A science overview of optical interferometry (continued)

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Observational methods

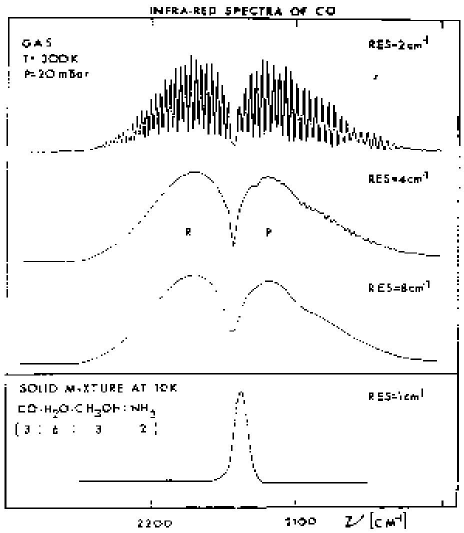
- Circumstellar matter is cool:
  observe at long wavelengths (IR, mm)
- Composition and kinematics: spectroscopy
- Geometry of environment: high resolution imaging

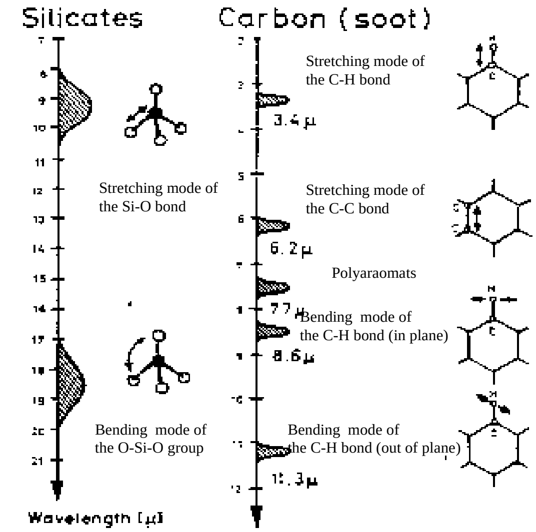
High angular resolution: stars

- Stellar surface structure
- Mass loss of stars (massive, low mass)
- Formation of stars and planetary systems

Some spectral diagnostics accessible at Infrared wavelengths

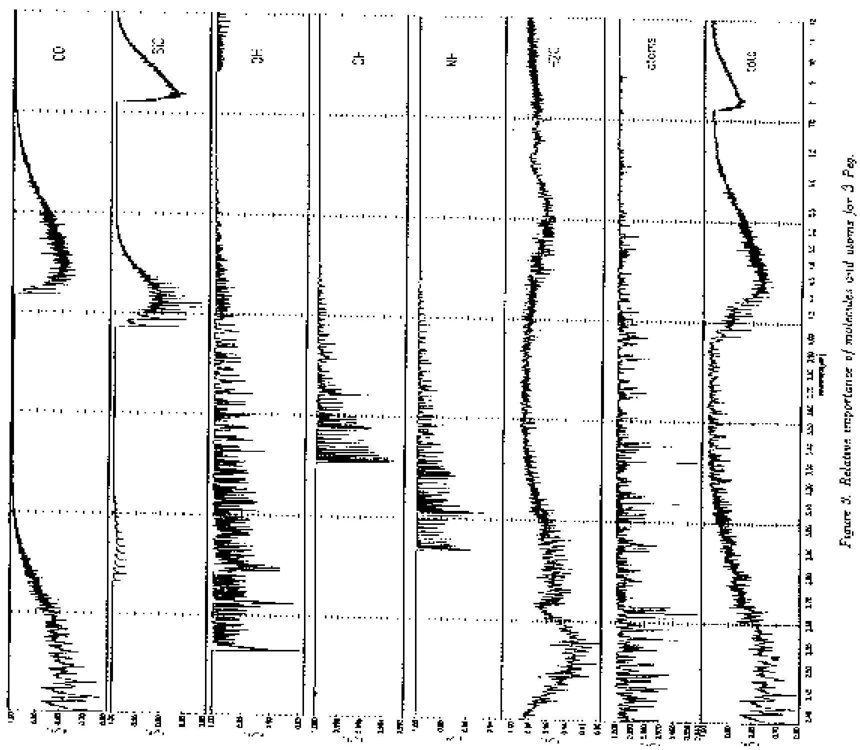
Diagnostic	example	application
HI recombination lines	Brα (4.05 μm) Huα (12.37 μm)	Hot star wind structure **OB stars, WR stars**
fine-structure lines (forbidden)	[FeII] 1.64 μm [NeII] 12.8 μm	Low-density gas (atomic/ionic) **YSO's, Planetary nebulae, WR stars**
Molecular lines	CO (2.3 μm; 4.7 μm) SiO (4 μm, 8 μm) H_2 (2.1 μm; 12 μm)	Cool, "dense" gas near stars, ISM **YSO disks, cool star outflows, ISM, ...**
Thermal emission from dust	λ ≳ 1 μm : continuum solid state resonances (e.g. silicate at 10 μm, 18 μm; SiC at 11.3 μm	cool regions near stars ISM **YSO disks, cool star outflows, ISM, --**





The spectrum of CO in the gas phase and in a molecular binding between 2000 and 2300 cm^{-1}. RES is resolution.

Some characteristic IR transitions of dust and the corresponding modes of active molecules in the dust material



M star molecular absorption bands
Model atmosphere
Decin, Gustafsson et al. (1998)
Cohen

Properties of dust

- near-IR, optical : scattering of photons
  (probes matter where photons can penetrate)

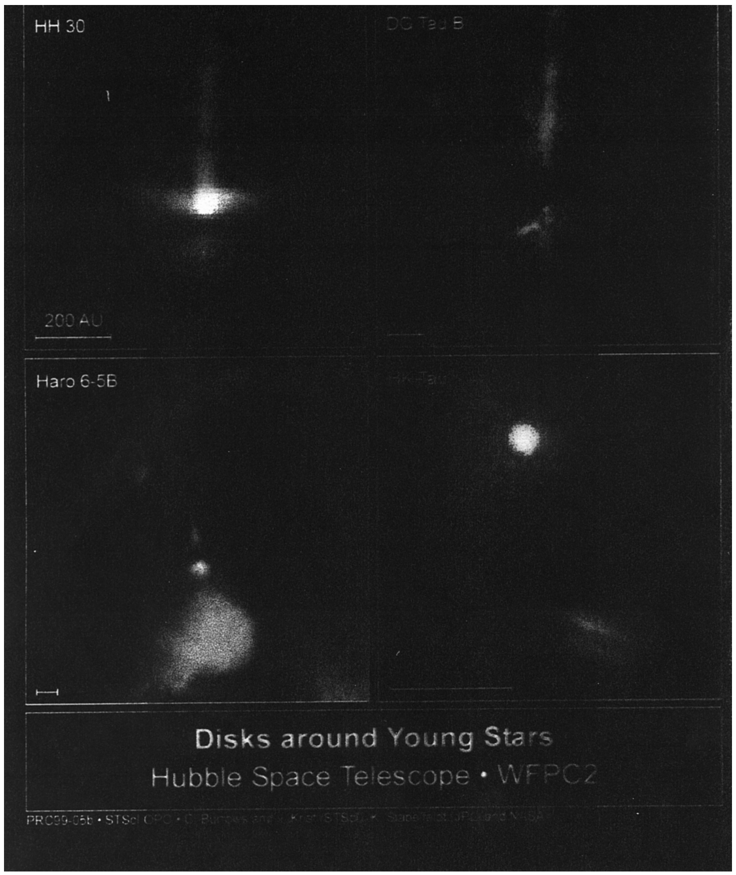
- mid, far-IR : thermal emission of photons
  (probes mass distribution of dust/gas)

