No Evidence of Intrinsic Optical/Near-Infrared Linear Polarization for V404 Cygni during Its Bright Outburst in 2015: Broadband Modeling And Constraint on Jet Parameters

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Cosmic jet sources

- Central BH + accretion disk system generates a powerful jet
- Universal mechanism for jet production??
SEDs of AGN jets: Enhancement of jet emission due to Relativistic beaming effect

- Luminosity is enhanced by $\delta^4$
- $\delta \sim 10$ for blazars
- $\delta \sim a$ few for radio galaxies (viewing angle $> a$ few degrees) and microquasars ($\Gamma \sim 2$-3)
- Strong optical polarization from blazars (40-50% P.D. at most, evidence of optically-thin synchrotron emission, see e.g., Ikejiri+11)

\[ \delta = \frac{1}{\Gamma (1 - \beta \cos \theta)}, \quad \beta = \frac{v}{c} \]
Microquasar jet:

Detection of jet component is not easy except radio band due to lack of amplification ($\delta$ is a few, like radio galaxies)

- Detection of jet component mostly relies only on the SED shape
- High polarization degree is expected from optically-thin synchrotron emission (as blazars)
- Polarization measurement in the optical/NIR band is another key to detect the jet component
- It is not easy to eliminate the interstellar polarization for objects in the Galactic Plane
Multiple bright X-ray bursts (Flux > 20 Crab) were detected by INTEGRAL (e.g., Rodriguez et al. 2015)

Note that X-ray flux comes from disk/corona, not from the jet
Bright (>1 Jy) radio flare (e.g., ATeI #7667, 7716)

- Radio emission is thought to be synchrotron by non-thermal MeV electrons
- Clear evidence of presence of jet component
Telescopes and instruments

Kanata 1.5m telescope: Optical/NIR polarimetry with HONIR (Akitaya+14)

Pirka 1.6m telescope: Optical polarimetry with MSI detector (Watanabe+12)
Optical and NIR *simultaneous* polarimetry with HONIR

- Hiroshima Optical and Near-InfraRed camera (HONIR, Akitaya+14), which is attached to the Cassegrain focus of 1.5-m Kanata telescope
- We can perform *simultaneous* polarimetry in 2 bands: one in optical (BVRI) and the other is in NIR (JHKs) band
- 10’x10’ FoV
- Imaging capability: J~18.2 mag, Ks~16.3 mag for S/N=10, 1200 s exposure
MSI (Multi-Spectral Imager) attached to 1.6m Pirka telescope in Hokkaido

• Located in Hokkaido, northern part of Japan and ~1500 km away from Hiroshima, so we can avoid weather constraint

• MSI (Watanabe+12) is attached to Cassegrain focus of 1.6-m Pirka telescope

• FoV is 3.3‘x3.3’

• Optical one-band polarimetry among UBVRI bands
Kimura+16

Black: Pirka/MSI R-band
Red: Kanata/HONIR Ks-band
Blue: Kanata/HONIR R-band

V-band magnitude
R-, Ks-band mag.
Polarization Degree
Pol. Position Angle

- Quite similar light curves in R- band Ks-bands except orphan NIR flare around MJD 57193.54
- Steady P. D. (R~8%, Ks~1.5%) and P.A. (~8 deg) despite the large flux variations
R-band P.D. and P.A. for V404 Cyg (blue) and surrounding objects (red) observed by HONIR:

Suggesting interstellar origin, rather than intrinsic. V404 Cyg intrinsic polarization is <2-3 %
Optical polarimetry in quiescent state

V404 Cygni taken by Pirka/MSI on 2015/09/27

<table>
<thead>
<tr>
<th></th>
<th>2015-06-23</th>
<th>2015-09-27</th>
</tr>
</thead>
<tbody>
<tr>
<td>光度 (mag.)</td>
<td>~11 mag</td>
<td>16.6 ± 0.1 mag.</td>
</tr>
<tr>
<td>偏光度 (P.D.)</td>
<td>7.9 ± 0.1 %</td>
<td>8.3 ± 2.6 %</td>
</tr>
<tr>
<td>偏光方位角 (P.A.)</td>
<td>5.3 ± 0.7 deg.</td>
<td>3.6 ± 5.7 deg.</td>
</tr>
</tbody>
</table>

P.D. and P.A. are comparable to those measured during the outburst, suggesting again the interstellar origin.
• Synchrotron Self-Absorption frequency and peak flux density allows us to estimate $B$ and $R$ at the emission site ($s$ is PL index of electron distribution, equipartition assumed)

\[
B \approx 1 \times 10^5 \left( \frac{\nu_{SSA}}{3 \times 10^{14} \text{ Hz}} \right)^{\frac{3s+10}{2s+13}} \left( \frac{F_\nu}{2 \text{ Jy}} \right)^{-\frac{2}{2s+13}} \left( \frac{D}{2.4 \text{ kpc}} \right)^{-\frac{4}{2s+13}} \text{ Gauss,}
\]

\[
R \approx 5 \times 10^8 \left( \frac{\nu_{SSA}}{3 \times 10^{14} \text{ Hz}} \right)^{-\frac{s+6}{2s+13}} \left( \frac{F_\nu}{2 \text{ Jy}} \right)^{s+6} \left( \frac{D}{2.4 \text{ kpc}} \right)^{\frac{2(s+6)}{2s+13}} \text{ cm,}
\]
• Assume electron distribution is cutoff-PL \[ \frac{dN}{d\gamma} = K \gamma^{-s} \exp\left(-\frac{\gamma}{\gamma_{\text{cut}}}\right) \]

• Swift/XRT flux comes from disk/corona, so upper limit for jet component \( \gamma_{\text{cut}} \sim 100 \)
Inefficient particle acceleration

- From SED modeling, we found that electron cutoff Lorentz factor is limited up to ~100, which is determined by the balance between acceleration and cooling time scales.

