The innermost circumstellar environment of massive young stellar objects revealed by infrared interferometry

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Spatial resolution at $D = 500$ pc:

- **HST, Adaptive Optics, Speckle:**
  - mirror $\varnothing \leq 8$ m
  - NIR resolution $\sim 0.05$ arcsec $= 25$ AU

- **Long-Baseline Interferometry:**
  - $B \leq 200$ m
  - NIR resolution $\sim 2$ mas $= 1$ AU

Dusty disk

Dust sublimation radius

$T_{\text{dust}} = 1500$ K

solar-mass star: $R_{\text{sub}} \sim 0.1$ AU,

$18 M_\odot$ star: $R_{\text{sub}} \sim 10$ AU $\sim 270 R_*$

The inner circumstellar regions of young stellar objects
Long Baseline Interferometry

Concept of the ESO Very Large Telescope Interferometer

Optical Path Difference

OPD compensation
Visibility := contrast of the fringe system

- **point source:**
  \[ \varnothing \ll \frac{\lambda}{B} \]
  100% contrast
  Visibility = 1
  unresolved

- **"small" source**
  \[ \varnothing < \frac{\lambda}{B} \]
  high contrast
  high Visibility
  marg. resolved

- **"large" source**
  \[ \varnothing \sim \frac{\lambda}{B} \]
  low contrast
  low Visibility
  resolved

- **extended source:**
  \[ \varnothing \gg \frac{\lambda}{B} \]
  0% contrast
  Visibility = 0
  over-resolved
Visibility as function of object size and baseline length

Gauss models

FWHM = 5, 10, 20 mas

\[ V = 0.42 \quad @ \quad B = 100 \text{ m} \quad \rightarrow \quad \text{Gauss } \varnothing = 10 \text{ mas} \]
1.) Interferometric NIR size estimates

Sublimation radius \( R_{\text{subl}} \propto L^{\frac{1}{2}} \)

Near-infrared emission comes (mainly) from hot dust near the inner edge of the dusty disk at the dust sublimation radius
Near- + mid-infrared spectro-interferometry with MIDI + AMBER at the ESO VLTI

**MIDI:** N-band (8–13 µm)
R = λ/Δλ = 30, 230

**AMBER:** J, H, K-band (1–2.5 µm)
R = 30, 1500, 12000
Near- and mid-infrared emission probe different regions:

- NIR: usually dominated by hot (1500 - 1000 K) dust at inner disk edge + scattered stellar light
- MIR: hot & warm dust (1500 - 300 K)

Combination of near- & mid-infrared spectro-interferometry can probe the detailed physical conditions in the disk, e.g. radial temperature profile, dust chemistry/grain size distribution, …
MWC 147 = HD259431

Monoceros OB1
(D=800 pc)

Hernandez et al (2004): SpT = B6, M = 7 M☉
L = 1,550 L☉; Teff = 14,000 K; Age ~ 0.3 Myr
MWC 147

- reflection nebulosity
- extended mid-infrared emission (6 arcsec)
- strong infrared excess

SED modeling:

estimated accretion rate
$\dot{M}_{\text{acc}} = 1.0 \times 10^{-5} \, M_\odot/\text{yr}$

(Hillenbrand et al. 1992)
Interferometric observations of MWC 147

VLTI / MIDI: 7 observations
- $8 - 13 \, \mu\text{m}$, $R = 30$
- $\text{Vis} = 0.5 \ldots 0.9$

VLTI / AMBER: 1 observation
- $2.0 - 2.4 \, \mu\text{m}$, $R = 35$
- $\text{Vis} = 0.75$

PTI (archive): 5 observations
- Broadband K
- $\text{Vis} = 0.8$
source seems to be elongated

→ flattened structure (disk)
Characteristic near-infrared size (ring model radius) of MWC 147: 0.7 AU

Expected dust sublimation radius: 2.5 AU
2.) Interferometric observations at different wavelengths and baselines → \textit{Parametric imaging}

Model images → Model visibilities → Comparison of predicted and observed visibilities \((+\text{ SED})\)

Constraints on model parameters
1: Spherical shell model

2: Disk model

Spherical Shell

Flared Keplerian Disk  Inclination: 45°

SED fits are highly ambiguous!
1: Spherical shell model
\[ \chi^2_r = 80 \]

2: Disk model
\[ \chi^2_r = 42 \]
NIR visibilities

1: Spherical shell model
\[ \chi_r^2 = 80 \]

2: Disk model
\[ \chi_r^2 = 42 \]

NIR model visibilities are much smaller than the observed visibilities

→ emission is more compact than assumed in the models
We model the gas in the inner accretion disk to be
- geometrically thin
- extend from $R_{\text{corot}}$ ($\sim 3 R_*$) to $R_{\text{subl}}$ ($\sim 2.5$ AU)
- follow the temperature-profile from Pringle (1981)

Muzerolle et al. 2004:
Emission from gas in the inner accretion disk can dominate near-infrared emission for accretion rates $\geq 10^{-6} \, M_\odot / \text{yr}$

\[ T_{\text{gas}}^4(r) = \left( \frac{3G M_* \dot{M}}{8\pi \sigma T^3} \right) \left( 1 - \sqrt{\frac{R_*}{r}} \right)^{1/2}. \]
$3: \text{Flared dusty disk } + \text{ inner gas disk: } \chi_r^2 = 1.28$

Inclination: $60^\circ$, $\dot{M}_{\text{acc}} = 9 \times 10^{-6} \text{ M}_\odot/\text{yr}$
Best-fit radiative transfer model images

NIR emission comes mainly from inner gas disk

MIR emission comes also from warm dust in the disk
NIR emission of massive young stars often dominated by gas emission
(see also Monnier et al. 2005, Eisner et al. 2005, Vinkovic & Jurkic 2007)

Muzerolle et al. 2004
Summary

- The combination of **spectro-interferometric observations** over a wide wavelength range + **radiation transfer modeling** can provide unique constraints on the geometry/physics of the inner circumstellar environment of young stellar objects.

- MWC 147:
  - resolved at near- and mid-infrared wavelengths
  - brightness distribution is **asymmetric** → flattened structure (disk)
  - size of NIR emission is **smaller** than expected dust sublimation radius
  - model of a **dust disk** + emission from an **inner gas disk**
    can simultaneously reproduce SED, near- and mid-infrared visibilities
    (Kraus, Preibisch, Ohnaka, submitted to ApJ)

- NIR contribution of **inner gas disk** seems to increase with stellar mass
The (near) future: **Interferometric imaging**

combine 3 (or more) telescopes (closure phase)

→ reconstruction of images with mas resolution

*Example:*

image reconstruction with
simulated VLTI / AMBER data:

4 nights with 3 ATs
K-band, S/N = 50

/model image \[ i = 45^\circ \]

/folded image

/reconstructed image

simulation by K.-H. Hofmann and S. Kraus, MPIfR Bonn