A Multiwavelength View of the Microquasar Cygnus X-1: variability and state transitions on timescales from hours to years

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13 December 2012
Talk Outline

1. Black Hole Binaries
2. Spectral Variability: A Multiwavelength View
3. Spectral Variability: A Long-Term View
4. Spectral Variability: Cygnus X-1
   - RXTE monitoring
   - A Fast State Transition
   - State Definitions with All Sky Monitors
5. Summary & Outlook
Galactic X-ray binaries:
Material flows from normal star onto neutron star or black hole

- accretion and ejection processes
- bulk of radiation in X-ray range
The geometry of the accretion flow is assumed to be very similar in AGN and black hole binaries (BHBs).

⇒ similar behaviour, scaled with mass

- **Size:** \( r \propto \frac{GM}{c^2} \propto M \)
  - BHBs: some 10 km
  - AGN: some AU

- **Variability:** \( \Delta t \propto M \)
  - BHBs: a few msec
  - AGN: up to tens of ksec

- **Temperature:** \( kT_{\text{in}} \propto M^{-1/4} \)
  - BHBs: disc observed in soft X-rays
  - AGN: disc observed in UV

Credit: ESO/WFI (visible); MPIfR/ESO/APEX/A. Weiss et al. (microwave); NASA/CXC/CfA/R. Kraft et al. (X-ray);
Cyg X-1 / HDE 226868 System

HMXB
(High Mass X-ray Binary)

companion:
HDE 226868, O-type supergiant, close to filling its Roche lobe

- strong stellar winds $\Rightarrow$ accretion via focused wind
- orbital period $\sim 5.6$ days; distance $\sim 1.86^{+0.12}_{-0.11}$ kpc (VLBA parallax, Reid et al., 2011)
- inclination of the system $i = 27^\circ$ (Orosz et al., 2011)
two distinct regimes:

1. **hard state**
   - lower flux at soft X-rays,
   - higher flux at hard X-rays

2. **soft state**
   - higher flux at soft X-rays,
   - lower flux at hard X-rays

Cygnus X-1; *Nowak et al., 2011b, Fig. 1*

Chandra • **Suzaku-XIS** • **Suzaku-GSO** • **RXTE-PCA** • **RXTE-HEXTE** • **INTEGRAL**
X-ray-radio Correlation

1.5–12 keV [cps]

15 GHz [mJy]

RXTE ASM

AMI (former: Ryle)

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Jets: Radio

Stirling et al., 2001, Fig. 3

Gallo et al., 2005, Fig. 1&2
coordinated mid-IR (*Spitzer*), X-ray (*RXTE*) and radio (*AMI*) observations

**hard state**

jets present in 2 out of 3 observations

detection of jet-break at about at about $2.9 \times 10^{13}$ Hz

Rahoui, ..., VG, 2011
γ-Rays: Hard Tail

P. Laurent, ..., VG, 2011, Science 332, 438

*INTEGRAL* monitoring of Cyg X-1: \( \approx 5 \text{Ms} \) of *INTEGRAL*/IBIS data between 2003 and 2009

two spectral components:

- \( \lesssim 400 \text{ keV} \): curved component \( \Rightarrow \) Comptonization/reflection
- \( \gtrsim 400 \text{ keV} \): nonthermal component, hard tail

Compton mode for 400–2000 keV data:
polarization fraction $67 \pm 30\%$ (90% conf.), polarization angle $40 \pm 15^\circ$
\Rightarrow cue towards synchrotron, i.e. jet, origin of the hard tail component
Possible X-ray Emission Geometry

The possible X-ray emitting regions are:

- accretion disc
- corona (two of many discussed geometries shown)
- jet

Nowak et al., 2011a, Fig. 9
Cyg X-1 hard state Suzaku/RXTE spectra; Nowak et al., 2011b, Fig. 4a

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Cyg X-1: Variability and State transitions

Spectral Variability: A Multiwavelength View

Non-thermal Comptonization:

Cyg X-1 hard state Suzaku/RXTE spectra; Nowak et al., 2011b, Fig. 4b

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jet model (radio data at 15 MHz not shown, but used in fit):

Cyg X-1 hard state Suzaku/RXTE spectra; Nowak et al., 2011b, Fig. 12
jet model, e.g. Markoff et al., 2005; Maitra et al., 2011

Cyg X-1 hard state Ryle/Suzaku/RXTE spectra, courtesy of M. Nowak; Nowak et al.,
ASM Lightcurve

Cyg X-1: Variability and State transitions  Spectral Variability: A Long-Term View

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An Empirical Measure for the Spectral State

X-ray hardness $\cong$

X-ray colour:

$$\text{Hardness} = \frac{\text{hard countrate}}{\text{soft countrate}}$$

Hardness intensity diagramm (HID)

$=$

hardness vs. total countrate
same kind of behaviour for different accreting objects

⇒

one unified scheme for state transitions: **q-Track**
in BHBs:

- soft X-rays: disc component
- hard X-rays: power law component

⇒ hardness is a ratio between disc and power law component
⇒ construct HID analogue for AGN: disc fraction luminosity diagram

*Koerding et al., 2006, Fig. 7*
A Transient Radio Jet in an Erupting Dwarf Nova

Elmar Körding,1* Michael Rupen,2 Christian Knigge,1 Rob Fender,1 Vivek ... Timing Explorer.

