Crustal cooling in accretion heated neutron stars

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• X-ray transients
• Accretion heated neutron stars
• Observing NS crusts cooling
• What next?
• *To answer Bob:* we can measure the thermal relaxation time of the crust (we think!)
X-ray Binaries

Low-mass X-ray binary (LMXB):

donor $\sim 1 \, M_\odot$
The variable X-ray sky

Credit: The RXTE ASM Team
Why are X-ray binaries transient?

- Majority of the time spent in quiescence - little or no accretion
- Matter builds up in outer disk
- Thermal instability triggers rapid accretion

→ outburst

see e.g., Lasota (2001)
Transients

- Increase by $10^3$ - $10^4$ in luminosity
- Outbursts last typically \textit{weeks} - \textit{months}
- Recurrence timescale typically \textit{years} - \textit{decades}

EXO 1745-248 in Terzan 5

Wijnands et al. 2005
Some transient lightcurves...

Count rate

Time (days)

Data from RXTE ASM Team
Why look at quiescent neutron stars?

- Outburst luminosity $10^{36} - 10^{38}$ erg s$^{-1}$
  - dominated by X-rays from accretion disk
- Quiescent luminosity $<10^{34}$ erg s$^{-1}$
  - mostly thermal X-rays NS
- But, NS in LMXBs are old
  - why is it still hot?
Deep crustal heating

Brown, Bildsten & Rutledge (1998)

- Energy deposited during outburst
- Freshly accreted material compresses inner crust (~300 m deep)
- Trigger nuclear reactions
- Repeated outbursts heat core (over $10^4$ yr)
- Get to a steady-state

Quiescent luminosity set by time-averaged accretion rate
Deep crustal heating continued.......

Quiescent Luminosity

Time-averaged mass accretion rate

\[ L_q = 8.7 \times 10^{33} \left( \frac{\langle \dot{M} \rangle}{10^{-10} \, M_\odot \, \text{yr}^{-1}} \right) \frac{Q}{1.45 \, \text{MeV}} \, \text{ergs s}^{-1} \]

Heat deposited in crust per accreted nucleon
Learning about NS interior

- Quiescent luminosity depends on level of neutrino emission
- Measure the quiescent fluxes (luminosities) of as many NS as possible
- Put them all together - can learn something about NS cooling.......leave for Craig Heinke
Observing neutron stars in quiescence

- Dominated by thermal emission (generally!)
- Blackbody: Flux \( \propto (\text{Radius}/\text{Distance})^2 \)
- But blackbody fits give too small a radius (e.g. Rutledge et al. 1999)
- Need to use atmosphere spectra (e.g. Zavlin et al. 1996)
- Simpler than in isolated neutron stars:
  - H dominant, and low B
Neutron star atmosphere spectrum

NSA model: Zavlin et al. (1996)

\[ T = 10^6 \text{ K} \]
\[ R = 10 \text{ km} \]
\[ M = 1.4 \text{ M}_\odot \]
\[ D = 10 \text{ kpc} \]
Neutron star atmosphere spectrum

- Example: fitting B-body to NSA
  \[ T = 1.7 \text{ km} \]
  \[ R = 2 \times 10^6 \text{ K} \]

- Temperature: too high
- Radius: too small

NSA model: Zavlin et al. (1996)
Transients with extra-long outbursts

Data from RXTE ASM Team
KS 1731-260

- 12.5 year outburst, no other outbursts seen
- Source goes into quiescence in Jan 2001 (Wijnands et al. 2001)
- Rutledge et al. (2002) predict crust will be heated significantly out of thermal equilibrium with interior, and should cool

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Rutledge et al. 2002
KS 1731-260: did it cool?

YES!

