AO-assisted high angular resolution observations of protostellar jets

Sub-0.1arcsec optical observations of the young binary Z CMa with SPHERE

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Protostellar jets

- fundamental for angular momentum removal
- excavate and disperse parental envelope
- likely affect disk structure and composition (and indirectly planet formation)
Jet-disk connection

Open questions:
- What is the jet launching mechanism?
- What is the jet feedback on the disk?

- MHD models: the jet is launched and accelerated by magneto-centrifugal forces
- Jets may remove angular momentum from the disk!

**STELLAR WIND**
Sauty+ 2002

**X-WIND**
Shu+ 1994, 2000
< 0.1 AU

**DISK WIND**
Konigl & Pudritz 2007
1-10 AU
Goals
• Understand **HOW** the jet is launched
• Understand **IF** and **HOW** the jet affects the disk structure
• Find direct evidence for **accretion and ejection events connection**
  → can we identify emission knots launched during enhanced accretion phases (outbursts?)

Needs
• Image the jet down to few AUs from the source (closest objects at ~150 pc)
  → **high spatial resolution** (< 0.1arcsec), **high contrast** ($10^2$–$10^5$) images
Previous high-angular-resolution observations of jets

Typical limitations of previous high-angular-resolution observations:
- Angular resolution $\geq 0.1$ arcsec
- Poor contrast for bright sources, e.g., Herbig's
- Coronagraphs $\geq 0.3$ arcsec

Narrow-band imaging

AO imaging
[S II] 6731 Å

long-slit spectrum
[S II] 6731 Å

IFU image
[Fe II] + H$_2$

HH 30 with HST
$\sim 0.1''$
Ray+ 1996, Bacciotti+ 1999

DG TAU with CFHT
$\sim 0.1''$
Dougados+ 2000

DG TAU with STIS/HST
$\sim 0.1''$ - R=6000
Maurri+ 2014

DG TAU with SINFONI
$\sim 0.2''$ - R=3000
Agra-Amboage+ 2014
• Extreme AO system and coronagraphic facility of the VLT.

• Common AO infrastructure (CPI+SAXO) feeding 3 instruments:
  > ZIMPOL (optical imager and polarimeter)
  > IRDIS (NIR imager and spectrograph)
  > IFS (NIR integral field spectrograph)

• Mainly devoted to exoplanet search.
• Observations of jets included in GTO “other science” (PI Antoniucci & Podio)
First target: Z CMa and its twin jets

- $V = 8.8$ mag, $K = 4.5$ mag, $d \approx 1150$ pc
- Binary system (0.1” sep)
  1. **Herbig Be star** (intermediate mass young star)
  2. **FU Ori star** (young eruptive star with massive disk, undergoing strong accretion outbursts ($\sim 10^4$-$10^5$ \(M_{\odot}/\text{yr}\)) with duration $\sim 10^2$ yr)

- The Herbig component has recurrent outbursts: most recent ones in 2008, 2010, 2015 (enhanced accretion events)
- Each component drives a jet detected in optical and NIR lines

Canovas+ 2012

Whelan+ 2010

[Fell] images
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Despite distance Z CMa is a unique laboratory to:

- investigate **connection between accretion and ejection** events
- test the magneto-centrifugal scenario and universality of MHD models for intermediate mass stars and FU Ori objects:
  - by measuring **collimation** and **accretion/ejection efficiency** ($M_{\text{loss}}/M_{\text{acc}}$) and from comparison with jets from low-mass stars (T Tauri stars)
- study **ejection in FU Ori objects** (no direct $M_{\text{loss}}$ determinations from jets observed close to the source)

Canovas+ 2012
Z CMa ZIMPOL observations

Observations:

- **Cnt_Hα**
- **Hα**
- **[OI]6300Å**

**Obs 1.**

- **Cnt_Hα** and **Hα** simultaneous acquisition

**Obs 2.**

- Narrow-band imaging ($\Delta \lambda \sim 5$ nm), pixel-scale = 3.6 mas/pix
- Exposure time = 30 min (frames with DIT of 30s)
- Field-stabilized mode
- Average seeing during observations ~ 1.0 arcsec, fairly stable conditions
[OI] and Hα images

**Tech 1.**
Subtraction of the Cnt_Hα exposure to remove stellar continua

**Tech 2.**
Deconvolution with the MC-RL method of *La Camera+ 2014* (reconstructs star + diffuse emission)
**[OI] and Hα images**

**Herbig.**
The collimated jet is not revealed. We see a compact **wide-angle wind** from the Herbig: possibly related to past accretion outbursts of this component.

**FUor.**
Highly **collimated jet** from the FU Ori component: *wigging!*

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Some numbers:

- at Z CMa distance 1 mas = 1.15 AU
- effective resolution ~ 30 mas
- effective (source-jet) contrast ~ $10^3$
- trace the jet down to ~70-80 mas (~80-90 AU)
- S/R (FUor jet) > 10
- binary separation: 114 mas, P.A. 136°
Jet wiggling: likely originates from orbital motion of the jet source around an undetected companion. Using a simple model (Anglada+ 2007) we infer the parameters of the binary:

\[ T_0 = 4.5 \text{ yr}, \quad r_0 = 1.3 \text{ AU} \]
with \( M_{\text{tot}} = 1-3 \, M_{\odot} \Rightarrow a = 2.7-3.9 \, \text{AU}, \, m_1-m_2 = 0.5-0.5 \, M_{\odot} - 2.0-1.0 \, M_{\odot} \)

Antoniucci+ 2016
The jet from FU Ori component

2. Jet profile width (FWHM)
   - FWHM of jet profile $\rightarrow$ ~30-50 mas
   - **Collimation** comparable with that observed in other classes of young sources with jets (Class 0/I, T Tauri)
   - Indicates **that launching mechanism is the same** (magneto-centrifugal) even in sources with massive disks like FU Ori objects!

![Graph showing jet intrinsic FWHM (AU)]

3. $M_{\text{loss}}$ and $M_{\text{acc}}$
   - **First** direct measurement of $M_{\text{loss}}$ in FU Ori objects!
     $\rightarrow$ from [OI] flux (e.g. Hartigan+ 1995, Giannini+ 2015) $\rightarrow$ $M_{\text{loss}} = 5 \times 10^{-7} \, M_{\odot}/\text{yr}$
   - In MHD models expected $M_{\text{loss}}/M_{\text{acc}}$ between 0.01-0.2 (e.g. Ferreira+ 2006) $\rightarrow$ indicates $M_{\text{acc}}$ between $3 \times 10^{-6} \, M_{\odot}/\text{yr}$ (not consistent with previous estimates) and $5 \times 10^{-5} \, M_{\odot}/\text{yr}$ (consistent) $\rightarrow$ possible **indication for low ejection efficiency** in FU Ori objects
AO-assisted observations of jets

Jets are wonderful scientific targets for AO-assisted instruments

• The closer we go, the better it is! To study the base of the jet within 10 AU in closest star-forming regions (150 pc) → go below 70 mas angular resolution!
• With this unprecedented resolution:
  → measure jet collimation, disentangle jet formation and launching mechanism
  → probe interaction with disk
  → directly connect accretion and ejection events
• … But central star typically has $R \geq 11$–$12$ mag
• Expected contrasts $10^3$ – $10^5$
• Important tracers in the optical: e.g. [OI] 6300Å, [SII] 6716Å & 6731Å, Hα
• Best scenario: couple the high-angular-resolution with high-spectral resolution!

What’s next

• Observations of classical T Tauri jets with SPHERE (DG Tau, T Tau)
• Simulations of jet observations with SHARK-VIS and SHARK-NIR @LBT
A che tante facelle? – G. Leopardi