Discs and Jets in X-ray Binaries: Confusion in the Optical and Infrared

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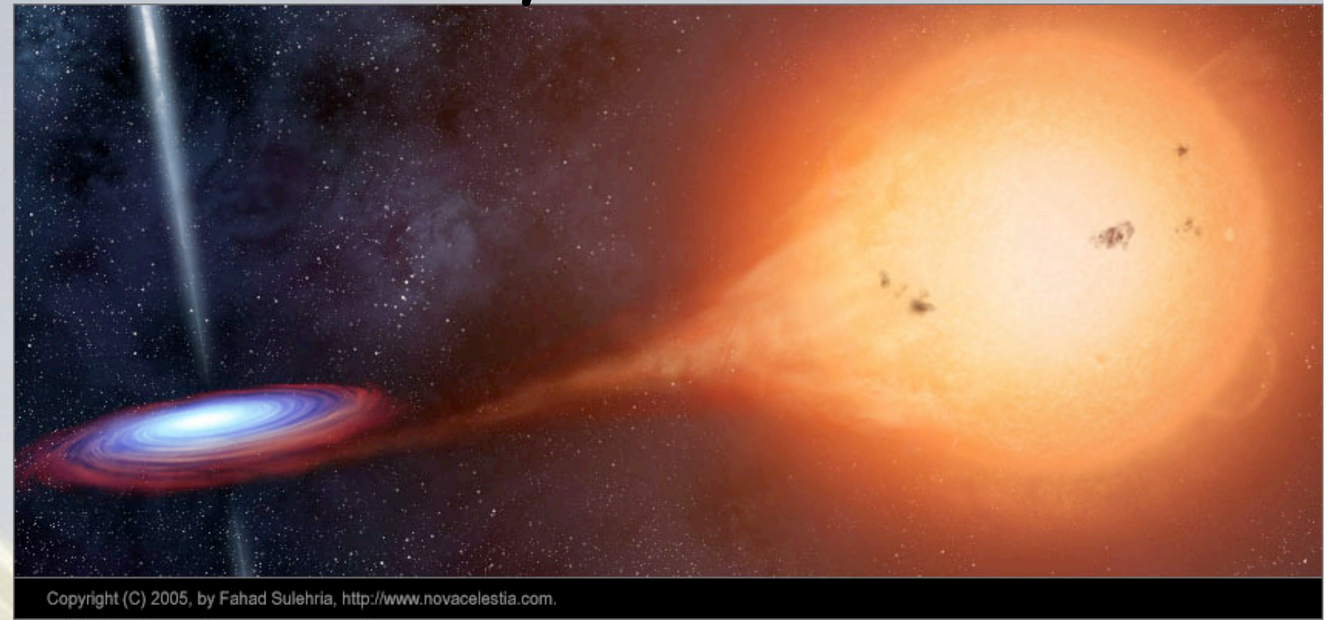
Introduction: X-ray Binaries

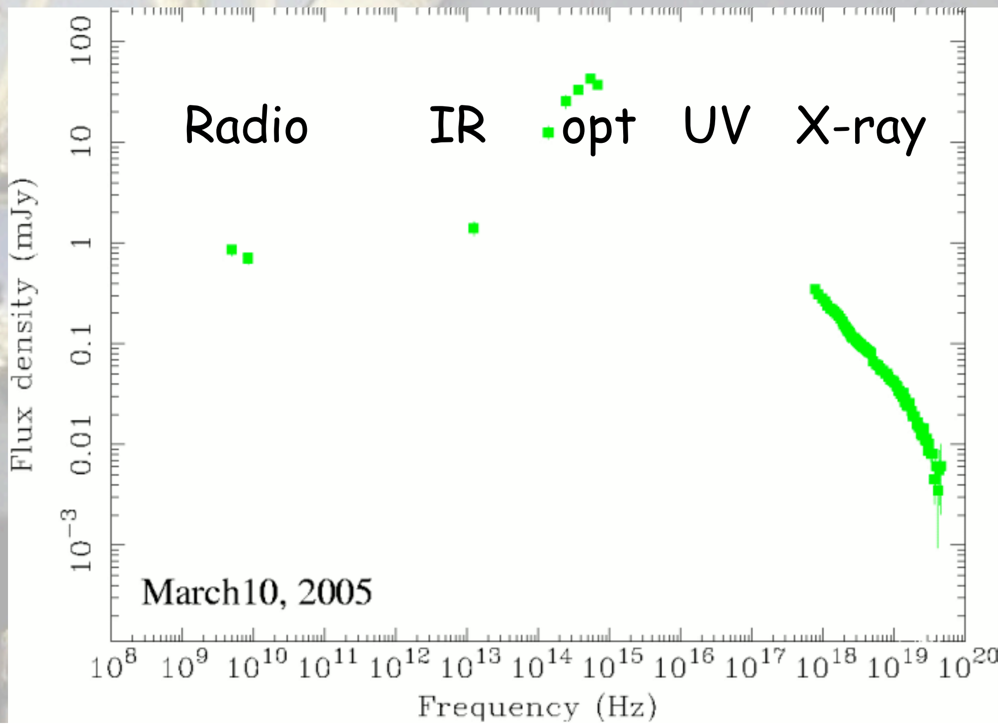
This is a low-mass X-ray binary (LMXB)



Physical components:
- → Star
- → Compact object
- → Accretion disc
- → Hot inner flow
- → Corona
- → Jets

Mass transfer causes an outburst when disc becomes unstable

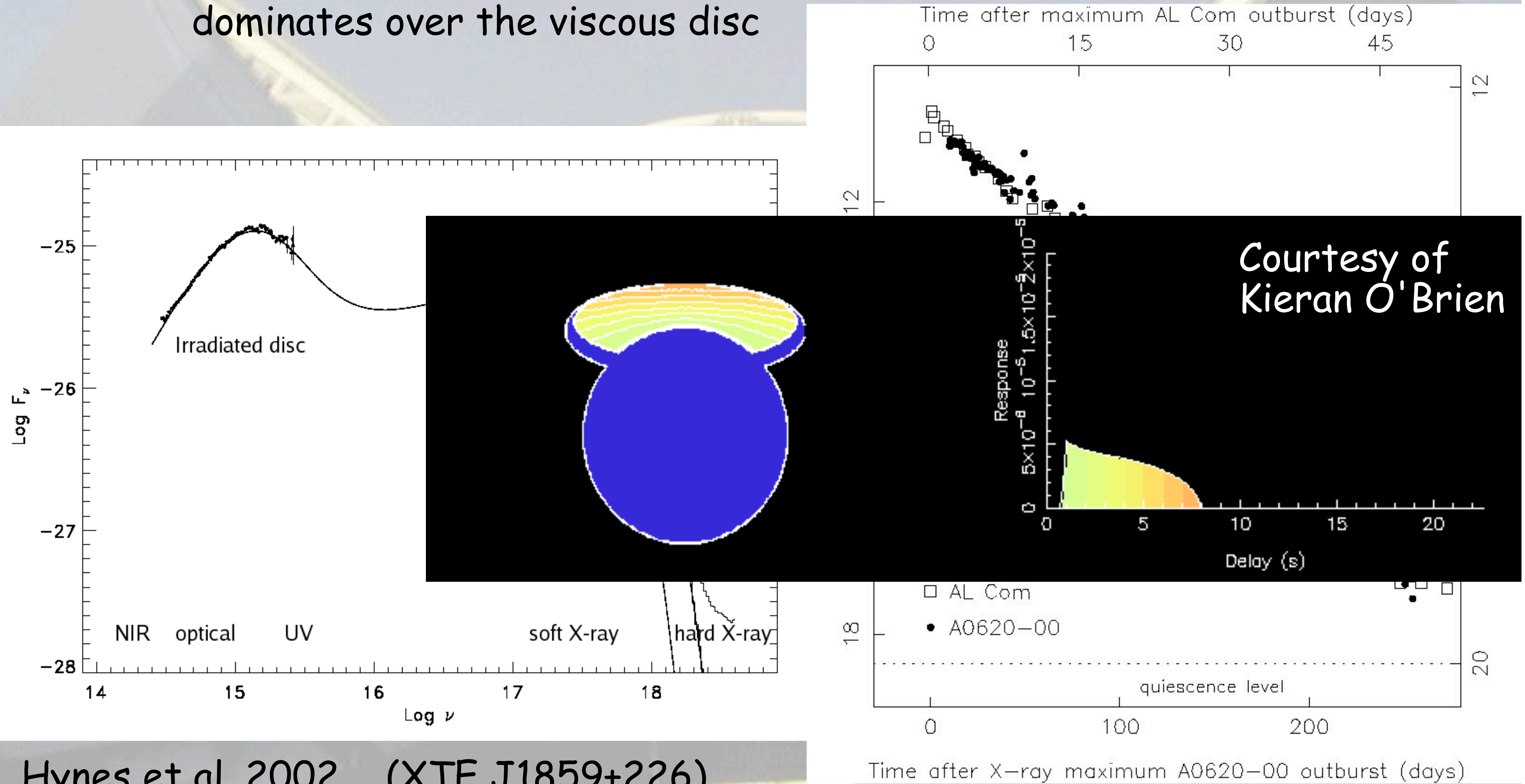
GRO J1655-40 outburst in 2005 →
(Migliari et al. 2007)



What does the optical/IR emission tell us?

→ outburst light curves and spectra similar to dwarf novae → disc

→ actually, the X-ray heated disc dominates over the viscous disc



Courtesy of Kieran O'Brien

Hynes et al. 2002 (XTE J1859+226)

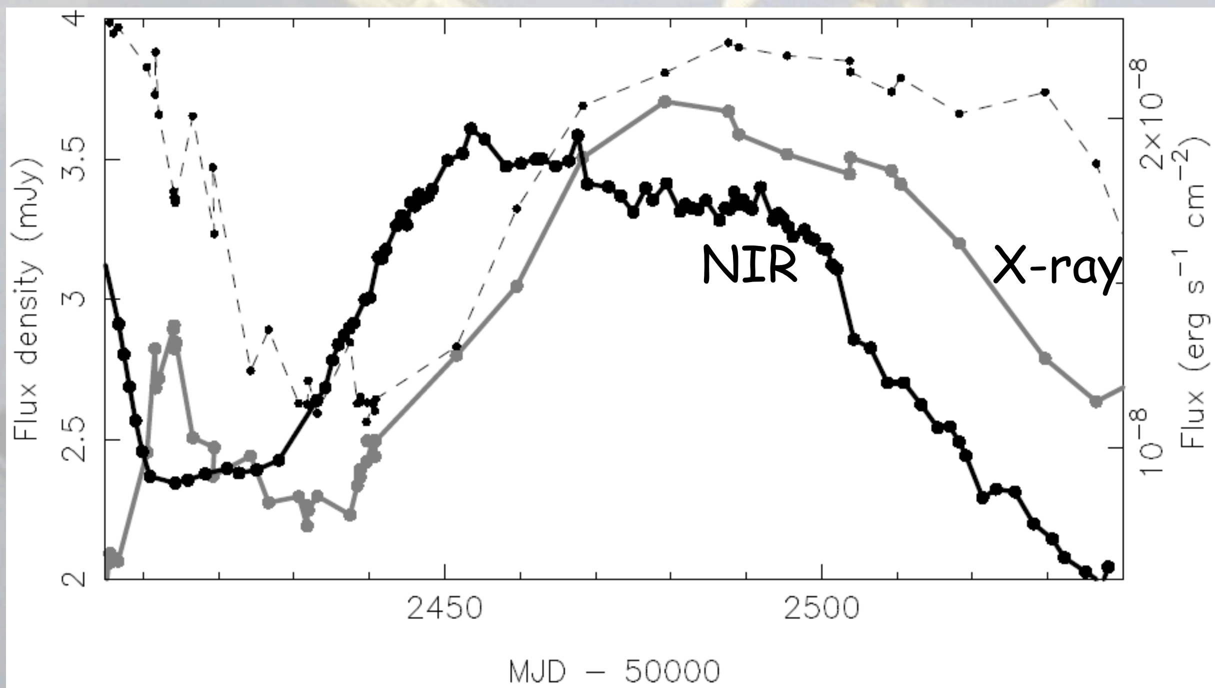
Kuulkers 1998

What does the optical/IR emission tell us?

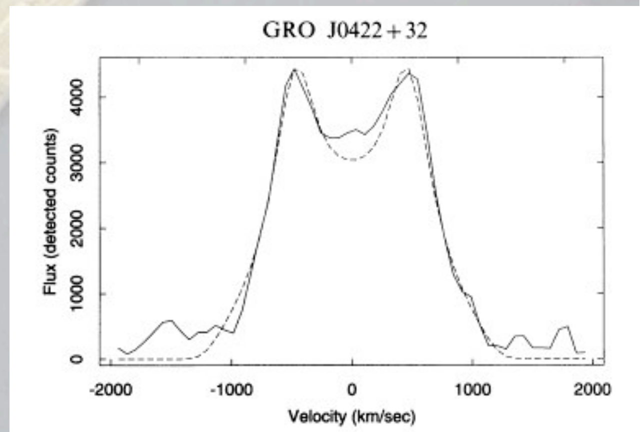
→ outburst light curves and spectra similar to dwarf novae → disc

