Disk Observations and Modeling

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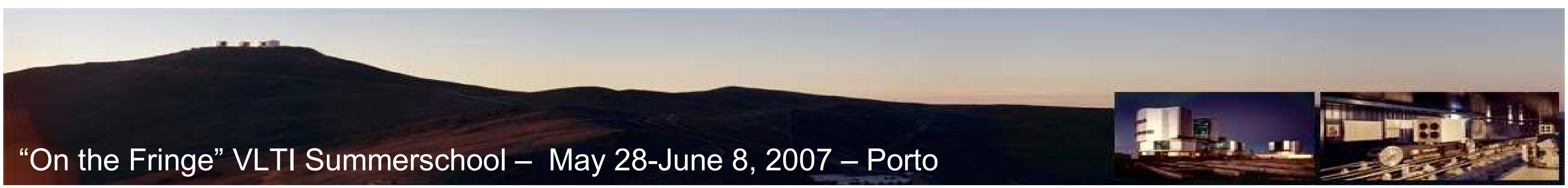
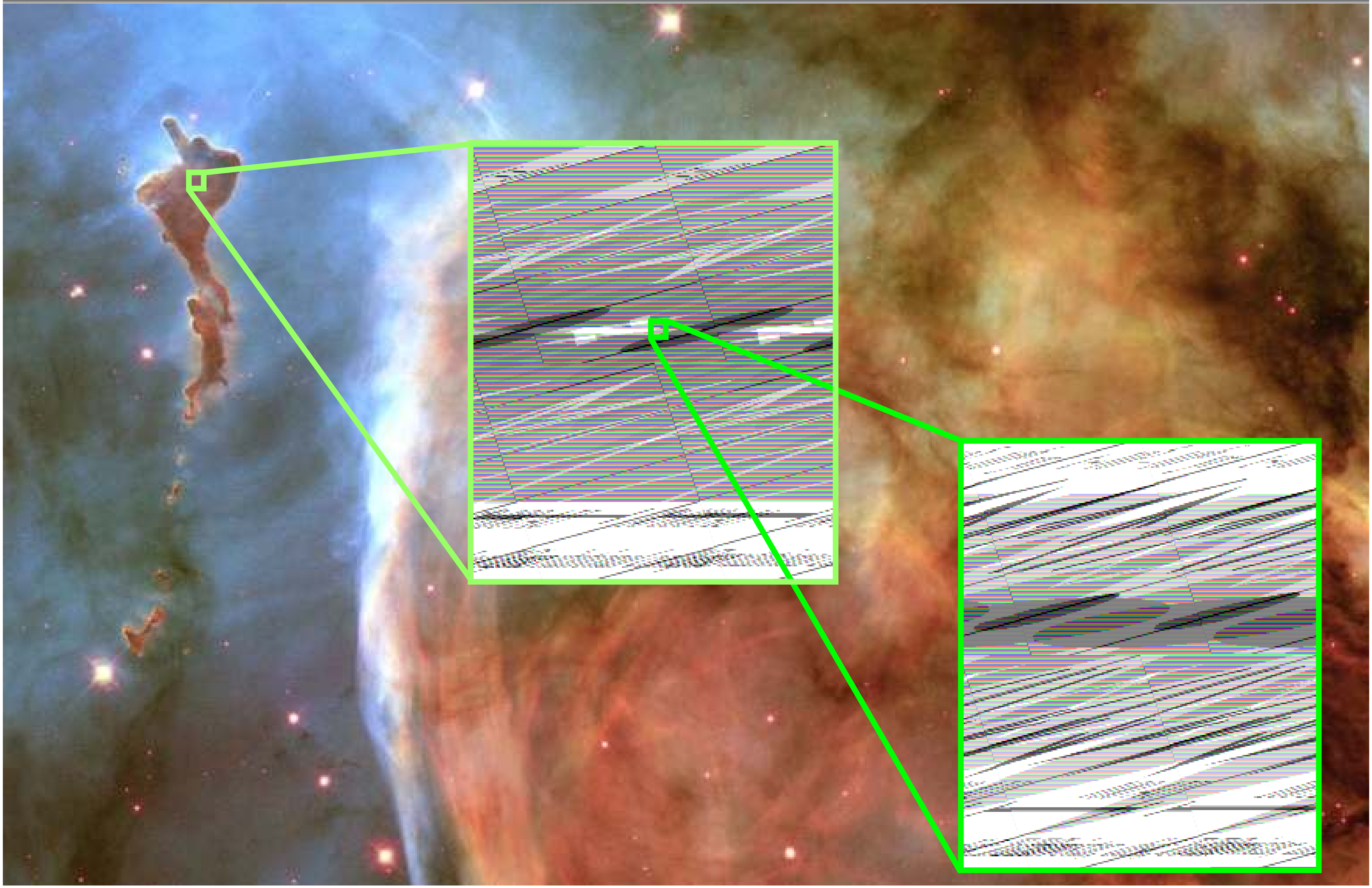
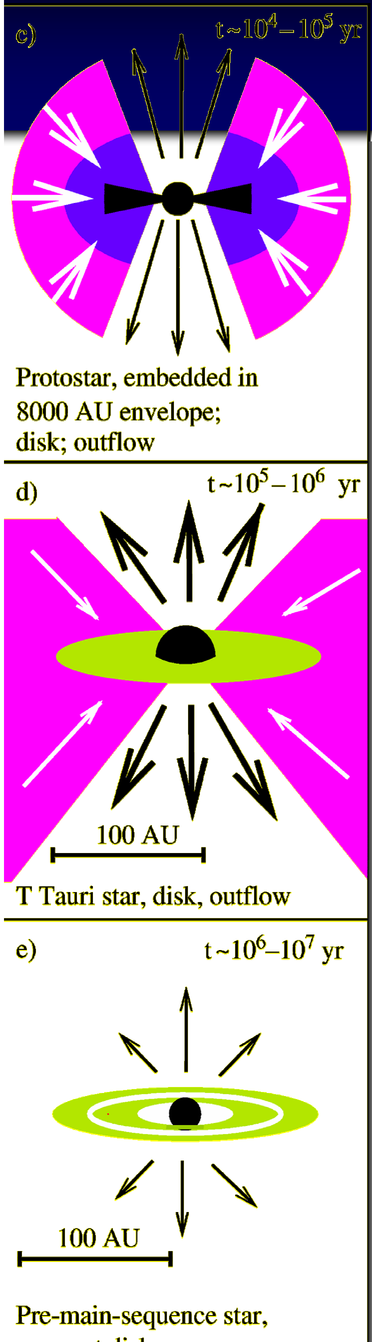
“Evolution of Circumstellar Dust Disks to Planetary Systems”
Max Planck Institute for Astronomy



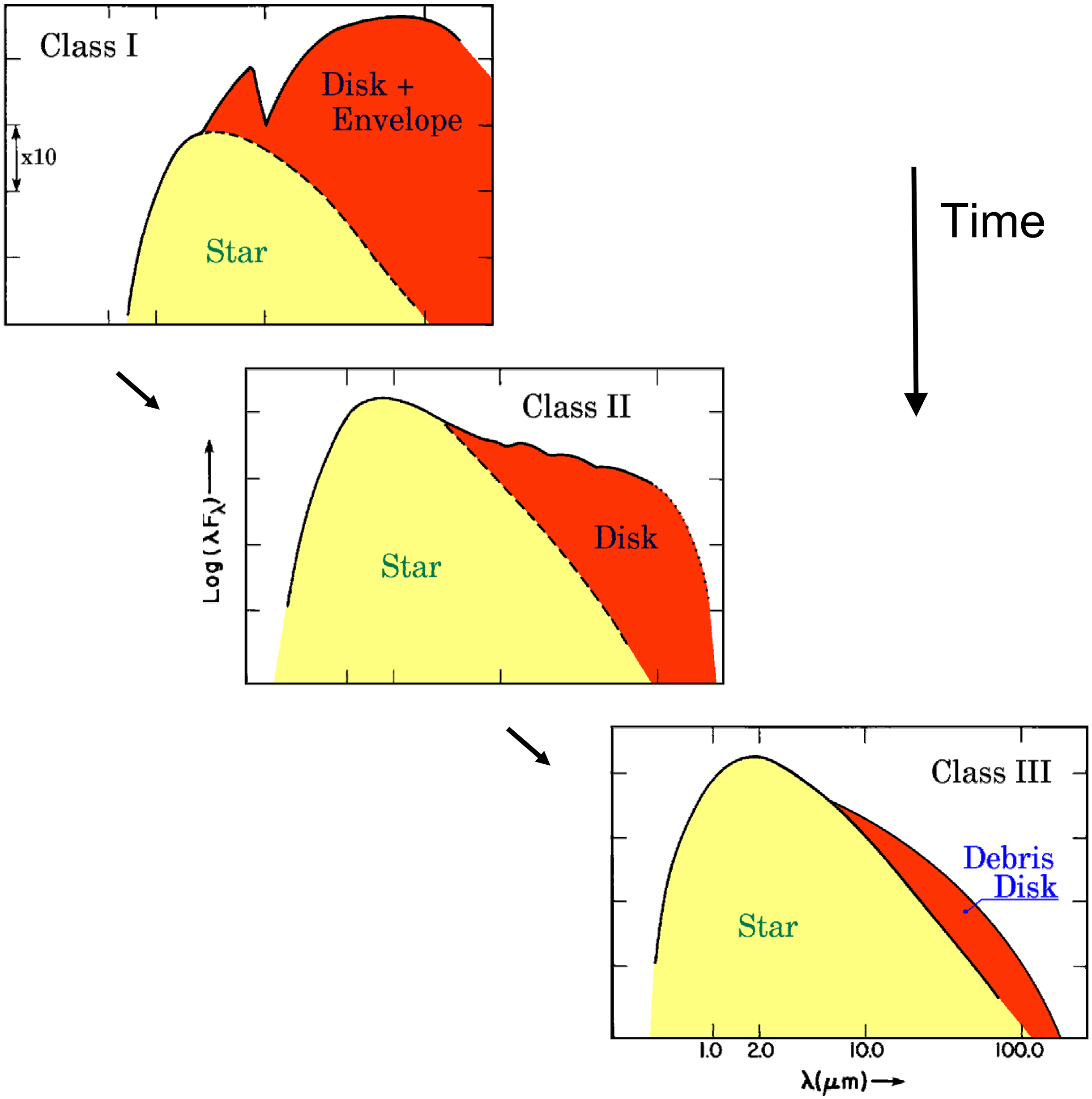
Disk Formation



Disk Evolution

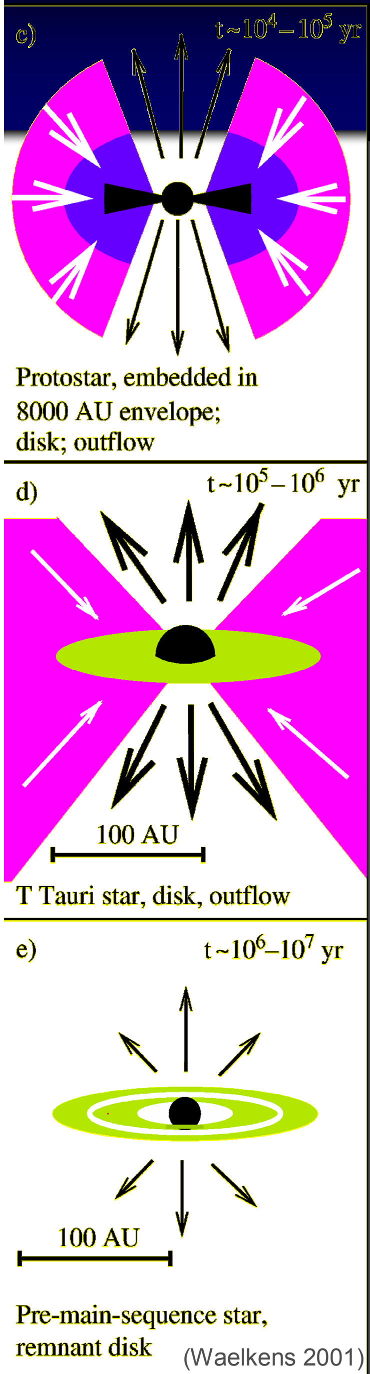


(Waelkens 2001)



