X-ray emission from neutron stars in low-mass X-ray binaries

Cooling of accretion-heated neutron stars

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Persistent and transient LMXBs

Outburst

NS heating

Quiescence

NS cooling
Study neutron stars in LMXBs

• Actively accreting
  – Difficult to observe the neutron star
    • Accretion luminosity usually outshines neutron star
    • Thermonuclear flashes
    • Quasi-stable burning
    • X-ray pulsars
  – Indirect studies
    • Spectral and variability studies (e.g., quasi-periodic oscillations, iron line studies)

• Transiently accreting neutron stars in LMXBs
  – Heating in outburst, cooling in quiescence
  – Study them in quiescence
Heating of accreting neutron stars

Envelope: accreted H, He

Outer crust: nuclei, e

Inner crust: nuclei, n, e

rp-process
Cignon

e capture

pychonuclear

outer core: npe

Inner core

Provided by Ed Brown
Do we detect cooling neutron star?

Asai et al. 1998
Lets assume: we detect cooling from reheated neutron star

Several ways to constrain properties of ultra dense matter in neutron stars

- Measure mass/radius from the thermal spectrum
  - Need distance ⇒ globular clusters
  - NSA model dependent + nasty power-law component

- Gravitational red-shifted lines
  - Only if residual accretion on NS surfaces occurs

- Inferred core temperature versus predicted one

- Crust cooling after prolonged (>years) outburst
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Need better data
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Calculations of cooling curves

- High heat conductivity in the crust
  - Rutledge et al. 2001; Shternin et al. 2008; Brown & Cumming 2009

MXB 1659-29
New results

- EXO 0748-676 and XTE J1701-462
- First EXO 0748-676
  - In outburst since approximately July 1984
  - Outburst stopped in August/September 2008
  - Many Swift, one XMM-Newton and 3 Chandra observations
  - Degenaar et al. 2009
Degenaar et al. 2009, in prep
Comparison with other two sources
XTE J1701-462

Fridriksson et al. 2009, in prep
Fridriksson et al. 2009
Most recent result

- More complicated than hoped
  - Likely some residual accretion during some observations
  - But still very promising
  - Cooling significantly faster than for the other sources
  - Fridriksson et al. 2009
Final remarks

• Potential to probe ultra-dense matter with the cooling of accretion heated neutron stars
• Crust cooling seems particularly interesting
  – High crustal heat conductivity
  – Need more sources
• Uncertainties in models
  – Cooling + heating
• Variability and non-thermal component complications
Complication: variability

Rutledge et al. 2002

Thermal or non-thermal?
- Accretion on surface?

Campana et al. 2004
Complication: non-thermal component

Wijnands et al. 2005

Jonker et al. 2007
Nasty non-thermal influences

• Seriously complicates our ability to measure the luminosity and temperature of the thermal component
  – And thus constrain M and/or R
Isolated neutron stars: cooling after formation
- E.g., talk by Dany Page

Yakovlev 2004

Reheating of neutron star in binaries

Colpi et al. 2001
XTE J1701-462

- Very bright transient
  - Near Eddington luminosity
- In outburst in 2006-2007
  - Outburst lasted approximately 1.5 years
  - Was the crust temperature profile that of a steady state?
- Excellent coverage when source decayed to quiescence again
  - RXTE $\Rightarrow$ Swift $\Rightarrow$ Chandra + XMM-Newton
Uncertainties

• Again the distance
  – Affects luminosity and inferred temperature

• Time averaged mass accretion rate
  – Core temperature determined over $> 10^{3-4}$ years
  – But only observe these systems for $< 40$ years
    • Significant errors in $\langle M_{\text{dot}} \rangle$ exist in the literature
    • Everybody uses his/her own estimates but unclear which are the best

• Uncertainties in heating and cooling models
### Cooling curves for KS 1731-260

- Rutledge et al. 2001
- Shternin et al. 2008
- Brown & Cumming 2009
- Need high heat conductivity in crust

<table>
<thead>
<tr>
<th>Curve</th>
<th>$T_{s0}^\infty$ (MK)</th>
<th>Crust model</th>
<th>Conduction in crust</th>
<th>Superfluid in crust</th>
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<tbody>
<tr>
<td>1a</td>
<td>0.8</td>
<td>A</td>
<td>normal</td>
<td>moderate</td>
</tr>
<tr>
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<td>1b</td>
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\[ (a) \ M = 1.6 \ M_\odot \]

\[ (b) \ M = 1.4 \ M_\odot \]
Calculating cooling curves

• The modeled curves depend on many parameters
  – Crust properties
    • Heat conductivity
    • Likely fully replaced crust
  – Crustal heating properties
    • Deep crustal heating and maybe also outer crust heating
    • Assume steady state temperature profile
  – Neutron star equation of state
  – Core cooling processes

• Observational uncertainties
  – Distance
  – Heat deposited in the crust during outburst
    • Time averaged accretion rate
  – When did accretion stop?
  – Residual accretion in quiescence