Interaction between disks and jets in black hole binaries: The case of KV UMa

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Outline

• Properties of stellar mass accreting black holes
• KV UMa (rapid X-ray and optical variability)
• An energy reservoir model for disc/jet coupling
• Consequences for KV UMa and other sources
X-ray spectral states of galactic black holes

• When $L_X > 0.01 L_{\text{Edd}}$
  - spectrum peaks in the X-rays
  - thermal disc spectrum
  + steep power law
⇒ HIGH SOFT STATE

• When $L_X < 0.01 L_{\text{Edd}}$
  - spectrum peaks in the hard X-rays
  - hard power law
  + cut-off
⇒ LOW HARD STATE

(from Grove et al. 1997)
Geometry of the accretion flow

High soft state:
- Cold geometrically thin disc down to the last stable orbit + weak corona
  (Shakura & Sunyaev 1973)
  ⇒ Thermal emission (mainly)

Low hard state:
- Cold disc truncated at ~ 100-1000 Rg + hot inner disc
  (Shapiro, Ligthman & Eardley 1976; Narayan & Yi 1994)
- Accretion disc corona atop a standard thin disc
  (Bisnovatyi-Kogan & Blinikov 1976; Haardt & Maraschi 1993; Beloborodov 1999)
  ⇒ Comptonisation in the hot (10^9 K) plasma
Evidence for compact radio jets in the hard state

Cygnus X-1
(Stirling et al. 2001)

⇒ Self-absorbed synchrotron from compact jets

Flat/inverted radio spectra
(Fender 2001)
X-ray/Radio correlations

⇒ Jet quenched in the high soft state
Radio/X-ray correlation in X-ray binaries

\[ S_{\text{radio}} = k \times (S_X)^{0.7} \]

\[ k = 223 \pm 156 \]

Existence of a jet dominated regime at low $\dot{m}$

Scaling laws for jet and X-ray luminosities with mass accretion rate:
(Fender, Gallo & Jonker 2003)

$$L_{\text{radio}} \propto P_X^{0.7}$$
$$L_{\text{radio}} \propto P_J^{1.4}$$

$$\Rightarrow P_J \propto P_X^{0.5}$$

$$\dot{m} = P_X + P_J$$

$$\dot{m} = A^{-2} P_J^2 + P_J$$

$$\dot{m} = P_X + A P_X^{0.5}$$

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Diagram:
- Black Holes:
  - $P_x \propto \dot{m}^2$
  - $P_x \propto \dot{m}$
- Jet dominated:
  - $P_j \propto \dot{m}^{1/2}$
- X-ray dominated:
  - $P_j \propto \dot{m}$
  - (radiatively inefficient)
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Origin of the radio/X-ray correlations?

- Standard hard state models are wrong: X-ray emission from the jet (Falcke et al. 2001; Markoff et al. 2003; Georganopoulos et al. 2002)

- Jet/corona association (Meier 2001; Merloni & Fabian 2001; Livio et al. 2003)

A possible explanation:

- MHD jets are driven by the poloidal component of the magnetic field $B_p$ (Blandford & Znajek 1977, Blandford & Payne 1982)

- If the field is generated by dynamo processes in the disc/corona: $B_p/B \sim H/R$ (Livio, Ogilvie & Pringle 1999; Meier 2001; Merloni & Fabian 2001)

$\Rightarrow$ geometrically thick accretion flows are more efficient at launching jets
The X-ray nova KV UMa (aka XTE J1118+480)
X-ray, UV, optical and IR flickering

(From Hynes et al. 2003)
Origin of the optical flickering?
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- Reprocessing of the X-rays in the outer disc?
  - optical varies on shorter time-scales than the X-rays
  - reprocessing models fail to reproduce the Opt/X CCF
Auto-correlation and X/opt. cross-correlation functions

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- Synchrotron emission in the Comptonising plasma:
  - requires \( R \sim 1000 R_s \)
  - problem to reproduce the IR/opt/UV variability
  - power-law spectrum?
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  \[\Rightarrow \text{unlikely}\]

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Auto-correlation and X/opt. cross-correlation functions

Dependence of the CCF on the time-scale of the fluctuations

Light curves filtered to keep only fluctuations of specified time-scales

⇒ Nearly scale-invariant CCF
⇒ The optical lag does depend on time-scale
Fourier Analysis

X-ray power spectrum typical of low/hard state sources

Coherence spectrum: Opt and X-rays mostly correlated for 1 to 10 s fluctuations

Opt. Phase lag $\varphi = 2\pi f \Delta t \sim \pi / 2$

$\Rightarrow \text{Opt} \propto -\frac{\partial X}{\partial t}$

(Malzac et al. 2003)
Event superposition analysis

\[ \text{Opt} \propto -\frac{dX}{dt} \]

(Malzac et al. 2003)
Origin of the optical flickering?

• Reprocessing of the X-rays in the outer disc:
  - optical varies on shorter time-scales than the X-rays
  - reprocessing models fail to reproduce the Opt/X CCF

  ⇒ ruled out

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  - requires $R \sim 1000 R_s$
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  ⇒ unlikely

• Synchrotron emission in the jet:
  - simple propagation models do not work

  ⇒ more complex jet/disc coupling?
Jet corona coupling through common energy reservoir

A simple analogue:

\[ P_i = P_j + P_X \]

- Steady state: \( P_j \) tap opened more:
  \( P_j \uparrow \), water level drops, \( P_X \downarrow \)

- \( P_j \) tap partly closed:
  \( P_j \downarrow \), water level rises, \( P_X \uparrow \)

taps controlled by a stochastic process \( \Rightarrow \) behaviour of KV UMa
Time dependent model