(Lada 1987)

Disk Evolution



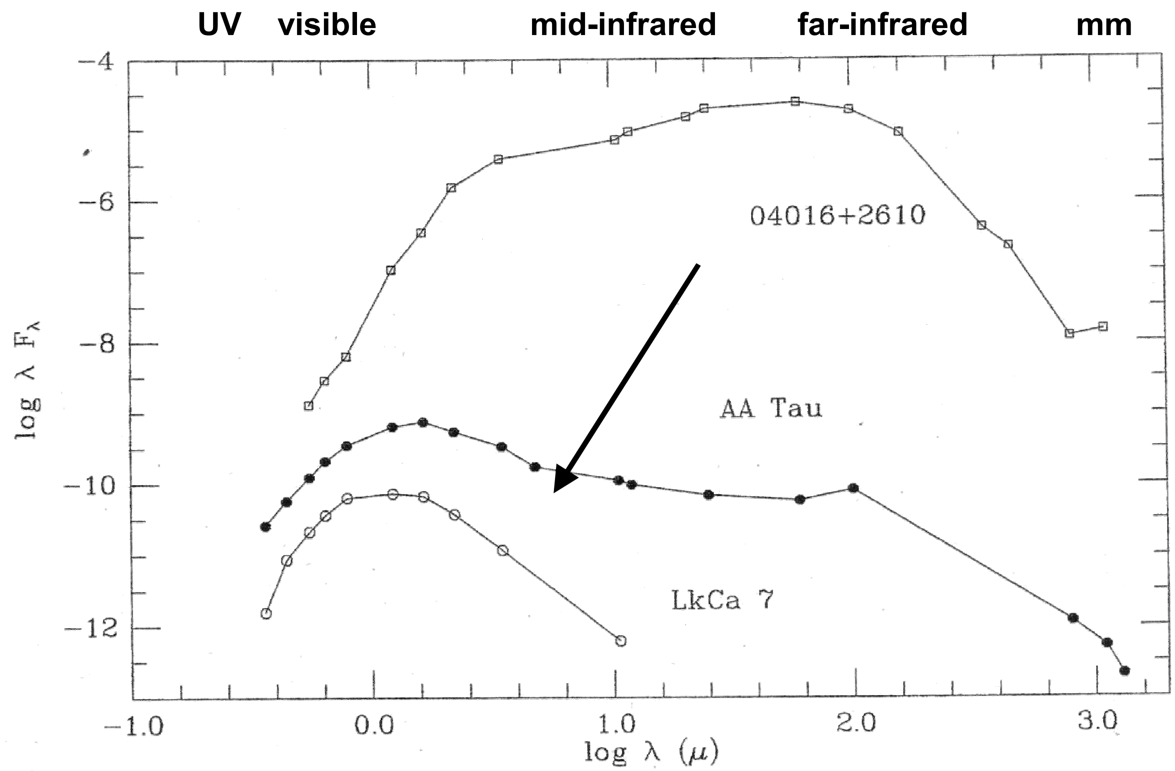


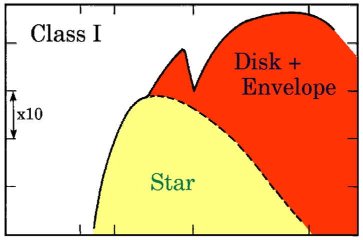
Fig. 1.3. Spectral energy distributions (SEDs) of three YSOs which typify the infrared classification system. The vertical axis is the flux at the Earth in arbitrary units. The Class I object IRAS 04016+2610 is probably a protostar hidden at optical wavelengths by its dusty infalling envelope; the dust absorbs the radiation from the central regions and re-emits it in the far-infrared. The CTTS or Class II object AA Tau is optically visible, but exhibits long-wavelength dust emission generally attributed to a circumstellar disk (see text). The WTTS or Class III object LkCa 7 does not exhibit detectable dust emission; its SED is nearly that of a single-temperature blackbody, and is typical of the photospheric emission of low-mass pre-main-sequence stars. Data from Kenyon & Hartmann (1995).

Disk Classification

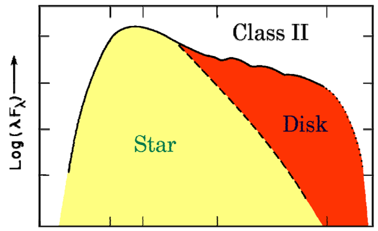
- Classification scheme:

  Based on spectral index ***s*** of the emitted flux in the wavelenth range: 2-50/100micron (Lada & Wilking 1984, Lada 1987):

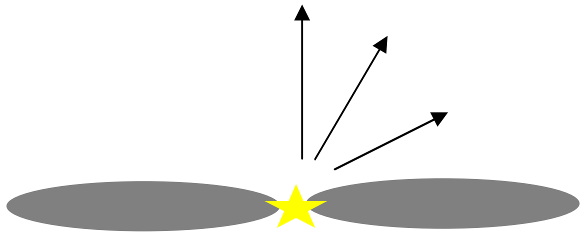
$$\nu F_\nu = \lambda F_\lambda \sim \lambda^s$$



- Class I :
  - s > 0 (SED increases with wavelength)
  - deeply embedded objects
  - SED = Reemission of infalling envelope



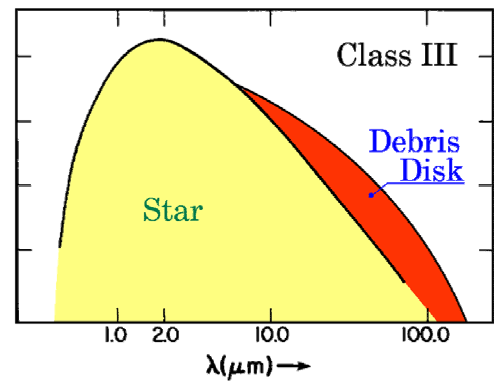
- Class II:
  - -4/3 < s < 0
  - SED of circumstellar disk (stellar and/or accretion heating)



here: SED depends on disk inclination!

Disk Classification

- Class III
  - s ~ -3
  - stellar photosphere (Rayleigh-Jeans Limit)
  - negligible infrared excess



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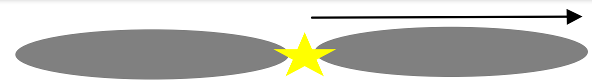
added:

- Class 0 (Andre, Ward-Thompson, & Barsony 1993) :
  - Emission mainly in the submm wavelength range
  - Evolutionary stage before Class I

Mass Estimation



The flux density, F_ν, from an optically thin disk at distance, D, is:

$$F_\nu = \frac{1}{D^2}\int_{R_{min}}^{R_{max}} B_\nu\left[T(r)\right]\tau_\nu(r)2\pi r dr,$$

$$B_\nu \approx 2kT\nu^2/c^2$$

[Rayleigh-Jeans Limit]

$$\tau_\nu(r) = \kappa_\nu \Sigma(r)$$

κ_ν – mass opacity coefficient
$\Sigma(r)$ – surface density

$$\Rightarrow F_\nu \approx \kappa_\nu \frac{2k\nu^2}{c^2D^2}\int_{R_{min}}^{R_{max}} T(r)\Sigma(r)2\pi r dr$$

$$\approx \kappa_\nu \frac{2k\langle T\rangle\nu^2}{c^2D^2}M_{dust}$$

$\langle T(r)\rangle$ - average temperature

$$M_{disk} = 0.03\,M_\odot\,\frac{F_\nu}{1\,\mathrm{Jy}}\left(\frac{D}{100\,\mathrm{pc}}\right)^2\left(\frac{\lambda}{1.3\,\mathrm{mm}}\right)^3\frac{50\,\mathrm{K}}{\langle T\rangle}\frac{0.02\,\mathrm{cm}^2\,\mathrm{g}^{-1}}{\kappa_{1.3\,\mathrm{mm}}}$$

$\langle T(r)\rangle = 50K$
$\kappa_\nu \sim 0.02\ (1.3mm/\lambda)\ cm^2/g$
$M_{gas}/M_{dust} = 100$

Mass Estimation

- Continuum SED:
  Warm dust (only 1% of total mass, but highly opaque)

λ ~ mm wavelength range

- Disks optically thin
- Typical disk mass:
  ~ 0.01 M_{sun}

comparable to "Minimum Mass Solar Nebula" (total mass of the original material of solar composition to form the planetary system)

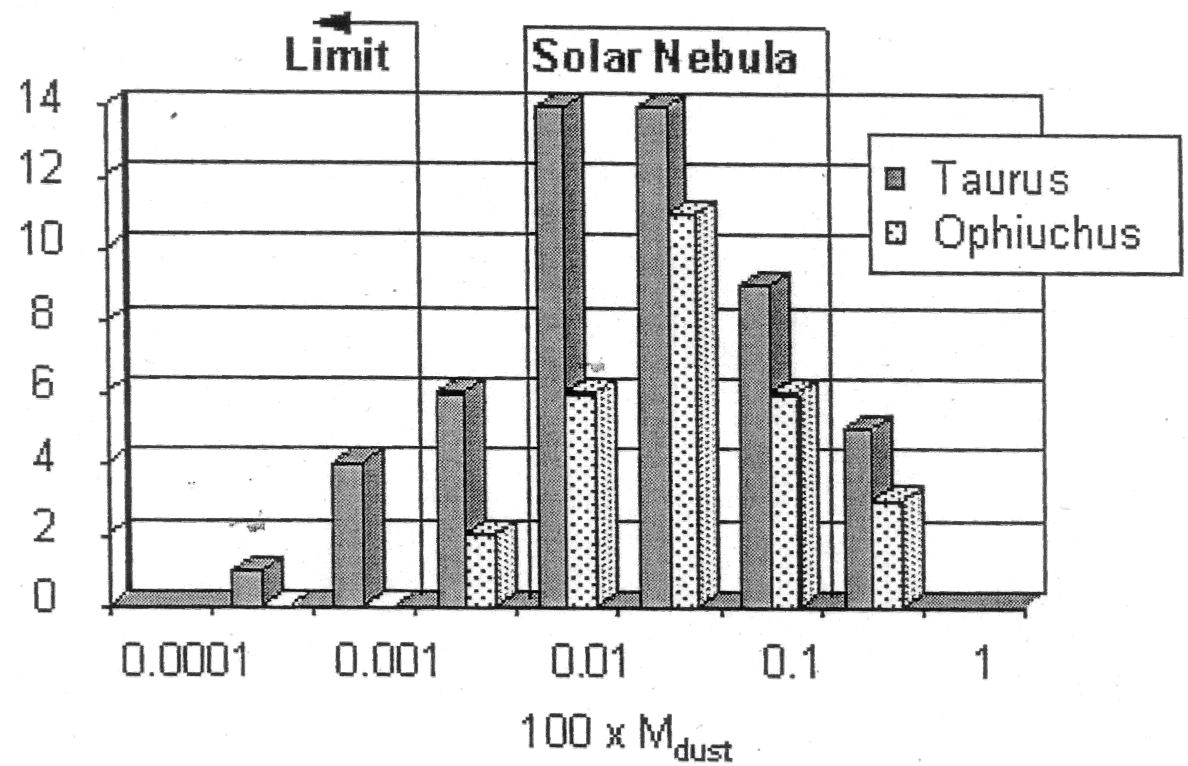


Figure 11. The histograms show the distribution of disk masses among stars in the Taurus and Ophiuchus star forming regions determined by Beckwith et al. (1990)and André et al. (1994).

