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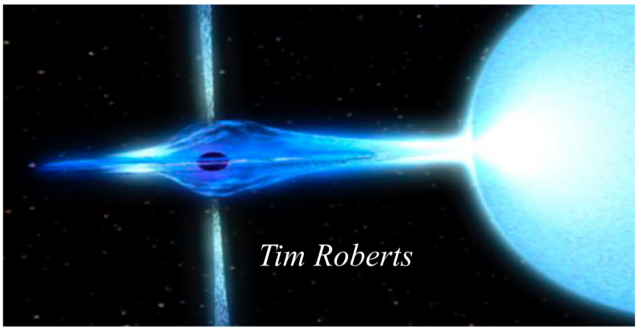
Durham Astronomy Postgraduate Course: Stellar Structure & Evolution lectures

5. Observations of Black Holes



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- *"Well, the thing about a black hole - its main distinguishing feature - is it's black. And the thing about space, the colour of space, your basic space colour, is black. So how are you supposed to see them?"*

Context

- Most exotic stellar endpoints: black holes
- In last 40 years have changed from theoretical peculiarity to important constituent of Universe
- In lectures to come with Prof Done should cover:
  - General relativity: curvature of space-time, event horizons
  - Formation of black holes, accretion discs as sources of X-rays, last stable orbit
- Also important: astrophysical emission processes
  - Comptonisation, synchrotron, bremsstrahlung etc…

Aims of this lecture

- How have we detected black holes?
- What do they look like?
  - Counterparts
  - Accretion states
  - Outburst cycles

Stellar Endpoints

- Low mass stars expel atmosphere to leave degenerate core: white dwarf (< 1.4 $M_{\odot}$)
- High mass stars go supernova!
  - Except type 1a: accreting white dwarf
  - Type 1b,c & type 2: massive stellar collapse
- Supernovae leave ultra-compact remnants
  - Usually neutron star (< 3 – 5 $M_{\odot}$)
  - But some larger objects: black holes

The beginnings of X-ray astronomy

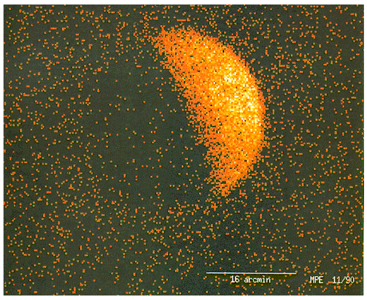
- Our atmosphere is a hindrance; absorbs X-rays!
- Earliest flights circa. 1949 - X-ray detectors in nose cone of V2 rocket, discover solar X-rays
- First cosmic X-ray source: Sco X-1, reported by Giacconi et al. in 1962

Top: Ricardo Giacconi.

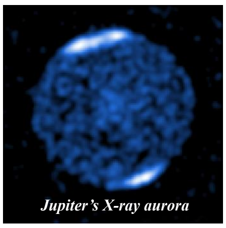
Left: Aerobee rocket, similar to that used to find Sco X-1

History of X-ray astronomy in a slide

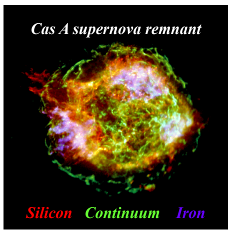
- Rocket & balloon flights dominated first decade (60s)
- From early 1970s - satellite observatories dominated (*Uhuru* the first)
- Notable missions: *HEAO-1* & *HEAO-2* (*Einstein*) (1977-1981); *EXOSAT*, *GINGA* (late 80s); *ROSAT*, *ASCA* (1990s); *RXTE* (late 90s/early 00s); *XMM-Newton & Chandra*

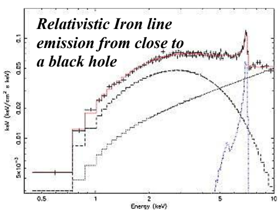


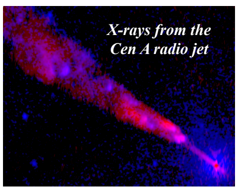
Extra-terrestrial X-ray sources

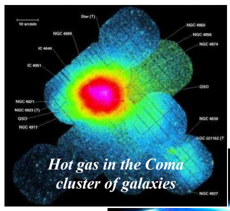

Jupiter's X-ray aurora


The nearest star in X-rays


Cas A supernova remnant


Relativistic Iron line emission from close to a black hole


X-rays from the Cen A radio jet

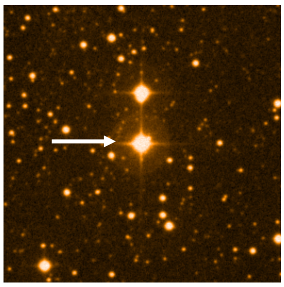

Hot gas in the Coma cluster of galaxies

RXTE and the variable X-ray sky

- Rossi X-ray Timing Explorer - small NASA mission launched in 1995 to study variable X-ray sky

Cygnus X-1

- Amongst earliest discovered celestial X-ray sources (1964)
- Varied in X-rays; radio variation gave accurate position
- Identified with $m_V \sim 8.95$, variable O9.7 Iab star HDE 226868 ($d \sim 2.5$ kpc)



5×5 arcminute DSS field, centered on Cyg X-1.

