Visions of Nature's Planet Foundry: Imaging of Circumstellar Disks

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As the number of detected extrasolar planetary systems has steadily grown over the past five years, so too has the number of circumstellar disks with resolved images. A variety of different observational techniques, most notably the Hubble Space Telescope and millimeter interferometry, have to date resolved dozens of disks associated with pre-main sequence and main sequence stars. A number of interesting results have flowed from these imaging studies. All of the resolved disks have a radial extent comparable to or larger than the size of our solar system's Kuiper Belt. In T Tauri star disks, kinematic mapping of molecular emission lines provides convincing evidence for Keplerian orbital motion of the circumstellar gas. The first measurements of disk scale heights have recently been made in these systems. In the outer regions of T Tauri disks, scattered light observations appear to rule out any major depletion of submicron-sized grains with respect to millimeter sized grains at ages of 500,000 yrs. Unexpected variability suggestive of moving illumination patterns has been observed within the scattered light nebula of one young disk. Circumstellar and circumbinary disks have been imaged in binary star systems, providing strong circumstantial evidence that planet formation is not precluded by multiplicity.

Attempts to unravel the internal density structure of dense young disks from images have yet to meet with much success. However, the situation is much better in the case of the more tenuous debris disks, where radial surface density profiles have been derived and central holes, warps, localized clumps, and radial gaps have been observed. Some of these features can plausibly arise from the dynamical influences of unseen substellar companions within the disks. Establishing the presence of such objects and quantifying their effects on a disk's structure remains a goal for the future. The advent of large new facilities such as ALMA and NGST will take us further toward this goal of understanding the organic relationship between disks and planets.

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Plan for this Talk

- Survey Overview
- Circumbinary Disks
- Circumstellar Disks in Binary Systems
- Envelopes, Outflows, and Jets
- A binary answer, a circumbinary question
- Conclusions

Introduction

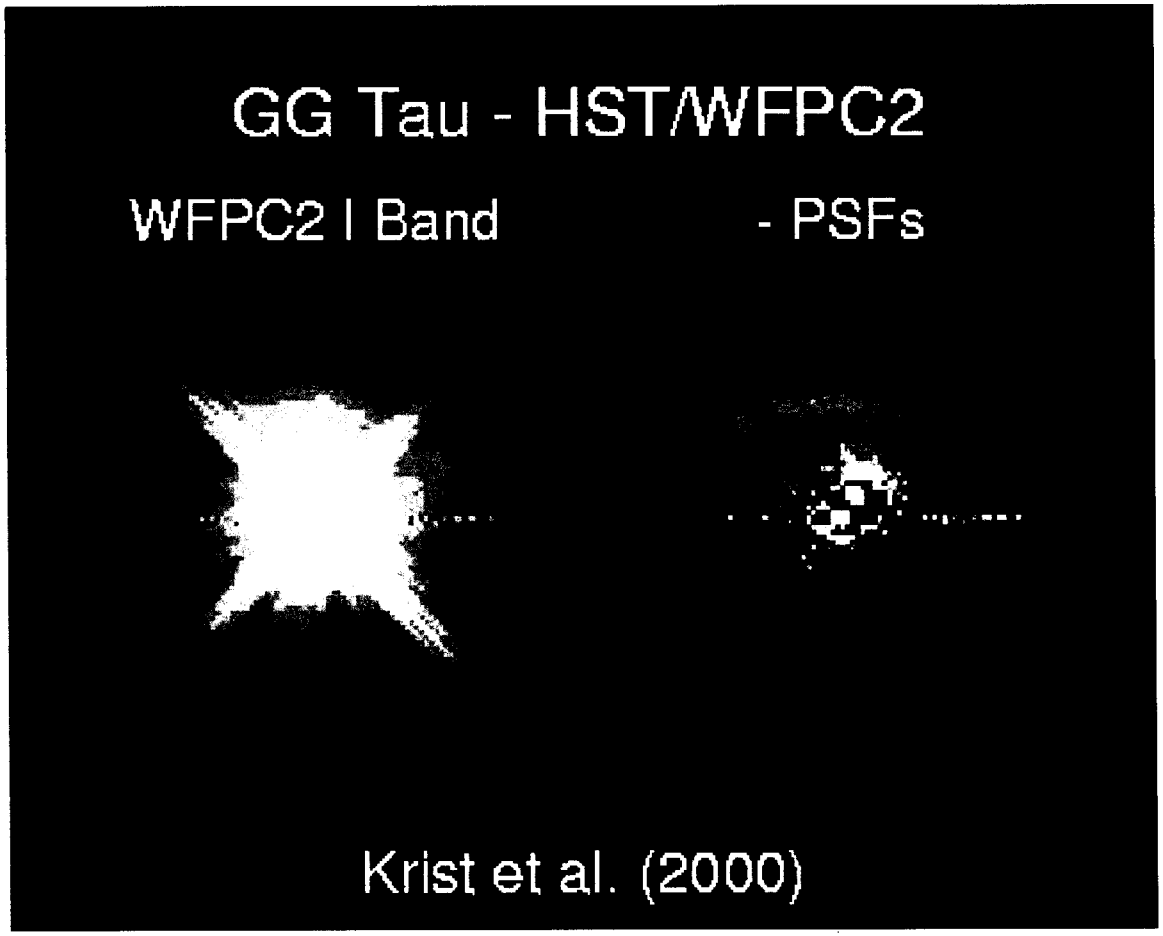
- **HST and Adaptive Optics provide the high resolution imaging necessary to resolve features on 10 AU scales in nearby clouds**
- **At optical/near-IR wavelengths, circum-stellar dust reflects the central star's light. Jet emission lines can also be seen**
- **High ISM dust opacity means**
  - Tenuous circumstellar clouds are detectable
  - Dense young disks should be very optically thick
- **Image contrast can be a challenge**

Observing Program

- **Imaging survey of young stars. Targets are selected by**
  - Resolved molecular gas disks
  - Millimeter continuum emission
  - Optical nebulosity or polarization
  - Strong Hα emission
  - Location in nearby clouds d< 160 pc
- **More than 100 YSOs now imaged with Hubble Space Telescope**
- **HST results are compared with Adaptive Optics and millimeter interferometry**

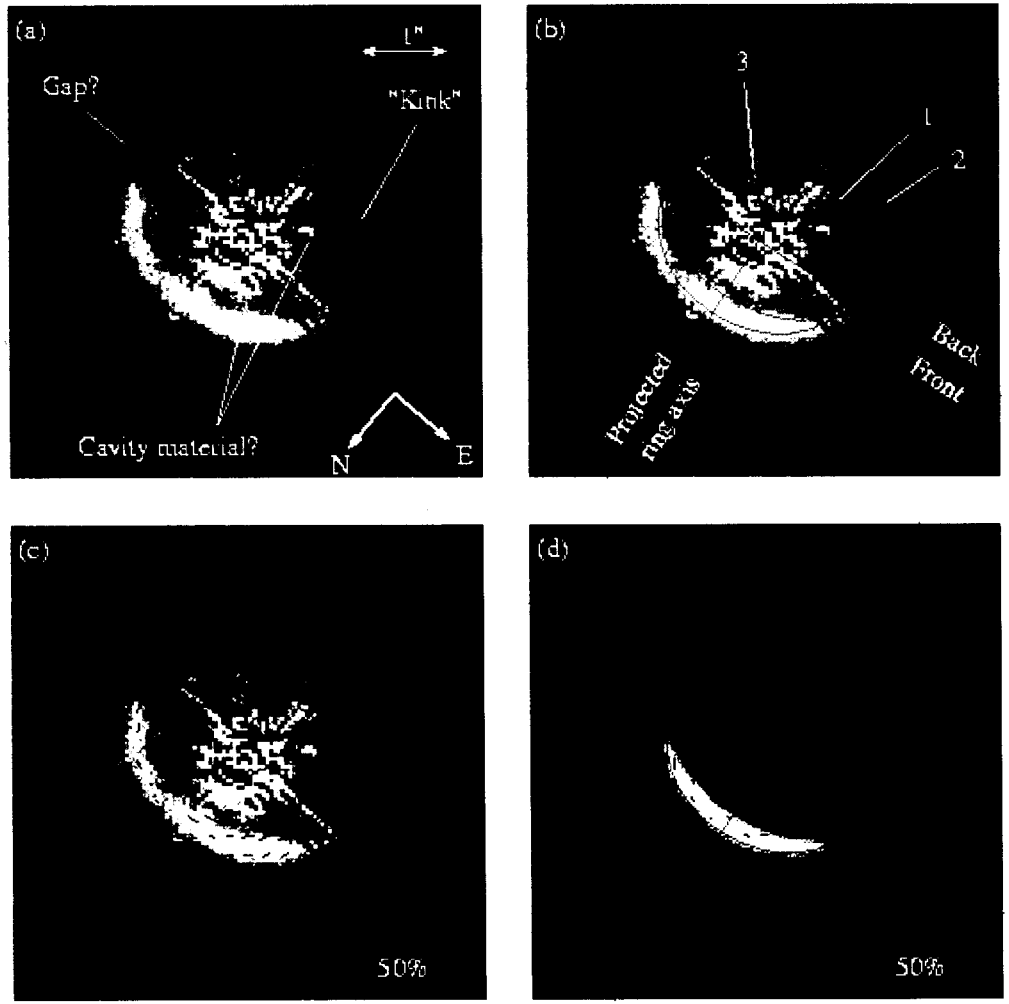
Young Binaries with Deep HST WFPC2 Images

