Sub-Eddington accreting neutron stars

Rudy Wijnands
Anton Pannekoek Institute for Astronomy
University of Amsterdam

15 December 2015
Texas Symposium 2015, Geneva
Low-mass X-ray binary transients

- NS heating
- NS cooling

Outburst

Disk Instability Model

Quiescence

Time in days

X-ray luminosity

0 20 40 60
Both states quite well studied!

How about the intermediate regime?

Outburst: Bright but short

Quiescence: Very dim but very long

1%-100% $L_{Edd}$

$< 0.01% \ L_{Edd}$
Both states quite well studied!

How about the intermediate regime?

Outburst

Bright but short

Sub-Eddington systems

Difficult to study!

Quiescence

Dim and very short

Very dim but very long
Final decay phase of bright transients

Disadvantage: it might only last for days
Difficult to get high quality data

Cooling NS kicks in

Fridriksson et al. 2010
Very-faint X-ray transients

- Never become brighter than $10^{36}$ erg s$^{-1}$
  - Difficult to find and typically only have low quality data
  - Outbursts tend to be brief so difficult to obtain data

Muno et al. 2005

Degenaar & Wijnands 2010
(Quasi-)stable subluminous systems

- Several NS systems are persistently subluminous
- Several NS transients are quasi-stable at very low luminosities
- This allows for more detailed studies

Jonker & Keek 2008

Degenaar et al. 2011
Neutron star

$\leq 0.01\% L_{\text{Edd}}$

$0.01\% - 1\% L_{\text{Edd}}$

$1\% - 10\% L_{\text{Edd}}$

Corona

$1\% - 10\% L_{\text{Edd}}$

Neutron star

$0.01\% - 1\% L_{\text{Edd}}$

$< 0.01\% L_{\text{Edd}}$

$< 0.01\% L_{\text{Edd}}$

Note: 1 type out of 3 possibilities
Studying the X-ray spectra

• Usually the data have low quality
  – Very few photons

• Only simple models can be fitted to the spectra
  – Typically power-law model \( (E^{-\Gamma}, \Gamma = \text{photon index}) \)

• Sometimes high(er) quality data are obtained!
Evolution of the photon index

Wijnands et al. 2015

[Graph showing the evolution of photon index vs. total X-ray luminosity for NSs and BHs]
Neutron star becomes visible

Appearance of strong black-body component, likely from low level accretion onto the NS surface, causes the spectrum to soften.

When NS component added to the model, power-law becomes much harder (photon index 1-1.5)!
NSs at extremely low accretion rates

- So what at lower ($< 10^{34}$ erg s$^{-1}$) luminosities?

![Graph showing photon index vs. total X-ray luminosity](image)
• Three options
  – Accretion totally switches off: “true” quiescence
    • Spectrum dominated by soft component
    • Cooling studies of accretion-heated neutron stars
  – Low-level accretion continues
    • Spectra very similar to those of the sub-Eddington systems!
    • Soft component with very hard power-law ($\Gamma \sim 1-1.5$)
  – Magnetic field effects state?
    • Power-law dominated spectrum, very hard
    • Connection with the ‘transitional ms pulsars’?
NSs at extremely low accretion rates

- True quiescence = no accretion onto the neutron star
- Cooling NS studies

Wijnands et al. 2003, 2015

MXB 1659-298
• Three options
  – Accretion totally switches off: “true” quiescence
    • Spectrum dominated by soft component
    • Cooling studies of accretion-heated neutron stars
  – Low-level accretion continues
    • Spectra very similar to those of the sub-Eddington systems!
    • Soft component with very hard power-law ($\Gamma \sim 1-1.5$)
  – Magnetic field effects state?
    • Power-law dominated spectrum, very hard
    • Connection with the ‘transitional ms pulsars’?
Comparison of spectra

Asai et al. 1998

$10^{32-33}$ erg s$^{-1}$

Very similar spectral shape!

Degenaar et al. 2013

$10^{34-35}$ erg s$^{-1}$

Very similar spectral shape!
• Intimate connection between the soft and the hard power-law components
  – Roughly equal flux (0.5-10 keV) in both components over a large luminosity range
    • By combining quiescent data with data from sub-Eddington systems
    • \( L_x = 10^{32} \) to \( 10^{35} \) erg s\(^{-1}\)
  – Likely soft and hard components originate from the same process
    • Very low level accretion onto NS!
    • Exact origin of the power law?
    • Boundary layer accretion?
      – Just a toy model idea!
      – E.g., D’Angelo et al. 2015
Boundary layer accretion

Boundary layer at high accretion rate assuming disk accretion

Black-body radiation
Bremsstrahlung

Quasi-spherical rotating inflow
1\%-10\% L_{Edd}

0.01\%-1\% L_{Edd}

< 0.01\% L_{Edd}

All accretion onto NS surface!
• **Three options**
  
  – Accretion totally switches off: “true” quiescence
    • Spectrum dominated by soft component
    • Cooling studies of accretion-heated neutron stars
  
  – Low-level accretion continues
    • Spectra very similar to those of the sub-Eddington systems!
    • Soft component with very hard power-law ($\Gamma \sim 1-1.5$)
  
  – Magnetic field effects state?
    • Power-law dominated spectrum, very hard
    • Connection with the ‘transitional ms pulsars’?
NSs at extremely low accretion rates

- Weird power-law dominated state; connection with transitional ms pulsars?
- Systems that have a magnetic field?
  - Magnetic accretion?

Heinke et al. 2009
Wijnands et al. 2015
Transitional millisecond pulsars

- Neutron star binaries (4 known) that switch between a millisecond radio pulsar phase and an accreting phase
  - Similar hard spectra and luminosities as very hard quiescent systems
  - Magnetic accretion? Propeller regime?

---

Radio pulsar

X-ray binary

Papitto et al. 2013

Image credit: NASA
Mode switching at low luminosity

M28I
Linares et al. 2014

PSR J1023+0038
Bogdanov et al. 2015
Main uncertainties

• Unclear if those hard quiescent spectra are caused by the same mechanism as the transitional system spectra
  – Very low quality data for the quiescent systems
  – Typically much farther away than the transitional systems
    • One has to worry (a lot) about selection effects

• At low accretion rate the accretion is not through a disk but through a radial/quasi-spherical, rotating radiatively inefficient inflow
  – Unclear how magnetic accretion happens in such cases
    • Unclear how accretion happens even in the absence of a magnetic field
  – What causes the mode switching?
Final model of the spectral evolution

- Power-law comes from (up to three) different physical mechanisms

Wijnands et al. 2015
Conclusions

• Studying low accretion rates is very important
  – Difficult to study and get high quality data
    • But making progress! New types of NS studies can be done now!
  – Neutron star is a very important player
  – The hard, power-law component is also due to accretion onto the surface of the neutron star!
    • Boundary layer accretion?

• Connection with very low accretion rates
  – Propeller accretion?
    • Neutron star magnetic field could become an important player
  – Boundary layer accretion?
    • Neutron star has no magnetic field?
  – Cooling neutron star if accretion has fully halted

• Lot of uncertainties in the data and models