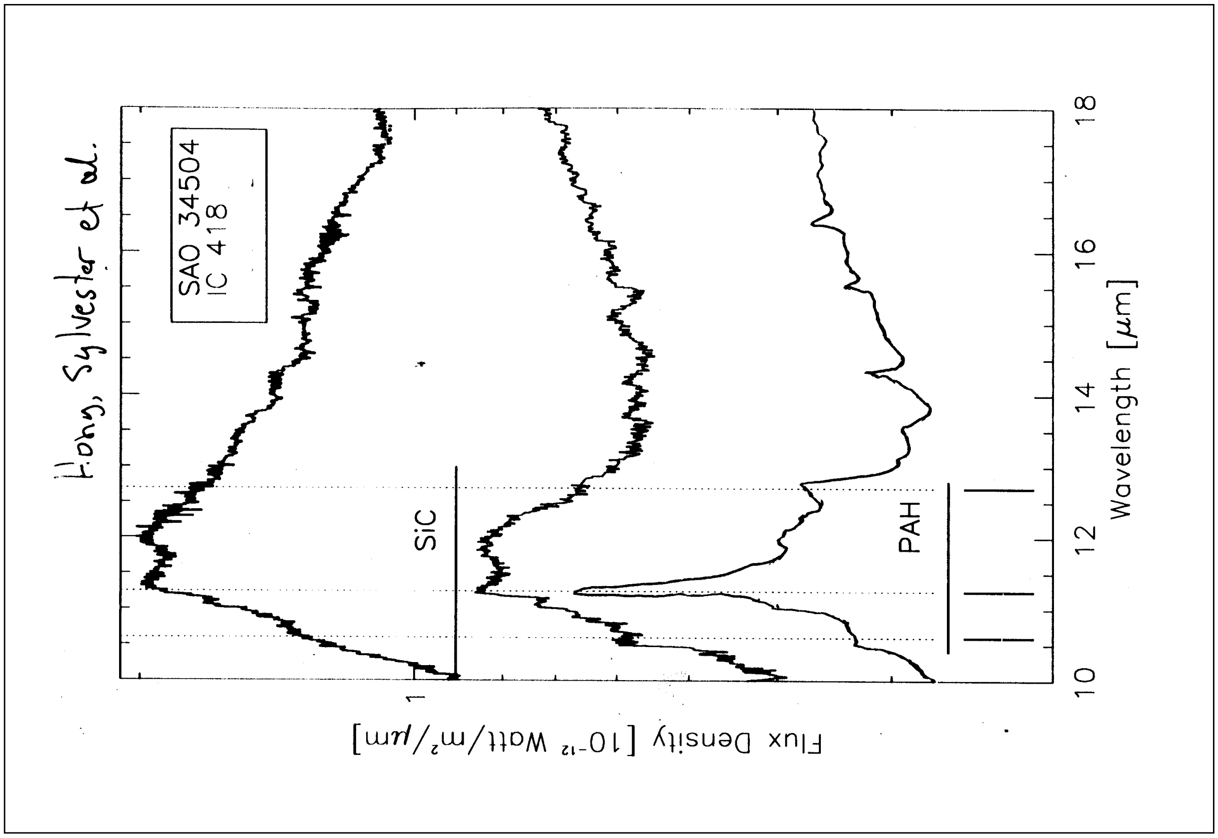
- Optically thin dust shells : scattering & thermal emission intensity distribution "similar"

- optically thick dust shells : very different scattering & thermal emission geometries possible !

Mid-IR spectral region : rich in vibrational resonances of abundant species :

Amorphous Silicates	9, 18 μm
Crystalline Silicates	~10, 11.3, 16.5, 19.5, ... μm
Al_2O_3	13 μm
Quartz (SiO_2)	9, 20.0 μm
FeO	18-23 μm
Polycyclic Aromatic Hydrocarbons	3.3, 7.7, 8.6, 11.3, 12.7 μm





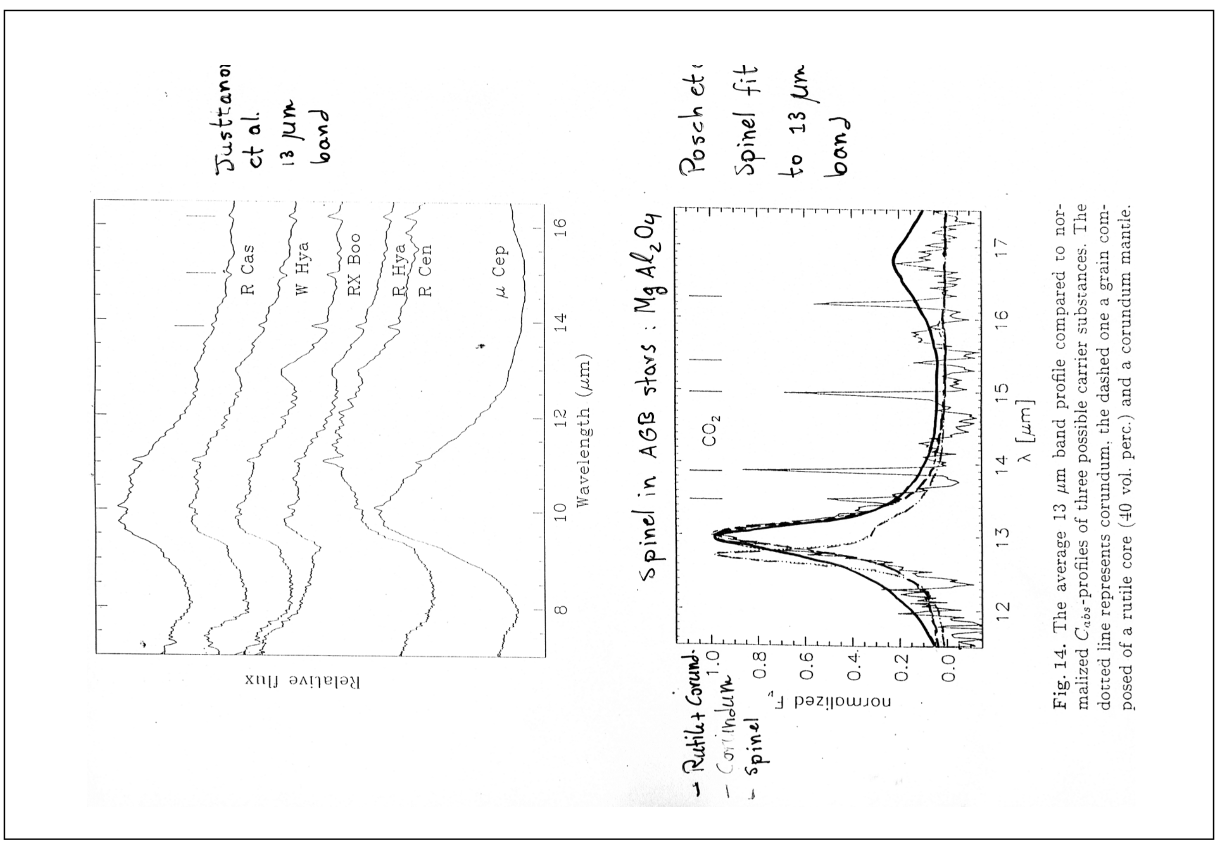
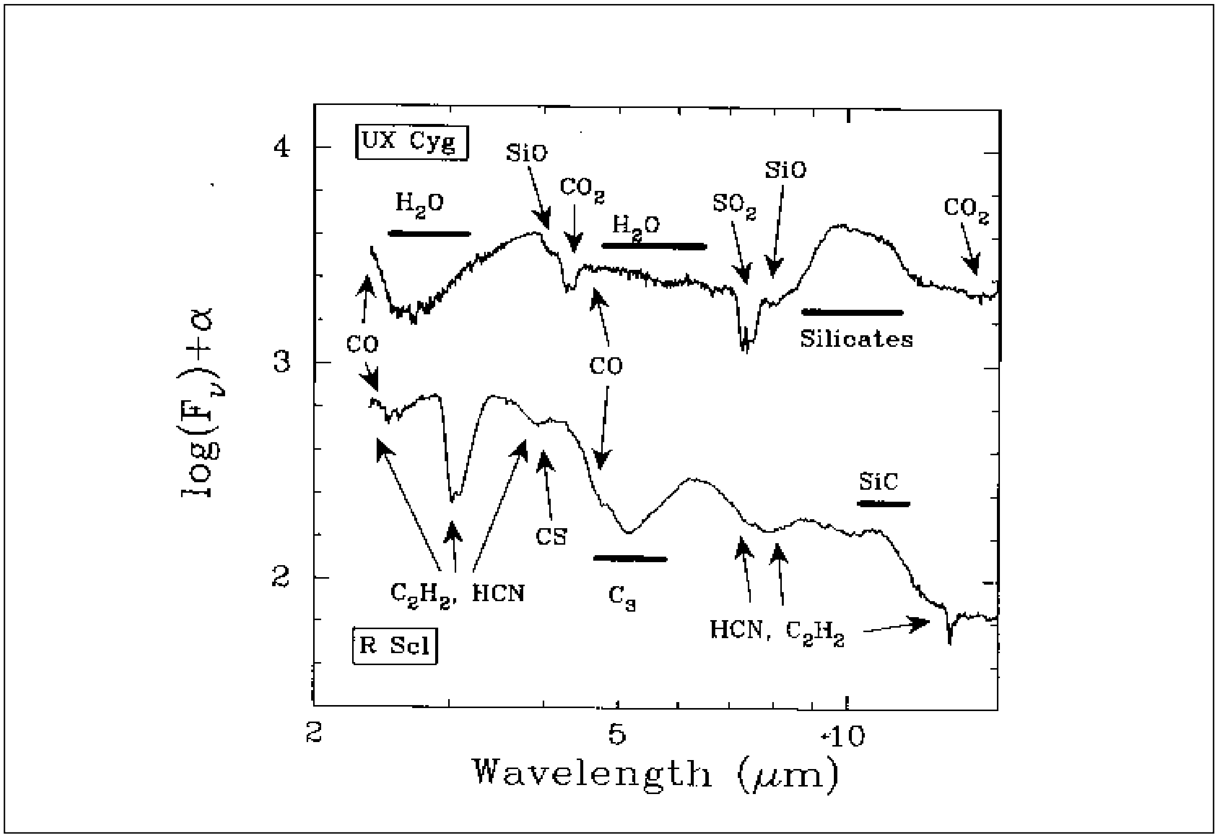


Fig. 14. The average 13 μm band profile compared to normalized C_{abs}-profiles of three possible carrier substances. The dotted line represents corundum, the dashed one a grain composed of a rutile core (40 vol. perc.) and a corundum mantle.