GG Tau: HST/WFPC2 Observations



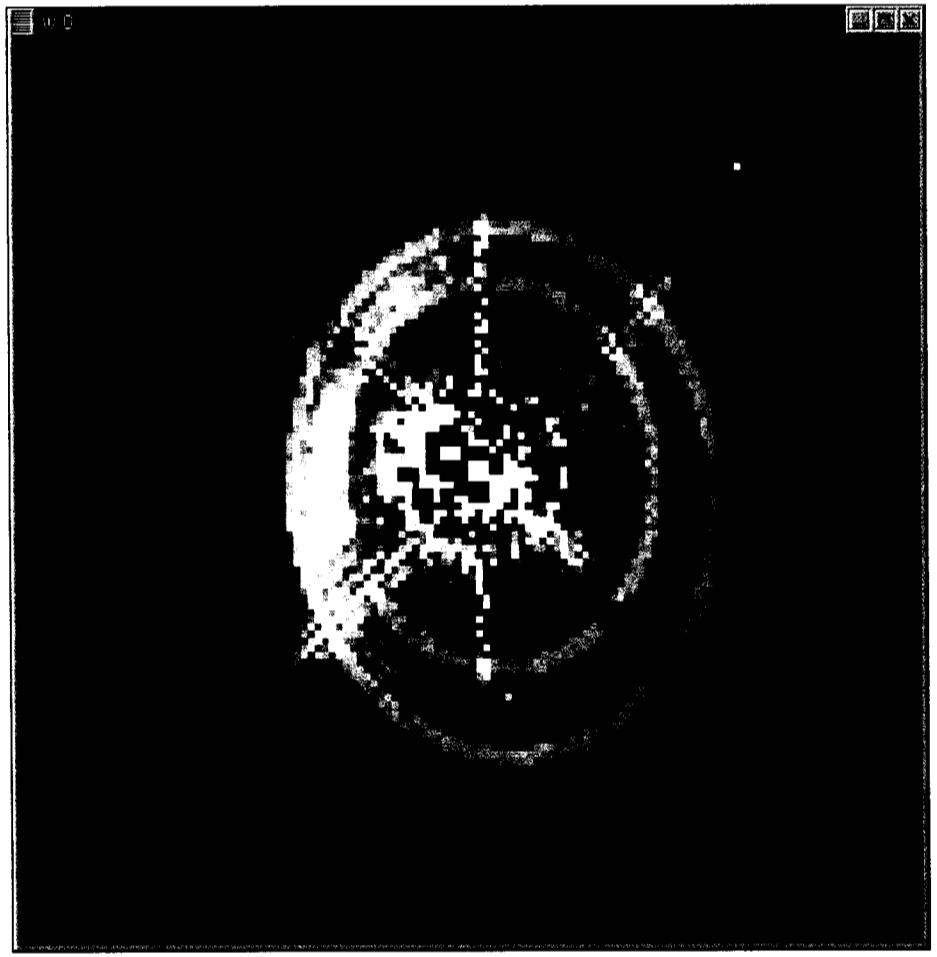
- **Ring appears to be smooth**
- **No evidence for radial "spokes"**
- **Dark sector is a real feature**
- **Binary displaced from apparent ring center**
- **Ring is red**

GG Tau: HST NICMOS Observations



- **Front/back intensity ratio = 3.3**
- **Polarisation is high ~50% back-side ~20% front-side**
- **implies small grains & thick disk**
  - assuming $I = 37^{o}$
- **observed brightness distribution is not symmetric about minor axis**

GG Tau: An elliptical ring?



Eyeball fit of inner & outer contours

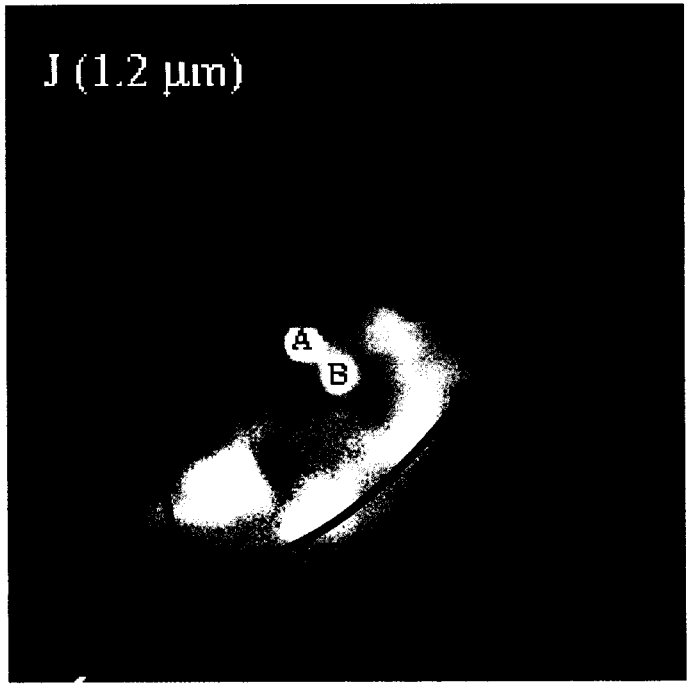
- **If flat elliptical ring: e= 0.2 (deprojected)**
- **Reproduces stellar offset**
- **Accounts better for asymmetries about minor axis**
- **Full scattering model of thick elliptical ring needed**

The case of UY Aurigae

- **Binary: 0.88" sep. @ 220°, two CTTS**
  - Spectral types: K7 & M2 *(Duchene et al 1999)*
- **Second example, after GG Tau, of circumbinary disk/ring**
  - Gas disk is large (Rout > 1000AU)
  - Thermal emission from dust in disk not detected
    → *Duvert et al. 1998*
  - Dust disk detected in scattered light
    → *Close et al. 1998*

UY Aur: A Complex environment

- **What is visible:**
  - a filamentary arc
  - a "patch" of complex nebulosity SE of UY Aur



CFHT Adaptive Optics

(Ménard et al. 2000)

UY Aur: A larger inclination is better

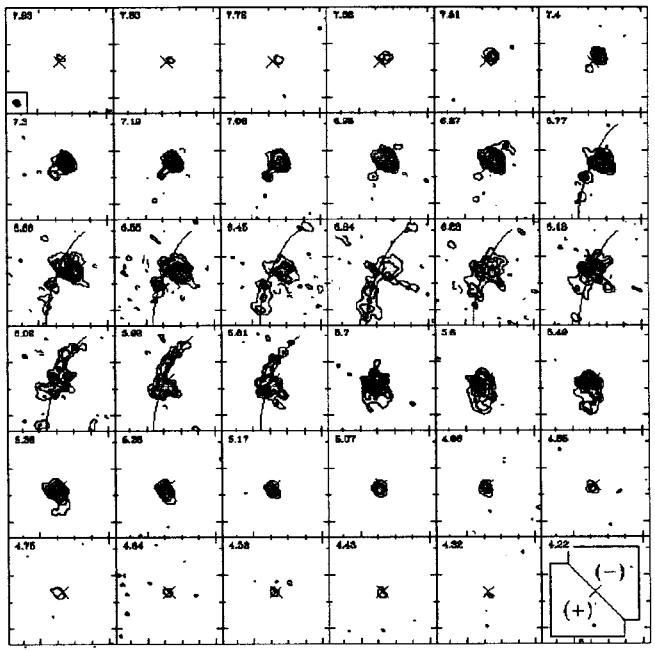
- **inclination larger than previously estimated,**