→ actually, the X-ray heated disc
dominates over the viscous disc

→ but not always



GX 339-4 (Homan et al. 2005)
→ X-ray lags NIR by 15-20 days



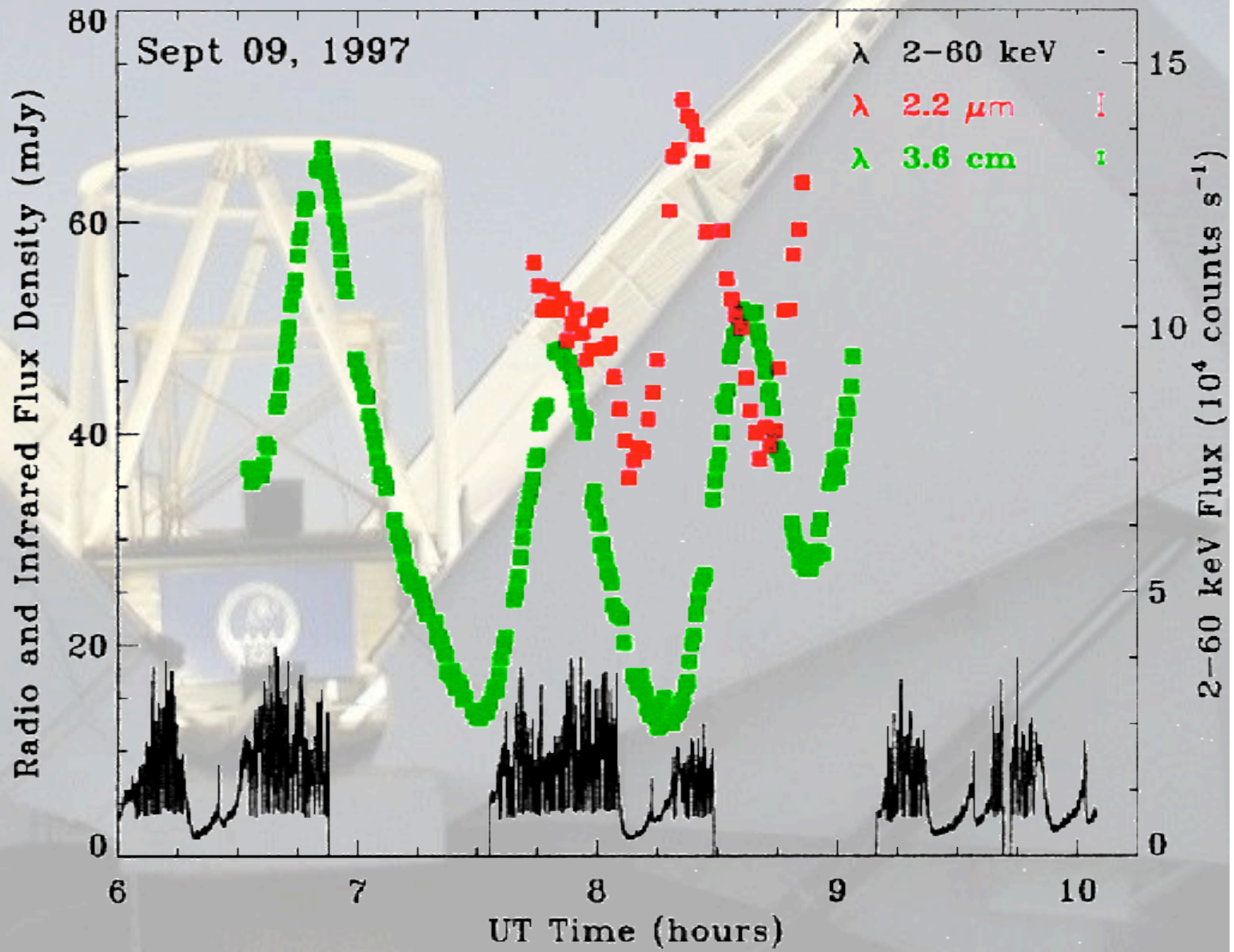
Garcia et al. 1996

But wait…

In the last decade evidence shows that:

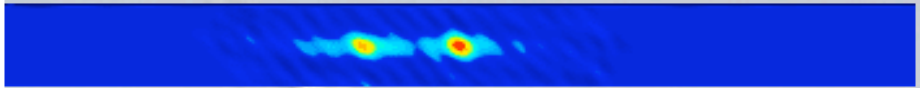
→ the jet is sometimes visible in optical and NIR

Mirabel et al. (1998) showed NIR flares from GRS 1915+105 (found by Fender et al. 1997) originate in the jets



X-ray Binary Jets

Black hole XB: GRO J1655-40



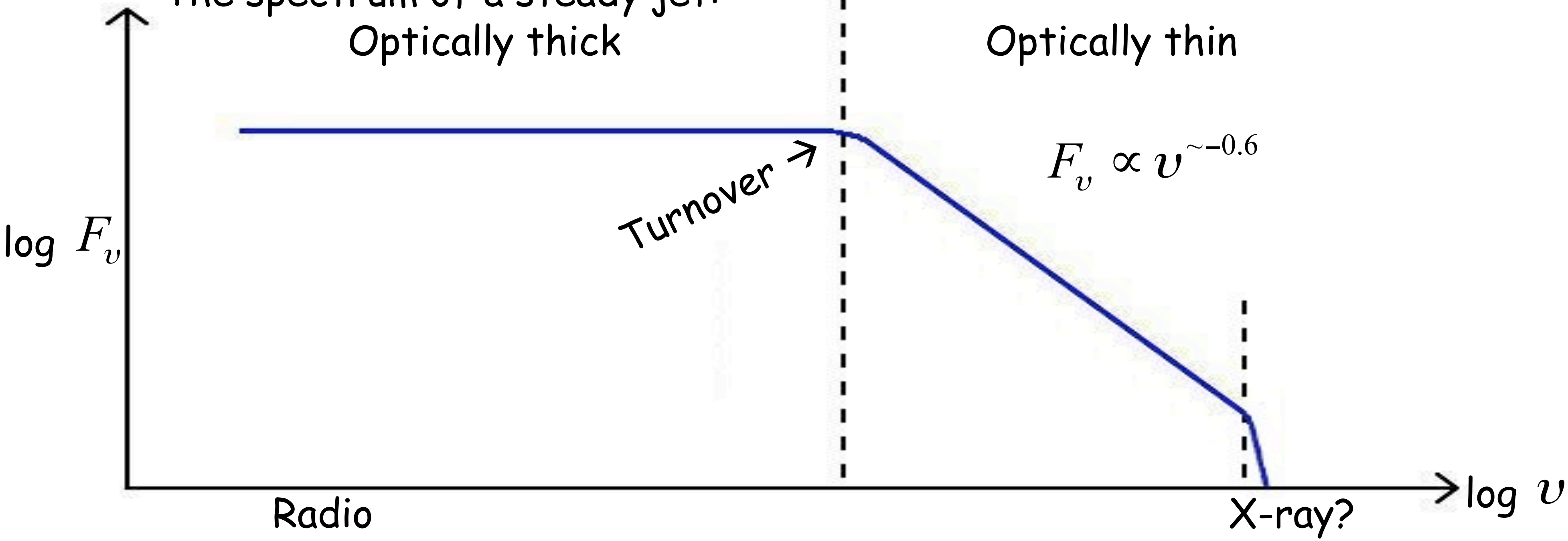
Tingay et al. 1995

Neutron star XB: Sco X-1

Fomalont et al. 2001

Radio emission: → is synchrotron in nature
→ unambiguously originates in collimated outflows (2 types of jet)

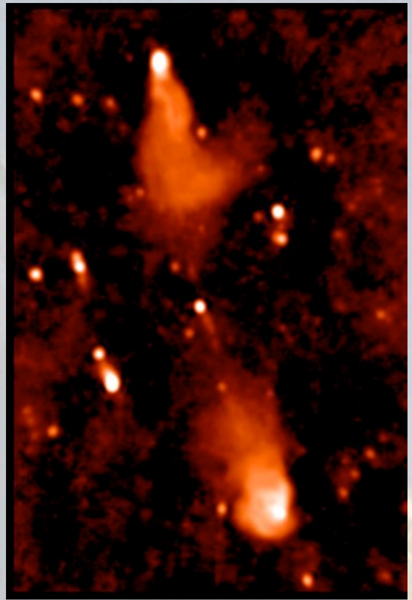
The spectrum of a steady jet:



The jets are radiatively inefficient, and the power carried in the jets is uncertain and highly dependent on the position of the turnover(s)

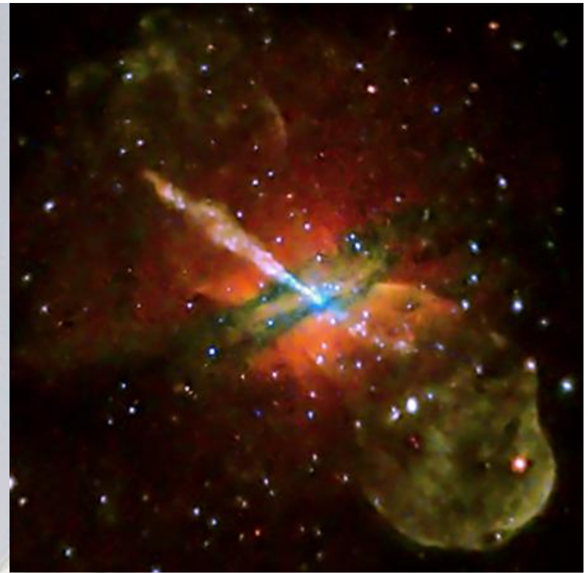
Quasars and Microquasars

Radio lobes



FR II Radio Galaxy
NVSS 2146+82
at 1.4 GHz
(Palma et al. 2000)

Cen A
Multiwavelength
(Kraft et al.
2008)



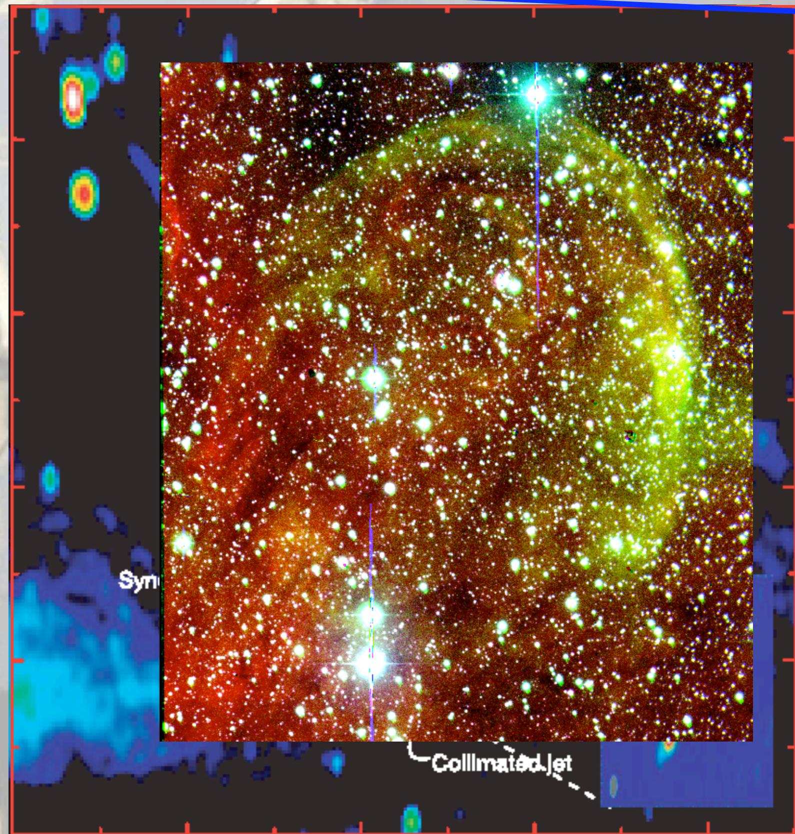
Supermassive black hole jets

Stellar-mass black hole jets

Black Hole X-ray Binary
1E 1740.7-2942
(Mirabel et al. 1992)

Black Hole X-ray Binary
GRS 1758-258
(Martí et al. 2002)

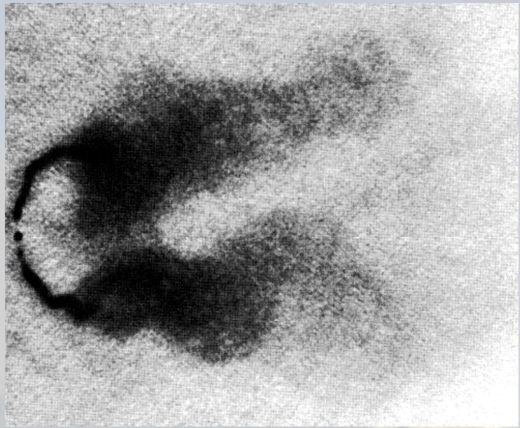
Bow shocks



Cygnus X-1: P_Jet = 30—100% Lx (Gallo et al. 2005, Russell et al. 2007)

Quasars and Microquasars

Head-tail trails



3C 83.1 (Odea & Owen 1986)

FR II Radio Galaxy
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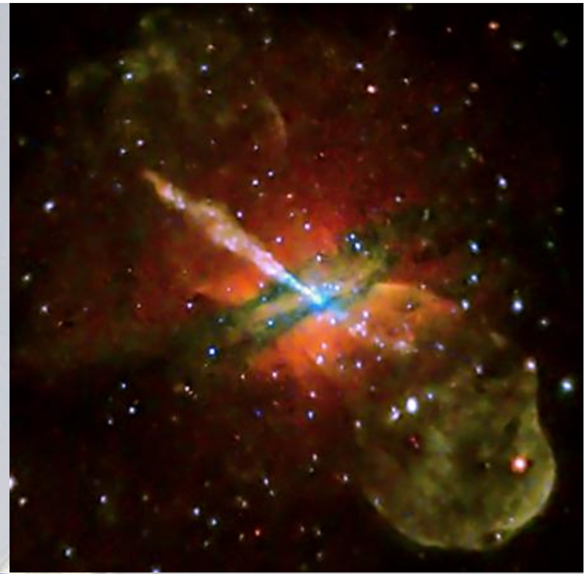
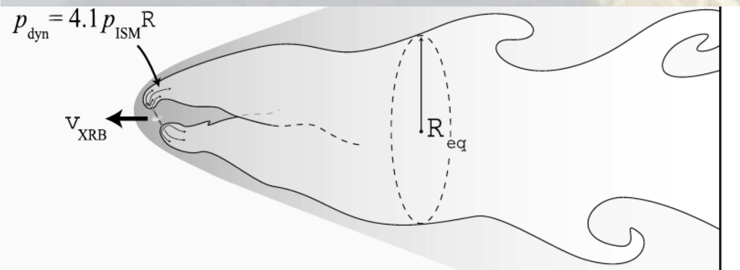
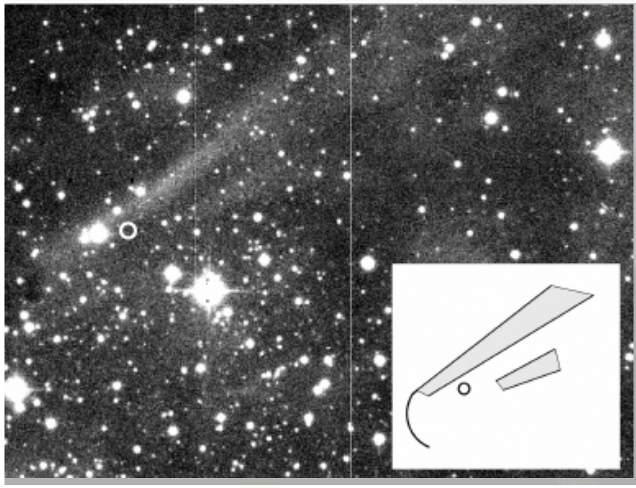


