Multi-wavelength jet studies in Cataclysmic Variables and Super-luminous Supernovae

Deanne Coppejans


Image credits: ESO and M. Garlick/University of Warwick/ESO
Cataclysmic Variables (CVs)

- Polars ($B \gtrsim 10^7$ G)
- Intermediate Polars ($10^6 \lesssim B \lesssim 10^7$ G)
- Dwarf Novae
- Novalikes

Magnetics

- Non-magnetics ($B \lesssim 10^6$ G)
CVs were believed to not launch jets

So CVs have been used to constrain jet-launching models in compact accretors (e.g. Livio 1999, Soker & Lasota 2004)
Figure 2 of Körding+ (2008), showing SS Cyg's 1.1 mJy flare at 8.5 GHz on the rise to outburst

• Körding+ (2008): Best explained as synchrotron emission from a transient jet
Cataclysmic Variables

- Körding+ (2008): Best explained as synchrotron emission from a transient jet
- Miller-jones+ (2011) confirmed this in separate outburst
- Russell+ (2016): Behaviour is reproducible
- Mooley+ (2017) detected a flare that showed spectral evolution
- V3885 Sgr (Körding+ 2011)
Do the rest of the CV population show this behaviour?

Prior to 2008...

- 1980s: Large number of surveys of non-magnetic CVs$^{1,2,3,4}$

- Only 2 detections out of 50 observations (Benz et al. 1996)

- Only three were detected:
  - SU UMa$^1$, EM Cyg$^2$, and TY Psc$^3$

- CVs were not detected in follow-up observations

Barrett+ 2017: Detected 19/121 magnetic CVs

Cataclysmic Variables

Difficulties:

- Flare predicted during rise
- Outbursts unpredictable
- Need to confirm outburst before triggering observations
- Takes time to get on telescope

Solution:
AAVSOnet campaign 505
Cataclysmic Variables are a new class of radio transient!

TT Ari, V603 Aql, RW Sex, V1084 Her, U Gem, YZ Cnc, SU UMa, Z Cam, RX And

Coppejans+ 2015, Coppejans+ 2016
Cataclysmic Variables

Emission Properties:

- **Radio specific luminosity:**
  \[ L_{_{10\text{GHz}}} \sim 4 \times 10^{15} \text{ to } 4 \times 10^{16} \text{ erg s}^{-1} \text{ Hz}^{-1} \]

- **Radio luminosity:**
  \[ L \sim 4 \times 10^{25} \text{ to } 4 \times 10^{26} \text{ erg s}^{-1} \]

Coppejans+ 2015, Coppejans+ 2016b
Cataclysmic Variables

Emission Properties:

- **Radio specific luminosity:**
  \[ L_{10 \, \text{GHz}} \sim 4 \times 10^{15} \text{ to } 4 \times 10^{16} \, \text{erg s}^{-1} \text{ Hz}^{-1} \]

- **Radio luminosity:**
  \[ L \sim 4 \times 10^{25} \text{ to } 4 \times 10^{26} \, \text{erg s}^{-1} \]

- **Measured Variability:** 200s – days

Coppejans+ 2015, Coppejans+ 2016b
Emission Properties:

- **Radio specific luminosity:**
  \[ L_{10\,\text{GHz}} \sim 4 \times 10^{15} \text{ to } 4 \times 10^{16} \text{ erg s}^{-1} \text{ Hz}^{-1} \]

- **Radio luminosity:**
  \[ L \sim 4 \times 10^{25} \text{ to } 4 \times 10^{26} \text{ erg s}^{-1} \]

- **Measured Variability:** 200s – days

- **Spectral indices:** Steep to inverted

Coppejans+ 2015, Coppejans+ 2016b
Cataclysmic Variables

Emission Properties:

- **Radio specific luminosity:** 
  \[ L_{10 \text{ GHz}} \approx 4 \times 10^{15} \text{ to } 4 \times 10^{16} \text{ erg s}^{-1} \text{ Hz}^{-1} \]

- **Radio luminosity:** 
  \[ L \approx 4 \times 10^{25} \text{ to } 4 \times 10^{26} \text{ erg s}^{-1} \]

- **Measured Variability:** 200s – days

- **Spectral indices:** Steep to inverted

- **Polarization:**
  - ≥75% Circular polarization in TT Ari

Coppejans+ 2015, Coppejans+ 2016b
Emission Properties:

- **Radio specific luminosity:**
  \[ L_{10\,\text{GHz}} \sim 4 \times 10^{15} \text{ to } 4 \times 10^{16} \text{ erg s}^{-1} \text{ Hz}^{-1} \]

- **Radio luminosity:**
  \[ L \sim 4 \times 10^{25} \text{ to } 4 \times 10^{26} \text{ erg s}^{-1} \]

- **Measured Variability:** 200s – days

- **Spectral indices:** Steep to inverted

- **Polarization:**
  \[ \geq 75\% \text{ Circular polarization in TT Ari} \]

- **No correlation with:**
  - Orbital period or Orbital phase,
  - CV subclass,
  - Outburst type,
  - Optical luminosity

**BUT** sparsely sampled observations of variable objects

Coppejans+ 2015, Coppejans+ 2016b
Coppejans+ (2016b)
Radio emission is dependent on accretion state!!!