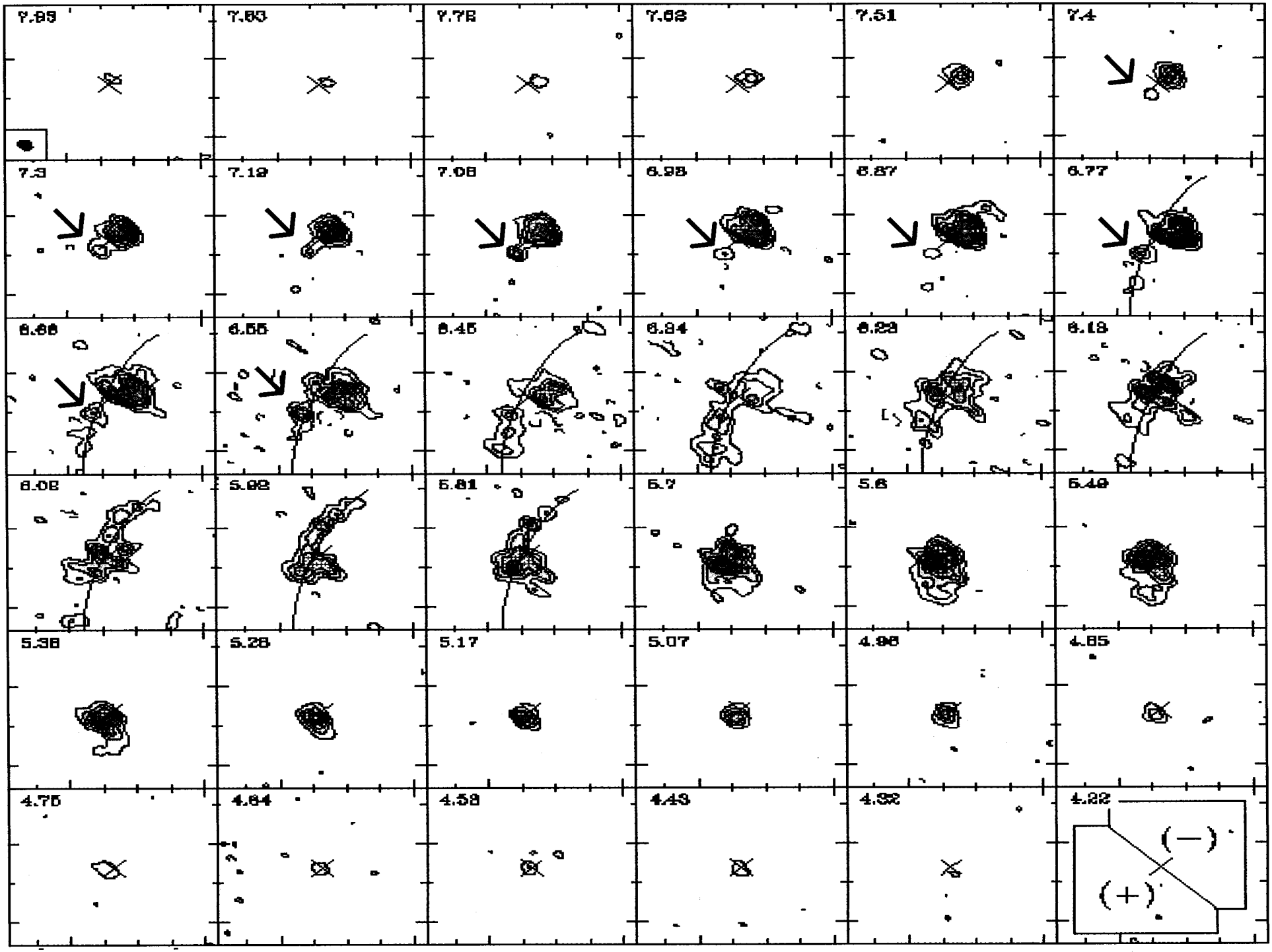
  → $i=65^{o}$ +/- 5^{o}

- **compatible with AO data**
- **allows to explain;**
  - back/front intensity contrast
  - gas emission in the central gap
  - smaller central mass needed
    - dynamic mass more in agreement w/evolutionary tracks

UY Aur: What is that "clump"?

- **Motions of the gas is complex and multiple components are detected:**
  - A Keplerian disk
  - A Streamer
  - A "knot" of emission, no spatial motion
    - velocity width > 1.0 km/sec
    - not part of Keplerian motion




7.93
7.83
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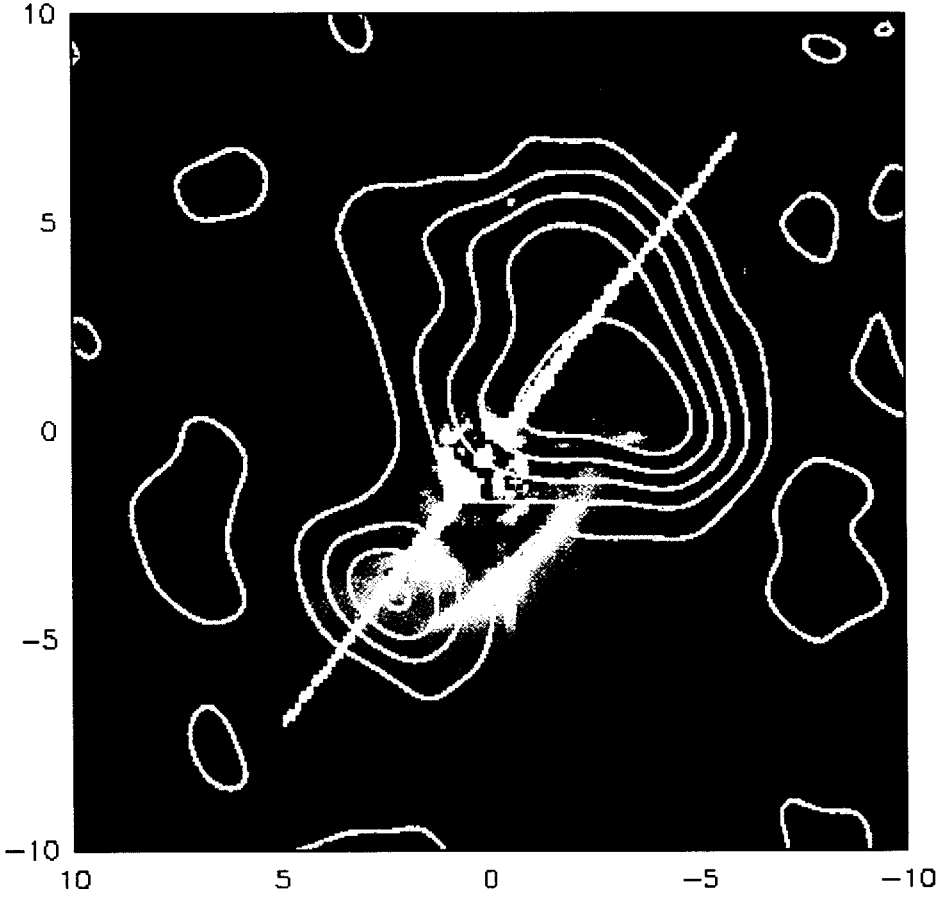
UY Aur: What is that "clump"?

- **Motion of the gas is complex**
  - multiple components are detected
- **"Clump" coincides with a feature in the ^{13}CO(2-1) channel maps**

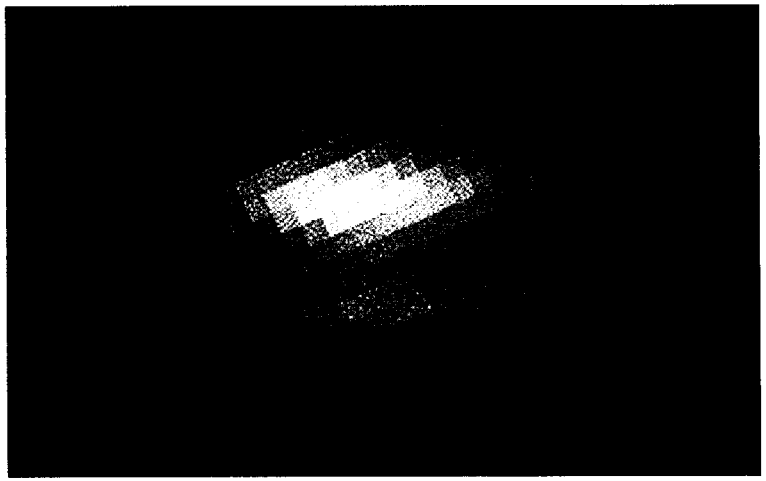


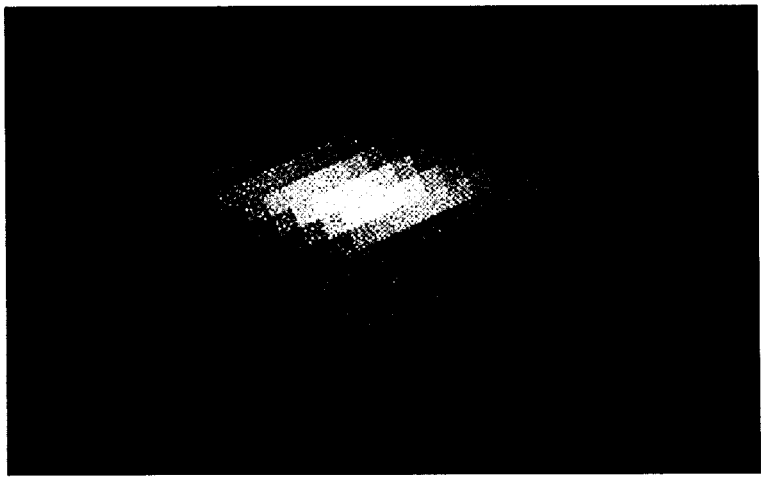
Circumstellar Disk in the HK Tauri Binary System

- **2.4" binary, both CTTS**
  - M1 primary, EW(Hα) = 50 Å
  - M2 secondary, EW(Hα) = 13 Å
- **Secondary has edge-on disk**
  - "small" outer radius= 105 AU
  - very narrow dust lane
- **Secondary star obscured to $\lambda > 2.3$ μm; $A_V > 80$ mag**
- **Disk truncated by tidal interactions?**