Supermassive black hole jets



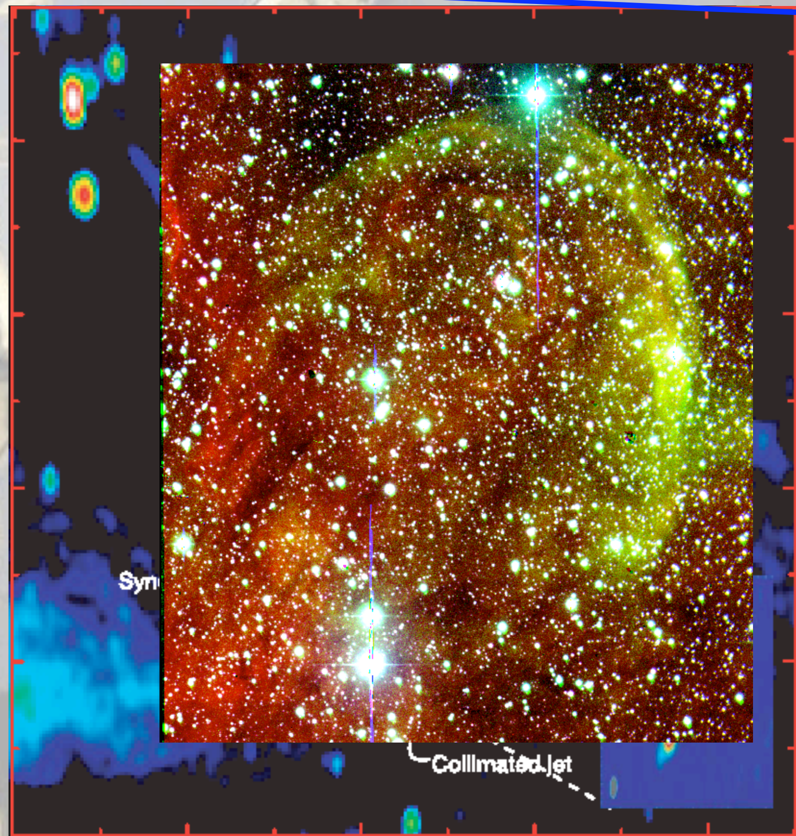
Stellar-mass black hole jets



Predicted by
Heinz et al. 2008 for
fast moving LMXBs

Bow shocks

Possible first
detected XB
head-tail source:
SAX J1712.6-3739
(Wiersema et al. 2009)



Cygnus X-1: Gallo et al. 2005, Russell et al. 2007

So where were we?

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→ the jet is sometimes visible in optical and NIR

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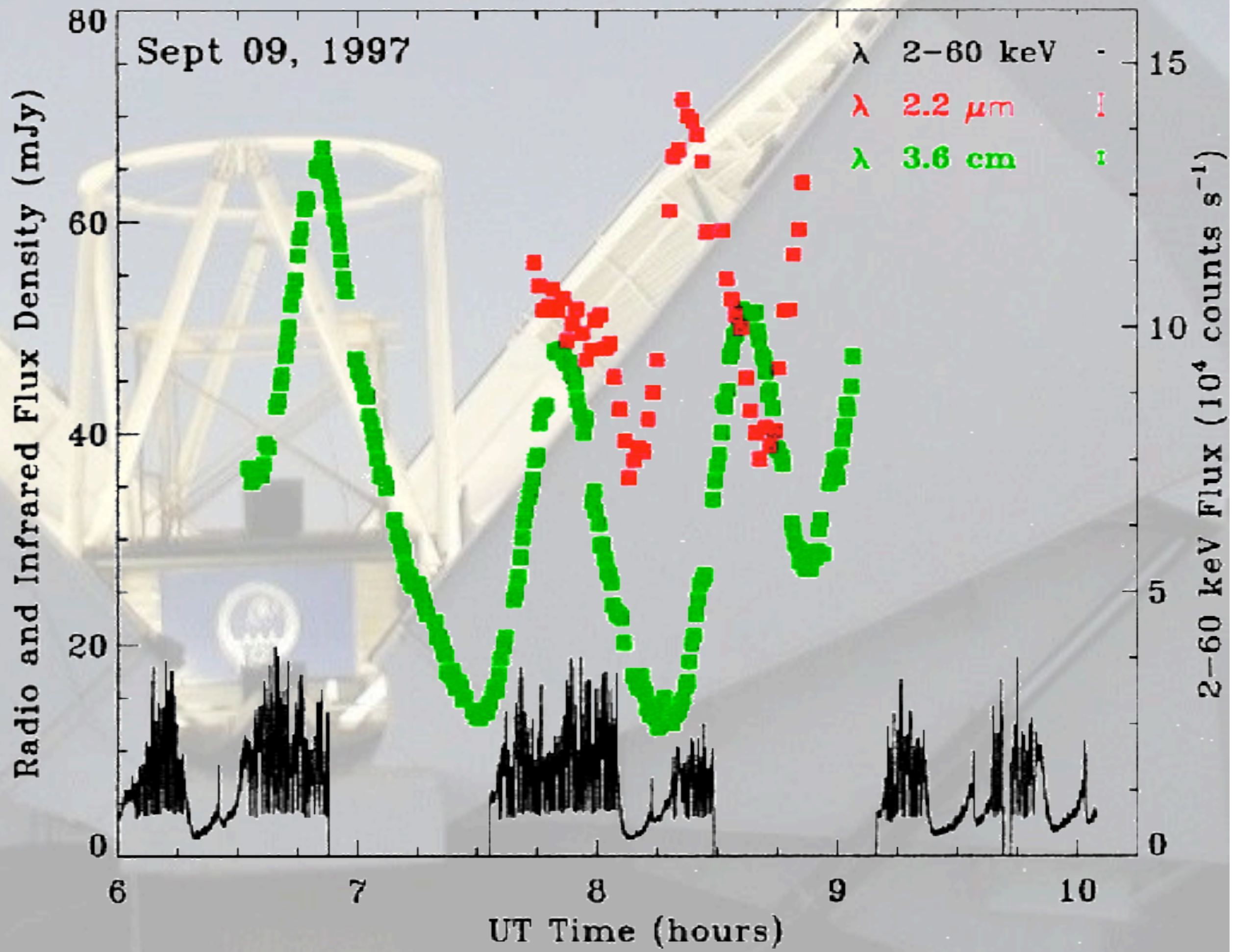

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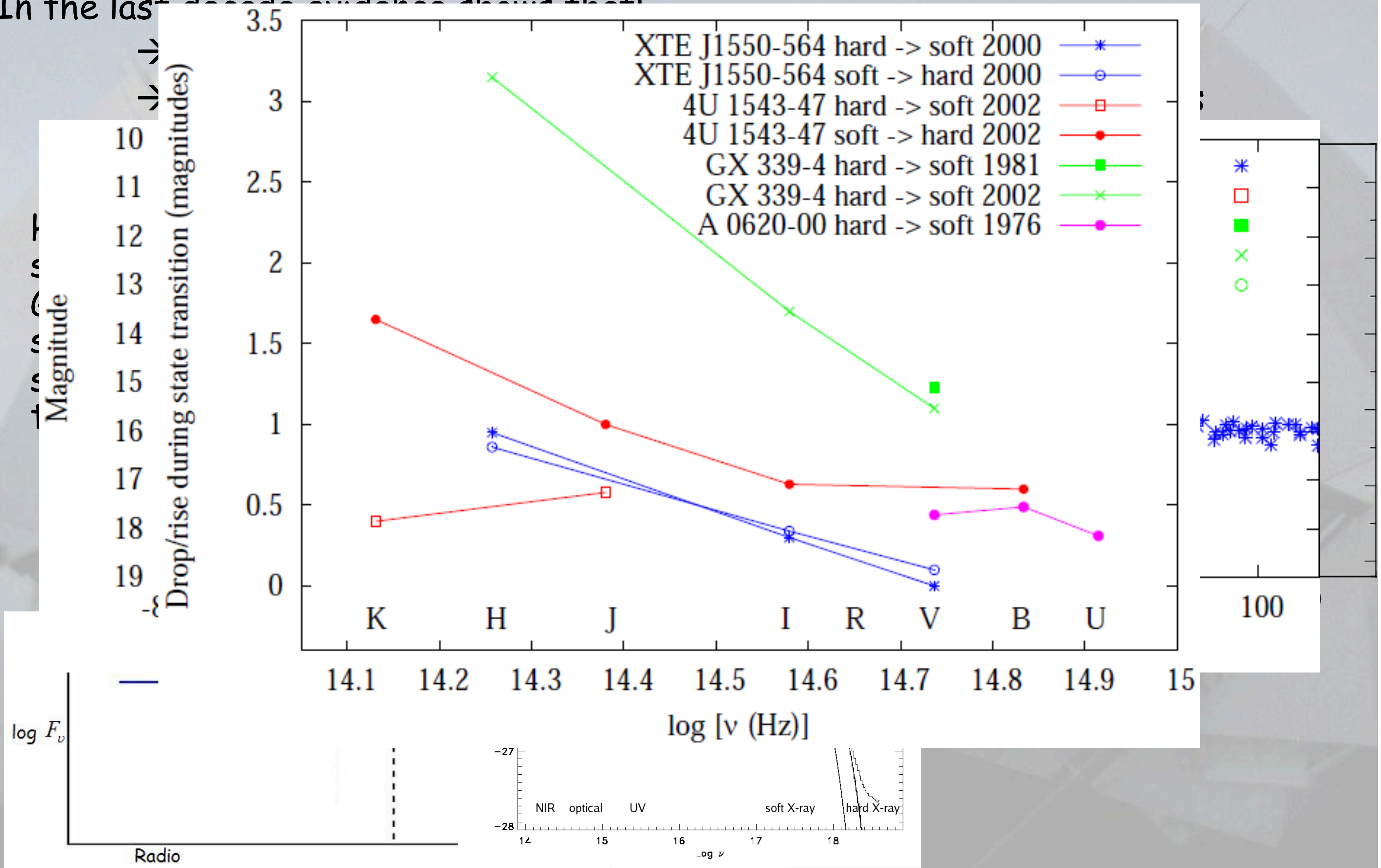
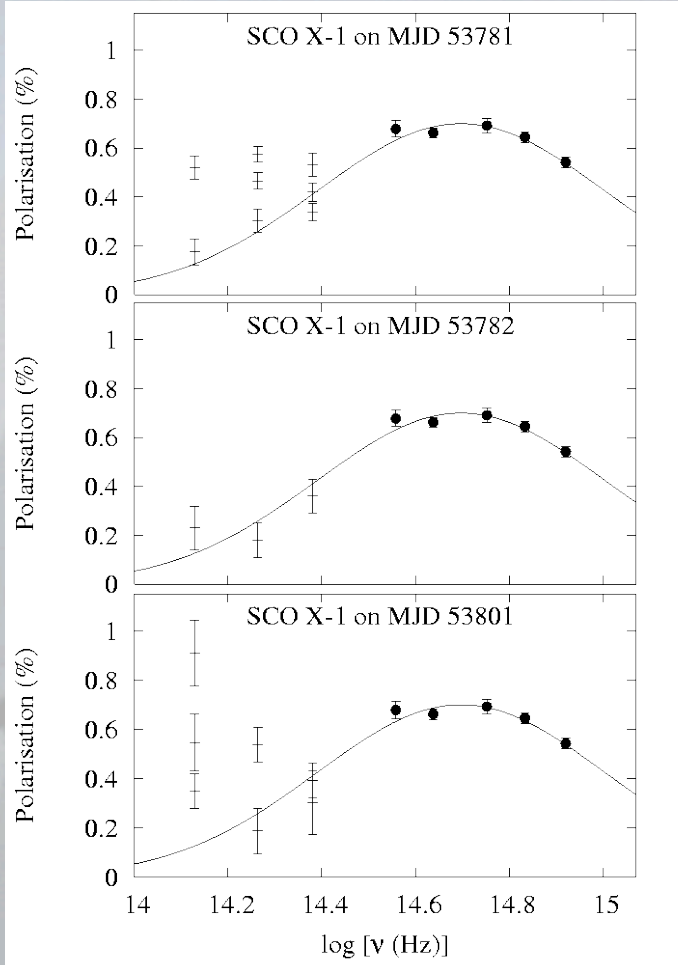
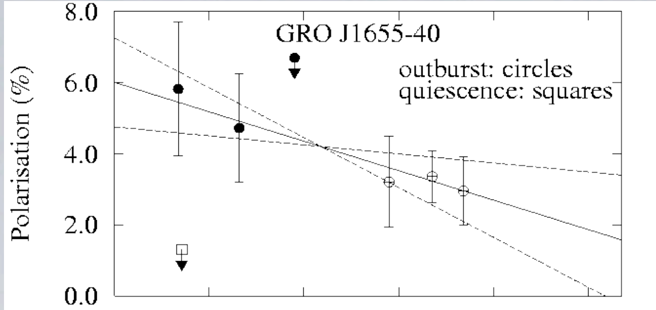


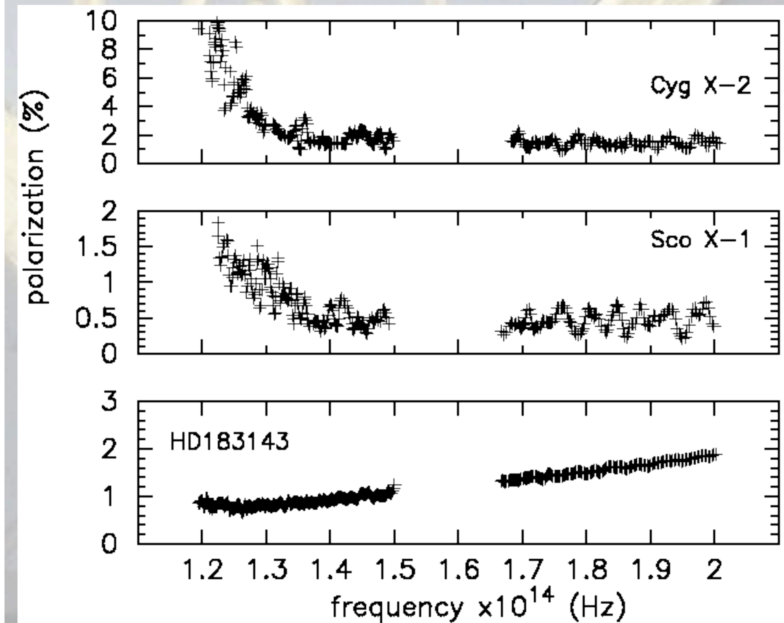
But wait…

Models predict linear polarisation from the optically thin synchrotron jet





Russell & Fender (2008)