Disk observations

Indirect evidence: Outflows

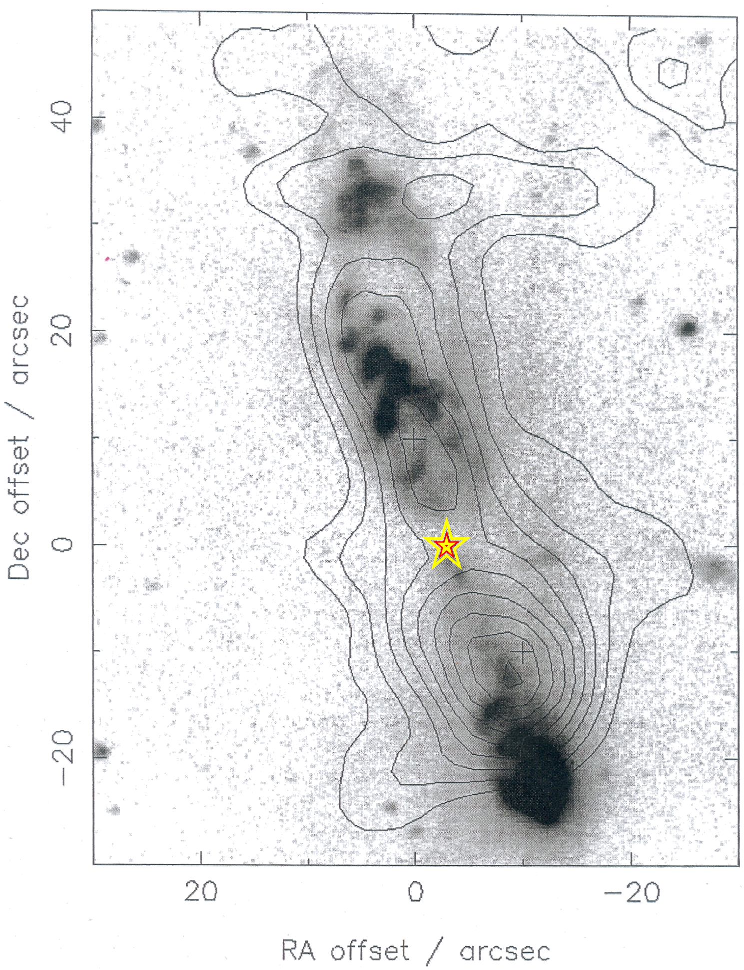


Fig. 1. Cep E ^{12}CO 4-3 map integrated from -33 to 14 km s^{-1} (contours) superimposed on continuum-subtracted H_2 2.12 μm image from Ladd & Hodapp (1997) (greyscale). Positions of CO bullet observations (to within 5″) are marked with crosses, and the driving source is marked with a star. Contours are every 30 K km s^{-1} from 60 K km s^{-1}.

[Hatchell et al. 1999]

1. Bipolar Molecular Outflows
   (weakly focussed)

2. OpticalJets
   (highly focussed)

   Collimation => focussing processes on size scales of < 100 AU

3. Polarization Maps
   (scattering in bipolar lobes)

Indirect Evidence: Jets

HH30 jet, NASA/Watson 2000

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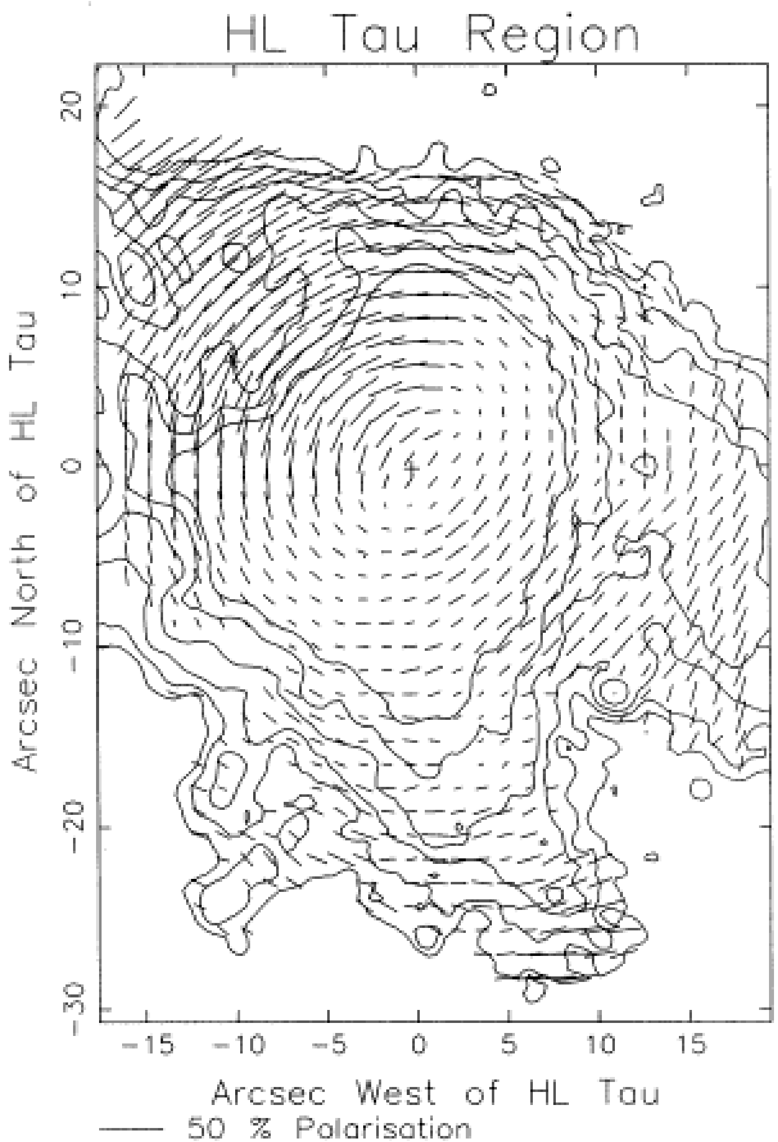
Indirect evidence: Polarization Maps



[Gledhill & Scarrott 1989]

1. Bipolar Molecular Outflows
   (weakly focussed)

2. OpticalJets
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Infrared Excess

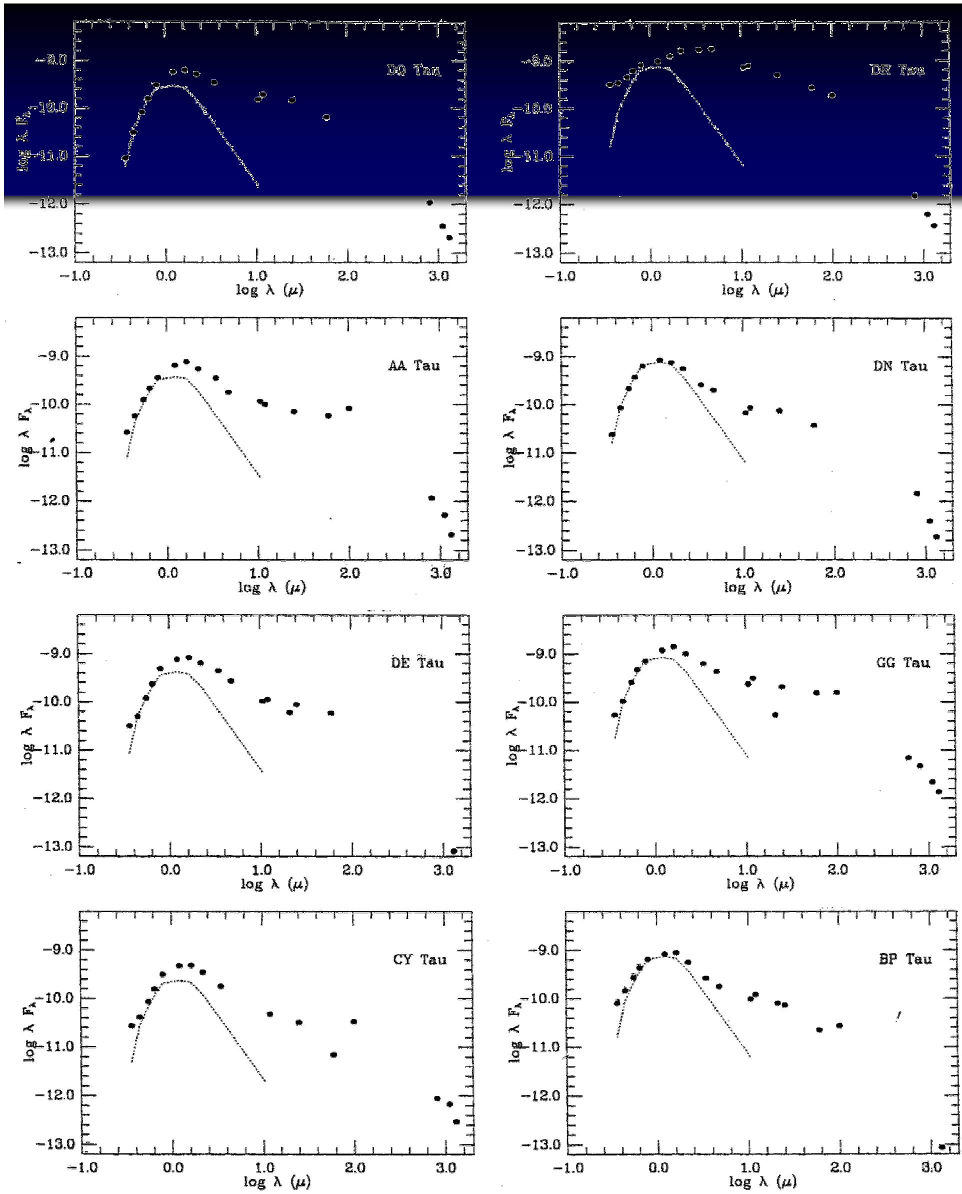


Fig. 6.2. SEDs of T Tauri stars in the Taurus molecular cloud. The vertical axes denote observed fluxes in erg cm^{-2} s^{-1}. The dotted curve denotes the SED for the WTTS LkCa7, which is a K7-M0 pre-main-sequence star that shows no evidence for accretion. The excess long-wavelength emission is immediately evident, but the short-wavelength excess emission is much more difficult to detect except in the strong-emission star DR Tau. Data from Kenyon & Hartmann (1995).

- Passive Disks:
  Dust reemission following stellar heating
  (Adams et al. 1987)

- Active Disks:
  Accretion
  (Lynden-Bell & Pringle 1974)

Can the reemission SED be considered as "Direct Evidence"?