6 JUNE 2008 VOL 320 SCIENCE www.sciencemag.org

suggesting that the disc/jet coupling mechanism is ubiquitous.

that is best explained as synchrotron emission originating in a transient jet. Both the inferred jet

radio observations of a dwarf nova in outburst showing variable flat-spectrum radio emission

disc/jet coupling has evolved and been extended to many accreting objects. The only major

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neries (WDs with thermonuclear burning)

soft sources (WDs with thermonuclear burning)

white dwarfs (WDs) has been reported for super-

trinsically coupled. Jet emission from accreting

emission originating from a jet (the hard state,

core radio emission is quenched in the soft

hard x-ray spectrum and usually shows radio

beginning of the outburst, the source shows a

truncated disc) are thought to be similar (RHMs)

Koerding et al., 2008, Fig. 1

Fig. 1. HID for a black hole, a neutron star, and the DN SS Cyg. The arrows indicate the temporal

states of ~10 when the source is in the analog state of

disc-fraction luminosity diagram (Koerding et al., 2008, Fig. 1 ,

neutron star XRBs, which does not exist in the

be due to the existence of a boundary layer in

XRBs: On its right side, one generally observes a compact jet; the crossing of this line usually coincides

making a transition to the soft state character-

once the source crosses the jet line; after this,

typically accompanied by a bright radio flare

emission from dwarf novae (DNe), a class of

X-ray binaries (XRBs), which do show

ranges from weeks to months (Koerding et al., 2008).

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Cyg X-1: Variability and State transitions

Spectral Variability: Cygnus X-1

Cyg X-1 on the q-Track

ASM hardness A/C (5-12keV / 1.5-3keV)
ASM total countrate [cps]

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The RXTE Campaign

Grinberg et al., 2013, in prep.
Cyg X-1: Variability and State transitions

**Spectral Variability:** Cygnus X-1

**Spectral Modelling**

two basic spectral models employed to describe the *RXTE* data:

- broken power law
- modified by a high energy cutoff

*Grinberg et al., 2013, in prep.*

- simple Comptonization model
  - (Titarchuk, 1994)
- modified by reflection

both models modified by an *Iron Kα-line* at \( \sim 6.4 \text{ keV} \) and by absorption

*Grinberg et al., 2013, in prep.*
Cyg X-1: Variability and State transitions

Spectral Variability: Cygnus X-1

Hard and Soft Spectra

hard state: no disk required

\[ \Gamma_1 \approx 1.7 \]

soft state: strong disk component

\[ \Gamma_1 \approx 3.1 \]

Grinberg et al., 2013, in prep.
**Presence of Disk Component**

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**red**: broken power law **without** disk

**black**: broken power law **with** disk

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*Grinberg et al., 2013, in prep.*
Orbital Coverage

Grinberg et al., 2013, in prep.
Orbital Modulation of \( N_H \)

inclination of the system:
\( i = 27^\circ \) (Orosz et al., 2011)

*here: hard observations, with no disk required*

\( \Rightarrow \) at \( \phi \approx 0 \) stronger absorption due to material local to the system, i.e. the stellar wind of the companion

Grinberg et al., 2013, in prep.
State Transitions

- hard to soft state transition observed to occur in **under 2.5 hours**
- similar behaviour on short and long timescales

*Böck, VG, et al., 2011*
State Transitions

- hard to soft state transition observed to occur in **under 2.5 hours**
- similar behaviour on short and long timescales
- radio flux and X-ray spectral shape correlated
- **tight correlations** between spectral and timing parameters

*Böck, VG, et al., 2011*

![Graph showing photon index vs. radio flux, with annotations for all RXTE data and this work.](image)
Cyg X-1 spectrum with INTEGRAL

exposure $\sim$ 1 day

exposure $\sim$ 1.4 days

$\nu F_{\nu} \, [\text{ergs cm}^{-2} \text{s}^{-1}]$

Energy [keV]

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idea: define states using ASM data ⇒ state definitions where no PCA data available
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simple solutions (using either only countrate or only the hardness)
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simple solutions (using either only countrate or only the hardness) do not clearly distinguish between states

Grinberg et al., 2012, to be submitted
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simple solutions (using either only countrate or only the hardness) do not clearly distinguish between states

solution: use a function of both countrate and hardness
ASM Mapping

Grinberg et al., 2012, to be submitted
ASM, MAXI, BAT and GBM Mapping

Grinberg et al., 2012, to be submitted
Summary

- Unique dataset covering different states and numerous state transitions
- Flux and hardness both important for state definitions in ASM
- Quick transitions, tight parameter correlations
- Orbital variations of $N_H$

Outlook

- full timing analysis of bi-weekly campaign data
- analysis of simultaneous RXTE and INTEGRAL observations for better broad band coverage and test of different physical models
- ASM (and BAT, MAXI, GBM) defined states for state-resolved polarisation analysis with INTEGRAL/IBIS