# High Resolution Near-Infrared Coronagraphic Images of the T Tauri Binary Systems

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## ☆Abstract☆

We present high resolution (sub-arcsec) near-infrared images of three T Tauri binary systems: UY Aur, XZ Tau, and FS Tau, taken with the Coronagraphic Imager with Adaptive Optics (CIAO) on the Subaru Telescope. We detected a half-ring-shaped circumbinary disk around UY Aur with a bright southwestern part but a barely detectable northeastern portion. The disk is not uniform but has three features. A structure extends to about 2.4" from the XZ Tau's secondary in the northeast region of the binary. Combining with the HST/ACS archival images and [Fe II] spectra taken with the Subaru/IRCS, the structure is identified as a wall of a cavity blown by the previously known outflow. Five circumbinary features were detected around FS Tau. NW, SW, and NE arms are indicative of cavity wall created by undetected bipolar outflow from the binary.

## 1. Introduction

### 1.1 Motivations

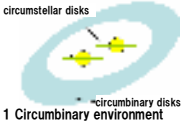

Fig 1 Circumbinary environment

- Many young low-mass stars (T Tauri stars) have protoplanetary disks and outflows.
- More than half of T Tauri stars are binaries in view of the observational results (e.g., Ghez et al. 1993) and theoretical predictions (e.g., Hennebelle & Teyssier 2008).
- A limited number of studies (several dozen) have so far examined the environments around T Tauri binary systems.
- The binary system is predicted to have two kinds of disks: a circumstellar (CS) disk associated with each star and a ring-shaped circumbinary (CB) disk around the binary system (Fig1; Artymowicz & Lubow 1996).

**To study CB environments, we observed various T Tauri binary systems with the Subaru/CIAO.**

### 1.2 CIAO – Coronagraphic Imager with Adaptive Optics

Coronagraphic + AO --> CIAO can detect the CB structures relative-easily.

**Example: GG Tau** (Fig2; e.g., Itoh et al. 2002)
- $a$ = 28AU, $q$ = 0.9
- A ring-shaped and smooth CB disk (inner radius of about 180AU)

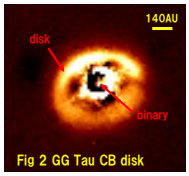

Fig 2 GG Tau CB disk

### 1.3 Targets

Three T Tauri binary systems in Taurus cloud ($d$~140 pc)

| | Semimajor axis $a$ [AU] | Mass ratio $q$ (primary mass [$M_{sun}$]) | H magnitude [mag] |
|---|---|---|---|
| UY Aur | 126 | 0.6(0.6) | 8.0 |
| XZ Tau | 42 | 0.8(0.4) | 8.1 |
| FS Tau | 56 | 0.4(0.5) | 9.2 |

### 1.4 Previous studies

①UY Aur (Close et al. 1998, Duvert et al. 1998, Potter et al. 2000)
- J, H, and K' with AO (Fig3)
- Millimeter continuum and $^{13}$CO line
- A centrosymmetric polarization pattern

→UY Aur has the CB disk of gas and dust.

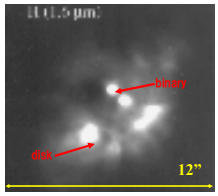

Fig3. UY Aur circumbinary disk (Close et al.)

②XZ Tau (Mundt et al. 1990, Krist et al. 2008)
- [S II] bipolar jet extended to 10"-20"
- A succession of a bubble created by the jet
- The jet sources of both binary components

③FS Tau A (Fig 4; e.g., Gledhill & Scarrott 1989, Krist et al. 1998)
- CS/CB disks indicated by polarization observation
- Surrounding reflection nebulae extended to 800AU
- $H_\alpha$ nebulosity at the north region of FS Tau

→The circumbinary nature is unknown so far.

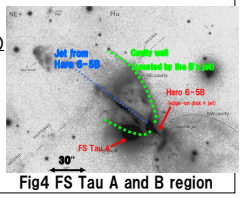

Fig4 FS Tau A and B region

## 2. Observations – Subaru/CIAO (H-band: 1.6 um)

| Targets | Obs Epoch | Mask size ["] | Int time [sec] | FWHM ["] | Additional data |
|---|---|---|---|---|---|
| UY Aur | 2005.11.9 | 2.0 | 1440 | 0.1 | - |
| XZ Tau | 2005.11.11 | 0.6 | 720 | 0.1 | HST/ACS polarization |
| FS Tau | 2007.12.15 | 0.8 | 390 | 0.3 | HST/ACS polarization |