Spatial extent of "dusty" objects.

- Spatial resolution of telescope $\propto \lambda^{-1}$
- Long wavelength (IR) observations → 'poor' spatial resolution

However...

- Observed size of dusty objects $= f(\lambda)$
- Typically: $T_{dust}(r) \propto r^{-\alpha}$

  $\alpha = 0.5$ for black-body grains

  $\alpha \simeq 0.4$ for small ($\sim 0.1\ \mu m$) grains

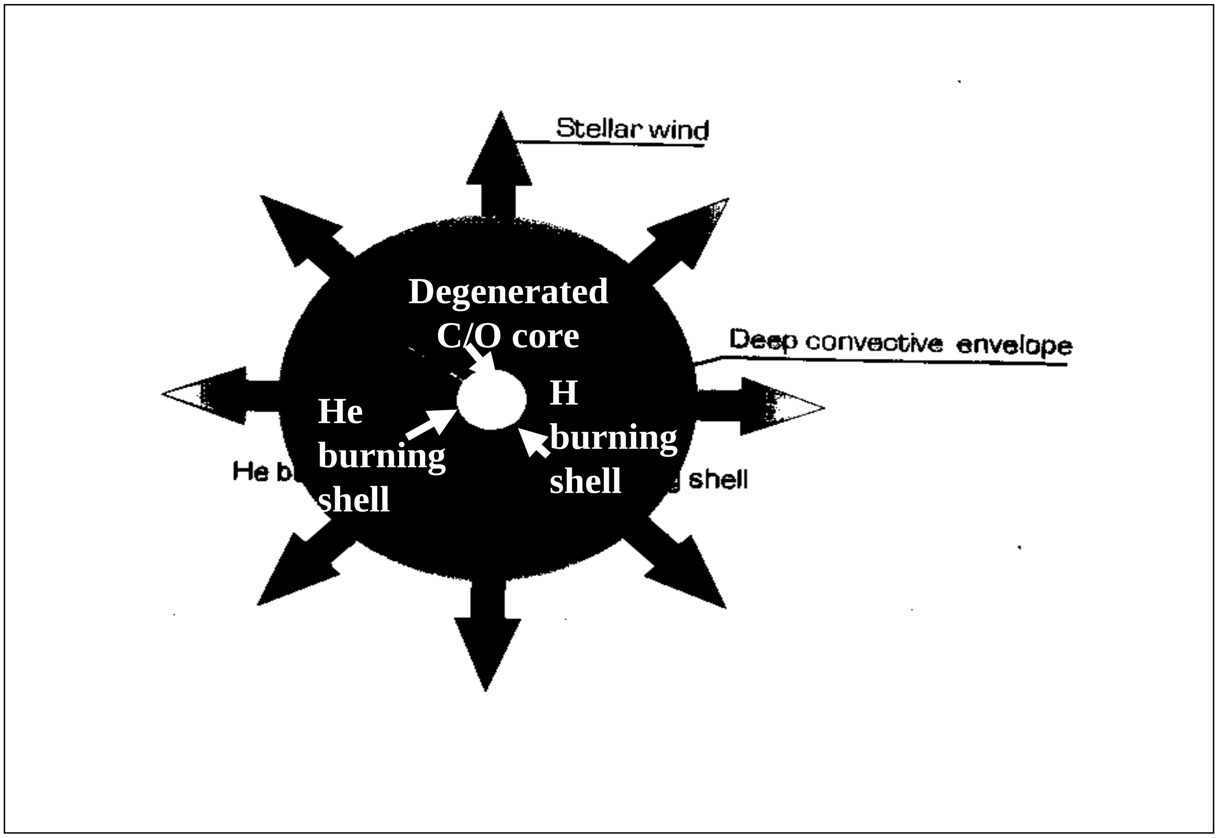
Use Wien displacement law $\lambda_{max} T = const$

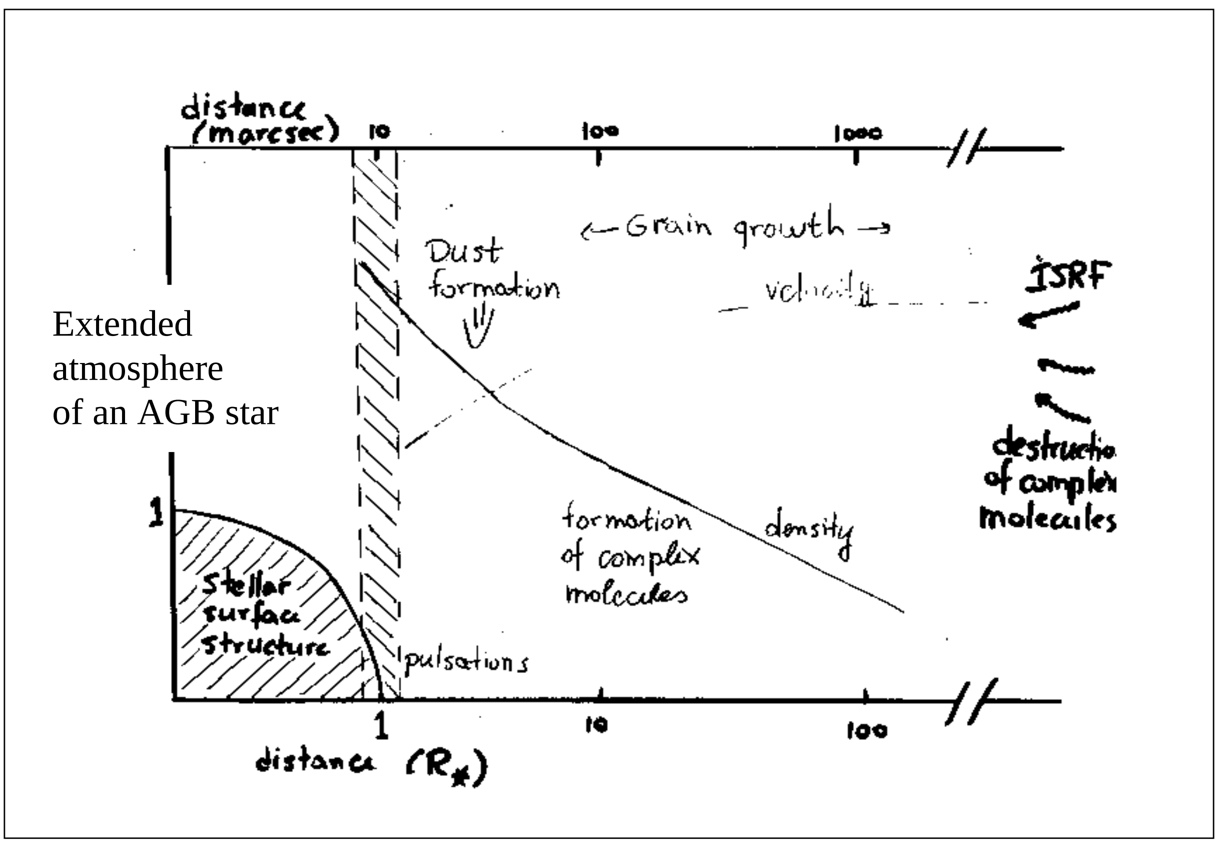
$\Rightarrow r(\lambda) \propto \lambda_{max}^{1/\alpha}$

(e.g. $r(\lambda) \propto \lambda^2$ for BB grains)

→ Size of dusty object still grows with respect to angular resolution of telescope ?

[note : density distribution + optical depth effects also play an important rôle !]