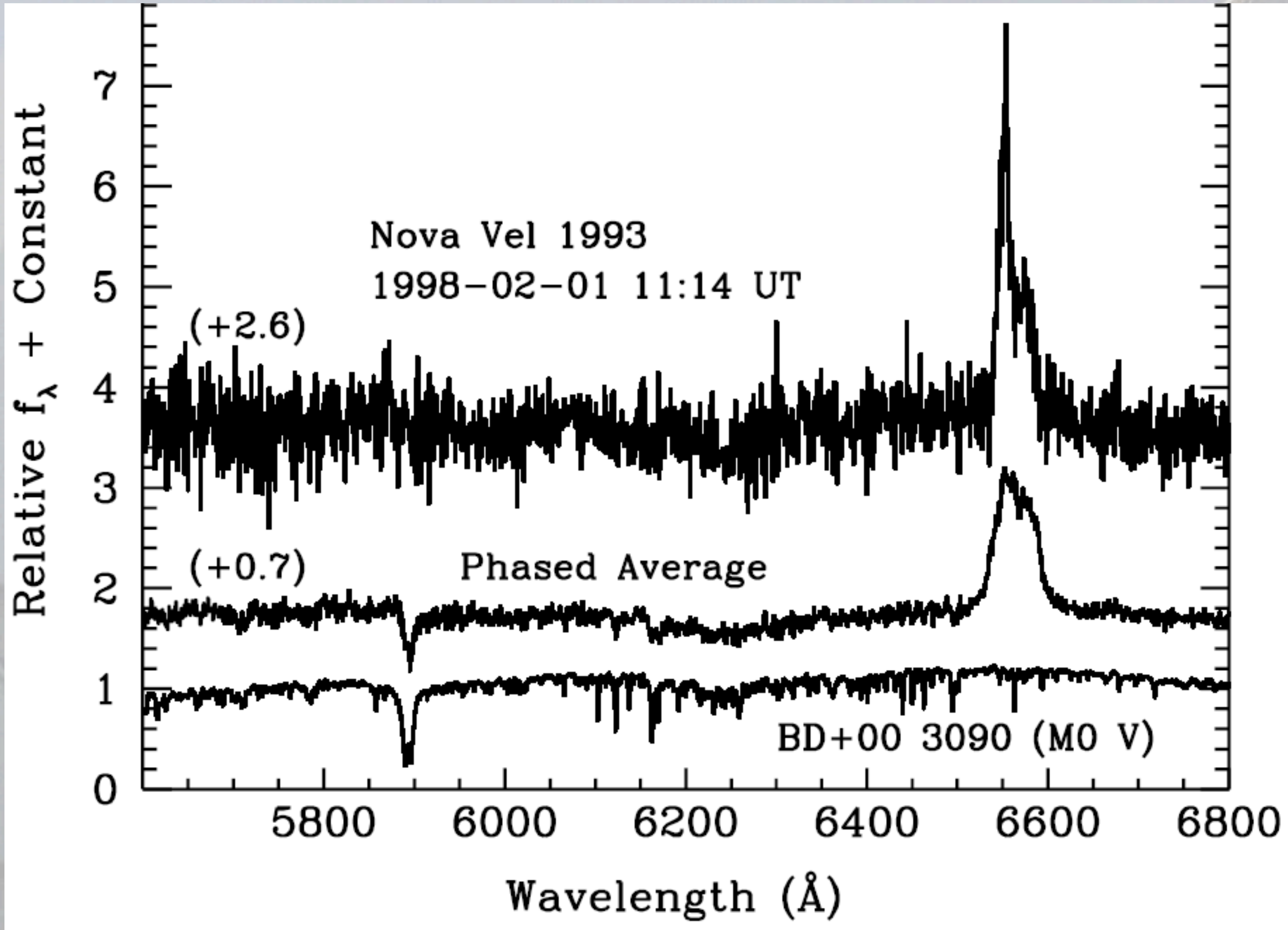


Shahbaz et al. (2007)

All detections are stronger at low frequencies

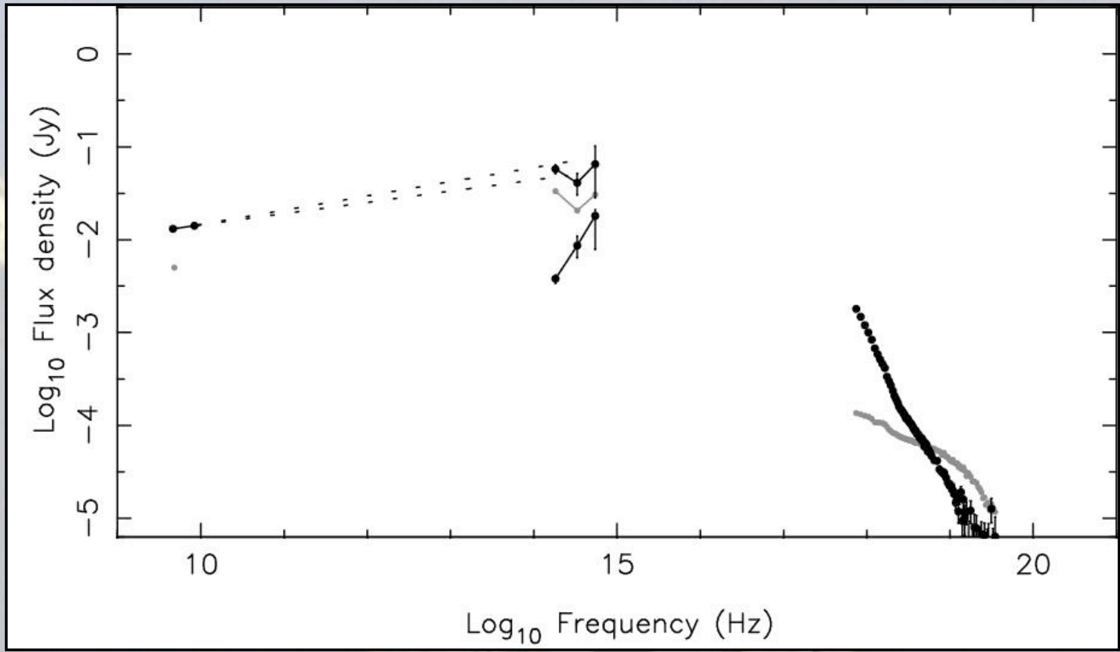
And in quiescence, the star

e.g. stellar absorption lines (Filippenko et al. 1999)



What can optical/IR studies tell us?

We see a red jet… We see a blue disc…



Can study:

- → properties of the inner jet/magnetic field (from e.g. polarization)
- → relations with inflow: disc/jet coupling (from optical+X-ray fast timing)
- → jet power, physical properties (from models of the total broadband spectrum of the jet)

Can study:

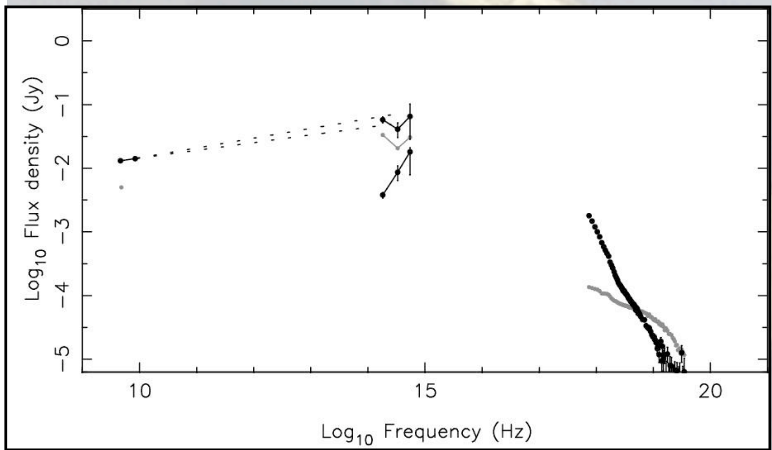
- → composition of disc (from spectral lines)
- → temperature and size of outer disc (from colours, and viscous timescale: optical+X-ray slow timing)
- → echo-mapping the disc (from optical+X-ray fast timing)

Disc/jet evolution during an outburst

We need to separate the disc and jet components

(1) Can use spectral energy distributions

Homan et al. 2005

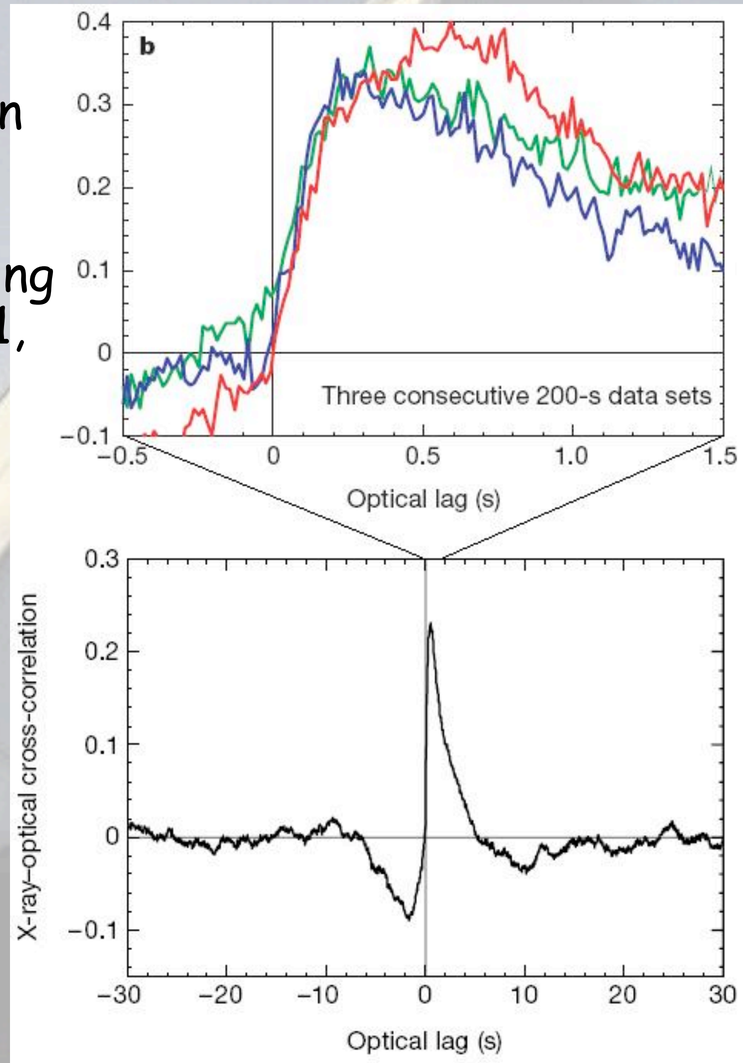


Optical dip *before* X-ray fluctuations in XTE J1118+480: cannot be explained by X-ray reprocessing (Kanbach et al. 2001, Malzac et al. 2004)

Need simultaneous X-ray and high time resolution

- At least 3 optical/IR wavebands typically required

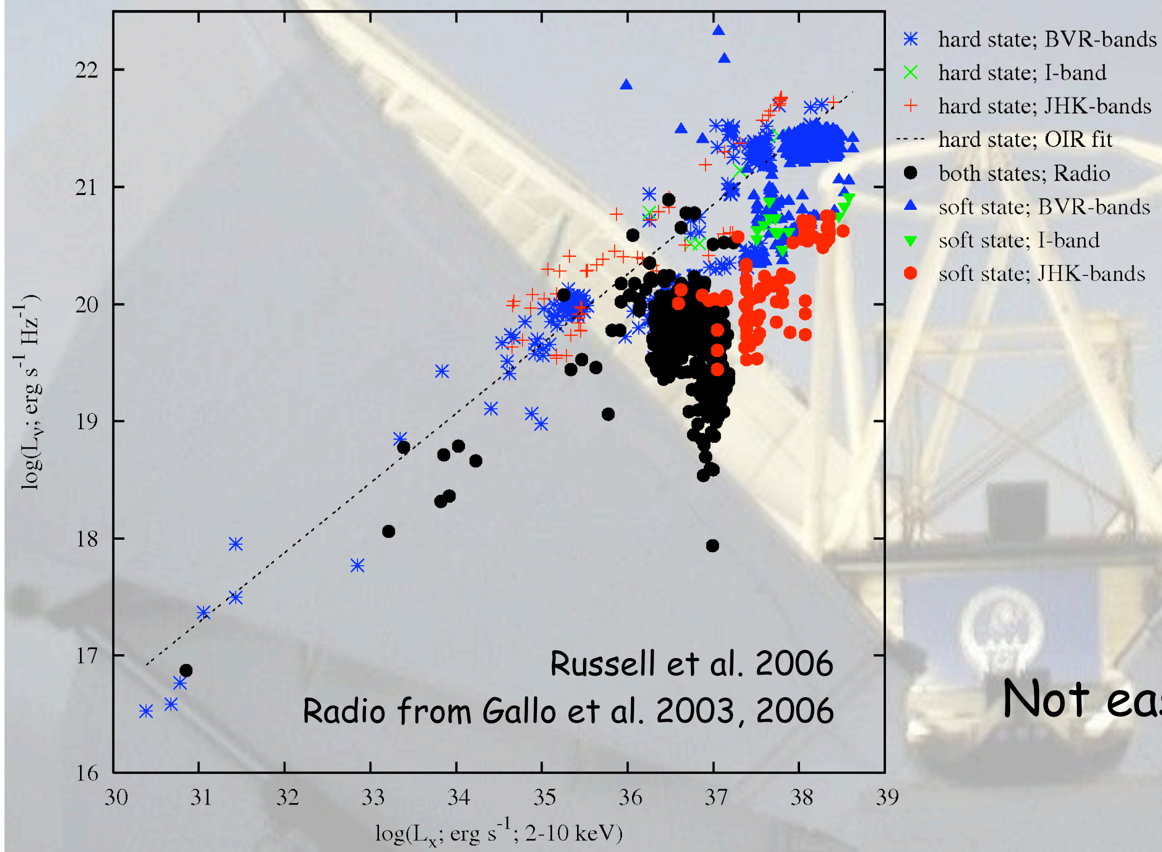
(2) Can use timing studies



Disc/jet evolution during an outburst

We need to separate the disc and jet components

(3) Can use correlations between wavebands



For black hole XBs:

Irradiated disc: $L_{OPT} \propto L_X^{0.5}$

van Paradijs & McClintock 1994

Viscous disc: $L_{OPT} \propto L_X^{0.25}$

Frank, King & Raine 2002

Jet: $L_{OPT} \propto L_{RADIO} \propto L_X^{0.7}$

Gallo, Fender & Pooley 2003

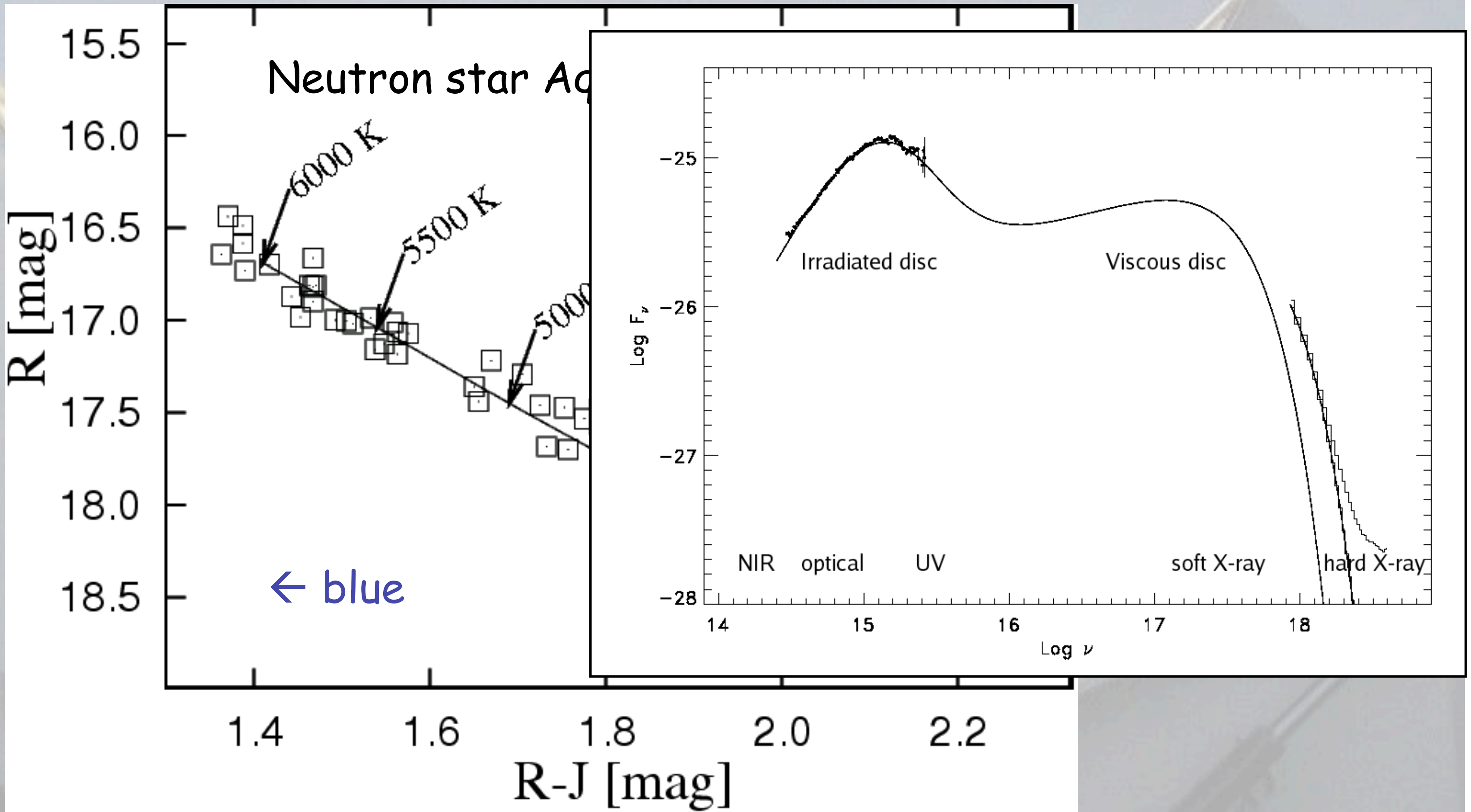
Not easy to distinguish between these

Observed: $L_{OPT} \propto L_{RADIO} \propto L_X^{0.6}$

NIR drops in soft state, optical remains bright

Colour-magnitude diagrams of outbursts

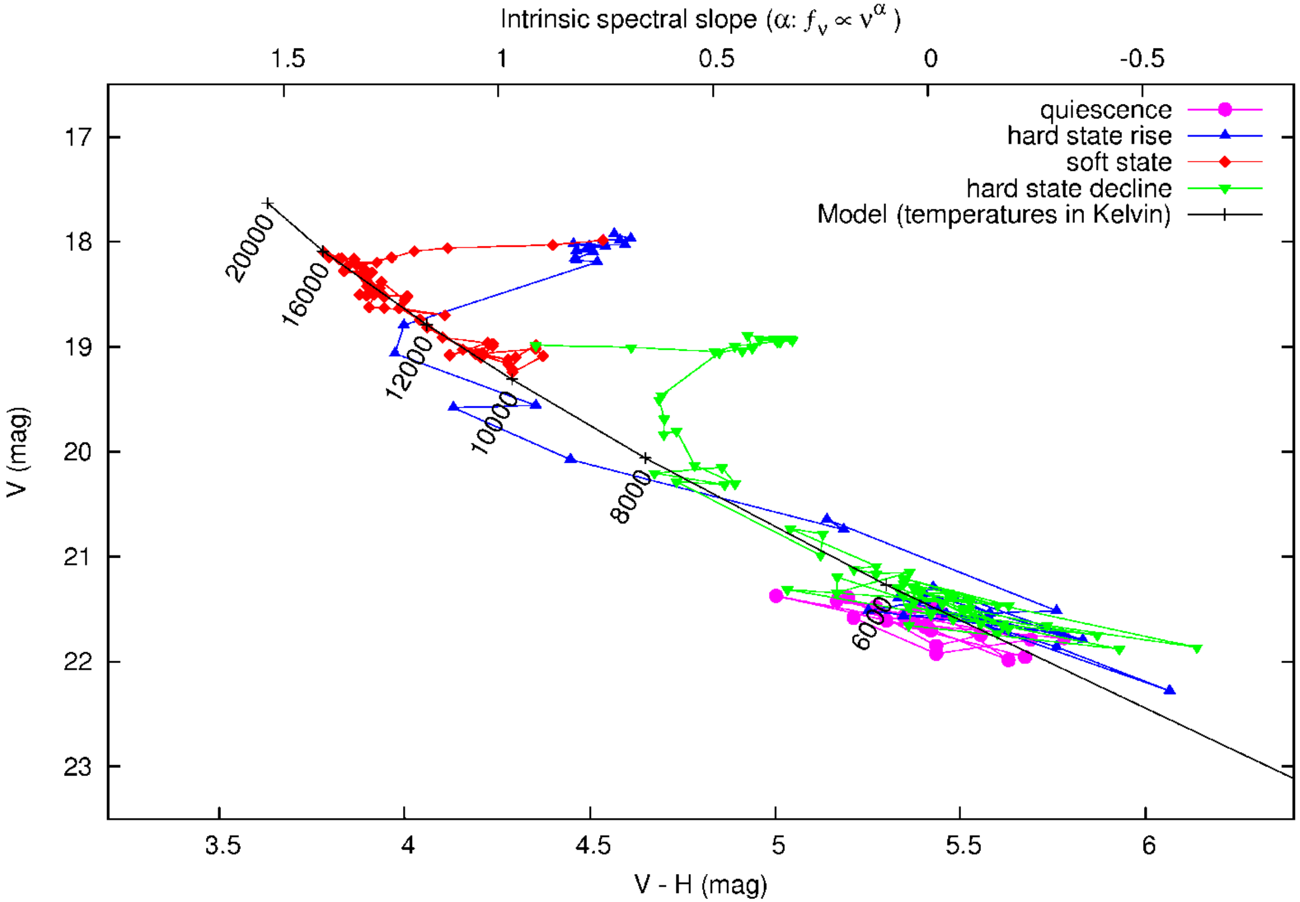
Can use colour-magnitude diagrams (CMDs) to distinguish jet from disc

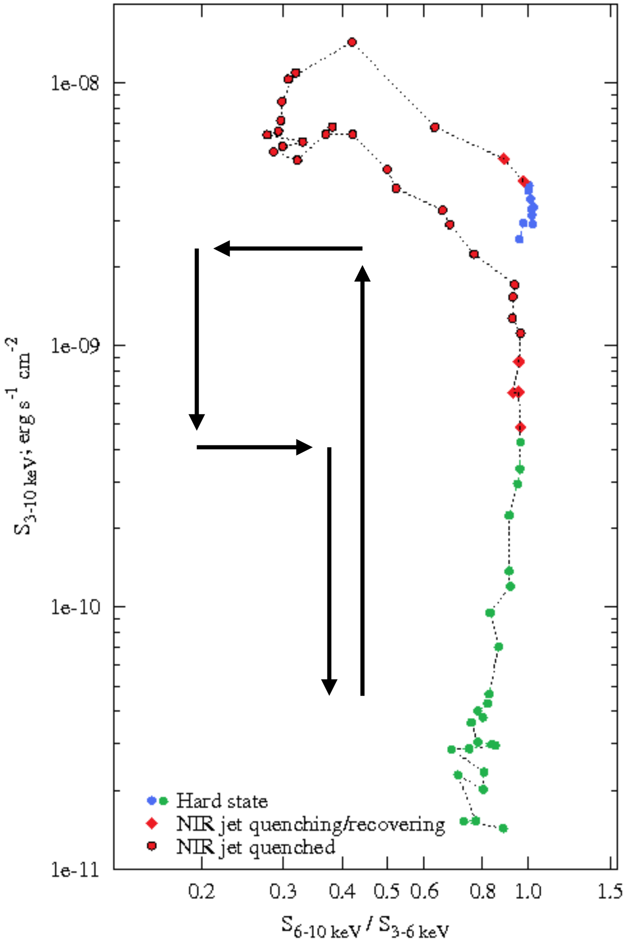


→ Model: a simple single-temperature blackbody heating up
→ Able to reproduce the CMDs of 8 outbursts of Aql X-1
→ Optical and NIR dominated by irradiated disc