HST R band image
Stapelfeldt et al. 1998

Scattered Light models for the HK Tau HST image



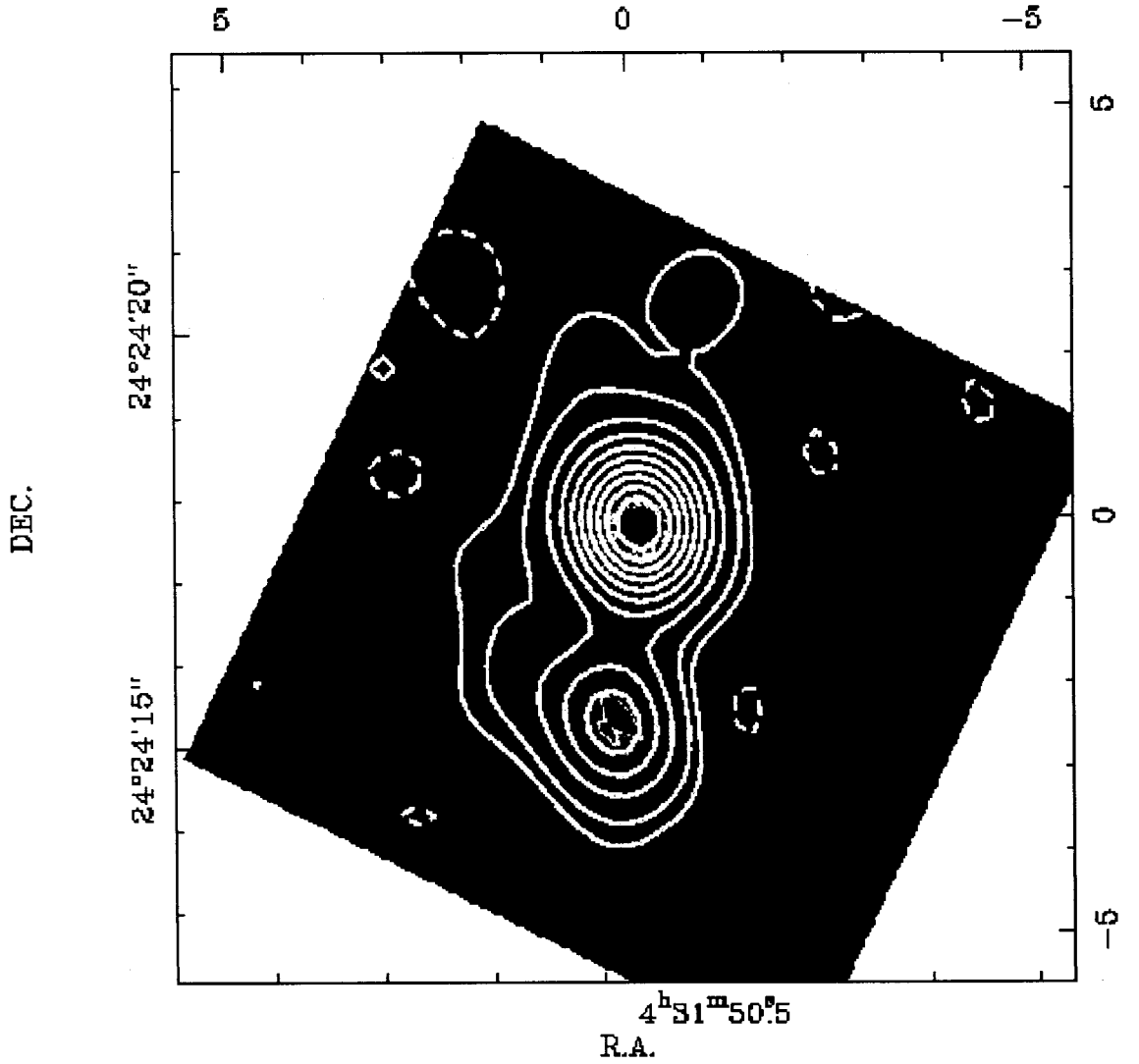


- **Inclination ~ 6 deg**
- **Small disk mass derived: ~0.0001 $M_{\odot}$. Assumes**
  - ISM dust properties
  - gas:dust ratio of 100
- **Disk is thin: Gaussian scale height of 8 AU at outer radius**
- **Disk is not perfectly axisymmetric**

HK Tau 1.3 Millimeter Continuum

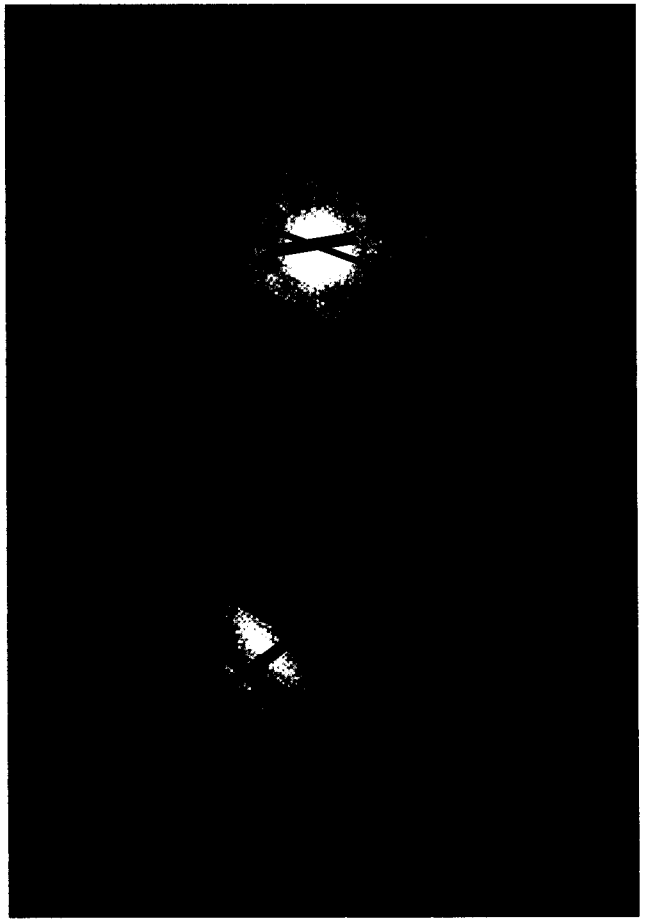
- PdB maps detect both stars; flux ratio is 3:1
- Circumstellar disks at each component !
- Secondary's mm flux suggests a disk mass close to the HST derived value

Ménard et al. 2000



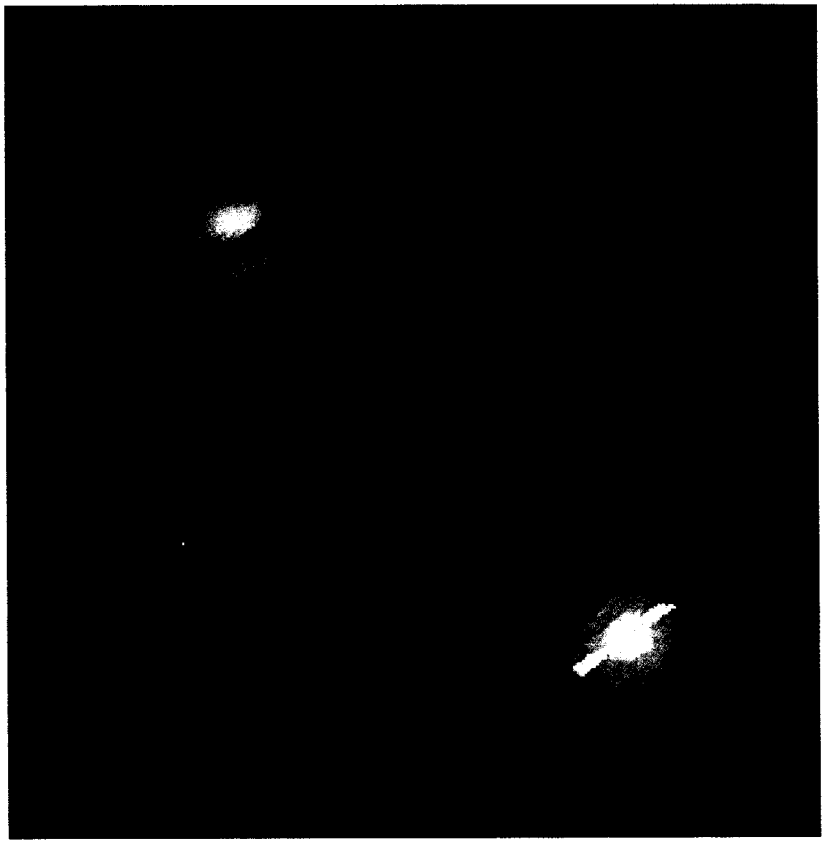
HK Tau: Misaligned disks?

- **Polarimetry finds different position angles for the two components**
  - Jensen, Donar & Mathieu (2000)
  - Menard & Chrysostomou, (2000)
- **Circumprimary disk is obviously not edge-on**
- **Very likely that the two disks are not coplanar**



