling

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, $L_{bol,NS}<10^{31}$ erg/s).

Suggests direct URCA, by nucleons or hyperons; rejects minimal cooling.

Luminosity vs. mass transfer rate, Heinke et al. 2008.
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
- Simplest sufficient model consists of n,p,e,μ only, with >10% protons in core to allow direct URCA.
FUTURE OBSERVATIONS

- More globular cluster quiescent LMXBs available for XMM (for the least dense clusters; see Webb 07) and Chandra studies (deep NGC 6397 taken, M28 coming soon). Con-X or XEUS will make major advances.

- Many more transient NSs available for study; distance measurements (e.g. X-ray bursts from RXTE/AstroSAT) are crucial.

- Focusing hard X-ray (>10 keV) instruments will better constrain the nature of the hard spectral component.
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
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
## transient lmxb observations

### Table 2. Luminosities and Mass Transfer Rates

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_H$ ($10^{22}$ cm$^{-2}$)</th>
<th>$kT$ (eV)</th>
<th>D (kpc)</th>
<th>Outbursts</th>
<th>Years</th>
<th>$\dot{M}$ ($M_\odot$ 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>
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<tr>
<td>EXO 1747–214</td>
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<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>
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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>
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<td>XTE2123–058</td>
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<td>$&lt; 1.5 \times 10^{-11}$</td>
<td>$&lt; 2.0 \times 10^{32}$</td>
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<td>2</td>
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<td>$1.8 \times 10^{-10}$</td>
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<td>1H1905+000</td>
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<td>$&lt; 50$</td>
<td>10</td>
<td>-</td>
<td>-</td>
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<td>16,15</td>
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<tr>
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<td>$&lt; 34$</td>
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<td>$1.0 \times 10^{-11}$</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