- Note that acceleration time can be expressed by a parameter $\eta$, the number of gyrations an electron makes while doubling its energy.

$$t_{\text{acc}} = \eta E / (eBc)$$

$$t_{\text{cool}} = 3\gamma m_e c / \left(8\sigma_T \gamma^2 (U_B + U_{\text{sync}})\right)$$

- $\eta \sim 10^6$, indicating very long acceleration time and inefficient particle acceleration (~10 for AGN jets).
Jet energetics (need for baryon loading) and radiative efficiency

Table 2: Model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>MJD 57193</th>
<th>MJD 57194</th>
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</thead>
<tbody>
<tr>
<td>Break frequency [Hz]</td>
<td>( \nu_{SSA} )</td>
<td>( 3 \times 10^{14} )</td>
<td>( 3 \times 10^{14} )</td>
</tr>
<tr>
<td>Magnetic Field [G]</td>
<td>( B )</td>
<td>( 1.4 \times 10^5 )</td>
<td>( 1.8 \times 10^5 )</td>
</tr>
<tr>
<td>Size of emission region [cm]</td>
<td>( R )</td>
<td>( 5.3 \times 10^8 )</td>
<td>( 1.7 \times 10^8 )</td>
</tr>
<tr>
<td>Jet velocity [c]</td>
<td>( \beta )</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Electron distribution normalization [electrons]</td>
<td>( K )</td>
<td>( 4.5 \times 10^{40} )</td>
<td>( 7.0 \times 10^{39} )</td>
</tr>
<tr>
<td>Electron Power-law Index</td>
<td>( s )</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Minimum Electron Lorentz Factor</td>
<td>( \gamma_{\text{min}} )</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cutoff Electron Lorentz Factor</td>
<td>( \gamma_{\text{cut}} )</td>
<td>( 10^2 )</td>
<td>( 10^2 )</td>
</tr>
<tr>
<td>Maximum Electron Lorentz Factor</td>
<td>( \gamma_{\text{max}} )</td>
<td>( 10^6 )</td>
<td>( 10^6 )</td>
</tr>
<tr>
<td>Synchrotron luminosity [erg s(^{-1})]</td>
<td>( L_{\text{sync}} )</td>
<td>( 2.8 \times 10^{37} )</td>
<td>( 4.3 \times 10^{36} )</td>
</tr>
<tr>
<td>SSC luminosity [erg s(^{-1})]</td>
<td>( L_{\text{SSC}} )</td>
<td>( 4.1 \times 10^{37} )</td>
<td>( 7.2 \times 10^{36} )</td>
</tr>
<tr>
<td>Total radiation luminosity [erg s(^{-1})]</td>
<td>( L_{\text{rad}} )</td>
<td>( 6.9 \times 10^{37} )</td>
<td>( 1.2 \times 10^{37} )</td>
</tr>
<tr>
<td>Jet Power in Magnetic Field [erg s(^{-1})]</td>
<td>( L_B )</td>
<td>( 3.7 \times 10^{37} )</td>
<td>( 6.3 \times 10^{36} )</td>
</tr>
<tr>
<td>Jet Power in Electrons [erg s(^{-1})]</td>
<td>( L_e )</td>
<td>( 7.8 \times 10^{36} )</td>
<td>( 3.7 \times 10^{36} )</td>
</tr>
<tr>
<td>Jet Power in Cold Protons [erg s(^{-1})]</td>
<td>( L_p )</td>
<td>( 2.1 \times 10^{39} )</td>
<td>( 2.0 \times 10^{39} )</td>
</tr>
<tr>
<td>Jet Radiative Efficiency [%]</td>
<td>( \epsilon_{\text{rad}} )</td>
<td>( \sim 3 )</td>
<td>( \sim 1 )</td>
</tr>
</tbody>
</table>

- \( L_{\text{rad}} > L_e + L_B \), requiring another source of energy to explain the luminosity (similar situation to AGN jets, see e.g., Ghisellini+14)
- Possible option is to assume that the jet contains cold proton (e.g., Ghisellini+14)
- 1-3% radiative efficiency by assuming “one cold proton per one emitting electron” (~10% for AGN jets, see e.g., Ghisellini+14)
Variable R-band polarization
(PD~1%)
Summary

- We did not find temporal variation of P.D. and P.A. even during large flux variations in optical and NIR bands.

- Both steady P.D. and P.A. for V404 Cygni suggests that intrinsic polarization is weak and mostly interstellar origin.

- Optical/NIR lights would be disk or optically-thick origin, and optically-thin synchrotron is clearly rejected due to low intrinsic P.D.

- Electron Lorentz factor is limited up to $\gamma \approx 100$.

- Inefficient particle acceleration ($\eta \approx 10^6$, very long acceleration time).

- $L_{\text{rad}} > L_e + L_B$, requiring another source of energy and implying loading of baryon component (cold protons).

- This situation is similar to the case of AGN jets.

- Radiative efficiency of $\sim 3\%$ for V404 Cygni jet ($\sim 10\%$ for AGN and GRB jets).

- Finally, we note that variable optical polarization is reported in Shahbaz+16 and Lipunov+16 during the intervals when Kanata did not observe, indicating that the jet component is rarely visible in optical band.