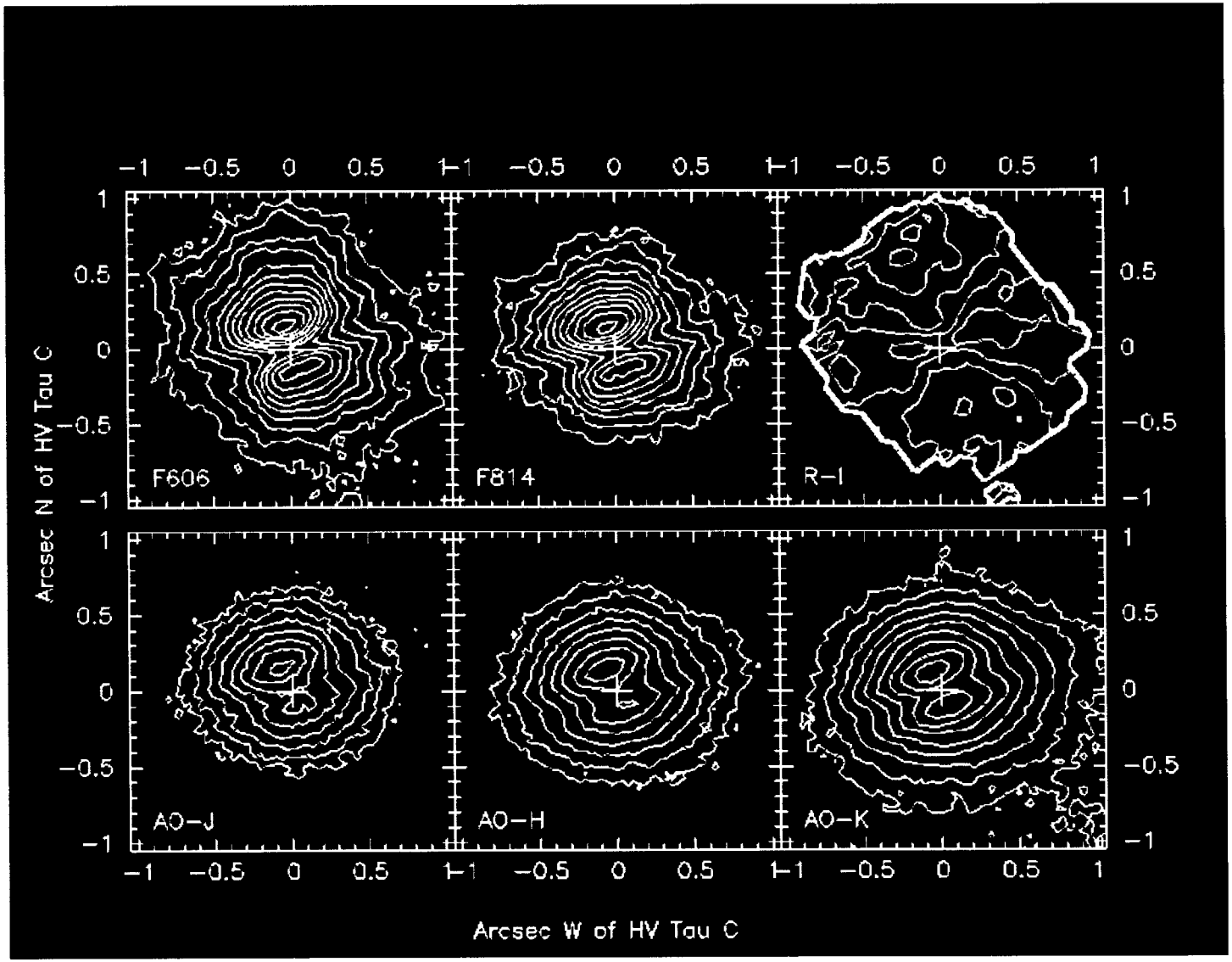
Circumstellar Disk in the HV Tauri Triple System

- **Heirarchical Triple, 4" sep**
  - HV Tau AB is 0.035" WTTs binary, EW(Hα)= 4 Å
  - HV Tau C has strong Hα, [S II], [O I] emission
- **Bipolar Nebula at Tertiary**
  - Edge-on disk with small outer radius ~ 85 AU
  - Some extended jet emission
- **System has 40 mJy of 1.3 mm continuum emission**
- **Disk tidally truncated ?**



HST image by Stapelfeldt et al. 2000
Green= R band, Red= I band

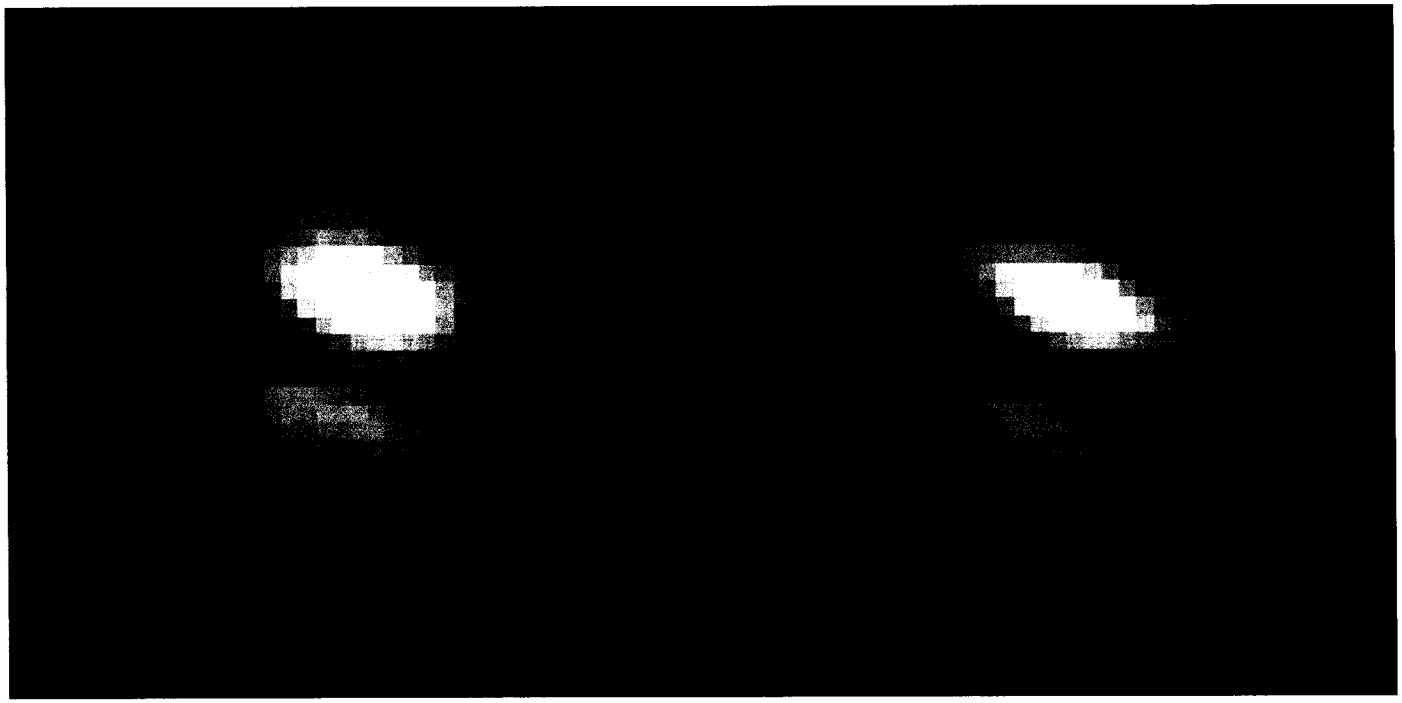
HV Tau C: HST and AO images



Scattered Light Model for the HV Tau C HST image

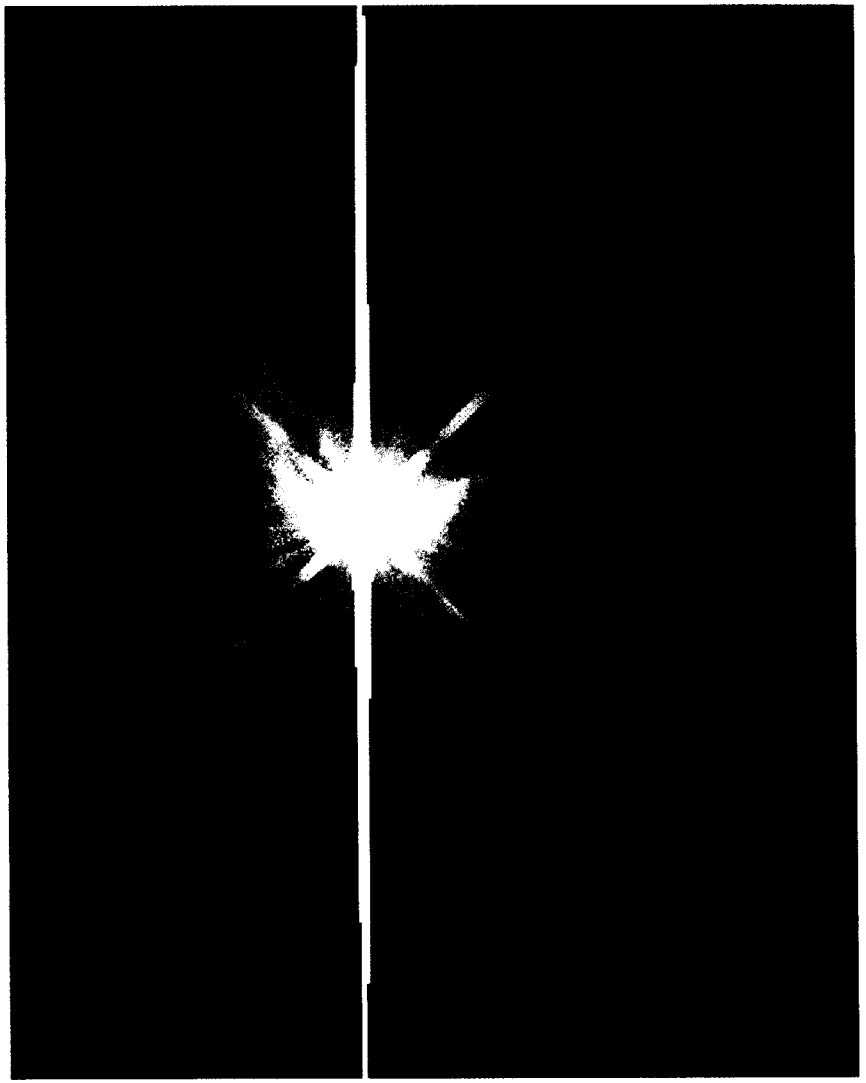
- Disk inclination ~ 6□
- Disk mass ~ 0.0004 $M_{\odot}$
- $H_0(R_{outer})$= 15.5 AU