=> "Opacity argument"

"Opacity Argument"

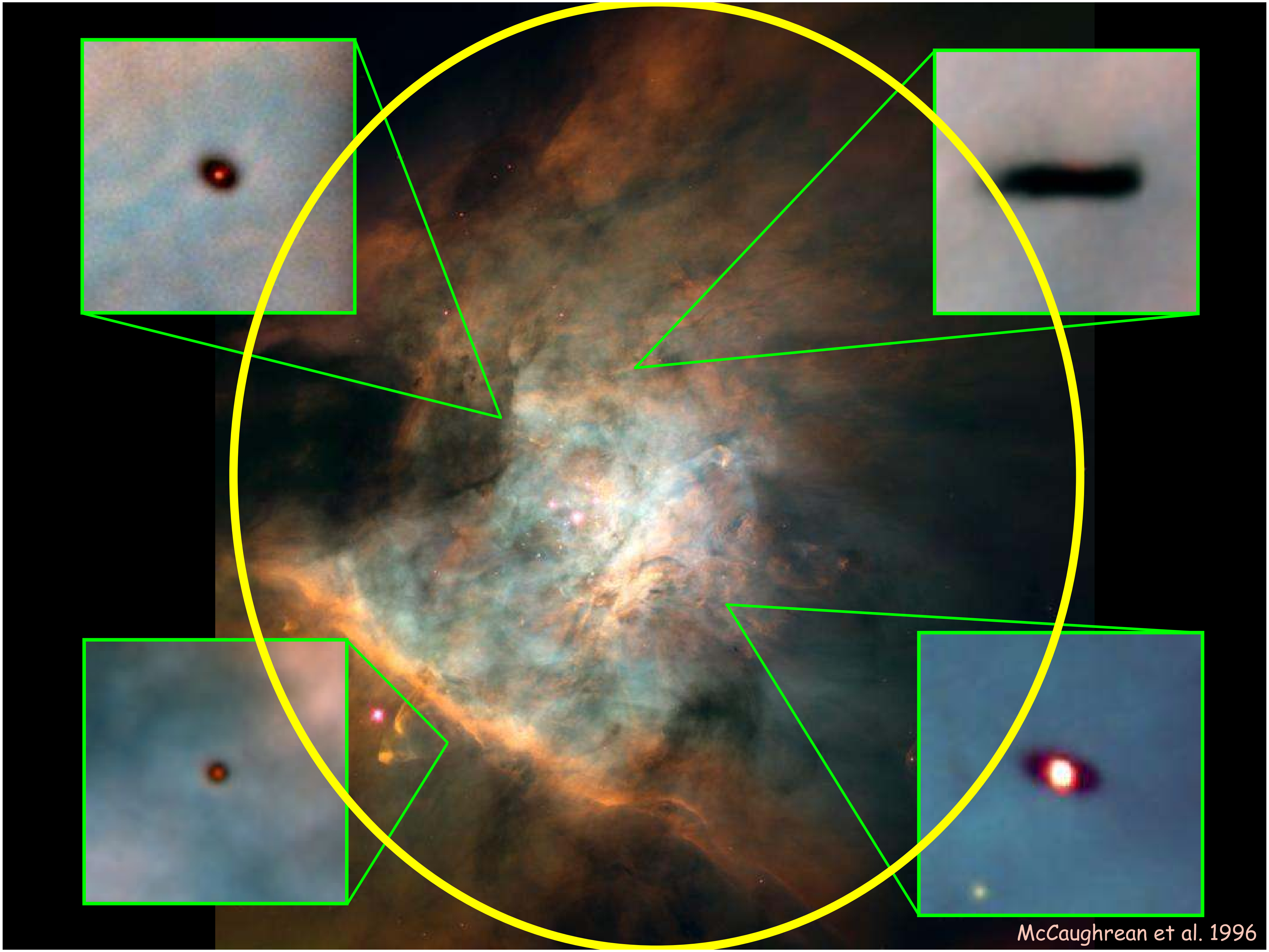
Problem:

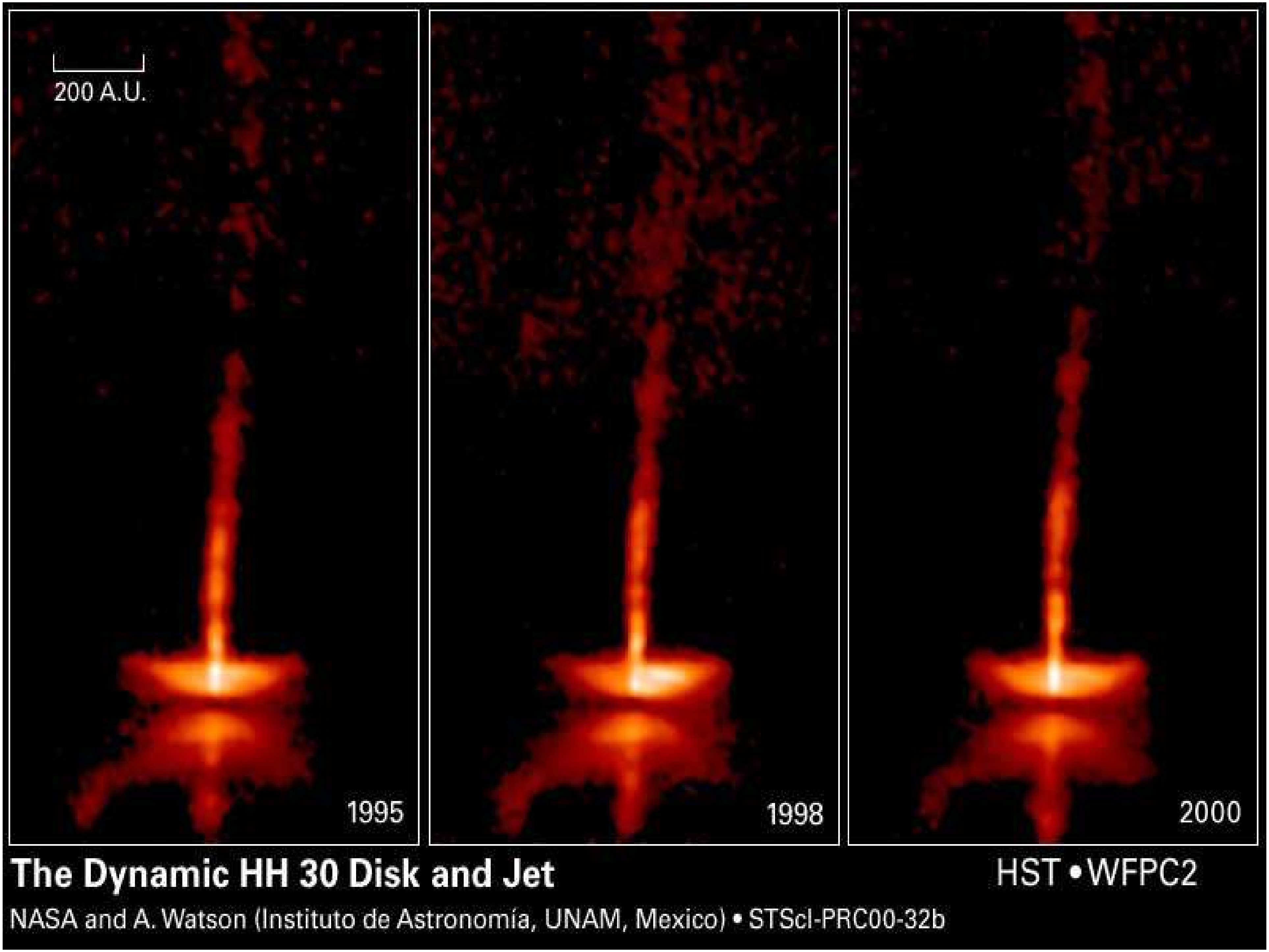
Is the emitting material really distributed in form of a ***disk***?

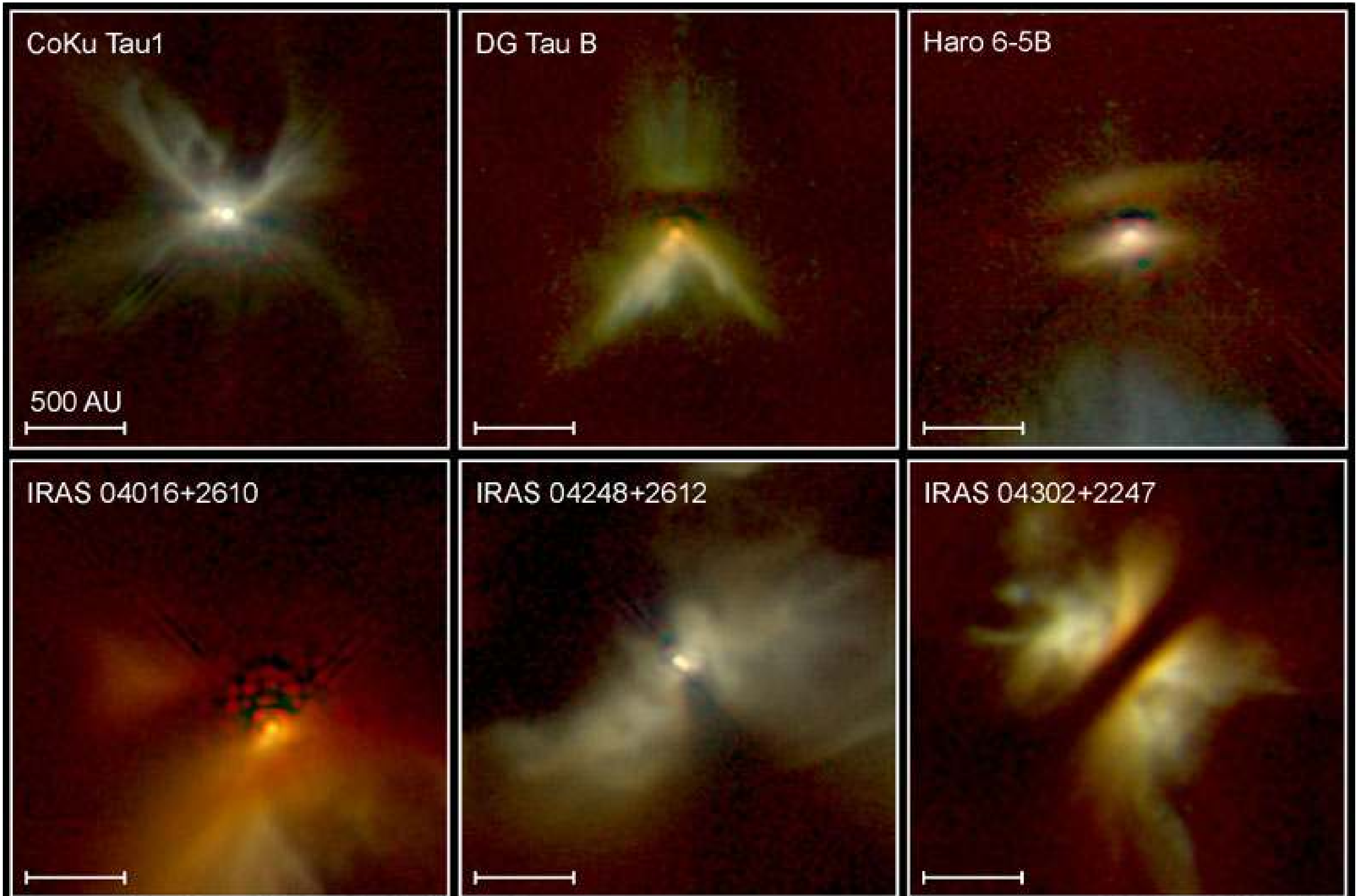
1. Argument:
   - mm observations / mm spectrum => mass of the disk (optically thin)
   - Derive optical depth, under the assumption of a spherical dust cloud => inconsistency with near-infrared absorption measurements

2. Observed SEDs can be well described by disks

but: final proof: IMAGES !!!