On short time-scales the system is out of equilibrium:

\[ \dot{E} = P_i(t) - K_j(t)E(t) - K_x(t)E(t) \]

\rightarrow \text{we impose independent random fluctuations of } P_i, K_x \text{ and } K_j

\text{and then solve the equation for } E(t)

We then generate synthetic light curves assuming:

\[ X(t) \propto P_x = K_x(t)E(t) \]

\[ \text{Opt}(t) \propto P_j(t - \Delta) = K_j(t - \Delta)E(t - \Delta) \]

Travel time from the disc to the jet optical photo-sphere

\Rightarrow \text{Time delay } \Delta \sim 0.05 \text{ s}

Main parameters:

Dissipation time of the energy reservoir:

\[ T_{\text{dis}} = \left[ K_x + K_j \right]^{-1} \]

Fraction of the power dissipated into the X-rays:

\[ f_X = K_x T_{\text{dis}} \]
Time dependent model

\[ f_X = 0.1 \]

\[ T_{dis} = 0.5 \text{ s} \]
Jet/corona coupling through a magnetic reservoir

- The energy content of the comptonising electrons is far too low to account for the observed luminosities. The electrons have to be connected to an energy reservoir. A natural candidate is the magnetic field: $E = VB^2/(8\pi)$

  Field amplification = storage of magnetic energy.

  → Dissipation through reconnection:

  $P_x = \frac{v_d}{R_x} E = K_x E$

- The jet is driven by the poloidal component of the magnetic field:

  $P_j = \frac{B^2_p}{8\pi} A R_c \Omega$

  If the field is amplified by the MRI, $B_p \simeq \frac{H}{R_c} B = hB$

  $P_j = \frac{A}{V} h^2 R_c \Omega E = K_j E$

  (Livio, Ogilvie & Pringle 1999; Meier 2001; Merloni & Fabian 2001)
Constraints on the accretion flow

Assuming a magnetic reservoir:

\[
\frac{v_d}{R_x} = \frac{f_x}{T_{\text{dis}}}, \quad \frac{A}{V} h^2 v_k(R_c) = \frac{1 - f_x}{T_{\text{dis}}}
\]

For \( f_x = 0.1, \ T_{\text{dis}} = 0.5 \) : \( v_d/c \simeq 2 \times 10^5 r_x, \ h \simeq 0.17(r_c/100)^{3/2} \)

\((r_x = R_x/R_s, r_c = R_c/R_s)\)

Inner hot disc: \( B \simeq 3 \times 10^6 (r_c/100)^{-9/4} \) G

Accretion disc corona: \( B \simeq 2 \times 10^7 (r_c/100)^{-5/4} \left[ \frac{N \ln(r_c/3)}{10 \ln(100/3)} \right]^{-1/2} \) G

\[
\frac{h}{a} \simeq 1.6(r_c/100)^{5/2} \frac{3}{r_x} \frac{\ln(r_c/3)}{\ln(100/3)}
\]

⇒ The parameters of the time-dependent model are consistent with both geometries
Constraint on the parameters

\[ P_j = P_i - \left( 1 - \frac{\dot{K}_x}{K_x^2} \right) P_x - \frac{\dot{P}_x}{K_x} \]

The observed relation \( Opt \propto -\frac{dX}{dt} \) i.e. \( P_j \propto -\dot{P}_x \) fulfilled if:

- \( P_i \simeq \text{const} \), \( K_x \simeq \text{const} \), \( \dot{K}_x << 1 \) \( \Rightarrow \) 1-10 s variability driven by \( K_j \)

\( \Rightarrow \) jet activity responsible for most of the X-ray variability

- \( P_x << P_i \) \( \Rightarrow \) jet power dominates over the X-ray emission \( (f_x << 1) \)

\( \Rightarrow \) jet dominates the energetic output of the system
**Time-scales**

- Fluctuations of $K_x$ ranging from 0.01 to 1 s corresponding to 10-100 Rs
  \[ \Rightarrow \] consistent with X-ray production in the hot phase (local process)

- Fluctuations of $K_j$ ranging from 0.01 and 10 s
  \[ \Rightarrow \] large scale coherent structures
  \[ \Rightarrow \] jet activity modulates the X-ray emission
rms-flux correlation
Jet dominance in KV UMa

Is it consistent with the spectral data?

- For the observed jet and X-ray luminosities: \( P_j/P_x \sim 10 \Rightarrow \eta_{\text{jet}} \sim 0.01 \)

- In KV UMa the observed thermal disc component enables one to estimate the mass accretion rate:

  Hot inner disc: \[ \dot{m} = 4\epsilon \left( \frac{R_{\text{in}}}{R_s} \right) L_{\text{disc}} \sim 200L_x \]

  Accretion disc corona: \[ \dot{m} = 4\epsilon \frac{R_{\text{in}}}{R_s} L_{\text{disc}}/(1 - f_h) \sim 10L_x \]

  \( \Rightarrow \) Radiatively inefficient
  \( \Rightarrow \) The total energy budget would allow for jet dominance
Jet dominance in the low hard state?

Scaling laws for jet and X-ray luminosities with mass accretion rate:
(Fender, Gallo & Jonker 2003)

Transition at the critical luminosity

If, in KV UMa,

\[ P_{j}/P_{x} \approx 10 \Rightarrow P_{x,cr} \approx 0.1L_{\text{Edd}} \]

⇒ All black holes in the low hard state are jet dominated and radiatively inefficient
Conclusions

• Fast optical/X-ray photometry provides a unique opportunity to study accretion/ejection processes on short time-scales

• Jet/disc coupling through a common energy reservoir can explain the complex behaviour of KV UMa

• Such models require $P_j >> P_x$ (possibly true for all hard state sources)