Stellar wind
Degenerated C/O core
Deep convective envelope
He burning shell
H burning shell


distance (marcsec)
10
100
1000
← Grain growth →
Dust formation
ISRF
Extended atmosphere of an AGB star
formation of complex molecules
density
Stellar surface structure
pulsations
1
1
10
100
distance (R*)

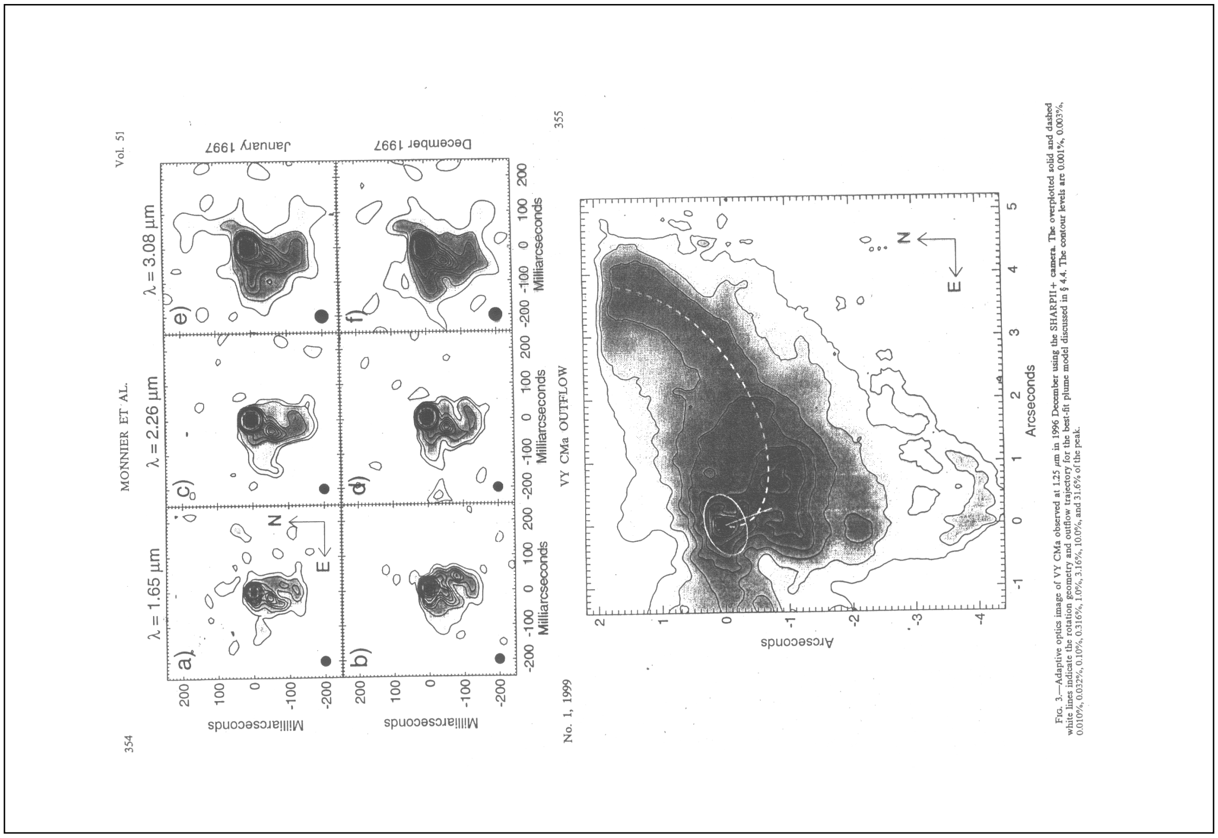
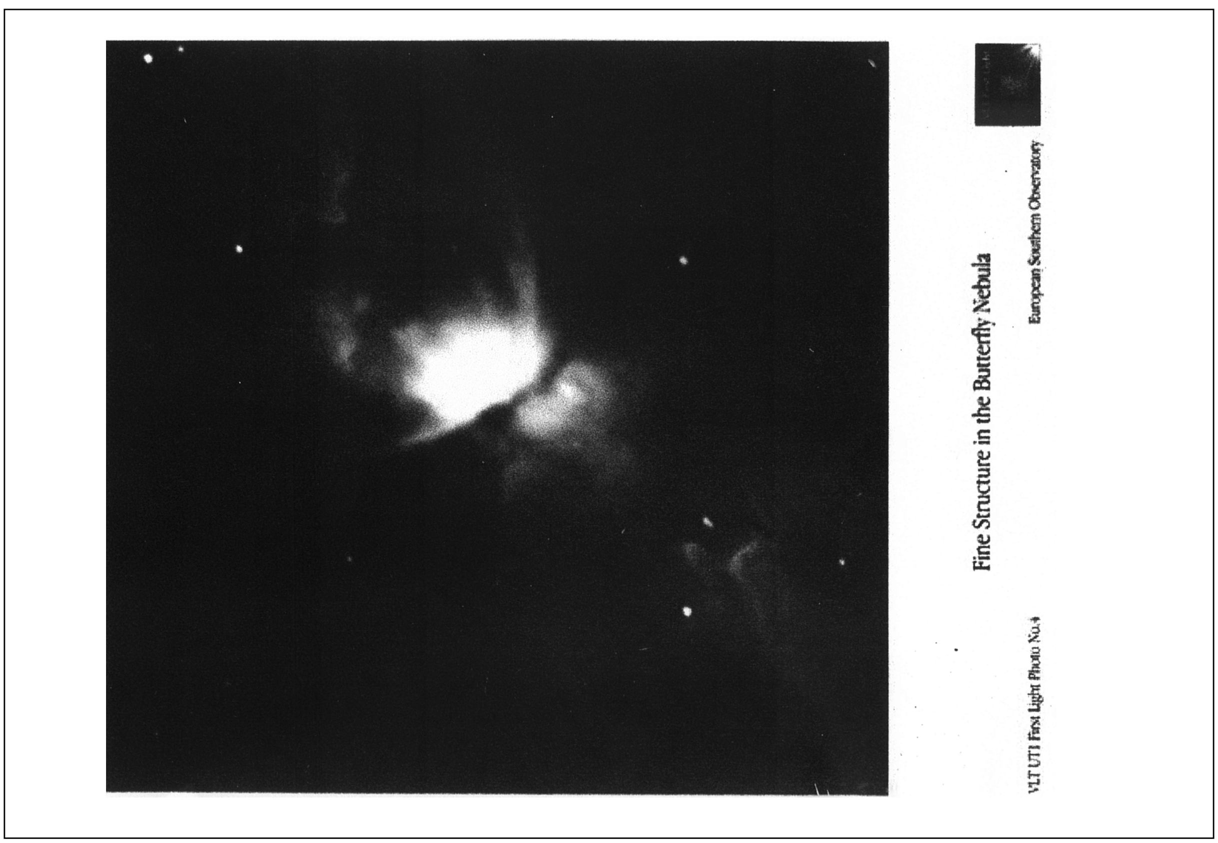


FIG. 3.—Adaptive optics image of VY CMa observed at 1.25 μm in 1996 December using the SHARPII+ camera. The overplotted solid and dashed white lines indicate the rotation geometry and outflow trajectory for the best-fit plume model discussed in § 4.4. The contour levels are 0.001%, 0.003%, 0.010%, 0.032%, 0.10%, 0.316%, 1.0%, 3.16%, 10.0%, and 31.6% of the peak.



Geometry of (dusty) stellar outflows

- Location of dust forming region
- Effects of stellar pulsation on dust formation
- Origin of non-spherical mass loss
- Binarity and AGB mass loss

High angular resolution observations : late type stars.

* Sub-structure on stellar surface ("star-spots")
* "Stellar" diameter as a function of wavelength.
  - Molecular absorption bands (OH, SiO, CO, C_2H_2, HCN, CS, ...) probe extended molecular layers
  - Spatial distribution of dust (continuum and solid state resonances) probes wind structure and geometry
* Angular size of dust shell thermal emission depends on :
  - temperature of central star
  - dust condensation temperature (dust chemistry)
  - "typical" grain size
  - temporal variation of dust production conditions (stellar pulsation)
  - density in outflow (mass loss rate) → optical depth of shell