McCaughrean et al. 1996


200 A.U.
1995
1998
2000
The Dynamic HH 30 Disk and Jet
HST • WFPC2
NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b



Young Stellar Disks in Infrared **HST • NICMOS**

PRC99-05a • STScI OPO

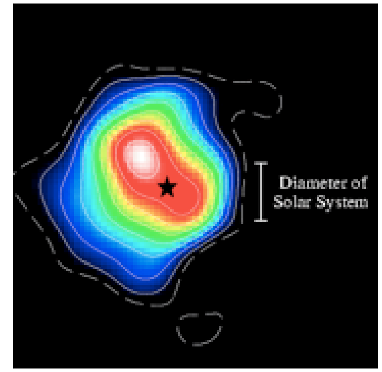
D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Resolved Circumstellar Disks

circumstellardisks.org

Catalog of Resolved Circumstellar Disks

Last updated: January 16 2007; maintained by Caer McCabe (JPL)



- What's new...
- Description of Catalog
- Contributing to the database

Total number of disks: 92 (Pre-Main Sequence disks: 79, Debris Disks: 13)

Object	SpTy	Category	Distance (pc)	R band (mag)	Disk Diameter (")	Disk Diameter (AU)	Inclination	How well Resolved	At ref. wavelength (micron)
2MASSI1628137-243139		TT	140	17.7	4.3	602	86	10.8	2.1
49 Cet	A1	Hae	61	5.6	0.8	48		3.9	10
AA Tau	M0	TT	140	11.8	1.34	187	75	1.0	2000
AB Aur	A0e	Hae	144	7.1	18	2592	21.5	367.4	0.57
AS 209	K5	TT	140	10.4	3.1	434	56	0.9	1300.39
ASR 41		TT	316		20	6320	80	97.0	2.2

Direct Evidence

1. **Hubble Space Telescope Images**
   a. HH30 (Burrows et al. 1996), further edge-on disks (Padgett et al. 1999): Size ~ several 100 AU
   b. "Silhouette Disks" in the Orion Nebula (McCaughrean & O'Dell 1996) Size ~ 50-1000 AU observed in absorption

2. **Millimeter Maps (Continuum / Lines)**
   - Subarcsec resolution => Interferometry
     (e.g., VLA, CSO + JCMT, OVRO/BIMA => CARMA)
   - Molecular lines: disk velocity structure (possible problems: mass infall, outflows dominate kinematic structure on large scales)

3. **Infrared spectroscopy**
   - Hot gas + dust at the inner disk radius
     (~100-5000 K within r < 5AU)
   - High gas density, high temperature
     => vibration-rotational transitions well populated
     => NIR/MIR spectroscopy (disk structure + kinematics)

Spectral Energy Distribution

Heating of the Dust

<u>Stellar Radiation</u>

- **Absorption** + Scattering of stellar radiation (UV – near-IR)
  => Dust temperature ~ 10… >10^3 K
- Reemission: near-IR … mm wavelength range

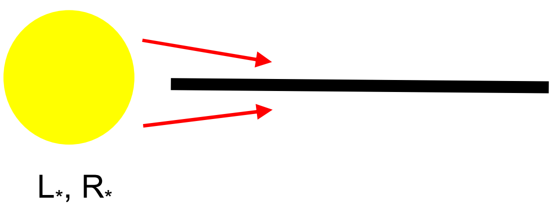
<u>Accretion</u>

- during early disk evolution
- dominating within the inner ~ 10 R_*

Spectral Energy Distribution

Assumption:

Geometrically thin disk



Problem:

Infrared excess*)
of this model weaker
than observed.

*) near-IR – mm flux above
the stellar photospheric flux

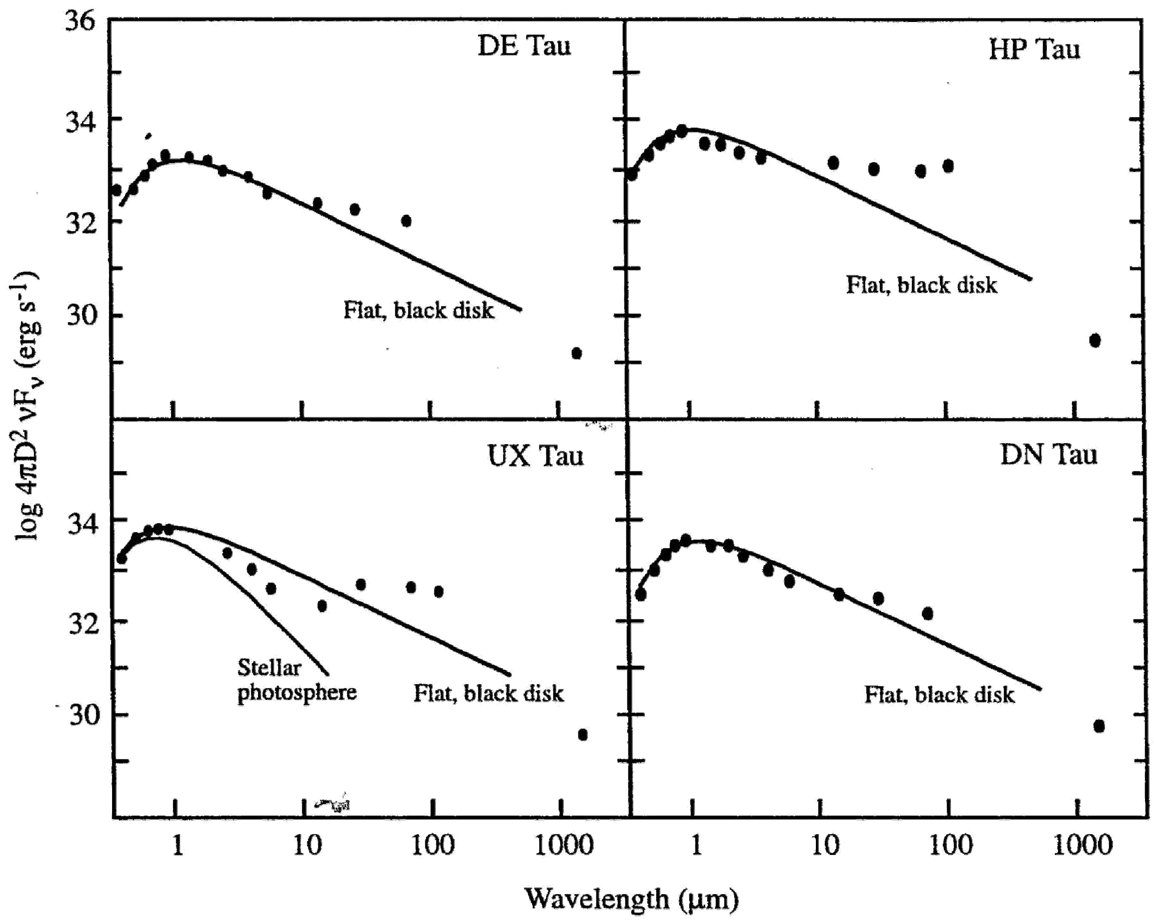


Figure 5. Observed spectral energy distributions are plotted on calculations of SEDs using the flat, black disk model. In general, the actual SEDs have more excess infrared radiation than predicted by the flat disk model.

Spectral Energy Distribution

Disk with vertical structure => “Disk flaring” (Kenyon & Hartmann 1987)

e.g.

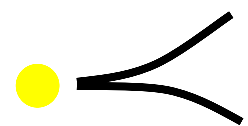
- $T(r) \sim r^{-3/4}$ (flat disk)

- Vertical gravitational potential dominated by central star

$$E_{vert} \sim -(z/r)\ G\,M_* / r \sim k\,T(r)$$

$M_* \sim 100\ M_{disk}$

- Scale height: $\boldsymbol{h_{scale}(r)} \sim k / (G\,M_*)\ \boldsymbol{r^{5/4}}$ **=> flaring**



Spectral Energy Distribution

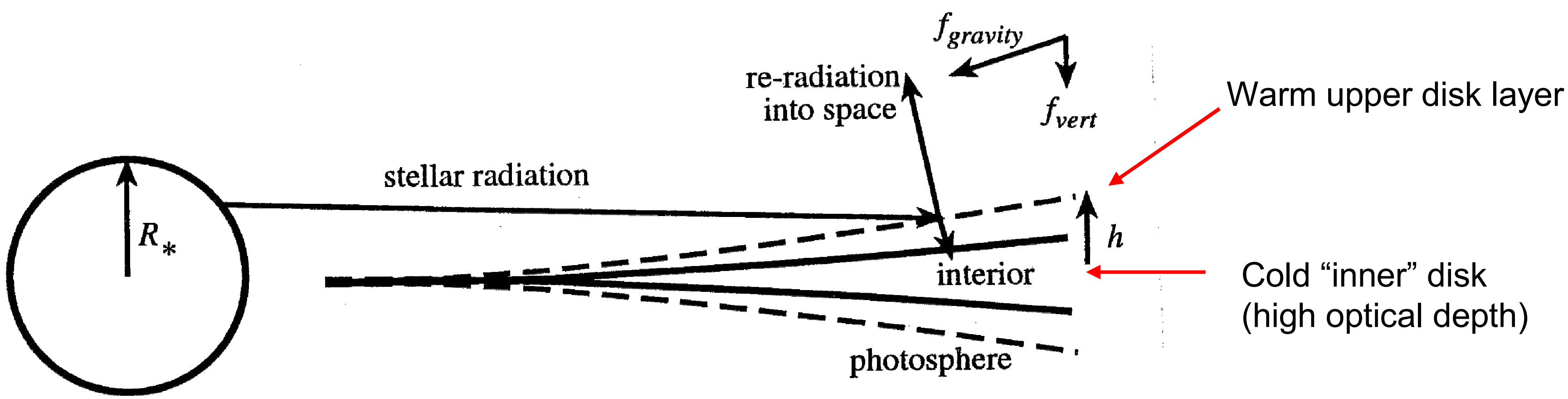


Figure 6. The flaring of a disk occurs naturally for a disk in hydrostatic equilibrium. The disk mass is assumed to be negligible; gravity from the star acts to keep the material in a plane. The scale height of the disk increases with radius, because the thermal energy decreases more slowly than the vertical gravitational energy as radius increases. The vertical gravitational force, f_{vert}, is shown as a component of the stellar gravitational force, $f_{gravity}$. The ray from the star shows the point at which short wavelength stellar radiation from the star is absorbed in the disk photosphere. The two other rays from this point show how the energy is reradiated into space and into the interior of the disk, thus heating the interior from the above.