Colour-magnitude diagrams of outbursts

X-ray Hardness-intensity diagram



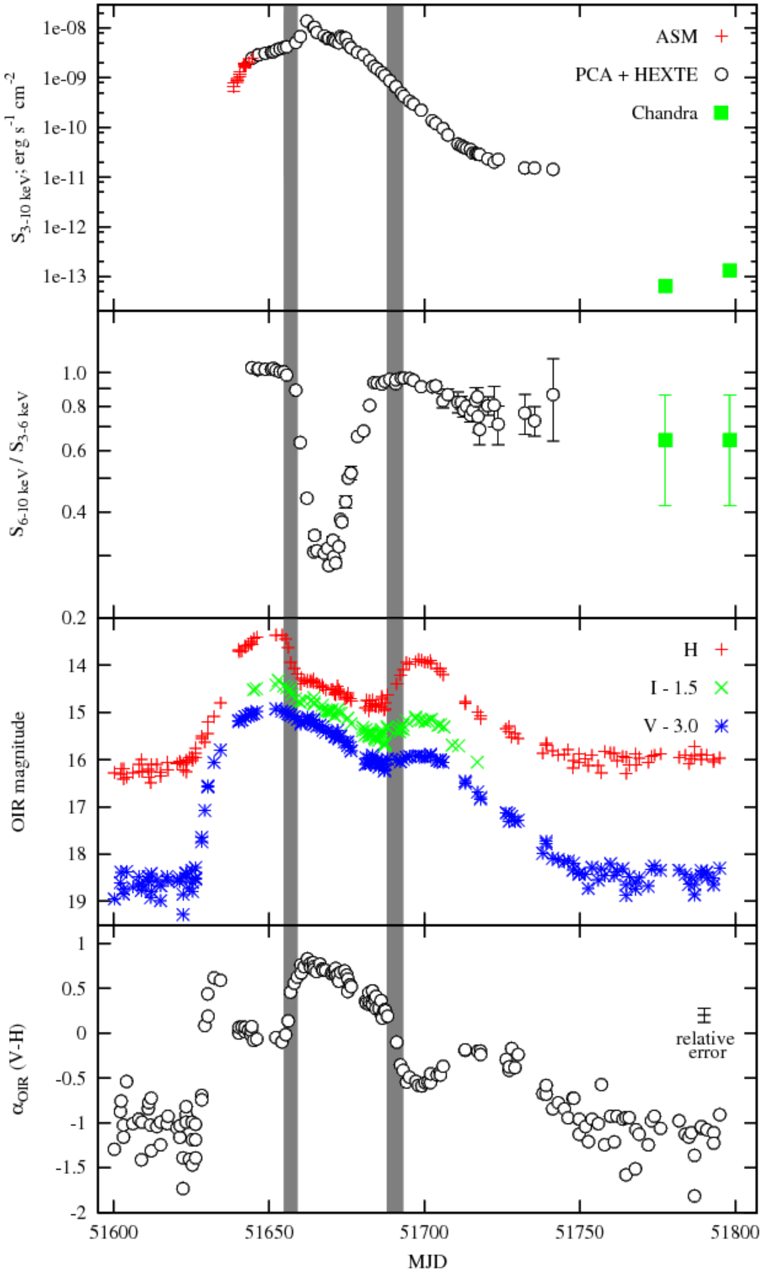


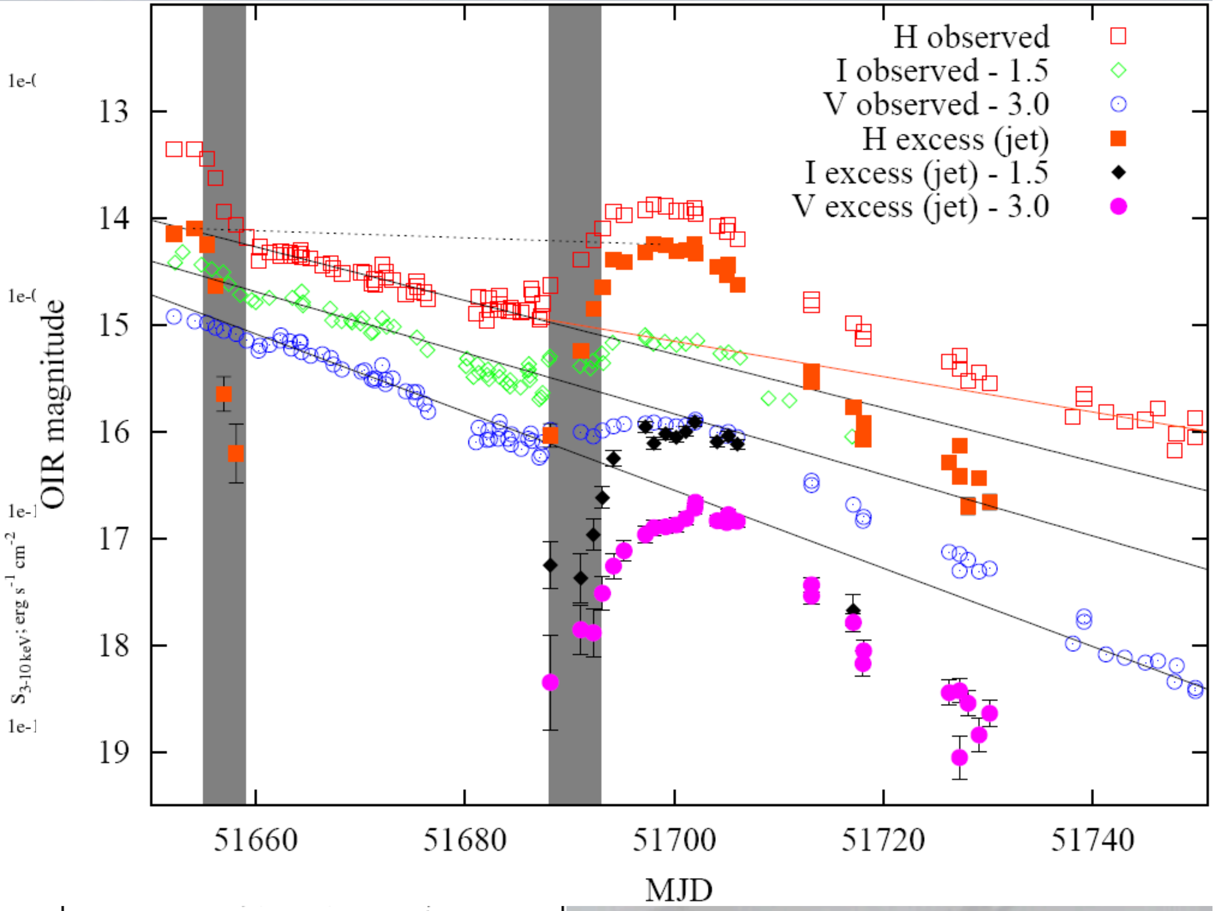
Outburst of XTE J1550-564 in 2000
Data from Jain et al. 2001

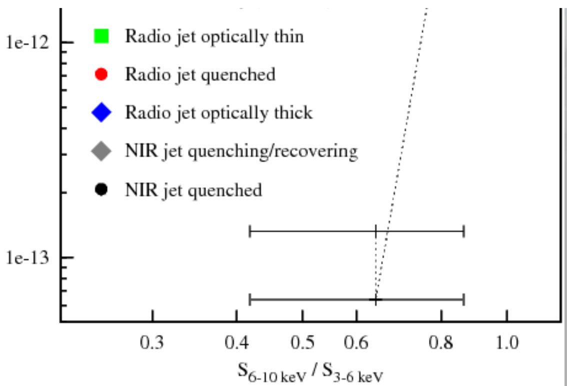
Russell, Maitra et al. in prep.

Isolating the disc and jet components

The light curves of XTE J1550-564







We can separate disc and jet emission

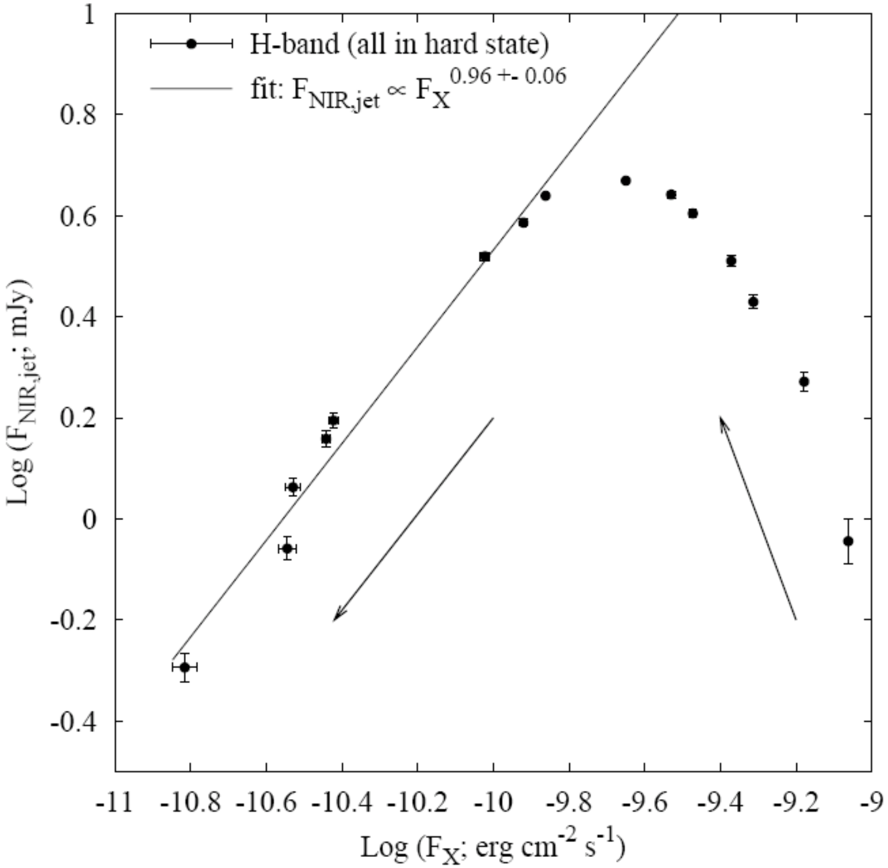
Assumes continuation of the exponential decay of disc flux

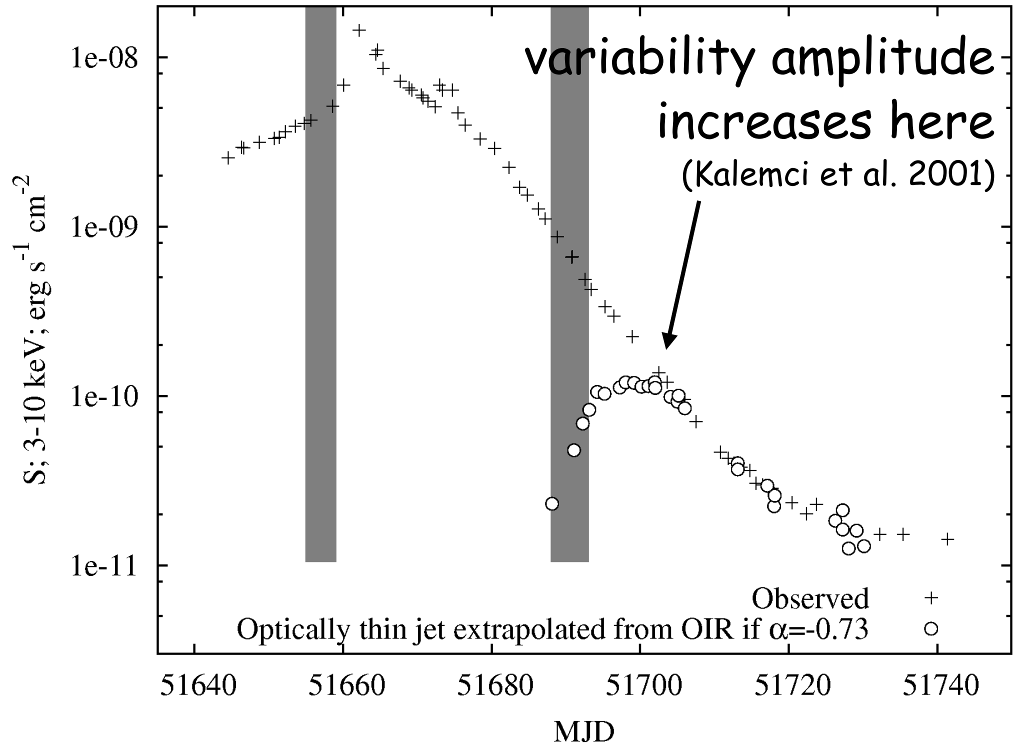
Jet has optically thin SED

A synchrotron jet dominating X-ray?

Russell et al. 2010, MNRAS, in press

NIR jet flux is proportional to X-ray flux





This is not expected if:

$L_{NIR} \propto L_{RADIO} \propto L_X^{0.7}$

Fender 2001; Gallo et al. 2003

alpha (OIR) ~ -0.7

alpha (OIR→X-ray) = -0.7

alpha (X-ray PL) ~ -0.9

(photon index ~ 1.9)

A synchrotron jet dominating X-ray?

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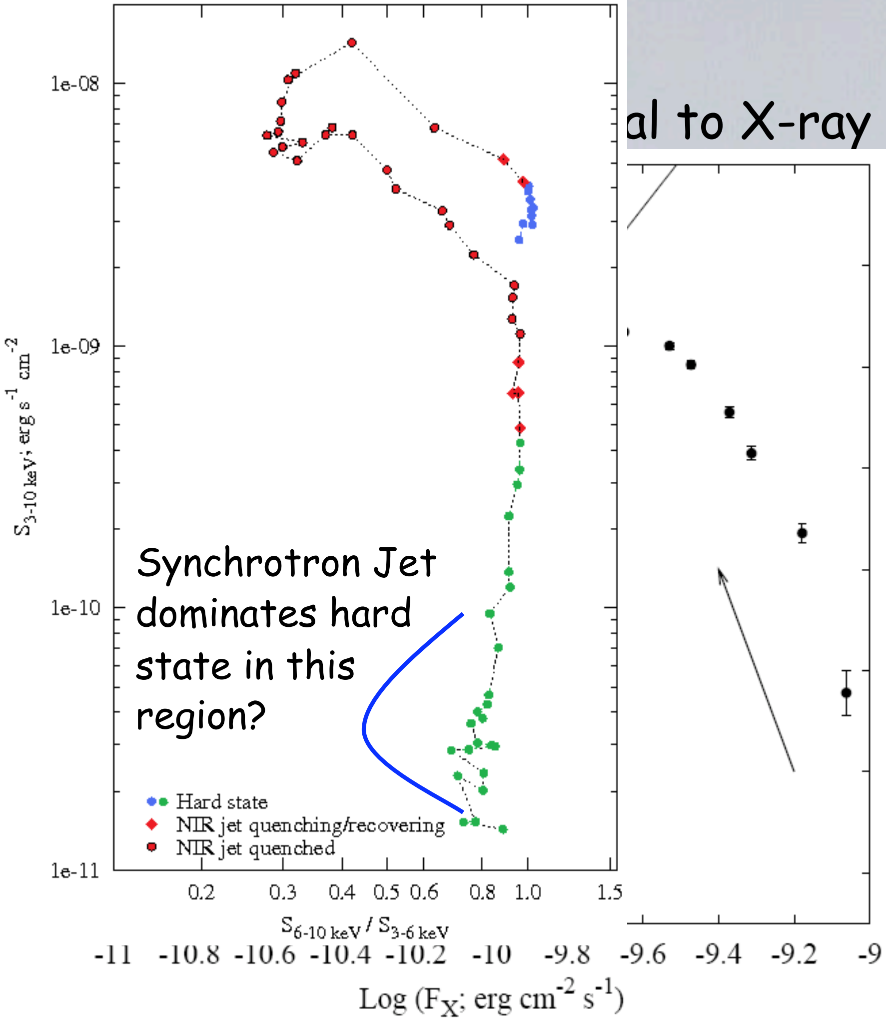
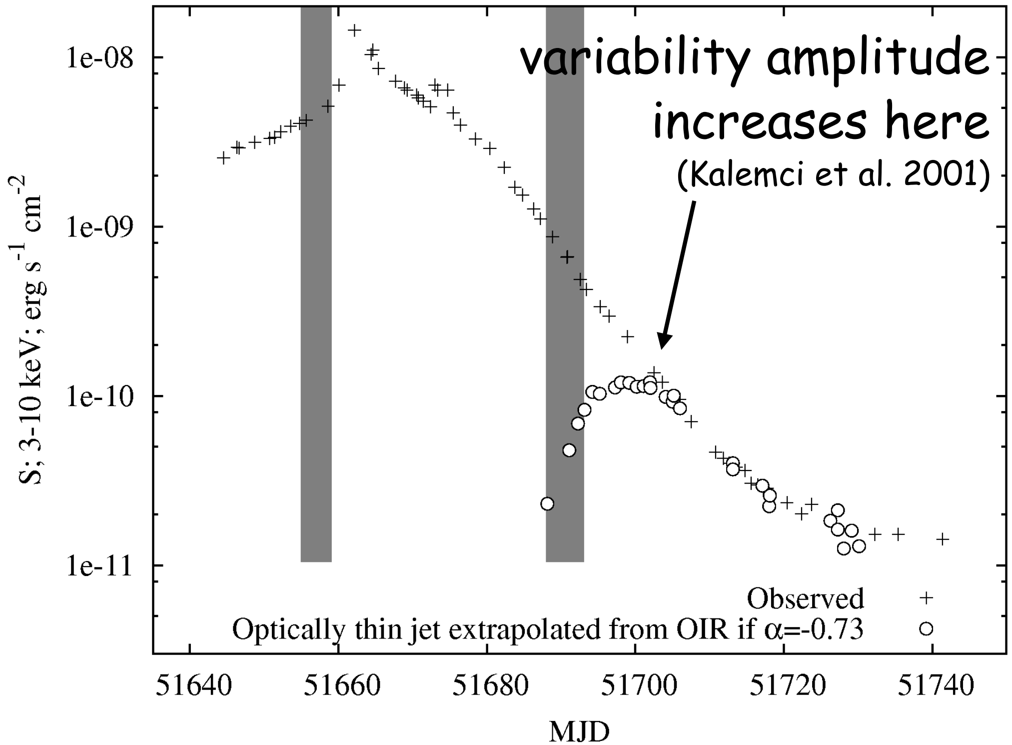
al to X-ray flux