Cataclysmic Variables

Coppejans+ (in prep)
Cataclysmic Variables

Synchrotron or gyrosynchrotron emission

- Spectral indices
- Brightness temperature
- Polarization fraction
- Variability time-scales

(except for TT Ari)

Electro-cyclotron Maser Emission

TT Ari

Coppejans+ (2015), Coppejans+ (2016b)
Do CVs as a class launch jets?

More observations needed…

- Higher cadence
- Higher resolution
- Multiple frequency, multi-wavelength
Super-luminous Supernovae (Hydrogen poor)

Radio Luminosity

SLSNe-I <10^{37} \text{ erg/s}

CVs 10^{25}-10^{26} \text{ erg/s}

What powers SLSN-I?
- Excessive amounts of radioactive material?
- Interaction?
- Central Engine?
Super-luminous Supernovae (Hydrogen poor)

On-axis jets like those detected in GRBs?

All SLSNe-I radio observations to date

Coppejans+ (submitted)
Super-luminous Supernovae (Hydrogen poor)

Off-axis collimated jets?

Radio Luminosity

Time since explosion
Super-luminous Supernovae (Hydrogen poor)

Off-axis collimated jets?

![Graph showing specific luminosity vs. days after explosion.](image)
Super-luminous Supernovae (Hydrogen poor)

Off-axis collimated jets?

Coppejans+ (submitted)
Super-luminous Supernovae (Hydrogen poor)

Off-axis collimated jets?

$5^\circ$ jet:
$M < 10^{-4} \, M_\odot \, yr^{-1}$ and $E_{k,iso} < 10^{53}$ erg

$30^\circ$ jet:
$M < 10^{-5} \, M_\odot \, yr^{-1}$ and $E_{k,iso} < 10^{53}$ erg

Coppejans+ (submitted)
Do Hydrogen poor Super-luminous Supernovae launch jets?

- We rule out on-axis jets like the kind detected in GRBs
- We constrain the phase space for off-axis GRB-like jets

More observations needed:

- Need nearby systems
- Earlier times
- Later times
Figure 1 from Körding et al. 2008
V603 Aql (novalike)

Coppejans+ 2015
Z Cam (DN)

Coppejans+ 2016b
YZ Cnc (DN)

Radio flux density (mJy)

Optical flux (mag)

MJD from the Start of Outburst

0 5 10 15

VLA non-detection

AAVSO V

VLA 10 GHz

Coppejans+ 2016b
Novalikes:

<table>
<thead>
<tr>
<th>Name</th>
<th>Radio Flux (uJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW Sex</td>
<td>33.6 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>26.8 ± 3.3</td>
</tr>
<tr>
<td>V1084 Her</td>
<td>&lt;10.2</td>
</tr>
<tr>
<td></td>
<td>&lt;11.4</td>
</tr>
<tr>
<td>TT Ari</td>
<td>39.6 ± 4.2</td>
</tr>
<tr>
<td></td>
<td>239.1 ± 5.5</td>
</tr>
<tr>
<td>V603 Aql</td>
<td>178.2 ± 4.3</td>
</tr>
<tr>
<td></td>
<td>190.5 ± 3.9</td>
</tr>
</tbody>
</table>

DN:

<table>
<thead>
<tr>
<th>Name</th>
<th>Radio Flux (uJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z Cam</td>
<td>25 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>40.3 ± 5.2</td>
</tr>
<tr>
<td></td>
<td>33.1 ± 4.4</td>
</tr>
<tr>
<td>RX And</td>
<td>13.6 ± 3.2</td>
</tr>
<tr>
<td></td>
<td>19.6 ± 4.4</td>
</tr>
<tr>
<td></td>
<td>&lt;14.4</td>
</tr>
<tr>
<td>SU UMa</td>
<td>35.5 ± 3.8</td>
</tr>
<tr>
<td></td>
<td>58.1 ± 5.7</td>
</tr>
<tr>
<td></td>
<td>19.1 ± 4.9</td>
</tr>
<tr>
<td>YZ Cnc</td>
<td>17.4 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>26.8 ± 5.2</td>
</tr>
<tr>
<td></td>
<td>&lt;18.9</td>
</tr>
<tr>
<td>U Gem</td>
<td>12.7 ± 2.8</td>
</tr>
<tr>
<td></td>
<td>&lt;16.8</td>
</tr>
<tr>
<td></td>
<td>&lt;17.5</td>
</tr>
</tbody>
</table>
Optically thick thermal emission