- Model matches the dust lane thickness over λ= 0.6-2.2 μm

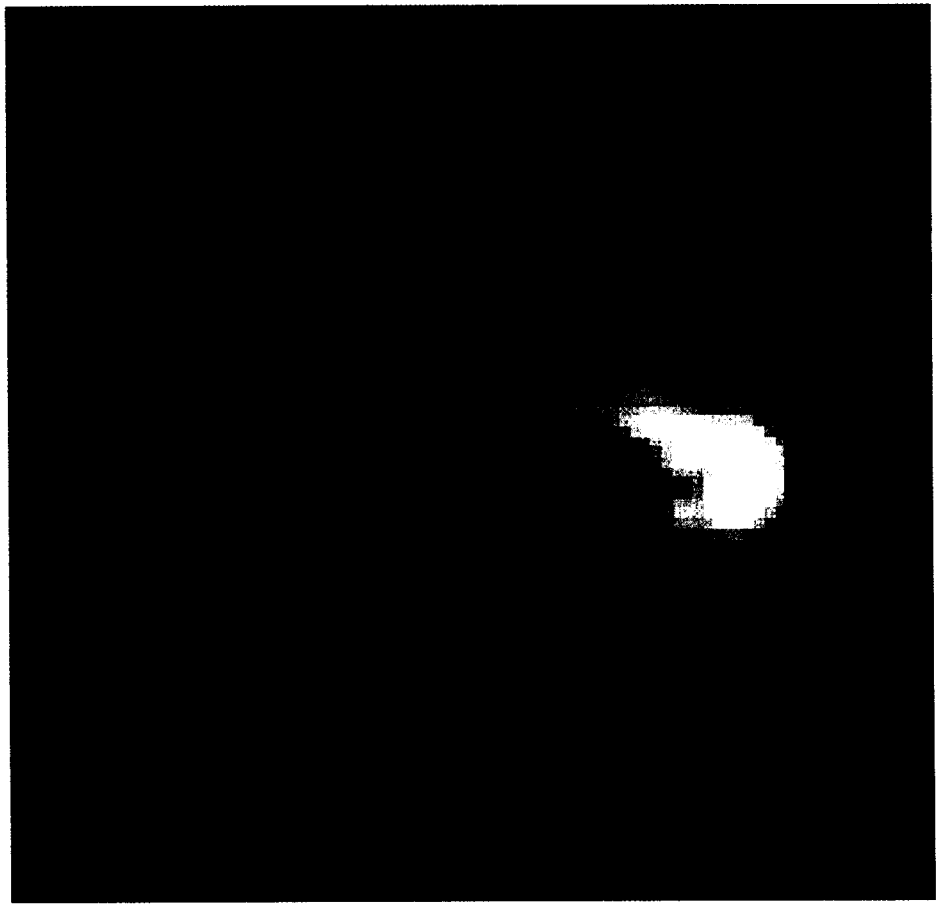


T Tauri: Envelope Nebulosity

- This flagship YSO is a prototype for complexity in circumstellar environments
- Strong IRAS, mm emission; strong outflows.
- Luminous IR companion at 0.7" (100 AU) may itself be a binary.
- HST finds irregular reflection nebulosity; outflow cavity? (Stapelfeldt et al. 1998)
- New, deeper image here shows still more complexity in the reflected light to the S



The Mystery of Haro 6-10

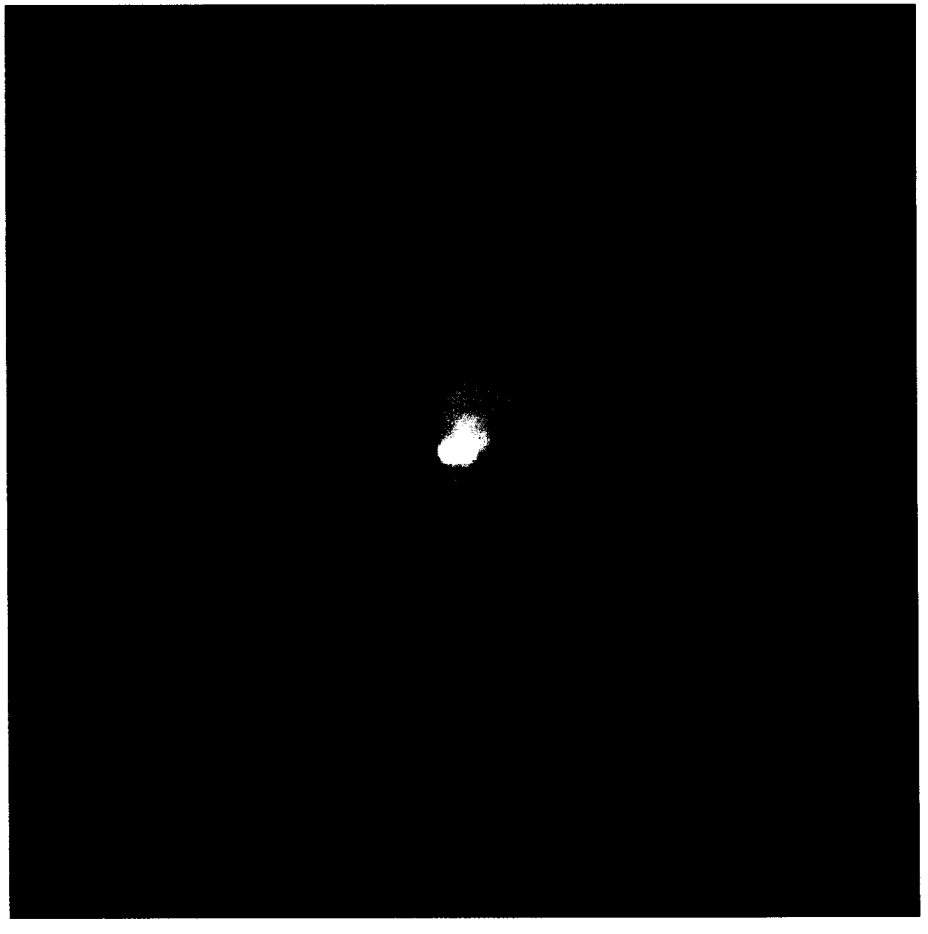


HST/WFPC2 image
Green= R band, Red= I band

- 1.2"(170 AU) binary
- Infrared companion (north) deeply embedded
- Source of giant Herbig-Haro flow spanning 1.6pc @ PA 230° (Devine 2000)
- Companion detected I= 21.5
- Streamer has both reflected light and HH emission
- Disconnected filament

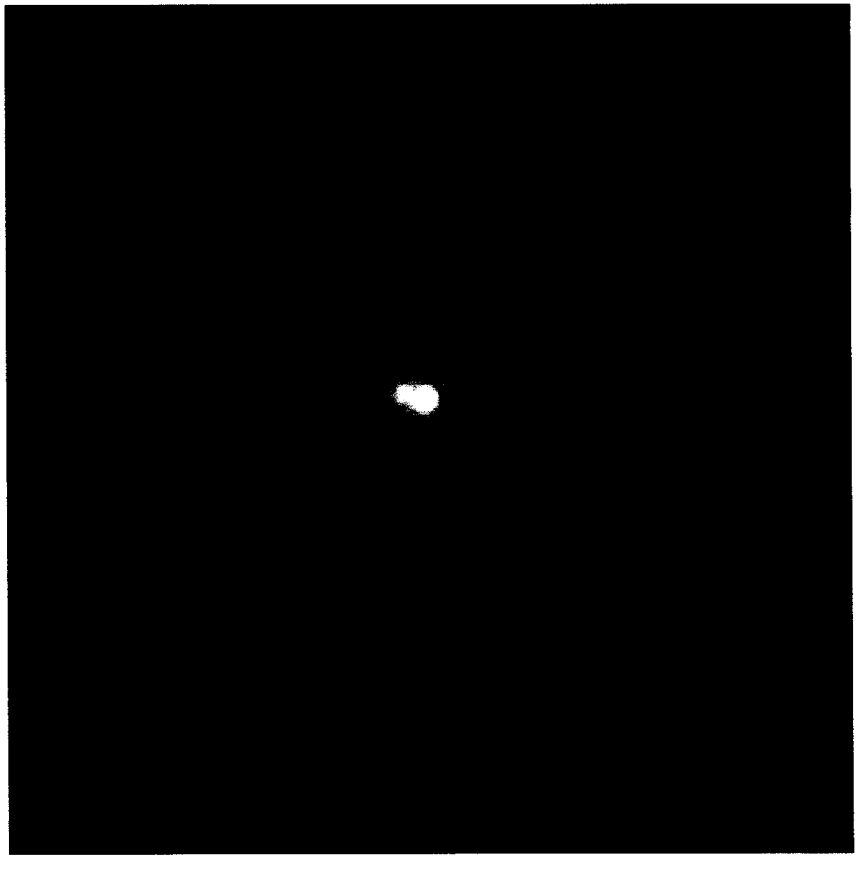
Dusty Bipolar Cavities of IRAS 04248+2612

- Class I YSO 0.36 $L_{\odot}$
- Spectral Type M2
- HH 31 exciting source; small molecular outflow
- 0.16" binary (23 AU) equal brightnesses
- "corkscrew" structure?
- FOV 9.6"= 1350 AU
- Dust lane suggests a circumbinary disk



