Transiently accreting neutron stars:

Peeking into their crusts
Transient x-ray binaries

- Accretion heats the neutron star crust, in quiescence it cools down
- Cooling is observable and probes the structure of the crust and several nuclear reactions processes
Neutron stars in transient X-ray binaries

Quiescence: X-ray emission from the neutron star surface

Accretion outburst: X-ray emission dominated by the accretion disk
Neutron star structure

Prior to an accretion outburst

Neutron star cools via:
1) Neutrino emission (not observable) core
2) Photon emissions (X-rays) surface

Neutron star interior nearly isothermal → surface temperature tracks core
Neutron star structure

During an accretion outburst

Crust compressed: nuclear reactions induced

Crust locally heated: heat conducted to core + surface

Neutron star not observable: emission accretion disk

Heanzel & Zdunik 1990; 2003; 2008
Gupta et al. 2007
Neutron star structure

After an accretion outburst

Neutron star crust hotter than core → surface temperature tracks crust!

Ushomirsky & Rutledge 2001
Rutledge et al. 2002
How to detect thermal emission
Quiescent X-ray spectra

Degenaar et al. 2009
How to detect thermal emission
Quiescent X-ray spectra

Possible components:
1) Soft, thermal
   - Peaks below 2 keV
   - Thermal emission neutron star surface
   - Atmosphere model → temperature
How to detect thermal emission

Quiescent X-ray spectra

Possible components:
1) Soft, thermal
   - Peaks below 2 keV
   - Thermal emission neutron star surface
   - Atmosphere model → temperature

2) Hard, non-thermal
   - Dominates > 2-3 keV
   - Contributes 0-100%
   - Origin unknown
Transient neutron stars accreting for years:
- Outburst: crust severely heated
- Quiescence: crust cools (Rutledge et al. 2001)

Two studied sources:
- KS 1731: active 12.5 yr
- MXB 1659: active 2.5 yr

Both quiescent since 2001 → Monitoring observations

Quiescent thermal emission: Can we detect a heated crust?
Can we detect a heated crust?
Yes! Cooling down in quiescence

Neutron star temperature (eV)

Time since accretion stopped (days)

Cackett et al. 2006, 2008, 2010
KS 1731-260
MXB 1659-29

$\sim 4$ yr
Can we detect a heated crust? 
Yes! Cooling down in quiescence

KS 1731-260 
MXB 1659-29

Neutron star temperature (eV)

Time since accretion stopped (days)

\[ t \sim 4 \text{ yr} \]
Can we detect a heated crust? Yes! Cooling down in quiescence

Properties core + accretion history

Neutron star temperature (eV)

Time since accretion stopped (days)

KS 1731-260
MXB 1659-29

t ~ 4 yr
Can we detect a heated crust? Yes! Cooling down in quiescence

Properties core + accretion history

Properties crust + last outburst

Neutron star temperature (eV)

Time since accretion stopped (days)

$\sim 4$ yr
Crust cooling: 2 more sources

1) XTE J1701-462:
   Active 1.5 yr
   Quiescent since 2007
   Fridriksson et al. 2010, 2011

2) EXO 0748-676:
   Active 24-28 years
   Quiescent since 2008
   Degenaar et al. 2010, 2011
   Diaz Trigo et al. 2011
What have we learned:
1) Crust cooling is observable!
2) Neutron star crust is highly conductive
3) Additional heat sources in crust?

Shternin et al. 2007
Brown & Cumming 2009
See poster by M. Fortin

Disadvantage:
Long outbursts are rare!
Few sources available for future study
What have we learned:
1) Crust cooling is observable!
2) Neutron star crust is highly conductive
3) Additional heat sources in crust?

Shternin et al. 2007
Brown & Cumming 2009
See poster by M. Fortin

Disadvantage:
Long outbursts are rare!
Few sources available for future study
Can we detect crust cooling if the outburst is short? – Test case!

Globular cluster Terzan 5

10-week accretion outburst 2010 October-December

IGR J17480-2446

Quiescence: Chandra

MAXI intensity (counts/s/cm²)

Time since 2009 July 1 (days)
Thermal evolution: crust cooling?

- Thermal emission initially enhanced, but decreasing

(Outburst: 2010 Oct-Dec)

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted
Thermal evolution: crust cooling?

Thermal emission initially enhanced, but decreasing

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Thermal evolution: crust cooling?

(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating \(\rightarrow\) no match!

Thermal evolution code
Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
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Thermal evolution: crust cooling!

(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating \(\rightarrow\) no match!
- Extra shallow heating \(\rightarrow\) match!

Thermal evolution code
Brown & Cumming 2009
Degenaar & Wijnands 2011a,b
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Thermal evolution: crust cooling!

(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating → no match!
- Extra shallow heating → match!

Quite high:
Current models 2 MeV/nucleon

Thermal evolution code
Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted
Thermal evolution: crust cooling!

(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating → no match!
- Extra shallow heating → match!

Can be crust cooling, but: substantial heating at shallow depth required

Thermal evolution code
Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted
Crust cooling: 4 sources

Time since accretion stopped (days)

Neutron star temperature (eV)

- EXO 0748–676
- XTE J1701–462
- MXB 1659–29
- KS 1731–260
Crust cooling observable also for short outbursts

- Heating at shallow depth required: has been hypothesized

Horowitz et al. 2007
Gupta et al. 2007
Brown & Cumming 2009
See also poster by M. Fortin

- More source available for study!
To take away

Transient neutron star X-ray binaries in quiescence

- Thermal emission from neutron star surface observable:
  Probe properties neutron star crust + core

- Cooling of the heated crust observed after long outbursts:
  Probe neutron star crust properties + nuclear physics

- Crust cooling now observed after a short outburst:
  More common, so more sources available for study
  Indications of extra heating sources at shallow depth
Quiescent X-ray spectra before and after 2010 accretion outburst

(Outburst: 2010 Oct-Dec)

- Thermal emission detectable!
- Clear difference before and after
  - 2 months after outburst
  - 4 months after outburst
  - 1 year before outburst

Crust cooling?

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted
Quiescent thermal emission: Probe neutron star interior

Isothermal interior: Thermal emission measures core temperature

Core temperature set by:
1) Time-averaged mass-accretion rate = heating
2) Rate of neutrino emission from core = cooling
Contribution powerlaw

**Hard powerlaw:**
- Contributes 0-100%
- Varies widely between sources
- Correlated with luminosity?

**AMXPs:**
> 50% powerlaw
- Pulsar wind mechanism
- Accretion onto the magnetosphere?
Pre- and post-outburst images

~64 weeks prior to the 2010 outburst
~8 weeks after the 2010 outburst

(exposure times are similar)