Brightness temperature is too high:

- Orbital Radius, \( R \sim 10^{11} \) cm
- Emitting region of the size of the binary gives \( T_B \sim 10^9 \) K
- Ionized gas typically has \( T_B \sim 10^{4-5} \) K → Emitting region of \( \sim 10^2-10^3 \) \( R \)

Variability time-scales are too fast:

- Fastest wind observed in a CV \( \sim 5000 \) km/s (Kafka+ 2009)
- Even a \( 10^4 \) km/s wind, it would take \( \sim 170 \) min to propagate changes over \( 10^{13} \) cm
- BUT variability time-scales down to \( \sim 4 \) min are observed

\[ T_B = \frac{S_v c^2}{2 k_B \Omega v^2} \]
Optically thin thermal emission

- Cannot be reprocessed optical radiation from CV: The radio does not lag the optical
- It would have to be produced from an outflow
- Mass transfer rate upper-limit $\sim 10^{-8} \text{ M}_o/\text{y} \rightarrow$ Upper-limit on outflow $\sim 10^{-8} \text{ M}_o/\text{y}$
- So assume all material is carried off in a wind, with a uniform of $\sim 10^3 \text{ km/s}$:
  - Then the upper-limit on the optically thin thermal flux density is $\sim 10^{-6} \text{ Jy}$ (Eqn 8 Wright & Barlow 1975)
  - This is orders of magnitude lower flux than we observe

Coppejans+ (2015), Coppejans+ (2016b)
These observations have already been used to classify radio transients (Miller-Jones+ 2015, Tetarenko+ 2016, Diaz Trigo+ 2017).

“Flaring dwarf novae... could be a source of confusion to neutron star classification” (Russell+ 2016)

Space density of non-magnetic CVs $\sim 10^{-6}$ pc$^{-3}$ (Pretorius+ 2012)
Extra Slides

Specific Optical Luminosity ($10^{19}$ erg/s/Hz) vs. Specific Radio Luminosity ($10^{16}$ erg/s/Hz)

- SS Cyg, flare
- RW Sex
- IX Vel
- U Gem
- SS Cyg, plateau
- V1084 Her
- AC Cnc
- YZ Cnc
- SS Cyg, faintest
- V603 Aql
- RX And
- Z Cam
- TT Ari
- V3885 Sgr
- SU UMa

Coppejans et al. 2016b
A new class of radio transient

Coppejans et al. 2015, Luminosities from McLean et al. 2012, upper-edge of quiescence from Guedel et al. 1993
A new class of radio transient

Coppejans+ 2016b
A new class of radio transient

- Radio specific luminosity: \( L_{10\,\text{GHz}} \sim 4 \times 10^{15} \) to \( 4 \times 10^{16} \) erg s\(^{-1}\) Hz\(^{-1}\)
- Radio luminosity: \( L \sim 4 \times 10^{25} \) to \( 4 \times 10^{26} \) erg s\(^{-1}\)
- Variability: 200s – days
- Spectral indices: Steep to inverted
- Polarization: One source showed circular polarization

Radio luminosity was not dependent on:
- orbital period
- orbital phase
- sub-class
- outburst type
- optical luminosity

<table>
<thead>
<tr>
<th>Object</th>
<th>Spectral index ((F=\nu^\alpha))</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW Sex</td>
<td>-0.5 ± 0.7</td>
</tr>
<tr>
<td>TT Ari, obs 1</td>
<td>1.6 ± 0.1</td>
</tr>
<tr>
<td>TT Ari, obs 2</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>V603 Aql, obs1</td>
<td>0.54 ± 0.05</td>
</tr>
<tr>
<td>V603 Aql, obs2</td>
<td>0.16 ± 0.08</td>
</tr>
<tr>
<td>Dwarf novae</td>
<td>Not constrained</td>
</tr>
</tbody>
</table>

Caveat – emission is highly variable

Coppejans+ (2015), Coppejans+ (2016b)
A new class of radio transient

Coppejans+ (submitted)
A new class of radio transient

Coppejans+ (submitted)