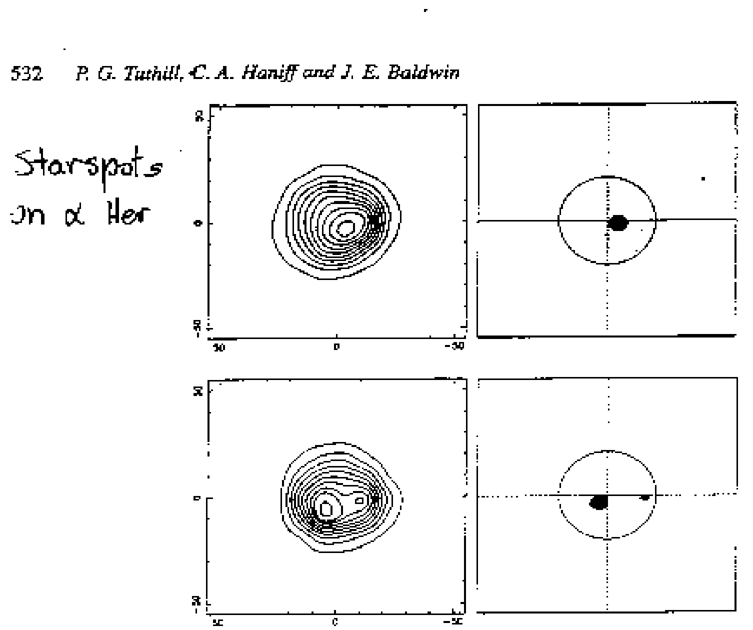
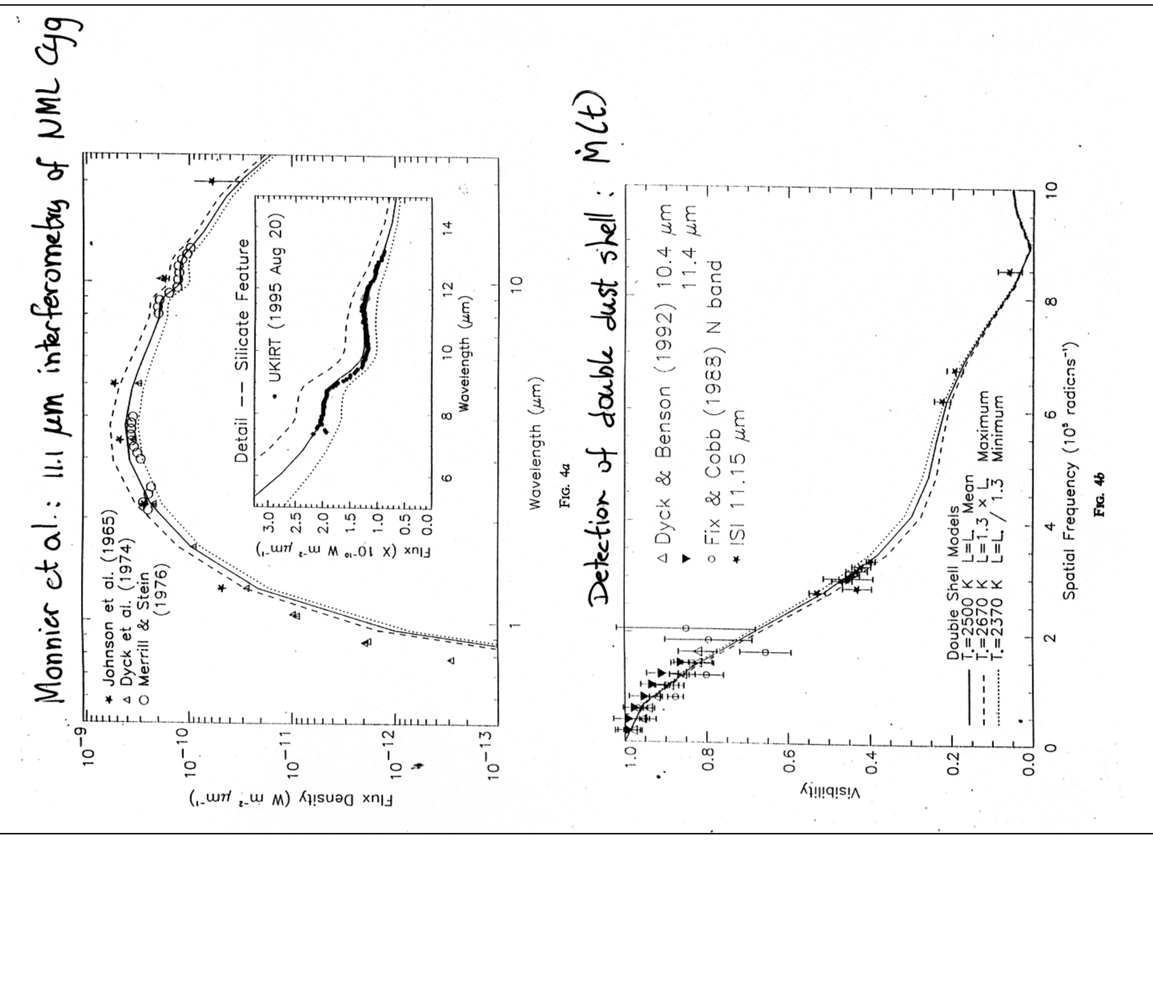
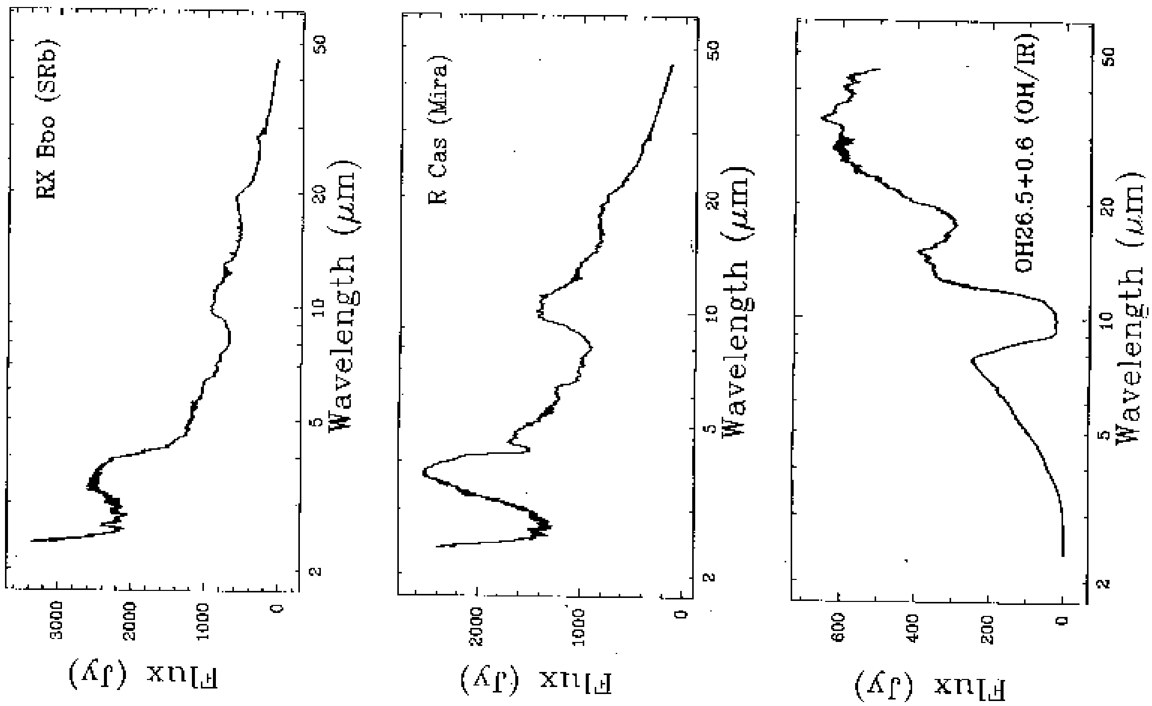
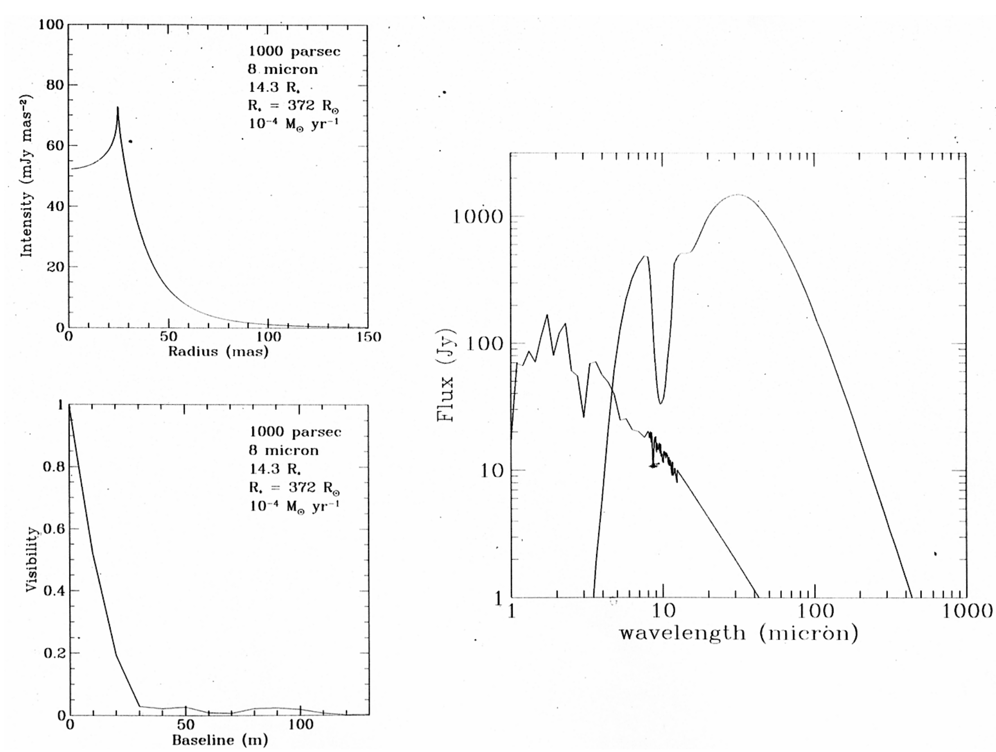
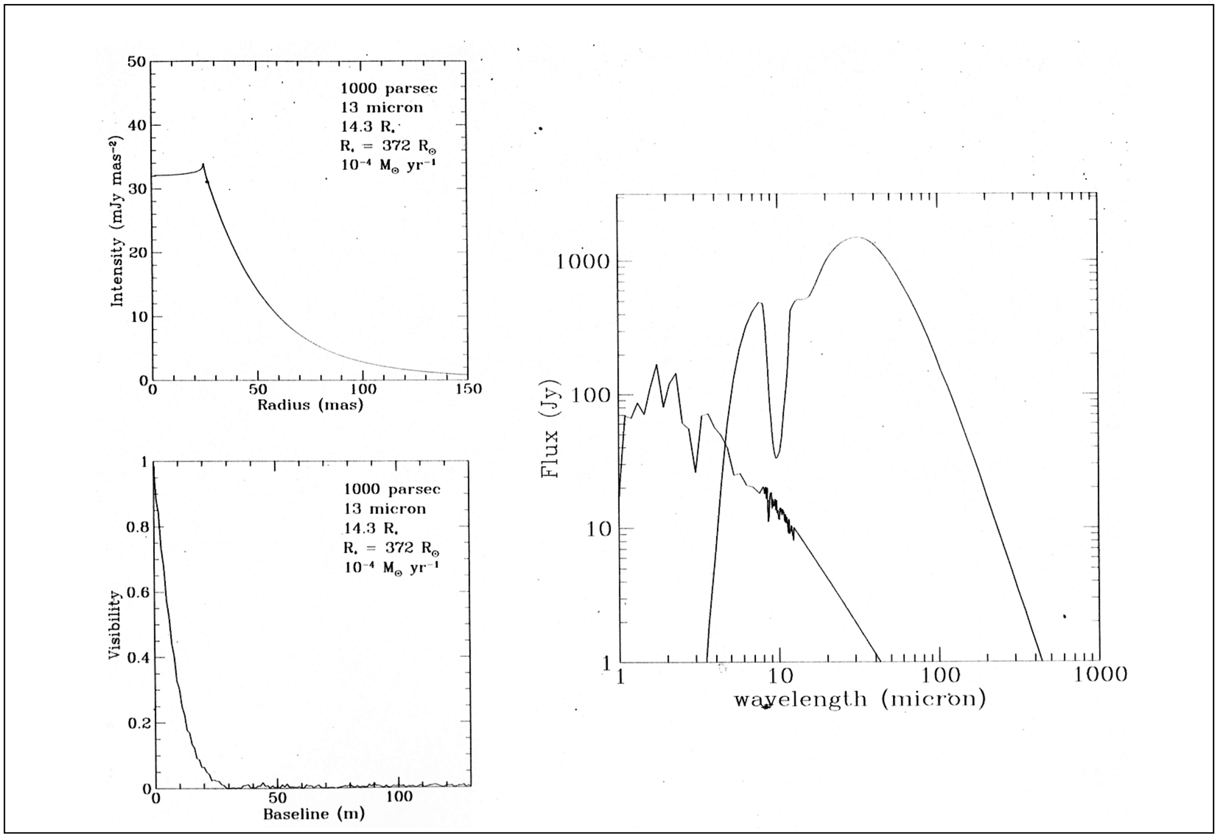