NICMOS image by Padgett et al. 1999

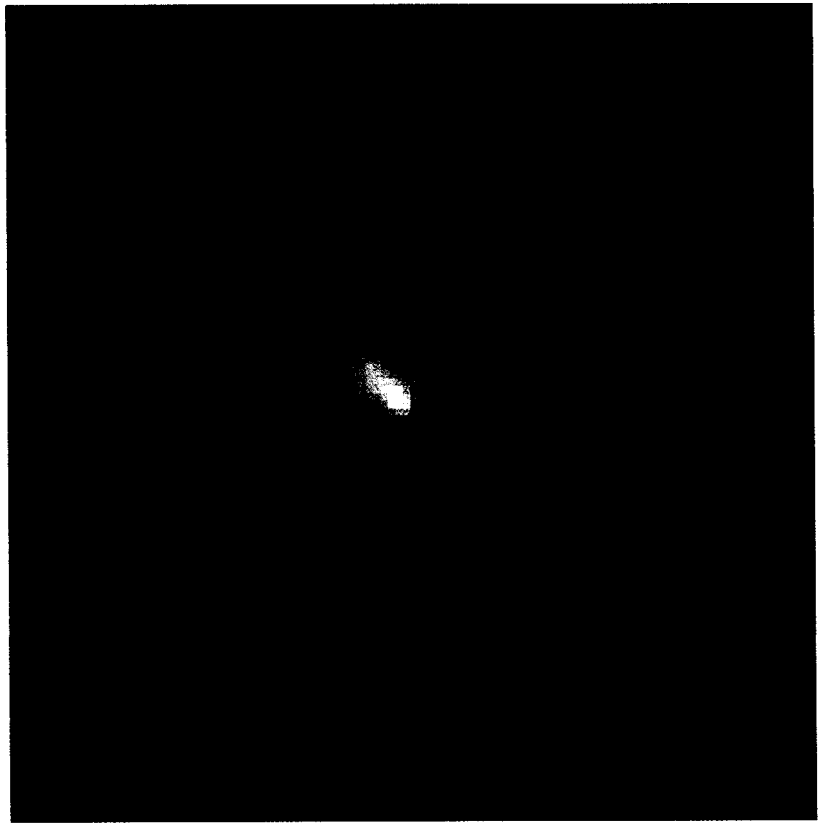
Circumbinary Envelope of CoKu Tauri/1



NICMOS image by Padgett et al. 1999

- V=19 jet source in L1495
- Little IRAS excess, no mm continuum detected
- 0.24" (34 AU) binary; companion 1-2 mags fainter than the primary
- Bipolar cavity "wings"
- Dark clump with d~200 AU lies NE of the binary
- Circumbinary dust lane?

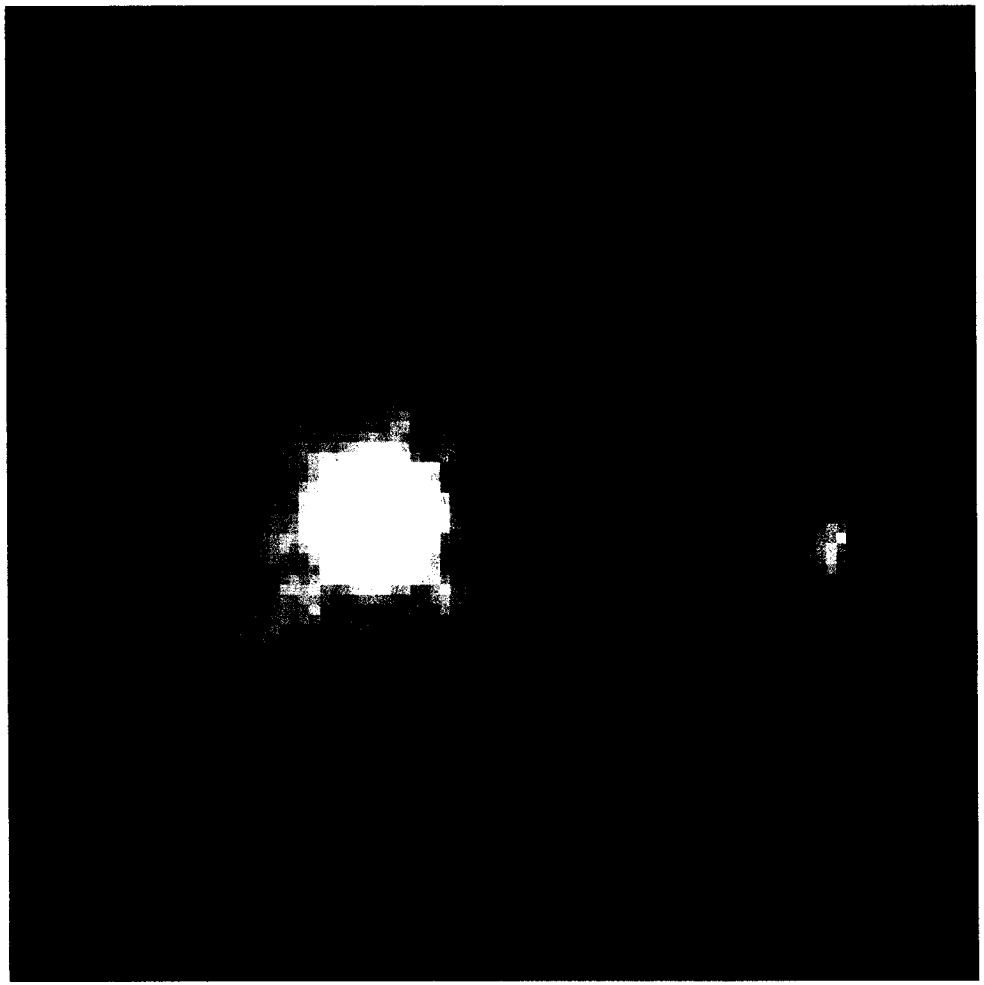
A View of the CoKu Tau/1 Jet



WFPC2 Image
Green= R band, Red= I band

- Bright SW jet (HH 156) is redshifted, with low V_{rad}.
- Outward proper motions of 180 km/sec (Eislöffel & Mundt 1998)
- Many jet knots appear in the HST image. Largest has a bow shape. Wide opening angle ~20°.
- Obscured companion is probably the jet source

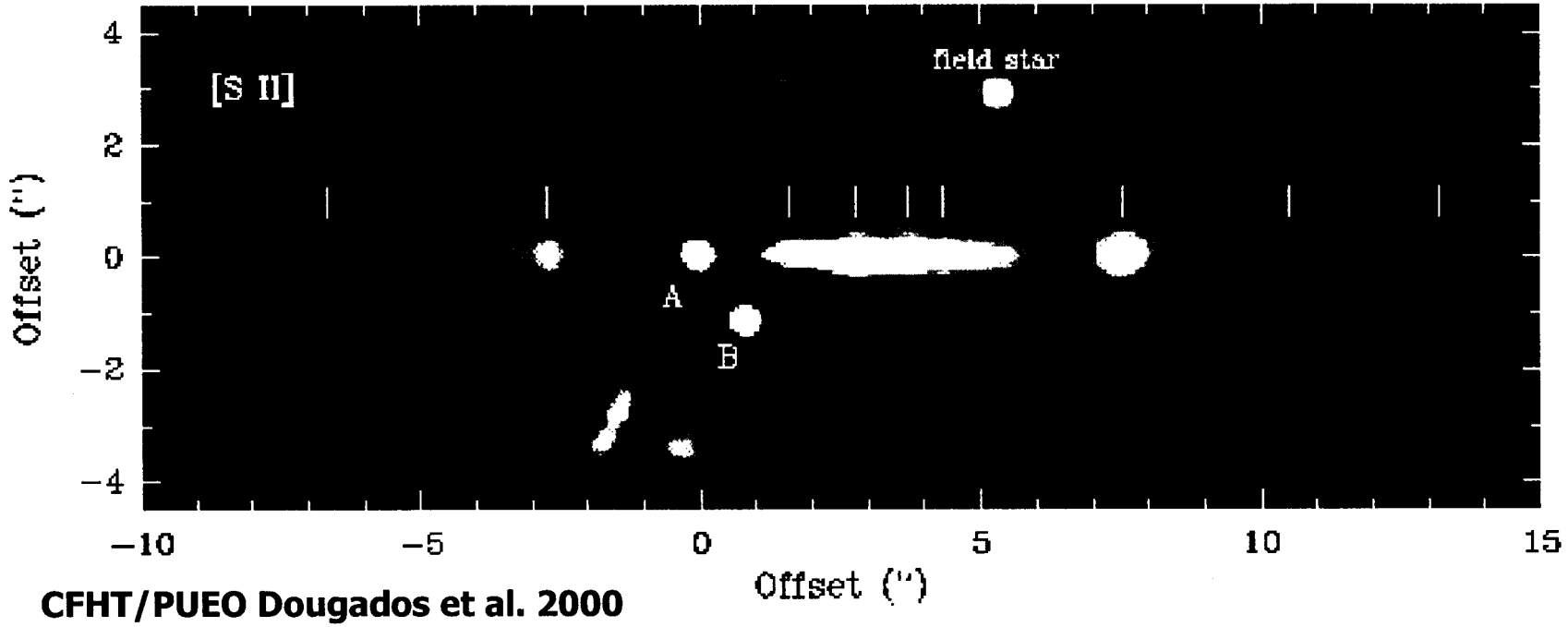
A Circumstellar Envelope and Jet in VV CrA B



HST/WFPC2 image
Green= R band, Red= I band

- 1.9" (270 AU) binary
- CTTS primary, highly polarized (4%).
- Bright IRAS source
- Strong variability in both components
- VV CrA B is cometary nebula in optical; no stellar image. Major AB extinction difference
- Faint wiggly jet from B

RW Aur: AO resolves the jet



CFHT/PUEO Dougados et al. 2000

- Hierarchical triple, jet is launched from the single (A)
- jet opening angles ~3° from 60 AU to 700 AU
- jet width ~35 AU from 60 to 400 AU