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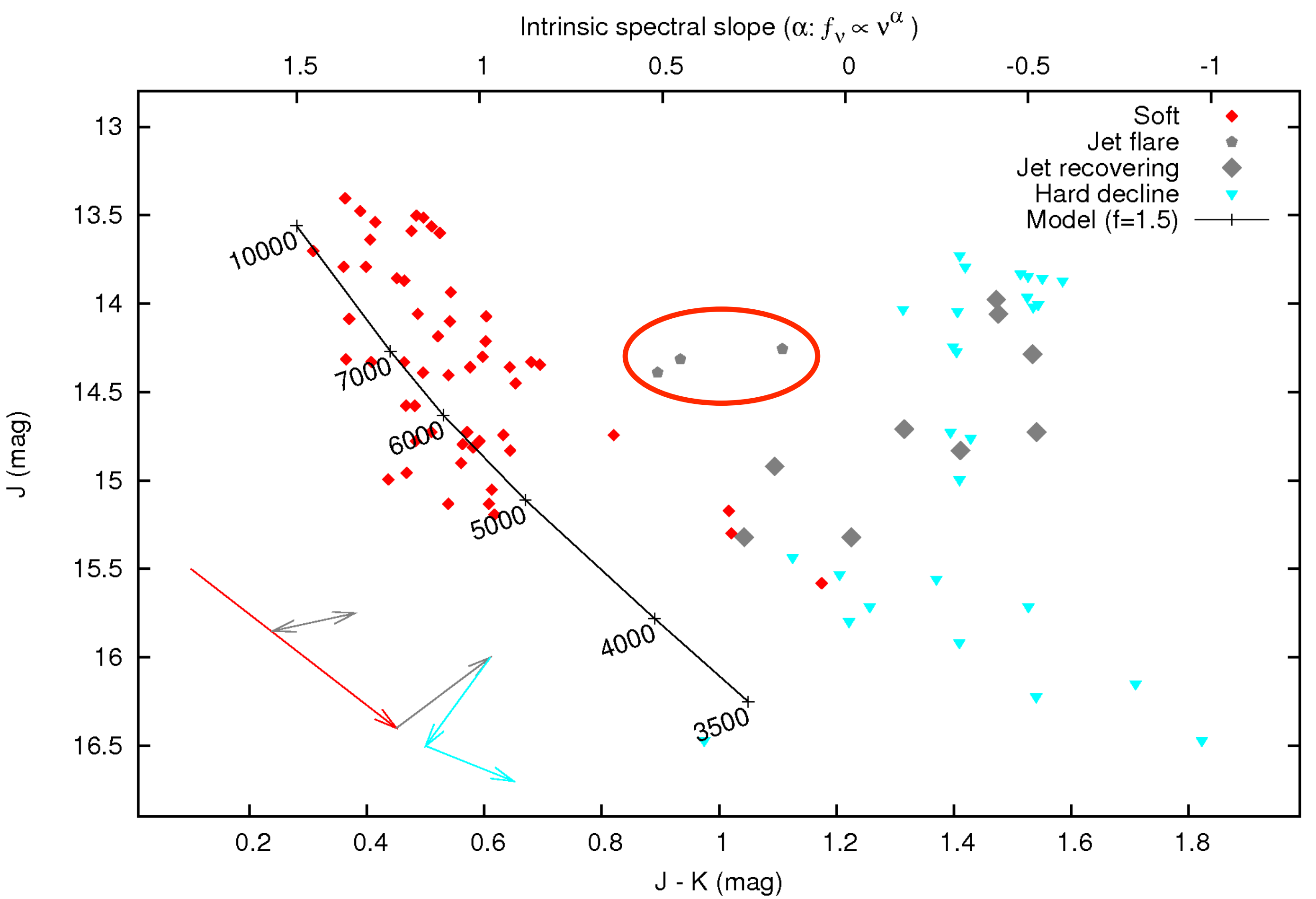
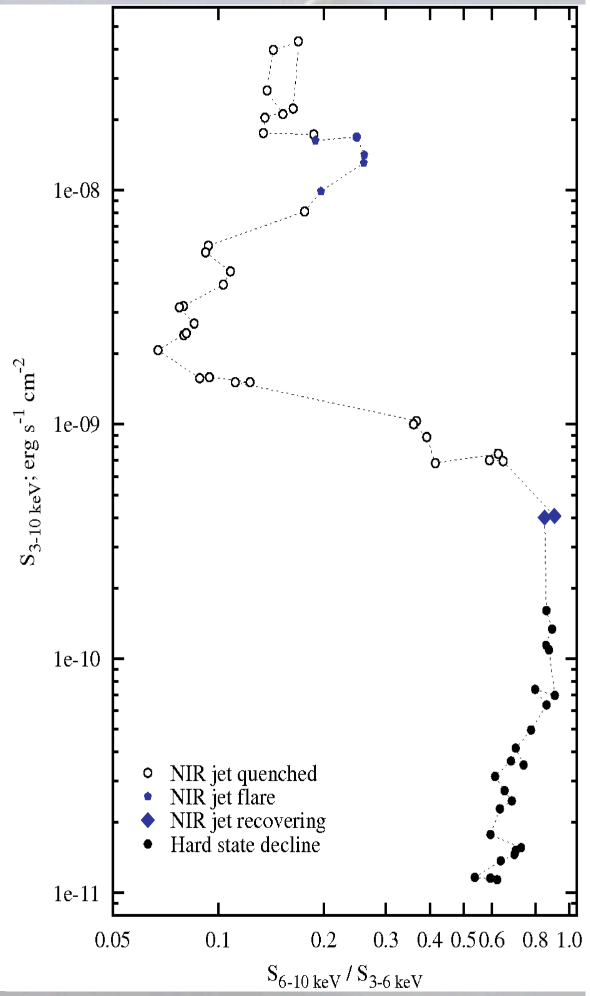
(photon index ~ 1.9)

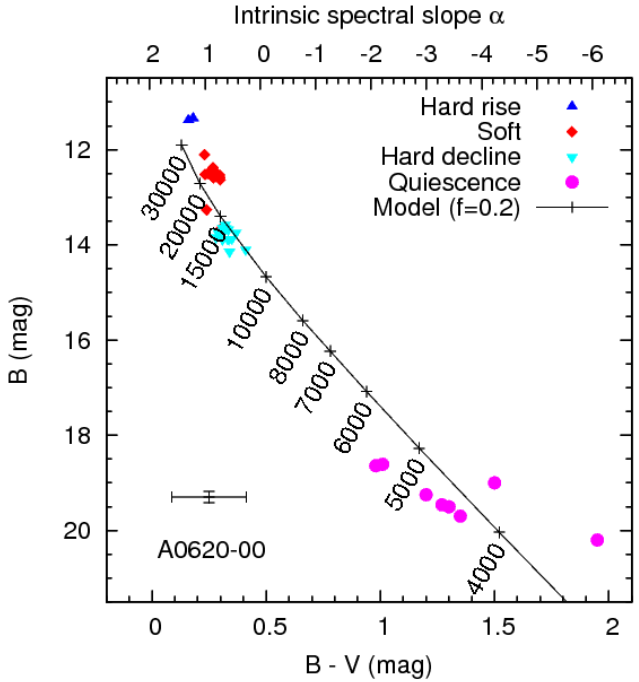
Jet could dominate X-ray flux in the hard state between $\sim (2 \times 10^{-4} - 2 \times 10^{-3})\ L_{\mathrm{Edd}}$

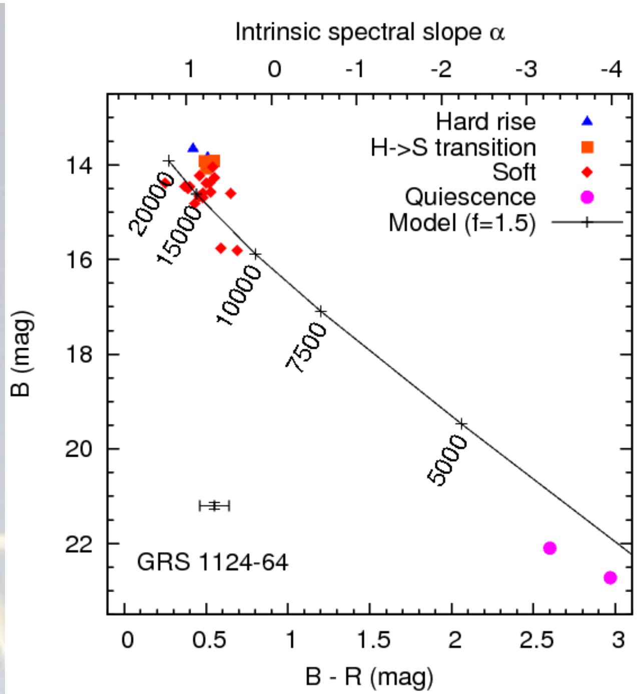
Colour-magnitude diagrams of outbursts



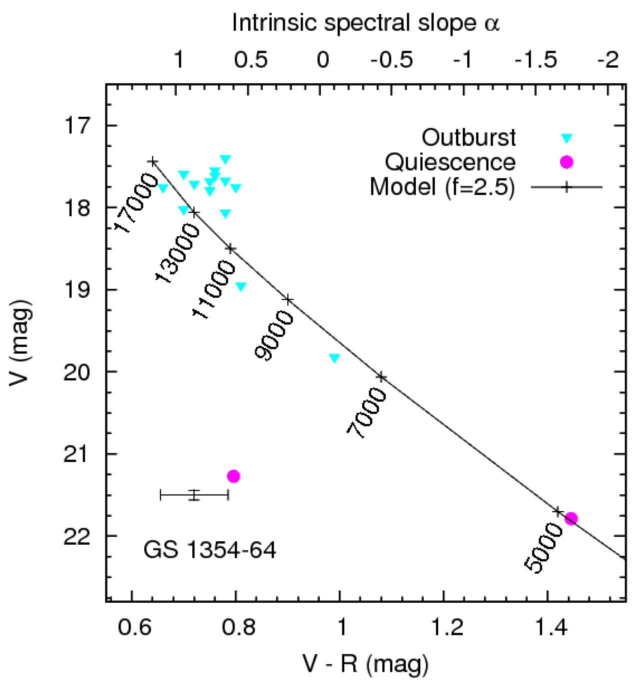


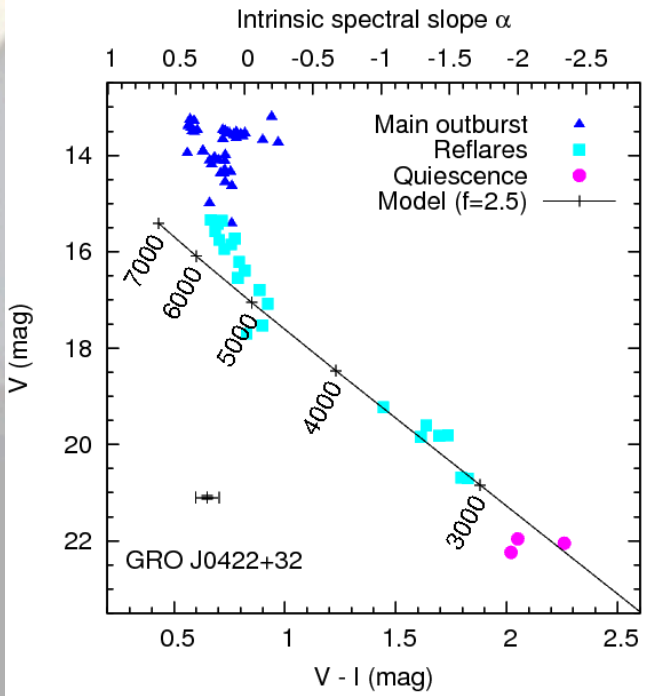
4U 1543-47 outburst
Data from Buxton & Bailyn 2004