Flaring => Star can heat the disk more efficiently

Spectral Energy Distribution

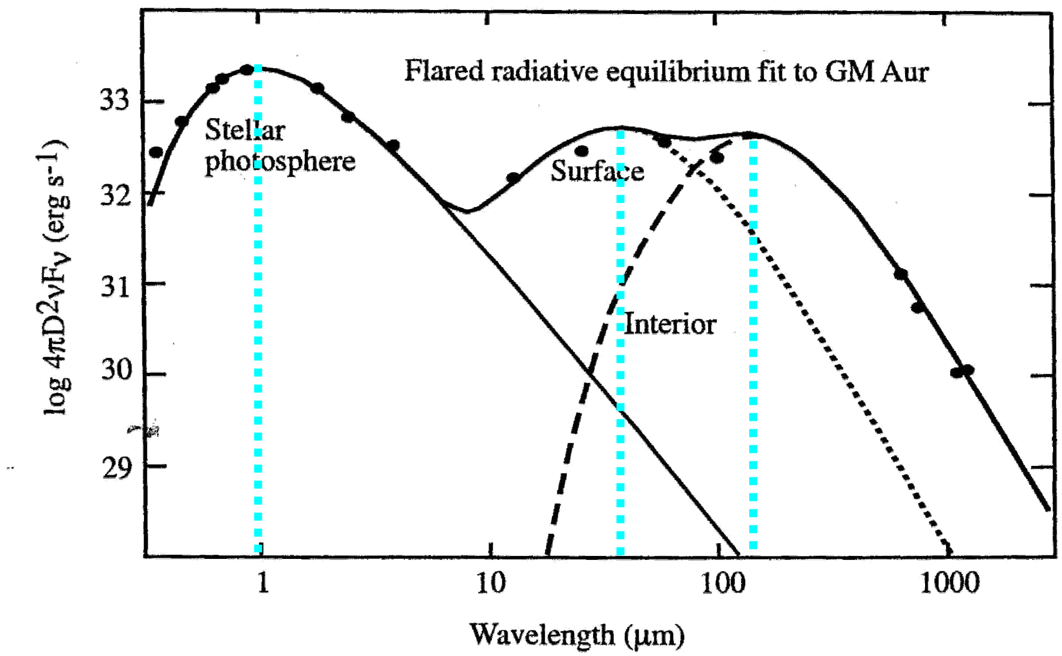
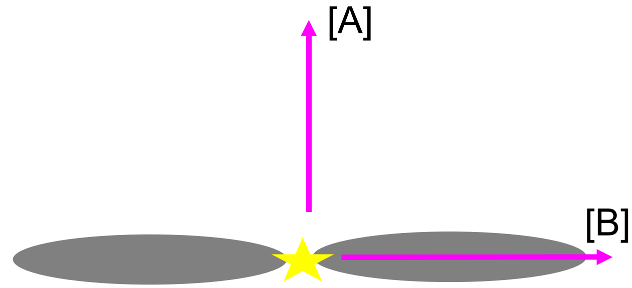
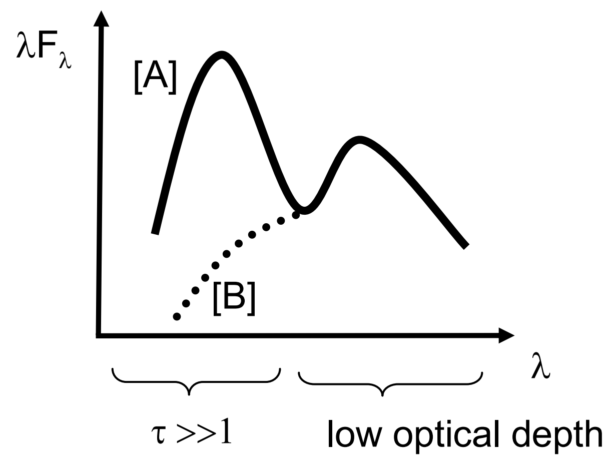


Figure 7. Figure 8 from Chiang and Goldreich (1997) showing how a flared disk with a photosphere reproduces one SED that differs substantially from a flat, black disk. They need a hole in the inner disk to account for the lack of disk emission short ward of about 5 μm.

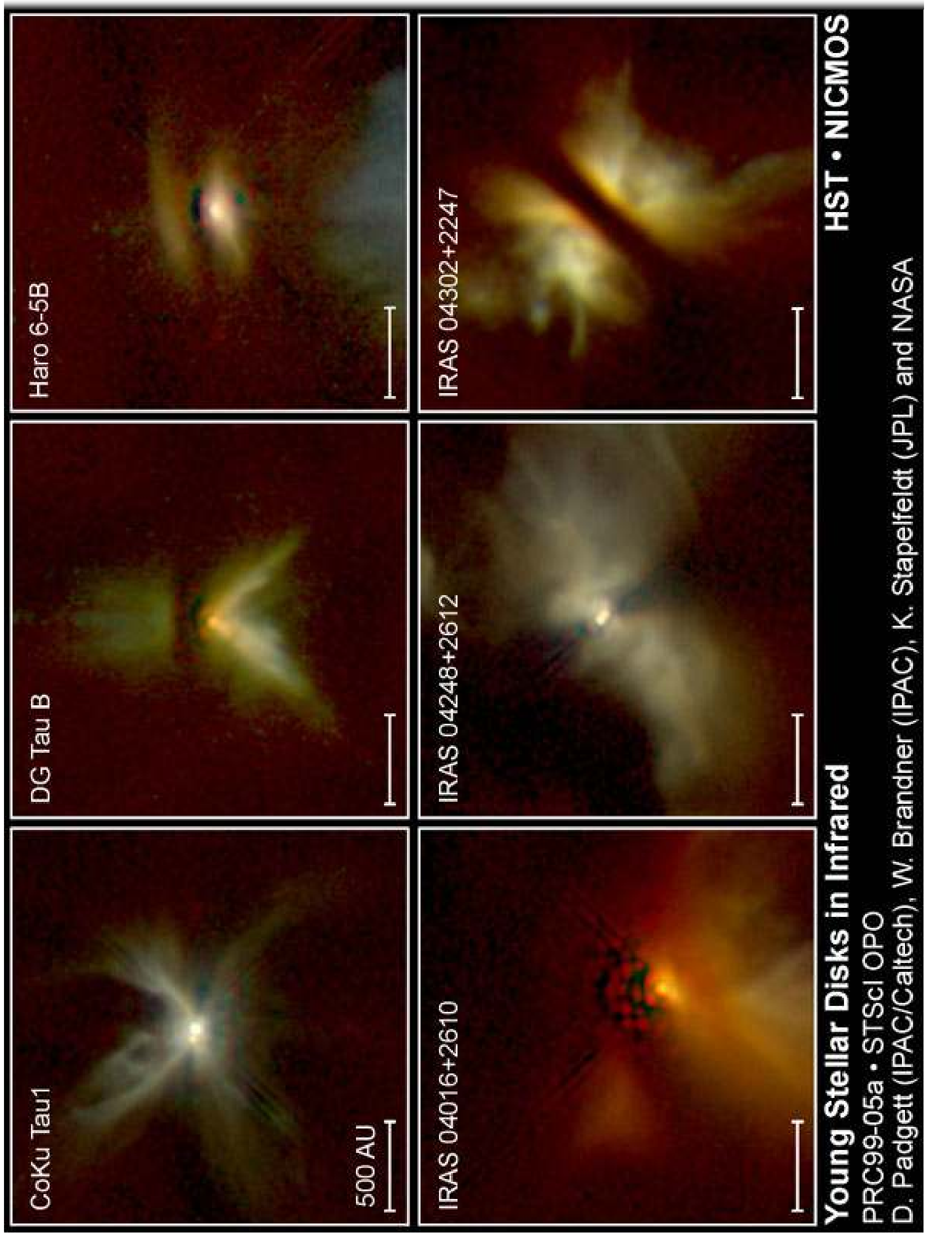
3 component SED

Inclination
dependence:





Spectral Energy Distribution



<u>To be considered:</u>

- Structure of a possibly remaining circumstellar envelope
- Dust Emission / Absorption features

=> **Radiative Transfer Simulations** (detailed numerical simulations taking into account absorption / scattering / heating / reemission processes)

Result: SEDs can be well reproduced, but not unambigiously

=> Images (Vis … mm) required

Spectral Energy Distribution

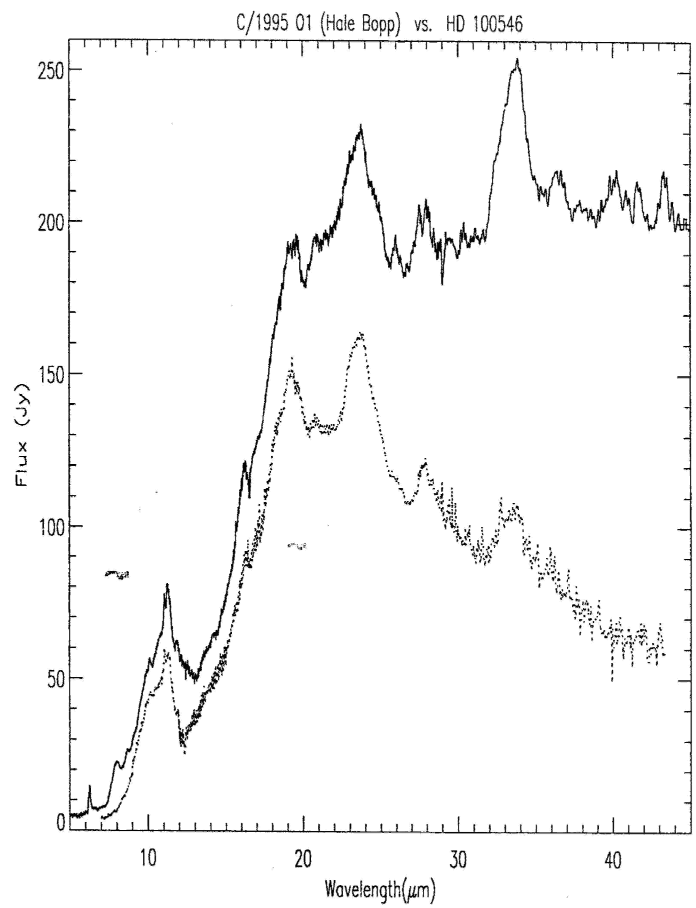


Figure 9. This is Figure 5 from Malfait et al. (1998) showing the detection of emission features in the disk around the Herbig Ae/Be star, HD 100546, (solid line at top) as predicted if the disk is heated by radiation from the central source. It is compared with the spectrum of comet Hale-Bopp (dotted line underneath). Notice the close correspondence between emission features in the comet and in the disk spectrum, indicating that the particles in the disk are made from similar material as particles in the early solar system that made up the comet.

<u>To be considered:</u>

- Structure of a possibly remaining circumstellar envelope
- Dust Emission / Absorption features

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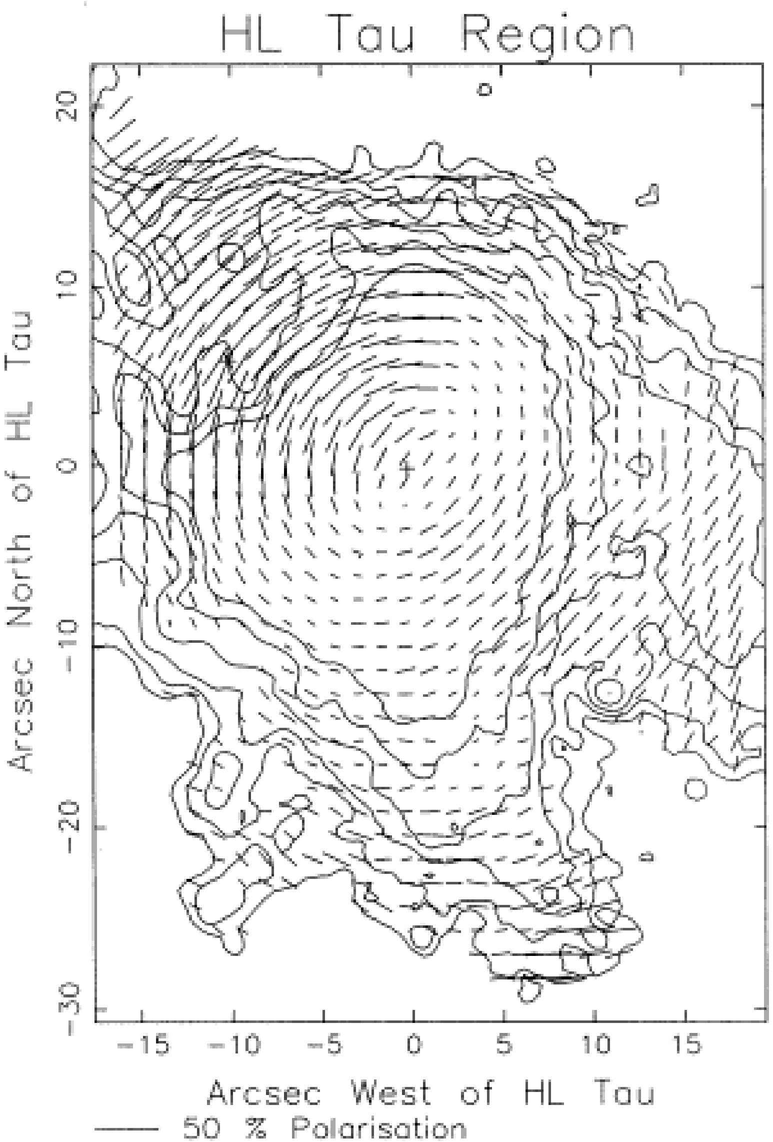
Polarization Maps