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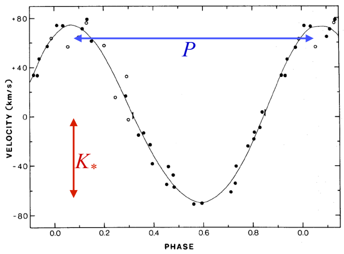
The first black hole

- X-ray emission obviously not coming from the star…
- Radial velocity curve - Doppler shifting lines with period 5.6 days.
  - From mass function, mass of HDE 226868 derive a companion mass of ~ 9 $M_\odot$.
- Too massive for a neutron star ($M_{NS,max}$ ~ 3 $M_\odot$) ; must be a black hole (Webster & Murdin 1972; Bolton 1972)

$$f(M) = \frac{M_X^3 \sin^3 i}{(M_* + M_X)^2} = \frac{PK_*^3}{2\pi G}$$



Radial velocity curve based on absorption features in the atmosphere of HDE 226868 (from Bolton 1975)

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Known stellar black hole masses

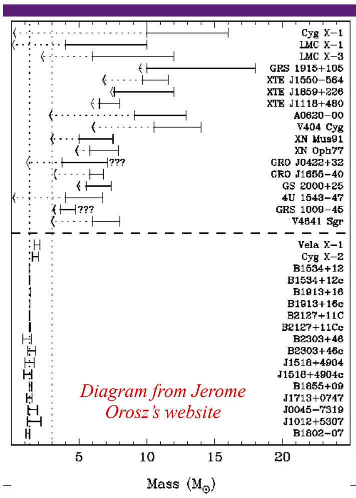
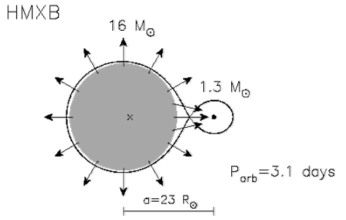


Diagram from Jerome Orosz's website

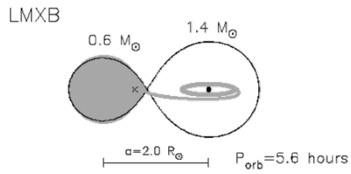
- Now up to 20 secure black hole IDs from dynamical masses (17 shown left)
- Divided into two types based on companion star: HMXBs and LMXBs

Black Holes

HMXBs vs LMXBs



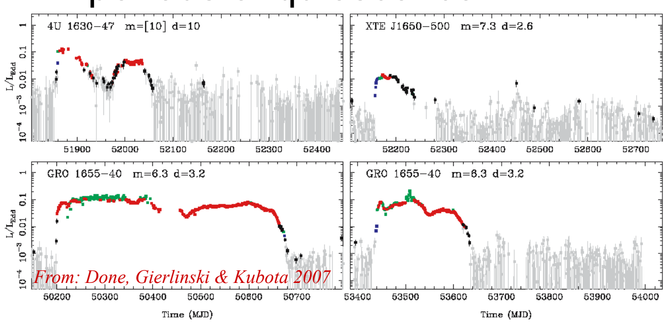
From: Tauris & van den Heuval 2006



- High-mass X-ray binaries: compact object fed by high velocity stellar wind and/or Roche-lobe overflow from massive star ($M_* > 10\ M_\odot$)
- Low-mass X-ray binaries: compact object fed by Roche-lobe overflow from low-mass star ($M_* < 1M_\odot$)

LMXBs as Soft X-ray Transients

- Behaviour of most LMXBs: outbursts of days to months followed by much longer periods of quiescence

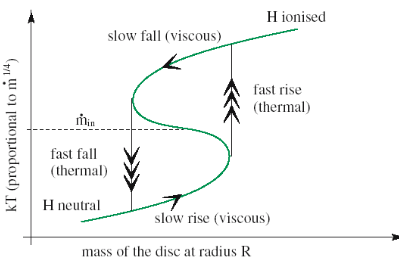


From: Done, Gierlinski & Kubota 2007

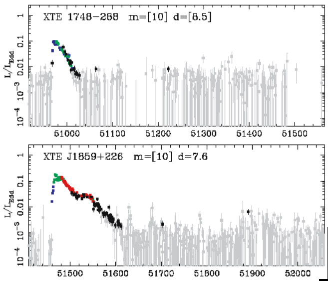
X-ray rise accompanied by 6 - 10 mag rise in optical light (i.e. nova). RV curves derived from counterpart in quiescence.