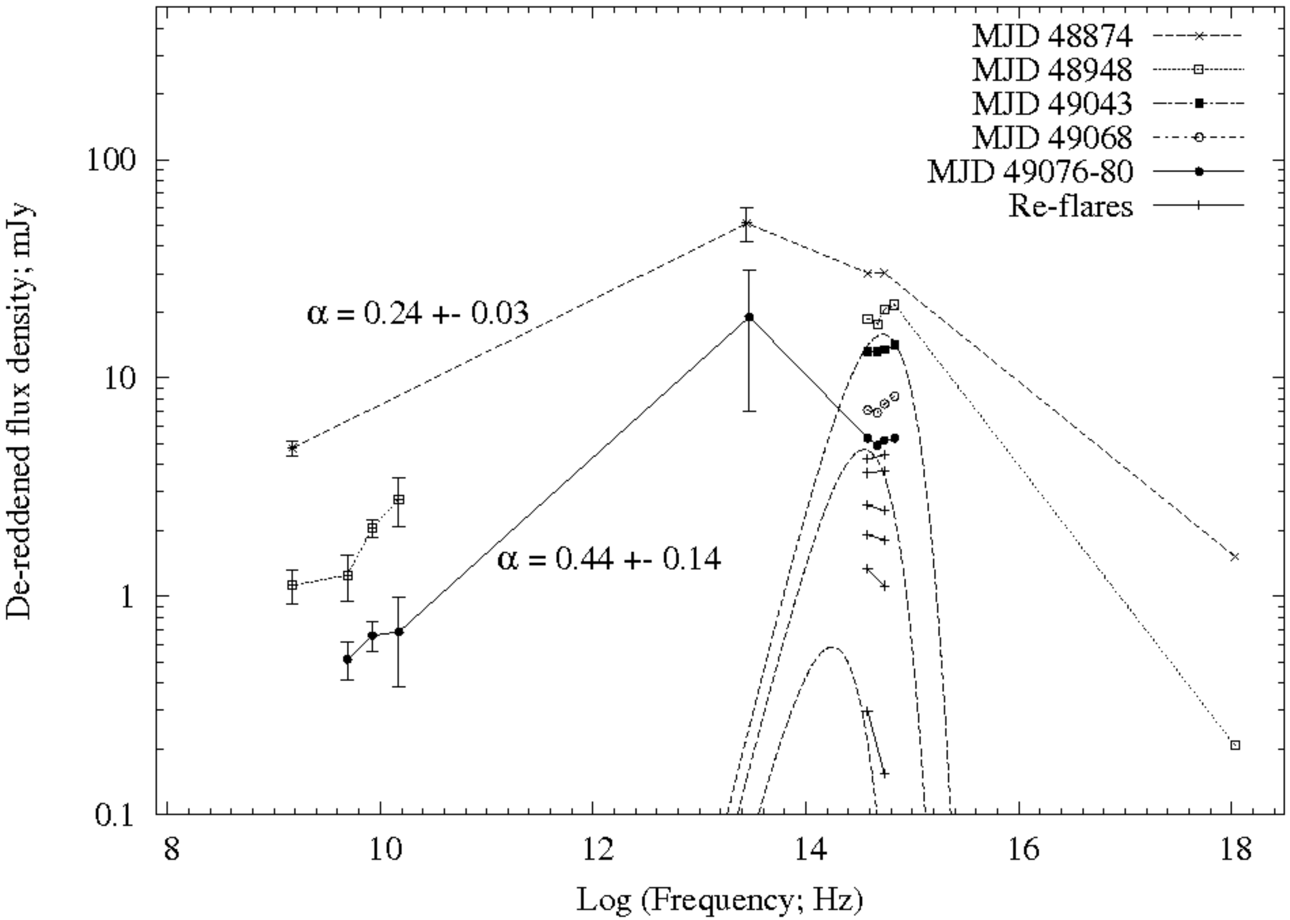


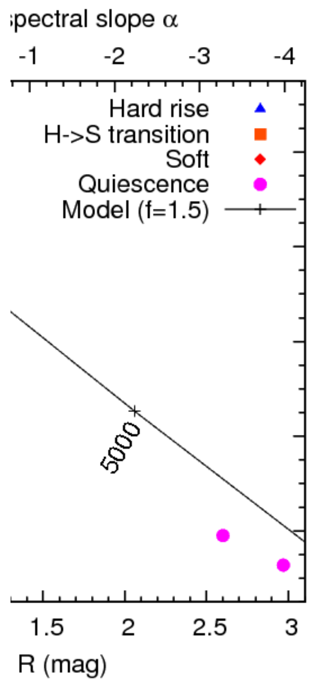


Four more colour-magnitude diagrams









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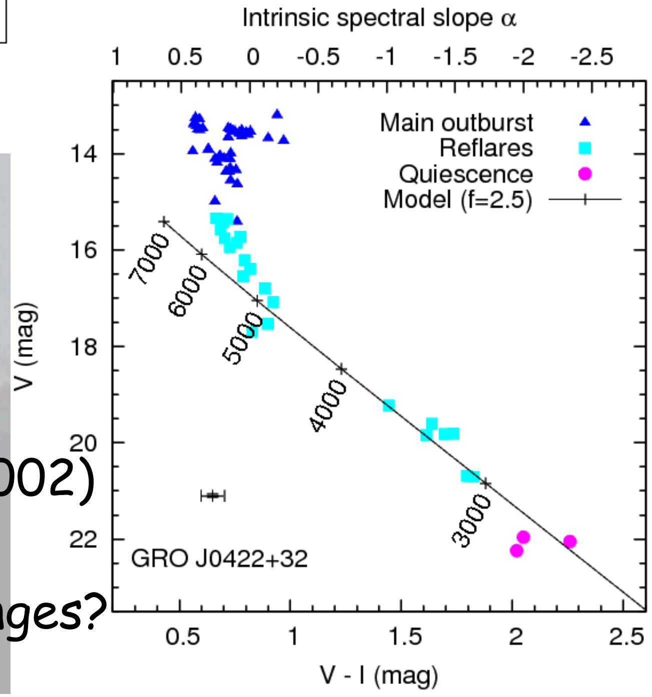


Could be:

(a) Viscous disc, with spectral index = +1/3

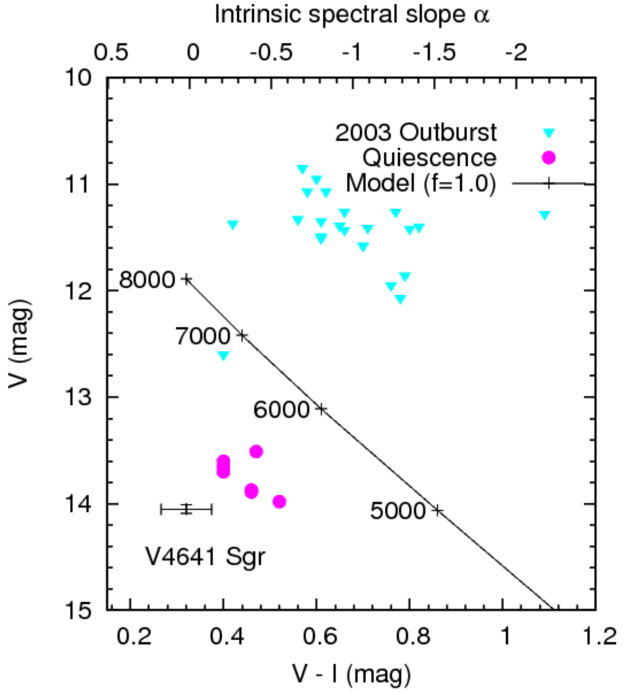
(b) Jet

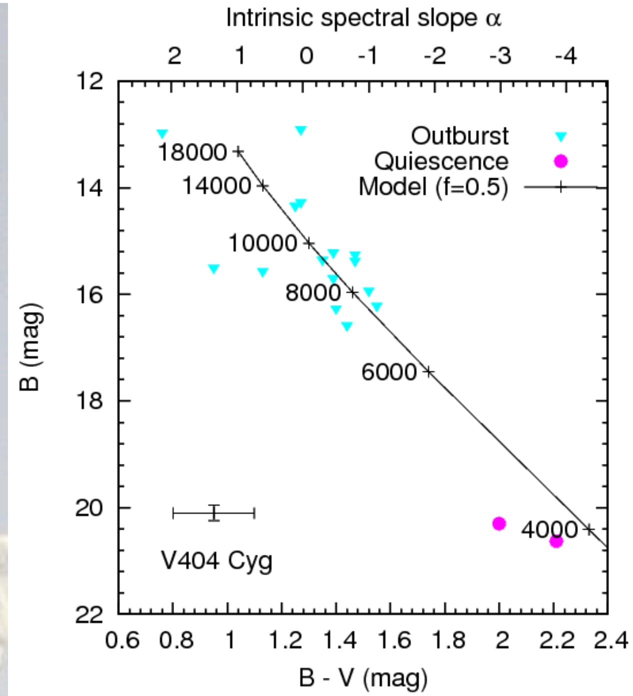
(c) Area of illuminated disc changes:

outer disc radius is larger? (Hynes et al. 2002)

disc is warped or puffed up?

Or perhaps location of illuminating photons changes?





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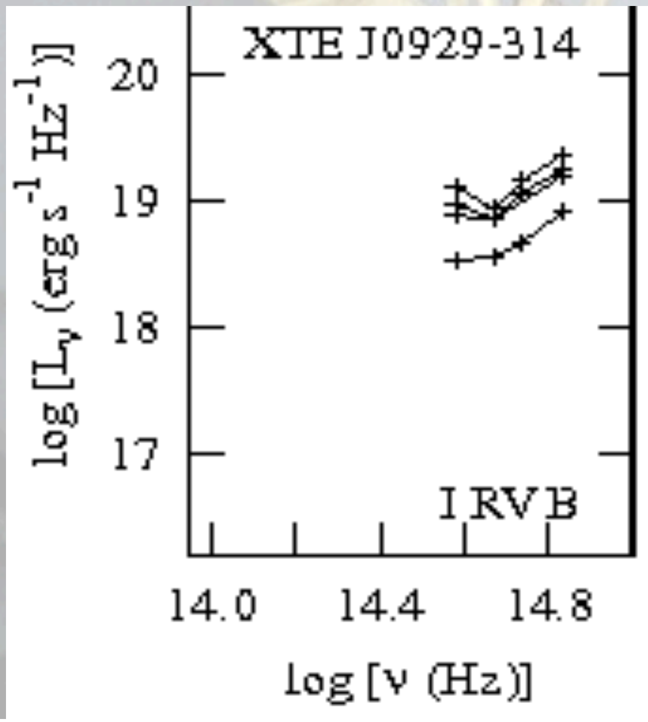
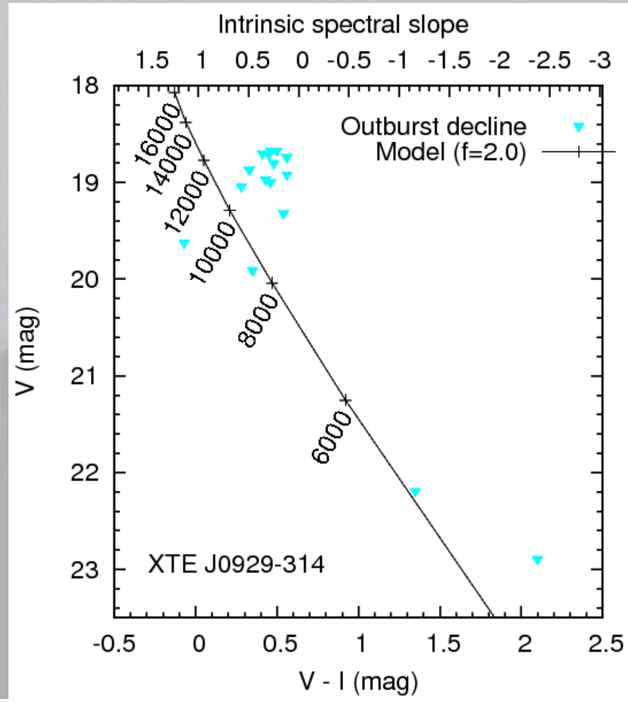




The story of a black hole outburst

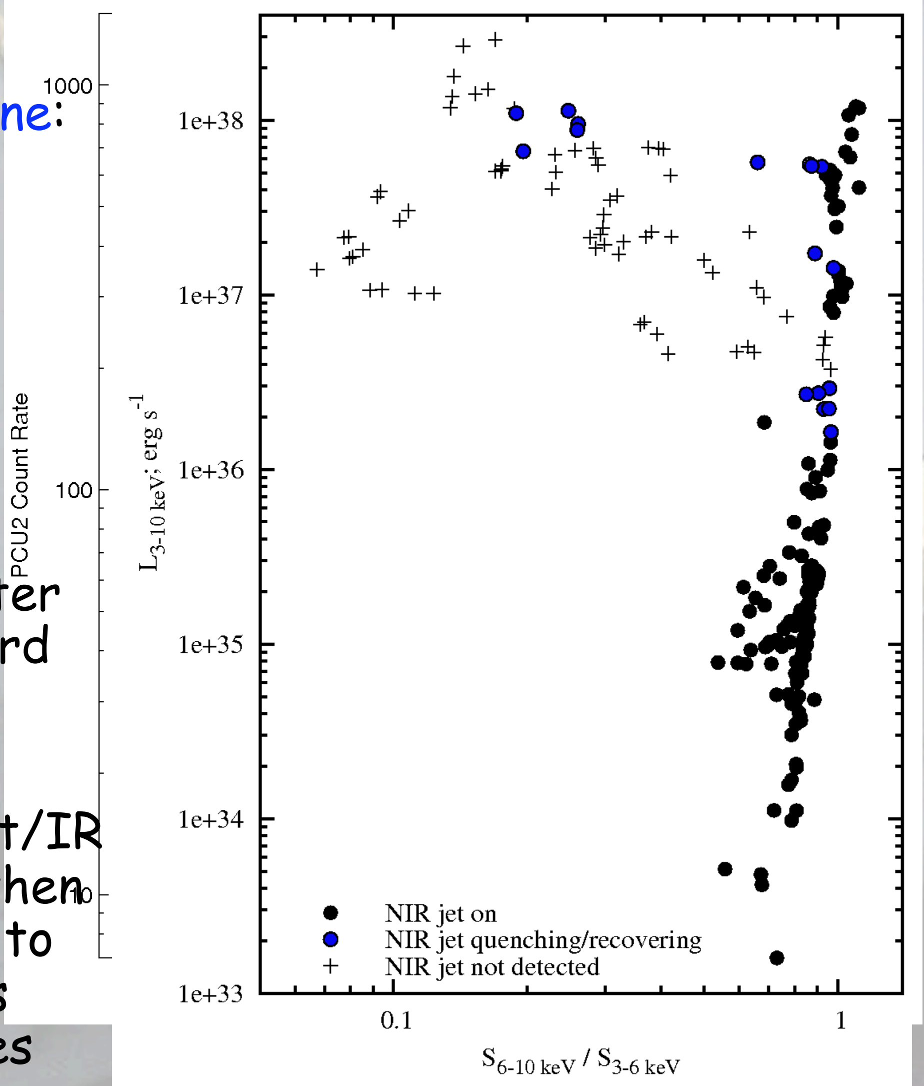
A picture of the X-ray behaviour of black hole XB outbursts has now emerged (Fender et al. 2004; 2009): We can add information from optical/IR

After jet line:

Soft state: optical/IR is all disc

IR rises after E, in the hard state

Reddens opt/IR spectrum, then disc begins to dominate as source fades



Jet line: Bright, optically thin radio flare

→ IR jet seen in one source when crossing left to right

B: Leaves the hard state

NIR drops: spectrum is blue

Area of outer accretion disc may be larger

A to B: Hard state rise

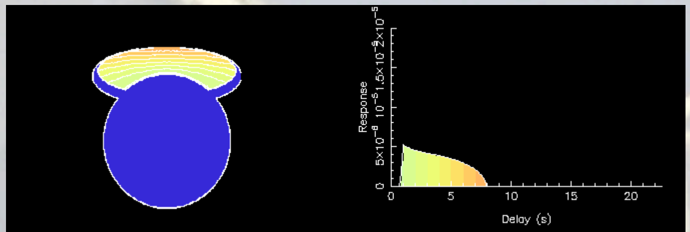
Optical/IR spectrum gets bluer

then redder when jet kicks in

Colour-magnitude diagrams can successfully separate disc / jet contributions and predict where a source lies in the X-ray hardness-intensity diagram

Optical/IR monitoring of LMXB outbursts is valuable

Conclusions about the outer disc



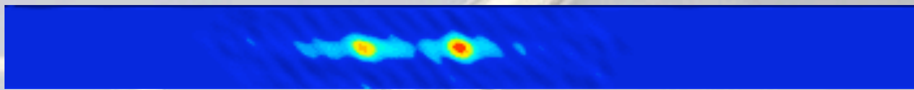
→ Irradiation by X-rays dominates over viscous heating in BHs and NSs

→ A single-temperature blackbody can approximate most of the data

→ viscous disc makes a contribution: from lags, can get viscous timescale

→ Outer disc may shrink in area as it fades in at least one case

Conclusions about the inner jet



→ Jet dominates optical/IR at high luminosities in the hard state for BHs

→ Also in NSs with small accretion discs (e.g. the milli-second X-ray pulsars)

→ IR jet exists only in hard state, and for one source briefly in a softer state

→ Jet does not dominate optical/NIR in quiescence but may in mid-IR