[Gledhill & Scarrott 1989]

Polarization mechanisms

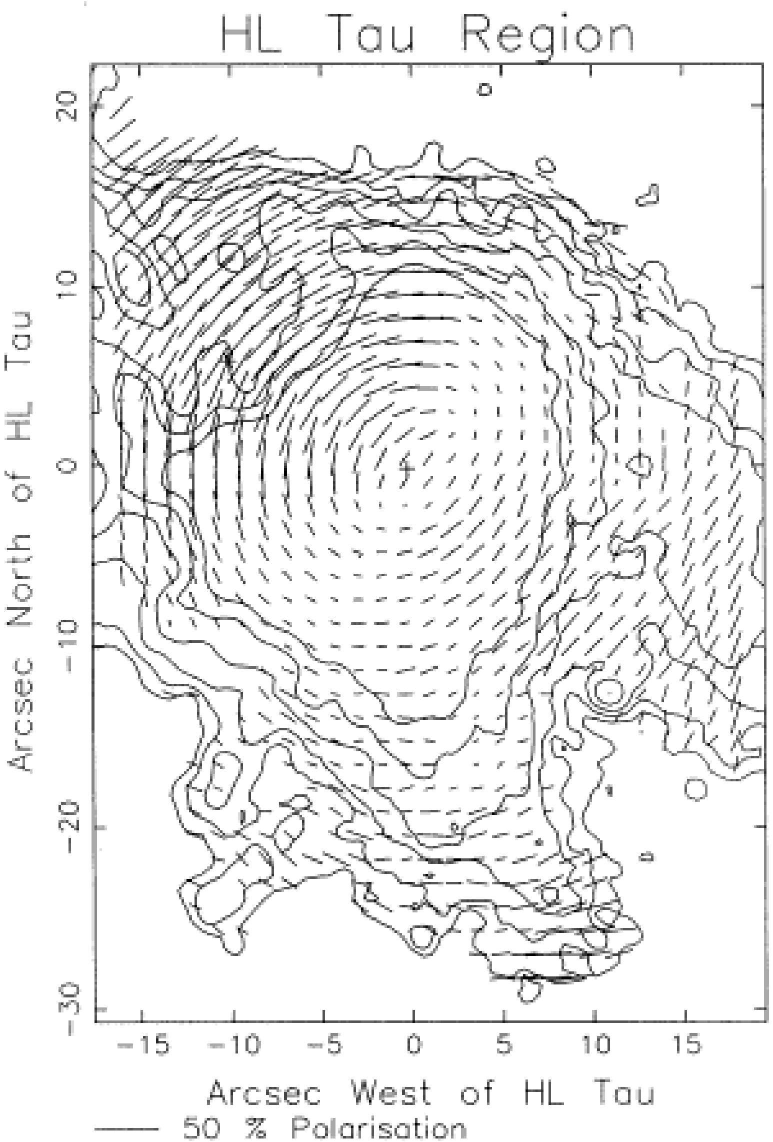
1. **Scattering**

   Even spherical grains cause polarization which allows to explain observed polarization patterns without further assumptions

2. **Dichroic Extinction**
   by aligned non-spherical grains or anisotropic particles

   - Efficient grain alignment mechanism required to explain observed polarization degrees
   - Important for interstellar polarization (magnetic alignment)

Polarization Maps



[Gledhill & Scarrott 1989]

__Observed Polarization Degree__

- Grain size: a=5-250nm, $n(a) \sim a^{-3.5}$ (Mathis et al. 1977)

  => efficient scattering / Polarization in the optical / near-IR wavelength range

- **ISM**

  P_{max} at 0.45 … 0.80 micron ("Serkowski law")

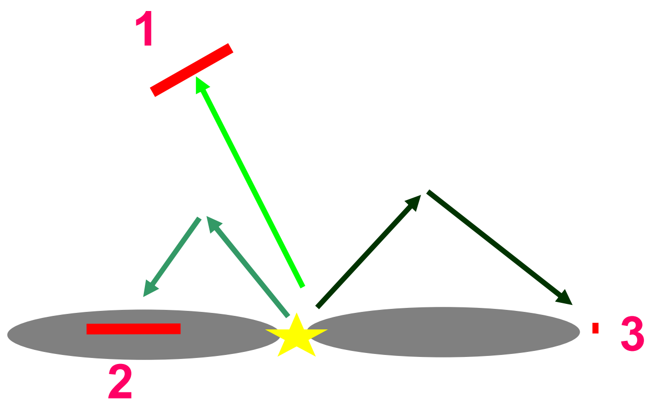
  YSOs

  Similar, but also at longer/shorter wavelengths

- Net polarization (optical/near-IR):
  - ISM < 5%
  - YSOs – usually larger (e.g. HL Tau 12%, V376Cass: 21%)

Optical / Near-IR Polarization

Spatially resolved Polarization Maps

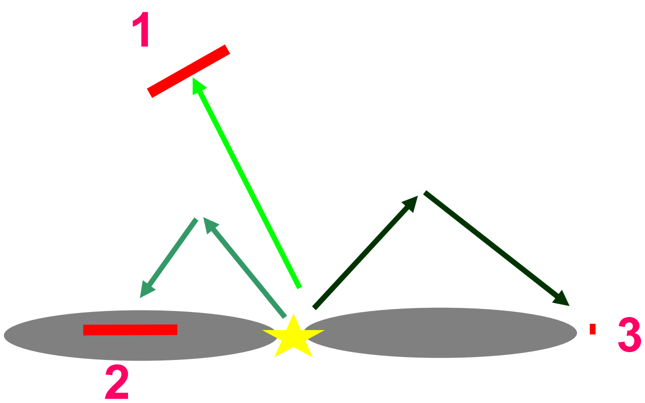


1) Single scattering in the envelope (low optical depth)
   => centro-symmetric orientation, high polarization degree

2) Multiple scattering
   => pol.vector parallel to disk plane, low polarization degree

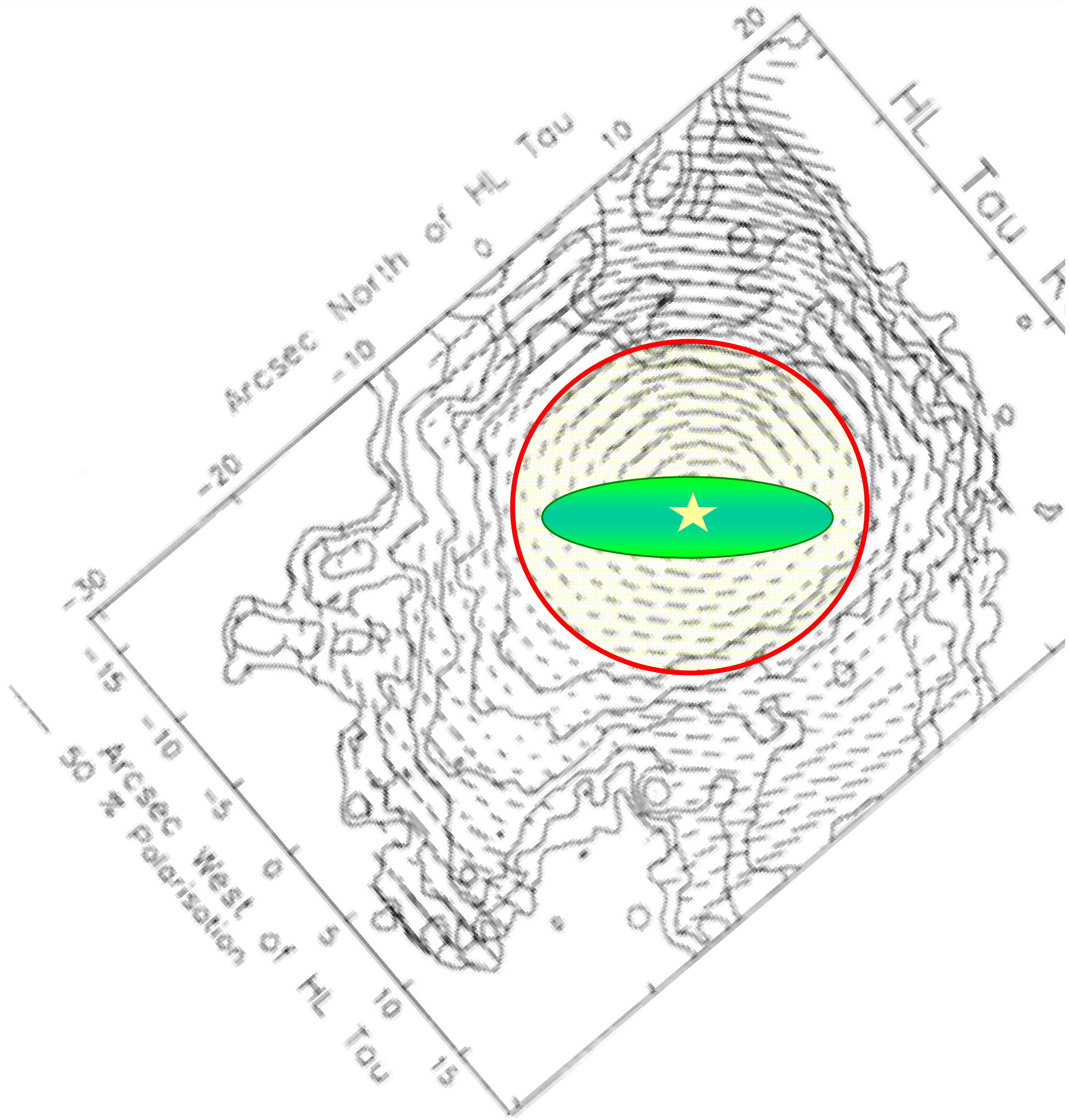
3) “Polarization Null point”
   Vanishing linear polarization at the disk “edge”