Figure 2 : Diffraction-limited image reconstructions of αHer at 633 nm obtained in 1992 July (top) and 1993 june (bottom). These were recovered from the Fourier measurements using an MEM-based self calibration algorithm. Each image can be represented as the superposition of a uniform disc together with a number of unresolved hot spots. For each image, the right-hand panel shows the location pf the model components, the relative flux of each hotspot being represented by its angular diameter. The contour levels are plotted from 5 to 95 per cent of the peak flux, at intervals of 10 per cent. North is to the top and east the left. The map scales are in milliarcseconds.




RX Boo (SRb)
R Cas (Mira)
OH26.5+0.6 (OH/IR)
Wavelength (μm)
Flux (Jy)


1000 parsec
8 micron
14.3 R*
R* = 372 R☉
10⁻⁴ M☉ yr⁻¹
Intensity (mJy mas⁻²)
Radius (mas)
Visibility
Baseline (m)
Flux (Jy)
wavelength (micron)


1000 parsec
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10⁻⁴ M⊙ yr⁻¹
Intensity (mJy mas⁻²)
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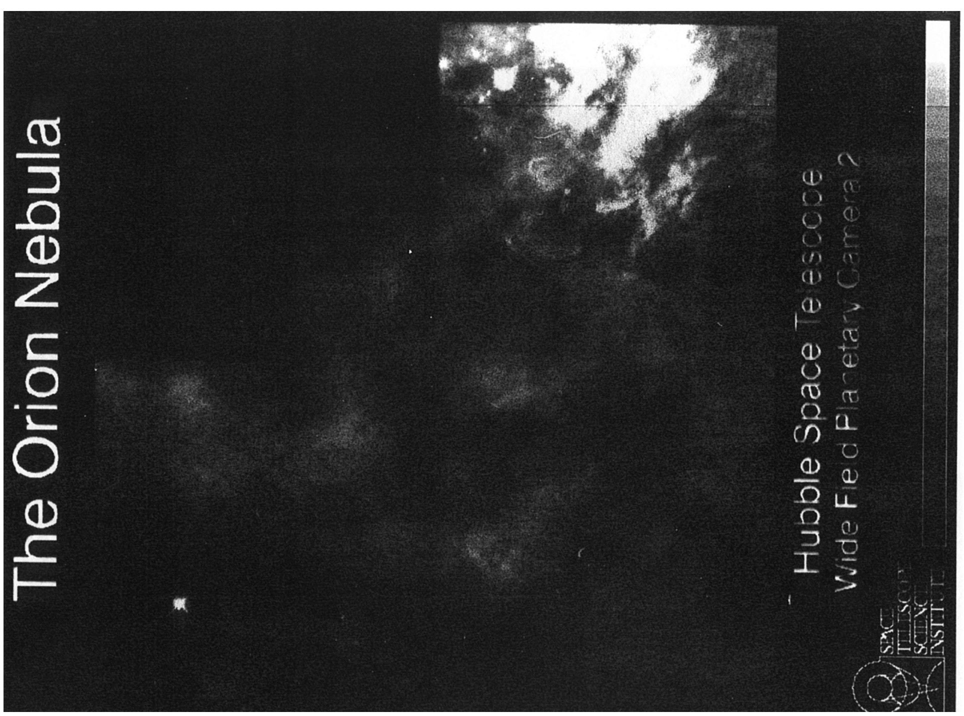
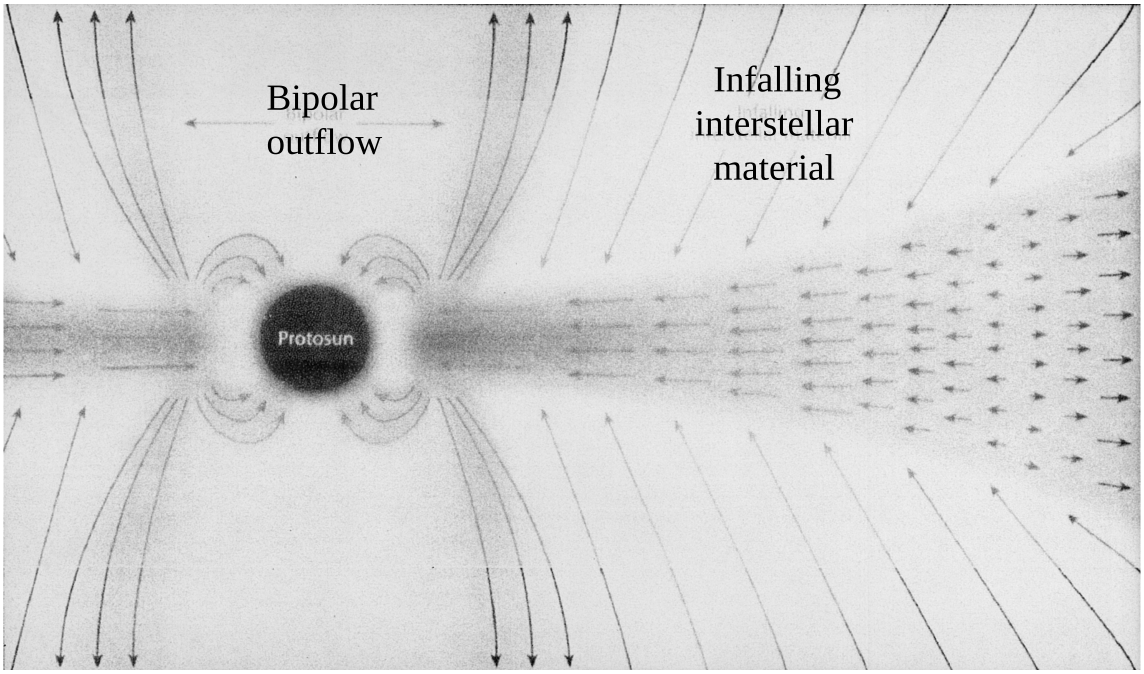
wavelength (micron)