## 3. Data Reduction (IRAF)

①Dark subtraction
②Flat-fielding by twilight-flat
③Hot and bad pixel removal
④Sky subtraction
⑤Shift each frame to adjust the position of the star
⑥Rotation of PSF reference-frames to adjust the position angle of the spider
⑦Combining (object-frames – PSF reference-frames)

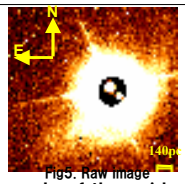

Fig5. Raw image

## 4. Results

### 4.1 UY Aur disk (Fig 6; Hioki et al. 2007)

- **CB disk: half ring-shaped, asymmetric brightness**
- A cavity between the binary and the disk

①Clumpy structure
- Distance~520 AU, Radius~90 AU
- Brightness: ~15.3 mag arcsec$^{-2}$

→A local peak of the dust density (~5.4×10-18 [g/cm$^3$])

②Material in the cavity
→Clumps or accretion material from the CB disk

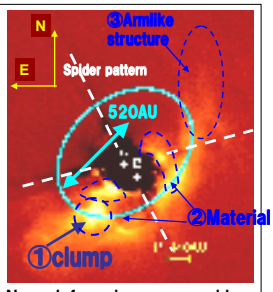

Fig 6. Near-infrared coronagraphic image of the UY Aur circumbinary disk

③Arm-like structure
→Due to dust accretion from the outer region of the disk or stellar encounter

### 4.2 FS Tau

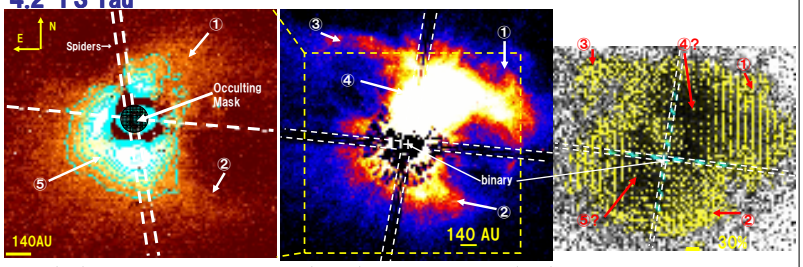

Fig 7 (left) H-band coronagraphic image (middle) HST V-band image (right) Storks P image

| | H: CIAO (Fig 7 left) | V: Storks I (Fig 7 mid) | Storks P (Fig 7 right) |
|---|---|---|---|
| ①NW arm | Yes | Yes | Yes |
| ②SW arm | Yes | Yes | Yes |
| ③NE arm | No | Yes | Yes |
| ④North bright feature | No | Yes | Yes? |
| ⑤SE bright feature | Yes | No | Yes? |

①②③ NW, SW, and NE arms
- Their radial profiles: $\propto r^{-2}$: more flared structures than an optically thick disk (Whitney & Hartmann 1992)
- Parts of cavity wall created by FS Tau's outflow? (Pair of NW and SW arms, given the outflow to the west of the binary)

④ North bright feature
- Brightness~18.9 mag arcsec$^{-2}$ at the $V$-band
- We could detect this feature in the $H$-band if it has similar $V$-$H$ color to FS Tau (4.3 mag; Kenyon & Hartmann 1995)
- Possibly not only dust scattering but also emission line ($H\alpha$)

⑤ SE bright feature
- Brightness~15.0 mag arcsec$^{-2}$ at the $H$-band
- Not detect in the $V$-band image but centro-symmetric polarized pattern

⇒ CB disk/envelope?

### 4.3 XZ Tau (Hioki et al., submitted)

CIAO detected an elongated structure!!

①A jet from XZ Tau S?
⇒We clear that [Fe II] emission was not detected around this structure with the Subaru/IRCS (Fig 9). Therefore, not jet!!

②A cavity wall created by the XZ Tau jet?
- The structure = edge of the north bubble (Fig 9)
- Radial profile: $\propto r^{-1.6}$ (optically thick flared structure)
- Centrosymmetric polarization pattern ($P$~6%)

⇒We conclude that the elongated structure is a wall of a cavity blown by the previously known blueshifted outflow.

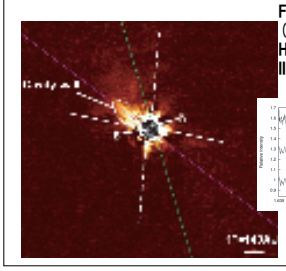
Fig 8 XZ Tau circumbinary structure (H-band coronagraphic image) with H-band echelle spectra around [Fe II] 1.644 um

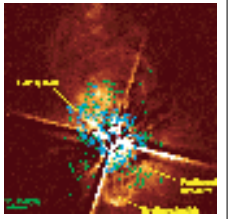
Fig 9 The H-band coronagraphic image (contour; same as Fig 8) overlaid on the HST optical image (color).