Wijnands et al. 2002
KS 1731-260: observations

5 Chandra

2 XMM-Newton
Cooling crust of KS 1731-260

- Require exponential that levels off to a non-zero value
  - returning to thermal equilibrium with core
- e-folding time:
  - $325 \pm 101$ d for temperature

Cackett et al. 2006
MXB 1659-29

- First detected in 1976
- Turned off in 1979, and remained in quiescence for 21 year
- Then, 2.5 year outburst
- Returned to quiescence in Sept. 2001
MXB 1659-29 in quiescence

- As in KS 1731: crust heated out of thermal equilibrium with core, and cools once in quiescence

Wijnands et al. (2004)
Cooling crust of MXB 1659-29

- Again, require exponential to level off

- e-folding time:
  - $505 \pm 59$ d for Temp

- e-folding times different:
  - KS 1731-260 cools faster by a factor $\sim 1.6$

Cackett et al. 2006
Crustal cooling

- So, in both objects we’ve seen the crust cool (apparently to thermal equilibrium with core)
- *We can measure the thermal relaxation time*
- But what does it tell us about the crust?

![Graphs showing temperature and flux over time for KS 1731 and MXB 1659](image)
What’s this tell us about the crust?

- In the Rutledge et al. models, implies crusts have high thermal conductivity.
- KS 1731 cools quicker by a factor of 1.6 - why?
  - Different compositions?
  - Different crust thickness?
Timescale vs. crust thickness

- Higher mass (surface gravity), thinner crust, faster cooling
- KS 1731 would need to be ~25% more massive

\[ \tau \sim (dR)^2 (1+z)^3 \]

Points: numerical results assuming Haensel & Zdunik (1990) composition

Dotted line: Lattimer et al. 1994 scaling
Is the thermal relaxation time model independent?

- We recover the same timescales if using a blackbody model.
- Or, just using raw Chandra count rates.
- Timescale, and observed trend is robust.
Further observational issues

• Is the spectrum purely thermal?

• Has it really stopped cooling - what will happen next?
Is the spectrum just thermal?

- Some quiescent neutron stars require power-law components (e.g. Cen X-4) in addition to the thermal component.
- Not needed in KS 1731-260 and MXB 1659-29, but what about the faintest observations.......can’t tell!

Cen X-4: PL about 50% of 0.5-10 keV flux
Is the spectrum really thermal?

- Power-law component becomes more prominent as sources fade
- Need deeper observations of these sources to tell the significance

Jonker et al. 2004
What will happen next?

- Possibilities:
  - Steady flux - great news, everything ok!
  - Continued cooling - what’s going on?
  - Variability around steady flux - residual accretion important
What do we need to do?

Observationally:

• Continued observations of KS 1731-260 and MXB 1659-29

• Monitoring of the next quasi-persistent source to go into quiescence

Theoretically:

• Can crust models explain these timescales?

• Why are the timescales different?
Other possible sources

- Want:
  - Long outburst (> 2ish years)
  - Ideally low hydrogen column density

GS 1826-238
Data from RXTE/ASM team

EXO 0748-676
Data from RXTE/ASM team
HETE J1900.1-2455

- Recently discovered accretion-powered millisecond X-ray pulsar (Kaaret et al. 2006)
- Accreting for ~2 years
- Looked like it was turning off..........
- ......but bounced back up again

Data from RXTE/ASM team
And finally: the next generation: Constellation-X

- NS radii: currently accurate to a few km at best
- Hard to get enough photons from most sources!
- With Con-X radius will be limited by accuracy of distance measurement and models

Credit: NASA
**Chandra**

- MXB 1659-29, 25 ks

**Constellation-X**

- 25 ks

**Graphs**

1. **Normalized counts s⁻¹ keV⁻¹**
   - Chandra
   - Constellation-X

2. **Radius (km)**
   - Chandra
   - Constellation-X

3. **Mass (M☉)**
   - Chandra
   - Constellation-X

**Data**

- Mass (M☉)
  - MXB 1659-29
  - Constellation-X

- Radius (km)
  - MXB 1659-29
  - Constellation-X
The one thing to take away:

Quasi-persistent sources provide a rare opportunity to observe crustal cooling and we think we’ve measured the thermal relaxation time of the crust in 2 sources.