The Orion Nebula
Hubble Space Telescope
Wide Field Planetary Camera 2



- Material in circumstellar disk: T = 40 - 1000 K
- Dust particles in thermal equilibrium
- Very efficient emitters at infrared wavelength
- Large effective surface: outshine star and (proto)-planet

Formation of stars and planetary systems

- Disk size, thickness as a function of wavelength
- Formation of inner hole
- Distribution of gas and dust components

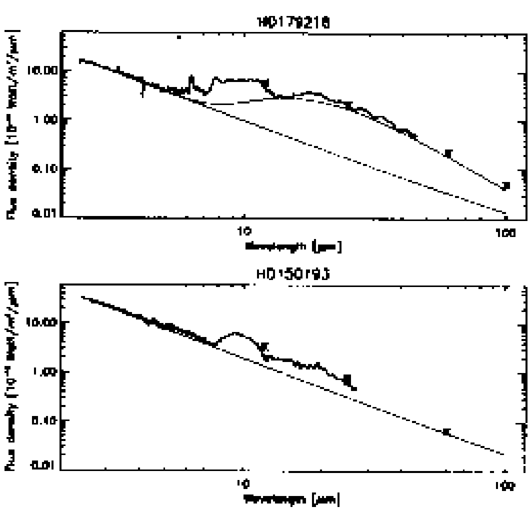
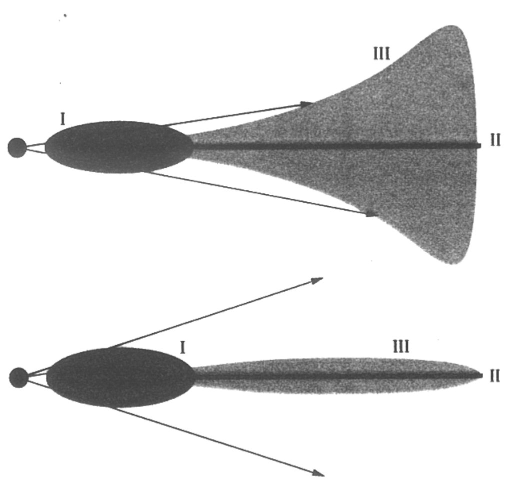


Figure 3: a) Group I and II spectra



b) Geometrical interpretation

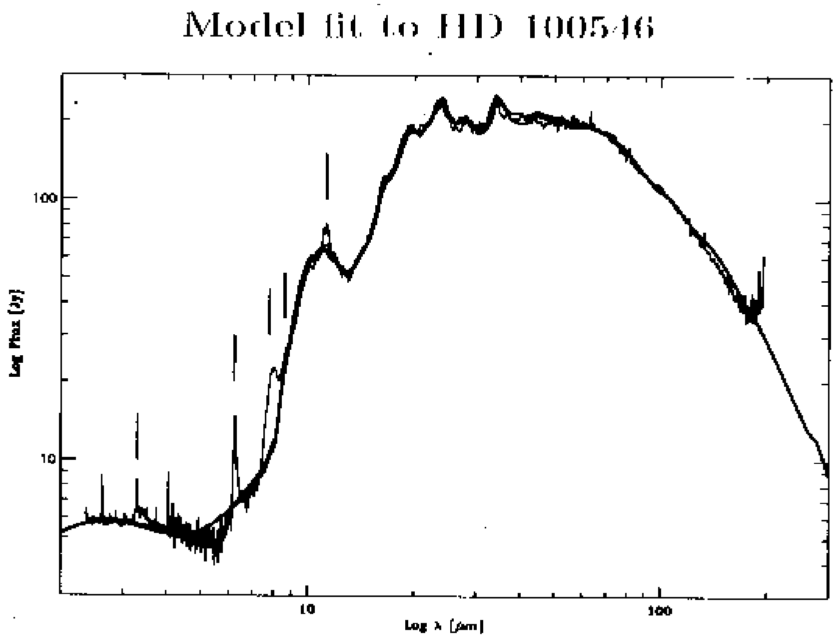
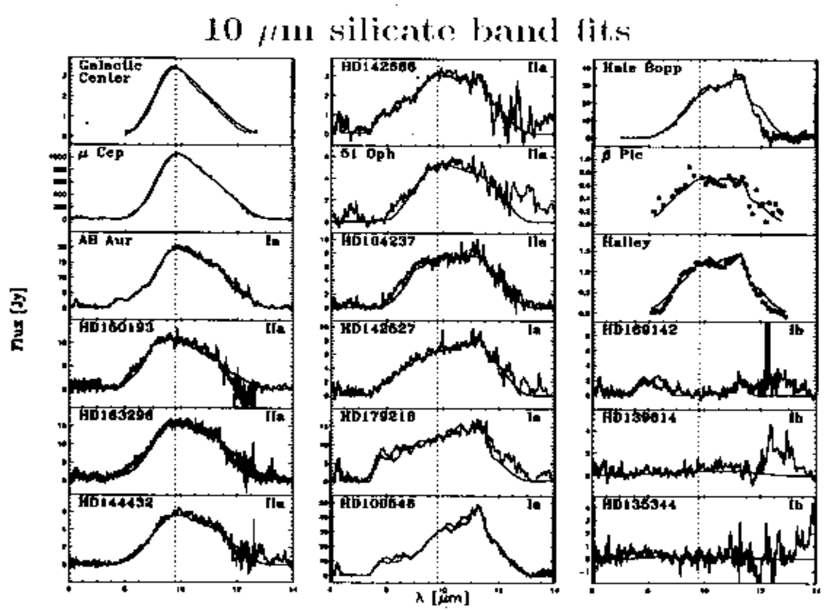
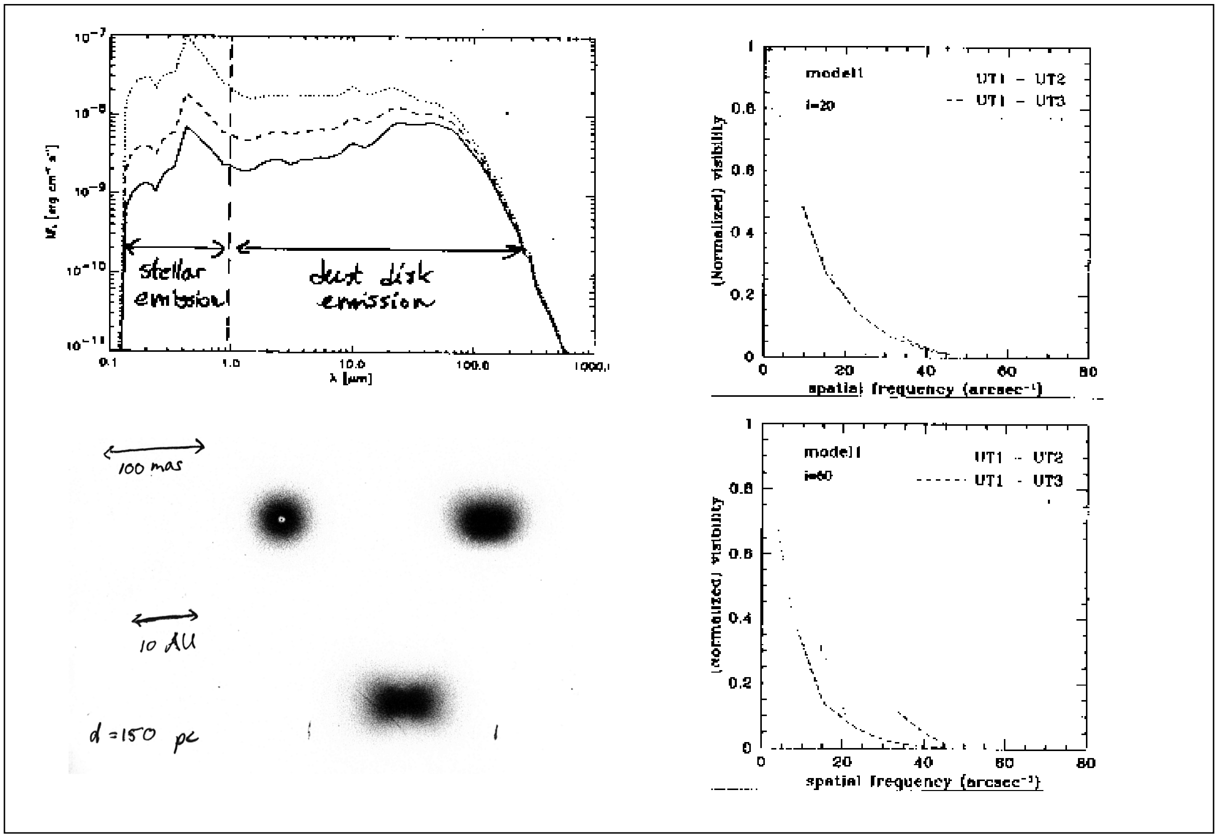