Hydrogen ionisation instability

- Accretion disc at low accretion rates is unstable both thermally & viscously for temperatures around H ionisation, i.e. ~ 10^{4-5} K.



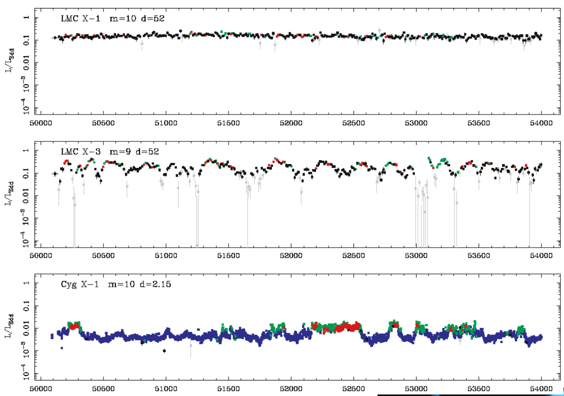
From: Done, Gierlinski & Kubota 2007



Examples of classic "FRED" (fast rise exponential decay) profile

HMXBs: stable accretors

- Higher mass accretion rate in HMXBs keeps outer disc above H ionisation instability - relatively persistent X-ray sources



From: Done, Gierlinski & Kubota 2007

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Accretion states

- Do all accreting black holes behave in the same way (at least during outburst)?
- Answer: no!
- Display different X-ray spectral and X-ray timing characteristics, dependent (to first order) upon the accretion rate
- Describe changes in the physical state of the system
  - See McClintock & Remillard (2006)

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Quiescent state

- Extraordinarily faint state - $L_X \sim 10^{30.5}$-$10^{33.5}$ erg s^{-1} - and hard, non-thermal spectrum (power-law photon index $\Gamma \sim 1.5 - 2.1$)
  - $\Gamma = \alpha + 1$ from power-law form $f(\nu) = Ae^{-\alpha\nu}$
- Five black holes now detected in quiescent state; Eddington ratios ~ $10^{-8.5}$
  - Similar NS binaries have quiescent luminosities ~ 100 times higher (e.g. Narayan et al. 2001)
  - Evidence for event horizon?

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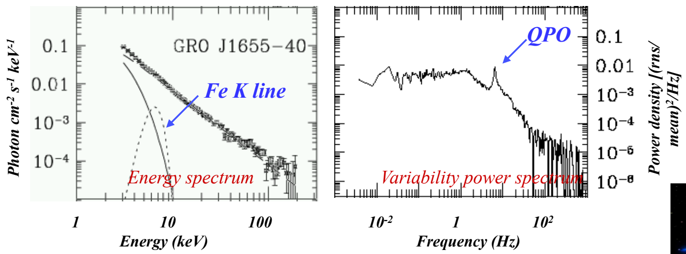
Hard X-ray state (formerly Low/Hard)

- Definition: >80% of 2-20 keV flux in power-law with 1.5 < Γ < 2.1, integrated 0.1-10 Hz power is strong (0.1 < *r* < 0.3)
- Disc absent or cool



From McClintock & Remillard 2006

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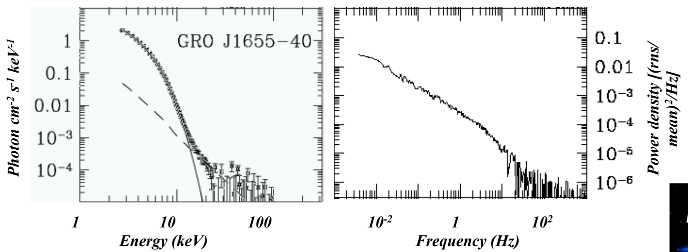
Thermal-dominant (High/Soft)

- Definition: disc dominates energy spectrum (> 75% of flux in 2-20 keV), power spectrum shows weak or no QPOs, little power (*r* < 0.06)



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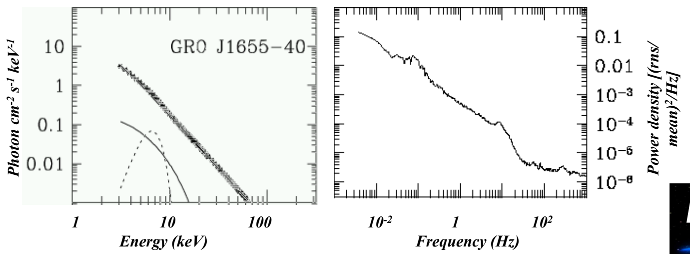
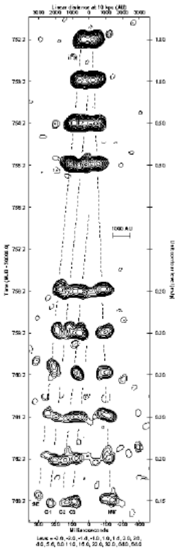
Steep power-law state (very high)