XZ Tauri Blows a Bubble

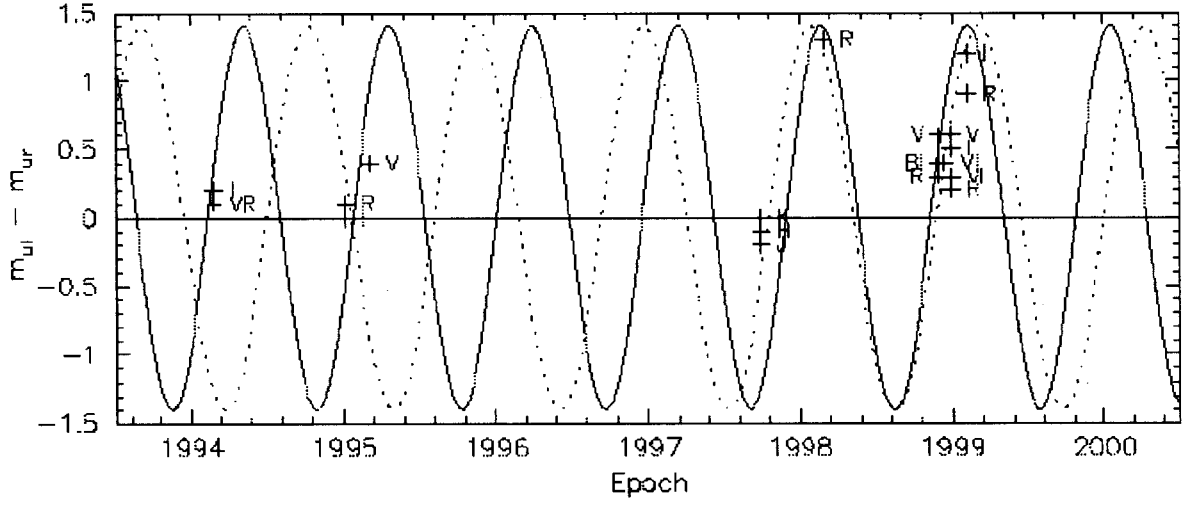
- M3 CTTS, 24″ E of HL Tau
- Companion at 0.3″ (42 AU) discovered by Haas et al. 1990
- Shocked gas to the NE with V_{rad} -60 km/sec (Mundt et al. 1990).
- HST: Rapidly expanding bubble of shocked gas 5″ (700 AU) long (Krist 1997,1999). Ejected ~1975. Prop mot 145 km/sec
- Complex internal structure
- First stages in the evolution of a Herbig-Haro bowshock?

Krist et al. 2001

Variable Illumination in the HH 30 edge-on disk: Is a companion involved?

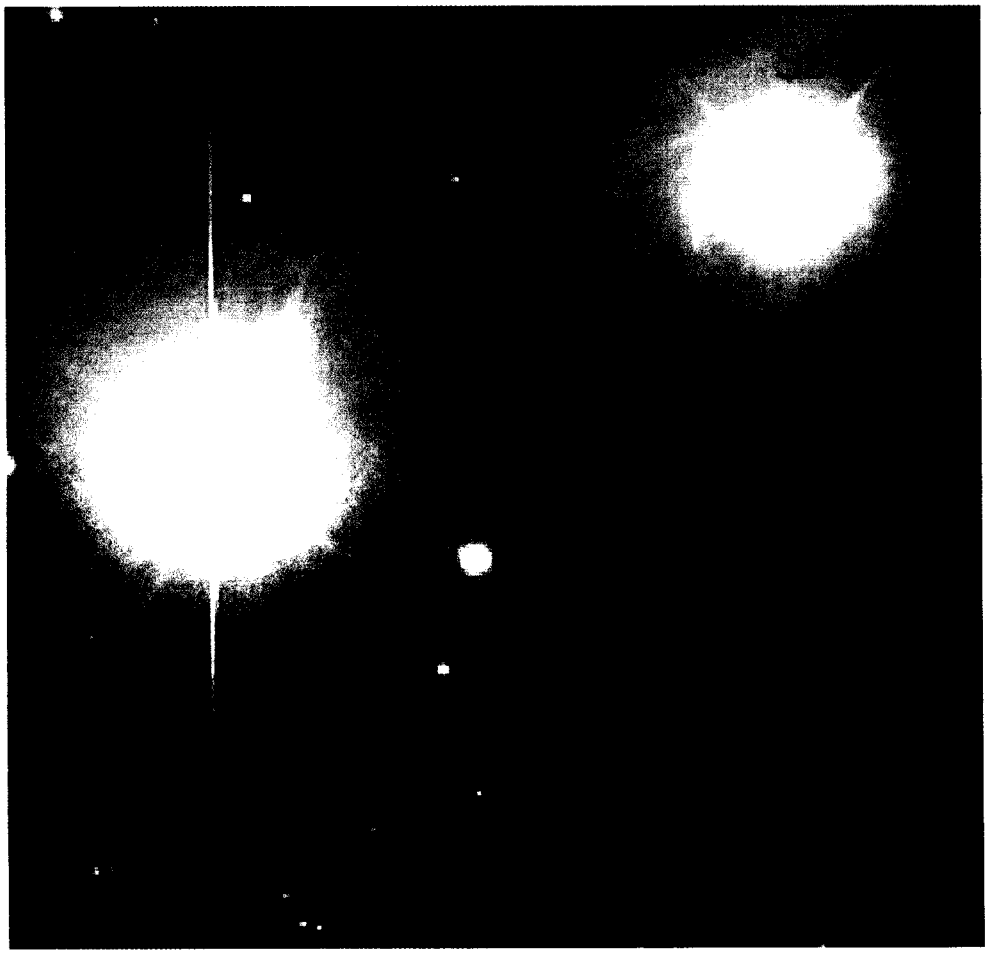
- **HH 30 is a classic accretion disk/jet system**
- **There is a variable lateral asymmetry in the disk scattered light ⇨ moving illumination patterns**
- **Temporal monitoring now shows that the variability is probably periodic on a timescale close to 1 year**
- **A companion near r= 1-2 AU is an attractive way to create & maintain this beaming pattern**

HH 30 Left-Right Photometric Asymmetry



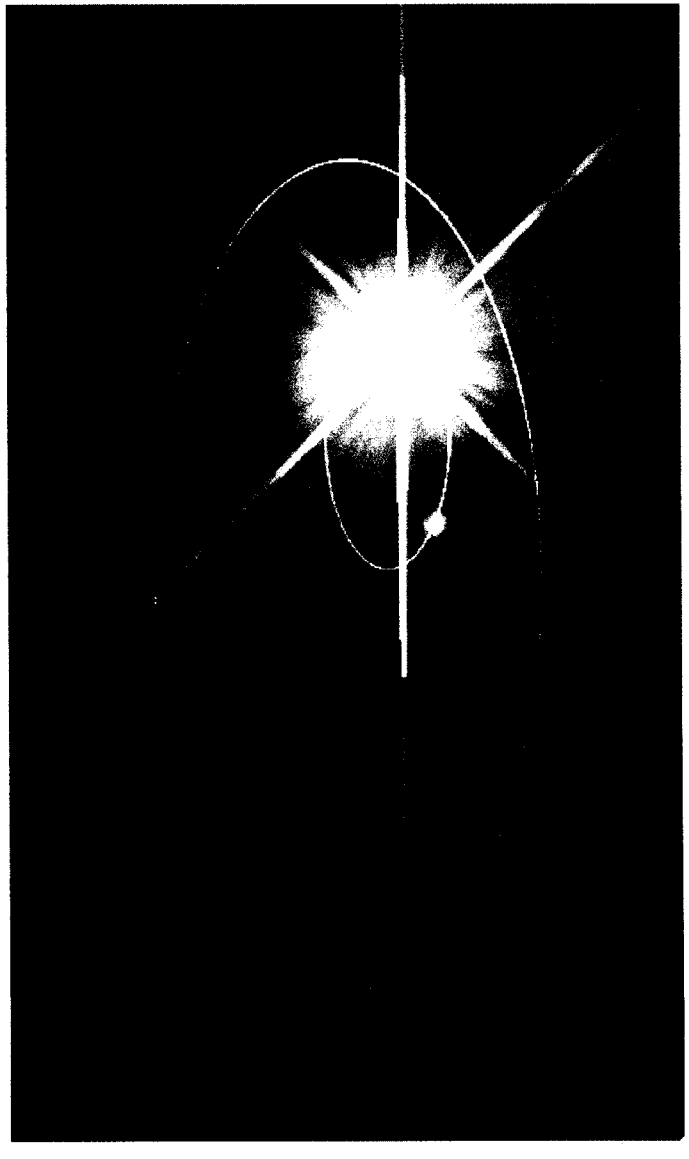
Schwartz 19 Background

- G2 star, 18 $L_{\odot}$ in the Chamaeleon I dark cloud.
- Weak Hα and mm continuum excess
- No known outflow
- Located near the top of an elongated dark clump 2' = 20,000 AU in length
- 4.8" (770 AU) binary



ESO/VLT optical image

Schwartz 19 HST Results: A Circumbinary Cavity?



- HST finds large elliptical cavity enclosing the binary
- Cavity is 23" (3700 AU) long, extended along the axis of the larger dark clump
- Cannot dismiss possibility of outflow origin ... but what if it were dynamically cleared?
- Cavity outline has unique fit deprojected ellipse e~0.6
- Aligned ellipse through the companion has semi-major axis ~✂ that of the cavity

Summary

- **Many sources with interesting nebular structure have been identified**
- **Follow-up studies**
  - Near-infrared, millimeter mapping, variability
- **Nebulosity detected in 50% of young binaries, and in 35% of young singles**
- **How to account for the non-detections? Most likely insufficient dynamic range of the data**