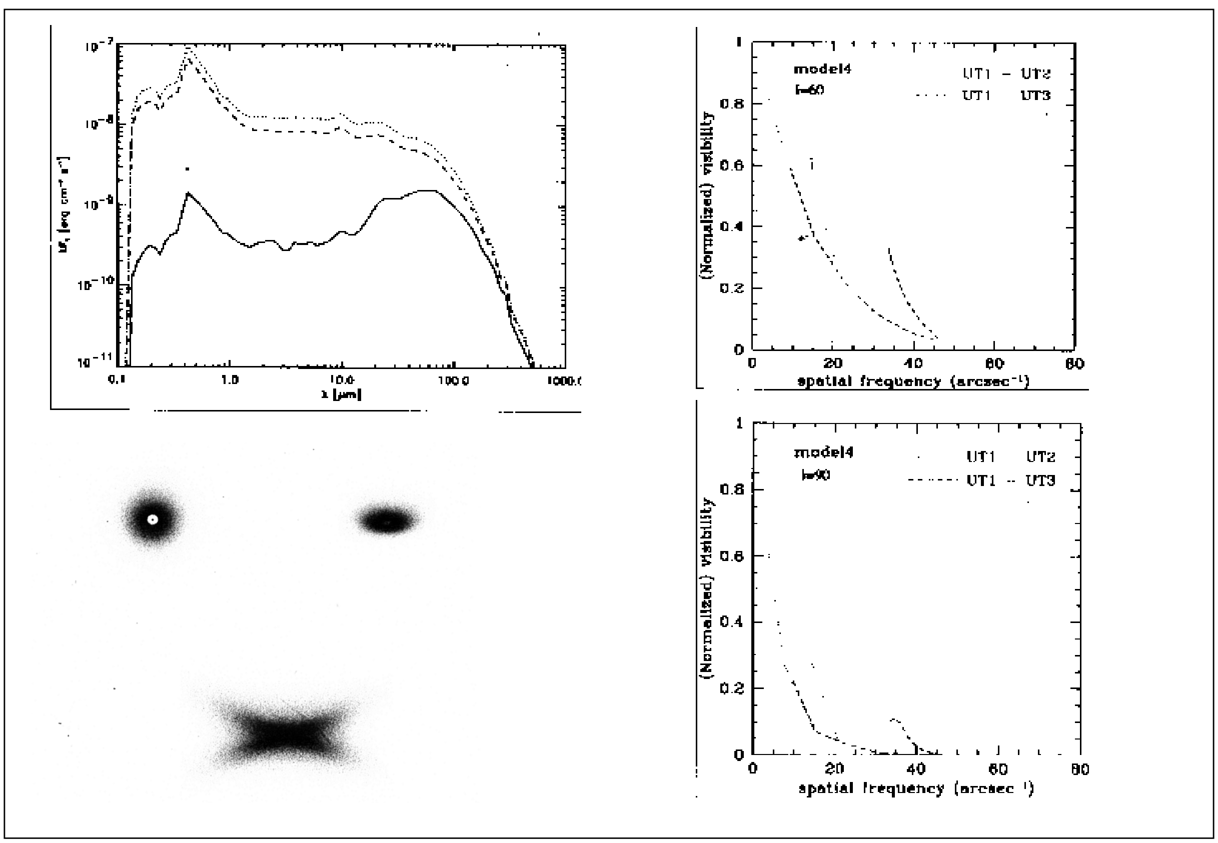
Figure 2: The combined ISO-SWS and LWS spectra of HD 100546. Over plotted are our best model fits. The red curve is a model assuming spherical forsterite grains containing a minor iron component. The blue line is a model which assumes non-spherical crystalline silicates. Marked in the figure are the positions of the features usually contributed to PAHs.

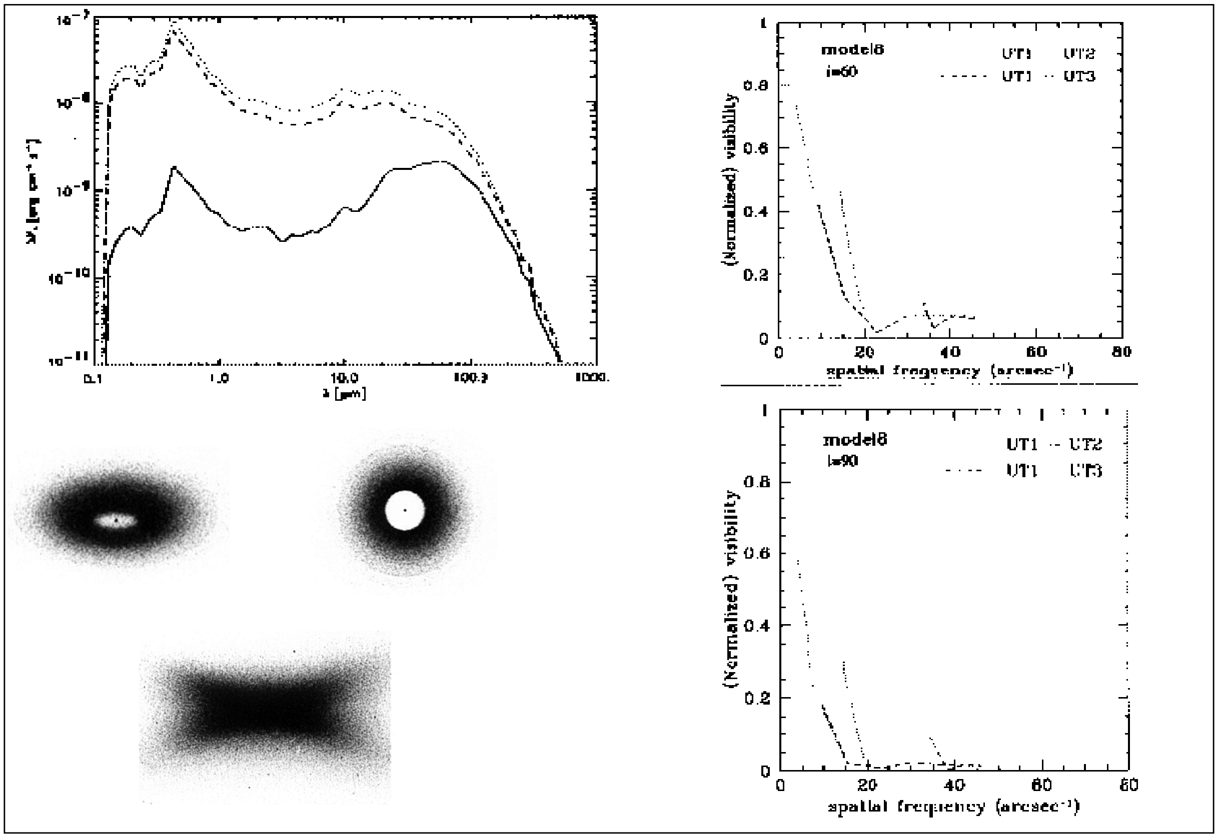


Contributions from :
- 0.1, 2 μm amorph. silicate grains
- crystalline silicate
- SiO_2 (quarz)

Figure 4: Fit to the 10 μm silicate feature as observed in the sample of Herbig Ae/Be stars. Plotted are the continuum subtracted ISO-SWS spectra and ground based spectrum of β-Pic over plotted with our best model fits. Also plotted in this figure for reference are the silicate bands of the ISM towards the galactic centre, μ Cep, a red super giant and of the comets Hale-Bopp and Halley. The dashed line indicates the position of the amorphous silicate band for small grains (~ 0.1μm) at 9.8 μm. Indicated in the panels are the group to which the individual systems can be classified


stellar emission
dust disk emission
λ [μm]
100 mas
10 AU
d = 150 pc
model1
i=20
UT1 - UT2
UT1 - UT3
(Normalized) visibility
spatial frequency (arcsec⁻¹)
model1
i=60


λ [μm]
model4
i=60
UT1 - UT2
UT1 UT3
(Normalized) visibility
spatial frequency (arcsec⁻¹)
model4
i=90
UT1 UT2
UT1 - UT3


model8
i=60
UT1 UT2
UT1 UT3
(Normalized) visibility
spatial frequency (arcsec⁻¹)
model8
i=90
UT1 UT2
UT1 UT3
λ [μm]

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