- Definition: power-law with $\Gamma > 2.4$; either QPOs present and power-law > 20% of 2-20 keV flux, or no QPO but power-law > 50% of flux; moderate power $r < 0.15$



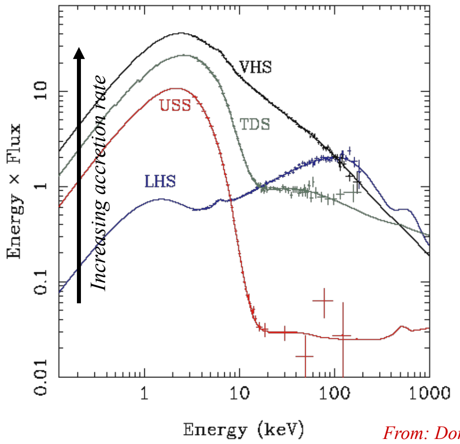
Radio emission

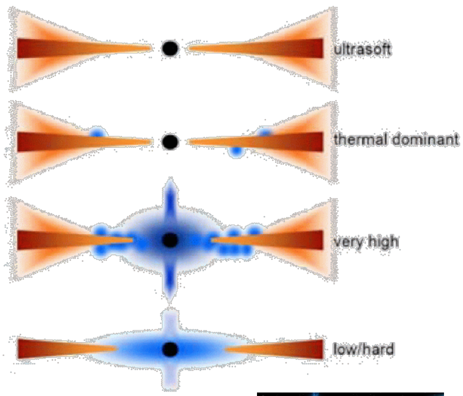


- Hard state: ubiquitous, steady mildly-relativistic radio emission (also seen in quiescence)
- Thermal-dominated: radio jets are quenched
- Steep power-law: radio quiet, but with occasional explosive relativistic jet formation - *microquasars*

From Fender (2006a)

Physical interpretation

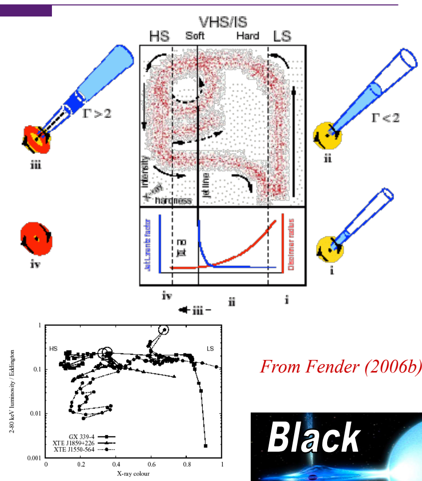




From: Done, Gierlinski & Kubota 2007

Outburst cycles

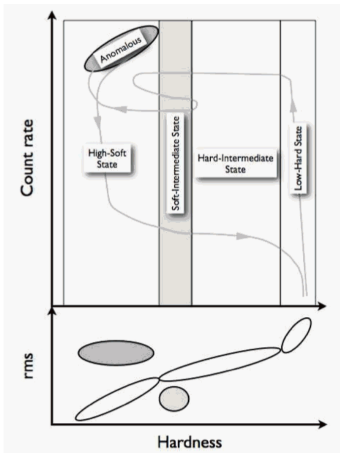
- How do we put these states together?
  - Observations - outburst cycles!
  - "q" diagrams
  - Note hysteresis: luminosity at which source leaves hard state varies, apparently at random



From Fender (2006b)

A new classification scheme

- ☐ Old classification based on original 1970s/80s snapshot observations
- ☐ Outburst cycles provide more holistic view of behaviour - base new classification scheme on this?
  - See Belloni (2009)



Summary

- ☐ Black holes discovered in binaries via X-rays
  - Dynamical mass functions from optical counterparts show they're probably black holes
- ☐ Two types: HMXBs (persistently X-ray bright) and LMXBs (a.k.a. Soft X-ray Transients due to outbursts)
- ☐ Different accretion states observed: quiescent, hard, thermal-dominated, steep power-law
- ☐ Outbursts follow a common cycle

Further reading: Compact Stellar X-ray Sources (Eds. Lewin & van der Klis, CUP)
Done, Gierlinski & Kubota 2007, ARA&A, 15, 1

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Next time…

Populations of black holes, black hole unification, and ultraluminous X-ray sources

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