Optical / Near-IR Polarization

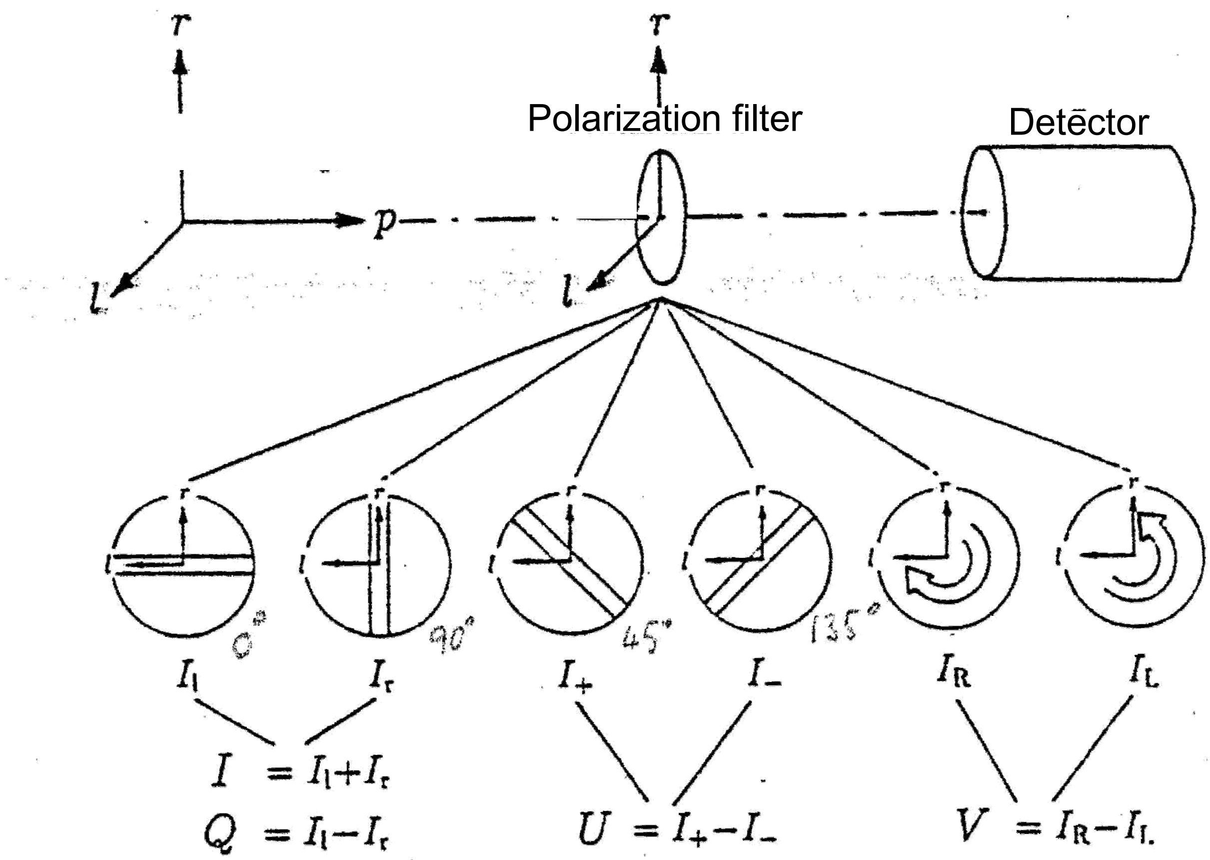


Polarization degree depends on

- Wavelength
- Grain size, chemical composition
- Density distribution (geometrical structure / dust opacity)



Optical / Near-IR Polarization



[Fischer 1995]

Linear polarization degree:

$P_{lin} = sqrt(Q^2 + U^2) / I$

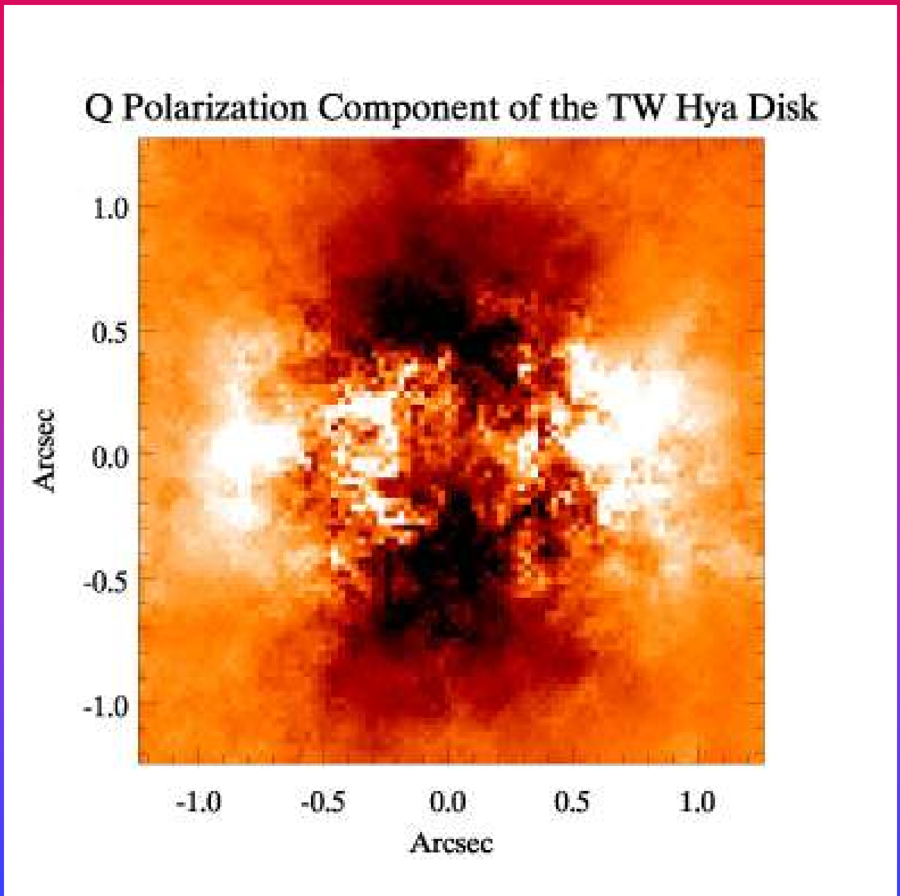
Circular polarization degree:

$P_{circ} = V / I$

Orientation

$\tan 2\gamma = U / Q$

Optical / Near-IR Polarization



Stokes Q(TW Hya) observed with NACO/VLT
[Apai, Pascucci, Brandner, Henning, Lenzen, et al., 2004]

<u>Goal:</u>

High-resolution disk mapping in the near-IR

<u>PDI Technique:</u>

Relies on the high contrast between the polarized and non-polarized radiation component of the scattered / non-scattered light

<u>Result:</u>

Radial density profil down to distances of 0.1” (6-10AU) to the central star

Modeling

‘Guidelines’

1. Take as many independent constraints as possible from observations into account
   - Spectral Energy Distribution *(mass, disk structure)*
   - Absorption/Emission Features *(dust properties)*
   - Polarization measurements *(dust properties)*
   - Spatially resolved images in various wavelength ranges *(tracing different physical processes)*
   - Single dish/telescope + Interferometric measurements *(tracing disks on various spatial scales)*
   - Characterize embedded source
   - Possible Influence of the environment? (e.g., nearby massive stars?)

Modeling

‘Guidelines’

2. Set up a disk model with as few parameters as necessary (which are the parameters do you really want/need to constrain?)

3. a) Radiative Transfer Modeling if necessary;

   b) Simple ‘Toy Model Fitting’ if sufficient

   (Problem here: Resulting model/parameters usually not selfconsistent)

General

Optical /Mid-Infrared Interferometric data:

- *Additional constraints for the structure, flux (and dust + gas properties) in the ~mas scale*
- *Most useful if considered in the context of complementary observations*

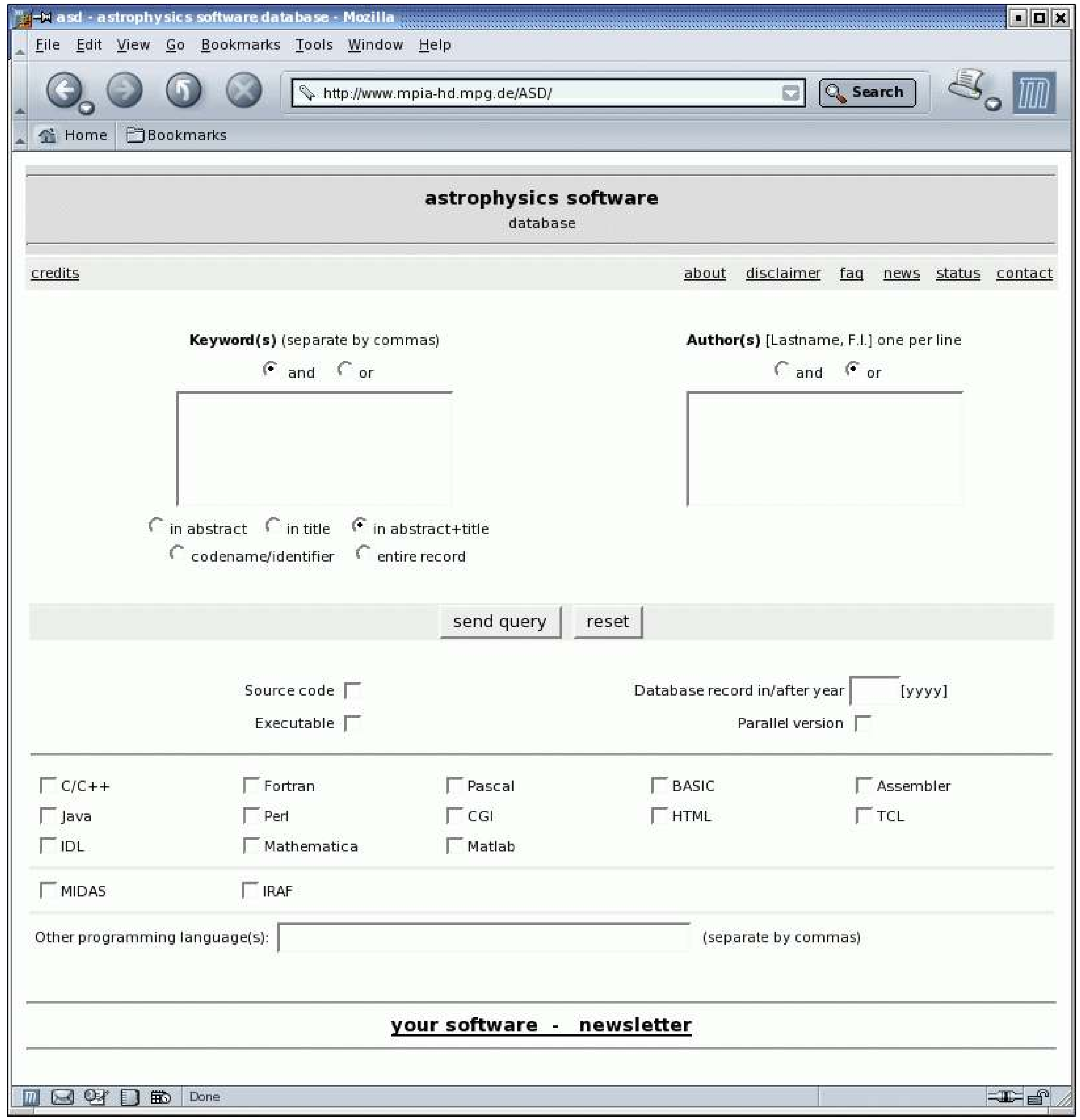
www.mpia.de / ASD

ASTROPHYSICS SOFTWARE DATABASE

Foster the communication between developers and users of astrophysical software

Provide an overview about existing software solutions in the community

Cross linked with the NASA ADS



Literature – Acknowledgements

Extrasolar Planets

http://www.mpia-hd.mpg.de/EXTRA2005/

Software

www.mpia.de/ASD

VLTI Summer School "On The Fringe"