Extreme Jet Ejections from the Black Hole X-ray Binary V404 Cygni: The Unique (Sub-) Millimetre Perspective

Alex Tetarenko
University of Alberta

J.C.A. Miller-Jones (ICRAR), G.R. Sivakoff & E. Rosolowsky (UAlberta), on behalf of a Larger X-ray Binary Collaboration

EAO Seminar
February 16, 2016
Black Hole X-ray Binaries (BHXBs)

- Compact object accreting from less-evolved companion
- Two phases:
  - Quiescence
  - Outburst
- Jet best detected during outburst
- Outbursts vary on short timescales

Adapted from Fender, 2000
Outburst and Jet Behaviour

Hard State
(<0.1 \text{ L}_{\text{edd}})

Alex Tetarenko – EAO
Seminar Feb 2016
Outburst and Jet Behaviour

Intermediate States
($\sim 0.3 \, L_{\text{edd}}$)

Hard State
($<0.1 \, L_{\text{edd}}$)

$F_v$

Time

$\nu_{\text{purple}} < \nu_{\text{white}}$

Hardness

Luminosity

Alex Tetarenko – EAO
Seminar Feb 2016
Outburst and Jet Behaviour

High State
(>0.5 L_{edd})

Intermediate States
(~ 0.3 L_{edd})

Hard State
(<0.1 L_{edd})

Fender & Pooley, 2000

Alex Tetarenko – EAO
Seminar Feb 2016
Outburst and Jet Behaviour

High State
(\(>0.5 \text{ L}_{\text{edd}}\))

Intermediate States
(\(\sim 0.3 \text{ L}_{\text{edd}}\))

Soft State

Hard State
(\(<0.1 \text{ L}_{\text{edd}}\))

Jet quenched in soft state

Luminosity

Hardness

Alex Tetarenko – EAO Seminar Feb 2016
V404 Cygni

- Prolonged quiescent period of 26 yrs.
- Well determined system parameters
- Low optical extinction
- Parallax distance

\[ d = 2.39 \pm 0.14 \text{ kpc} \]
\[ P_{\text{orb}} = 6.5 \text{ days} \]
\[ i = 80.1 \pm 5.1 \text{ degrees} \]
\[ M_{\text{BH}} = 7.15 \pm 0.35 \, M_{\odot} \]
\[ E(B-V) = 0.1 \]

Credit: R. Hynes

Alex Tetarenko – EAO
Seminar Feb 2016
June 2015 Outburst

- On June 15, 2015, X-ray flaring activity detected by Swift BAT, MAXI and INTEGRAL
- Extraordinary multi-wavelength flaring activity followed
- Brightest BHXB outburst in the past decade

Rare, bright accretion state  +  Well-known system parameters  +  Close Proximity parameters
On June 15, 2015 X-ray flaring activity detected by Swift BAT, MAXI and INTEGRAL.

Extraordinary multi-wavelength flaring activity followed.

Brightest BHXB outburst in the past decade (~ 50% Ledd at maximum).

http://deneb.astro.warwick.ac.uk/phsaap/v404cyg/data/
The “Golden Data Set”

VLA + JCMT + SMA + VLBA = Unprecedented multi-wavelength view
“Golden Data Set” Part 1

- Flares reach extremely bright flux levels
- Lower $\nu$ are delayed, smoothed version of higher $\nu$
- (sub-)mm substructure not visible in cm emission

Tetarenko et al., 2016, in prep
Light Curve Modeling

Preliminary Results

Tetarenko et al., 2016, in prep

- Simultaneously fit all 6 frequencies with MCMC algorithm
- Light curves well described by van der Laan Models
- 13 ejection events!
Modeling the Ejecta

- We can model each ejection with,
  - Ejection time
  - Peak Flux
  - Expansion speed
  - Optical depth/\rho
- We adopt linear expansion model + deceleration

\[ v_{\text{exp}} \sim 0.01 \text{ to } 0.05 \, c \]
Modeling the Ejecta

- We can model each ejection with,
  - Ejection time
  - Peak Flux
  - Expansion speed
  - Optical depth/\( \rho \)
- We adopt linear expansion model + deceleration

\[ \tau \sim 1.0-2.0 \]
Modeling the Ejecta

• We can model each ejection with,
  – Ejection time
  – Peak Flux
  – Expansion speed
  – Optical depth/p

• We adopt linear expansion model + deceleration

\[ p \sim 1.0 - 3.0 \]
Modeling the Ejecta

- Estimate ejecta size scales
  - Initial radius at moment of particle injection
  - Track changes as a function of time and frequency

Initial Radii $\sim 10^5 R_G$
Could the jet spectral break occur between C and K band?

\[ \nu_{\text{break}} \approx 15 \text{ GHz} \]

- SMA (230 GHz)
- K band (18-26 GHz)
- C band (5-8 GHz)
Importance of the mm/sub-mm

• Substructure in mm/sub-mm light curves critical in modeling
• Why not include JCMT data?
• Evolution in C band?

Tetarenko et al., 2016, in prep
“Golden Data Set” Part 2

VLBA Movie

Preliminary Results
Tetarenko et al., 2016, in prep

Alex Tetarenko – EAO
Seminar Feb 2016
• Imaging and self-calibration procedure of > 100 individual frames

• Astrometric Measurements:
  • Proper Motion
  • Bulk Jet Speed
  • Ejection Times

• VLBA ejection times coincide with those inferred from our modeling!

Preliminary measurements suggest atypical behavior of some ejecta

Tetarenko et al., 2016, in prep
Combining the Two

- Unique probes of jet speed, structure and size scale

- This is the first time expansion speeds and proper motions of ejecta have been simultaneously measured!

\[
\begin{align*}
\nu_{\text{exp}} & \sim 0.01-0.05c \\
\mu & \sim 0.25-0.50c \\
\text{Opening angle} & \sim 3-4 \text{ degrees}
\end{align*}
\]
Relationship to X-ray Emission

- Predicted ejection times do not appear to correlate well with X-ray emission
- Does the X-ray probe synchrotron emission from jet or accretion flow emission?

Preliminary Results
Tetarenko et al., 2016, in prep

Data from Rodriguez et al., 2015

Alex Tetarenko – EAO
Seminar Feb 2016
Dip-type oscillations are seen at optical wavelengths.

Same type of oscillations seen in GRS 1915+105, associated with repeated ejection and refilling of inner disk.
Comparing to GRS 1915+105

- Only other source to show repeated multi-wavelength flaring

**Similarities**
- Enter high luminosity state
- Repeated flaring events
- Low frequencies delayed versions of high frequencies

**Differences**
- Rise and decay times similar at all frequencies
- No jet ejecta resolved with VLBA
- GRS 1915+105 in outburst state for last 25yrs, V404 transient
High Time Resolution Measurements

- Our team has developed a custom timing script for interferometric data that runs in CASA
- Produces light curves on user specified time bin
- Many customizable options:
  - UV or Image plane
  - Object Detection
  - Fixed Target Position
  - And many more…

Tetarenko & Koch et al., 2016, in prep

https://github.com/Astroua/AstroCompute_Scripts
Summary

• Analysis is ongoing
• Simultaneous multi-wavelength coverage essential to unlocking complicated physics.
• Rapid response and specialized observing techniques, like sub-arrays and VLBI, make this possible.

• mm/sub-mm data provides a unique, more detailed view of the jet compared to cm.

Thank you!

Alex Tetarenko – EAO
Seminar Feb 2016