Protoplanetary gas disks –

Accretion disks I

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Formation of a disk

let us assume that material has specific angul. momentum j and falls in grav. field of central mass M

$$R = \frac{j^2}{GM} \quad \text{with } j = R^2 \omega$$

$$\left(m v^2 / R = G M m / R^2 \Rightarrow v^2 = GM/R \Rightarrow \right.$$

$$\omega^2 R^2 = GM/R$$

$$\left. j = R^2 \omega \Rightarrow j^2/R^2 = GM/R \right)$$

let us assume that material comes from r_0 in a cloud core with uniform rotation $\Omega \Rightarrow$

$j = \Omega r_0^2 \sin \Theta$ (Θ - angle from rot. axis)

$\Rightarrow$ Material close to rot. axis has low angul. momentum $\rightarrow$ falls close to the star

$\Rightarrow$ Mass falling from $\Theta = \pi/2$ will fall to maximum "centrifugal radius".

$$R_c = \frac{\Omega^2 r_0^4}{GM}$$

Shu's similarity solution (free-fall collapse at steady mass accretion rate)

$M = m_0 \, c_s^3 \cdot t / G$ in region with

$r_0 = (m_0/2) \, c_s \cdot t$ (If at $t=0$ a perturbation causes the central region to collapse, the infall region will expand outward)

$$\left(r_0^4 = \frac{m_0^4}{16} c_s^4 \cdot t^4 \right)$$

$$\Rightarrow \quad R_c = \omega^2 \frac{m_0^4}{16} \frac{c_s^4 \cdot t^4}{m_0 c_s^3 \cdot t}$$

$$R_c = \frac{\omega^2 m_0^3 c_s \cdot t^3}{16} =$$

$$R_c = 0.3 \text{ AU} \; (T/10 \text{ K})^{1/2} \cdot (\omega / 10^{-14} s^{-1})^2 \cdot (t/10^5 yr)^3$$

Important $\boxed{R_c \sim t^3}$

Initially most of the mass falls close to the center because material has small angular momentum. As collapse proceeds material from larger radii is added and material is then added to a "disk" rather than to the "star".

Observation of protoplanetary disks

- Solar system (~100 AU) @ distance of 140 pc (nearest star-forming regions - Taurus) angular size of 0.″7. Emission from hot inner regions on even smaller scales.

Best resolution

a) ALMA Long Baselines (2015): 0.″025 at 870 μm

b) VLT SPHERE (2015): 0.″027 at 1 μm
(IWA) → 0.″093)

What do we see:

a) long λ → Thermal emission from dust (larger sizes)

b) short λ → Scattered light from dust particles (smaller sizes, well coupled)

Historically (1990)

- Strom & Strom (1989) → Detection of IR excess
- Beckwith et al. (1990) → Detection of mm emission

$$S_\nu = \tau_\nu B_\nu(T)$$

(Emission at long wavelength is optically thin)

$$\tau(\nu) \sim \kappa(\nu) \sim \lambda^{-\beta} \qquad \beta \approx 2$$

Emission in sphere would be optically thick in the visible, but star is visible ⇒ Disk geometry

Additional evidence for disks

(1) Bipolar molecular flows and high-velocity optical jets

(2) Images in polarized light

(3) Direct images in the NIR & submm/mm

Typical masses of disks/radii/ages

- $\sim 10^{-2} M_\odot$ (Dust opacity & M_{gas}/M_{dust})
- 100 AU with spread
- few Myrs from disk frequency
- Composition: Mostly H_2 Dust: Silicates

Analysis of spectral energy distributions (flat disk)

$$\nu S_\nu = \frac{\cos\Theta}{D^2} \int_{r_1}^{r_2} \nu B_\nu(T(r)) \, (1 - \exp(-\tau(\nu)/\cos\Theta)) \, 2\pi r \, dr$$

($\Theta = 0°$ – Seen on the disk "pole-on")

- In the IR optically thick $\nu F_\nu \leftrightarrow T(r)$

  Let us assume $T(r) \sim r^{-q}$ and $F_\nu \sim \nu^{\alpha}$

  $$\alpha = 4 - 2/q$$

- In the mm disk is optically thin

  $$F_\nu \sim \nu^{\alpha}$$

  $$\kappa(\nu) \sim \nu^{\beta}$$

  R.J. approximation $\beta = \alpha - 2$

  (one can derive rough estimate of grain size)

Flat disk

a) accretion disk: $T(r) \sim r^{-3/4}$

b) Passively irradiate disk: $T(r) \sim r^{-3/4}$

(Cannot be distinguished by SED)

Data indicated that outer regions are hotter than anticipated from flat disk → Disk flaring

Scale height of a disk:

$E_{vert, grav} \approx E_{therm.}$

$h/r \; G M_* / r \approx k T(r)$ Let us assume $T(r) \sim r^{-3/4}$

$h \sim k / G M_* \; r^{5/4}$

Radiative transfer models of disks in hydrostatic equilibrium:

Stellar radiation (NIR) + Disk surface (MIR) + Interior (mm λ)

Addition:

a) Grain sedimentation

b) Gap formation → Disk flaring

Gas Disks

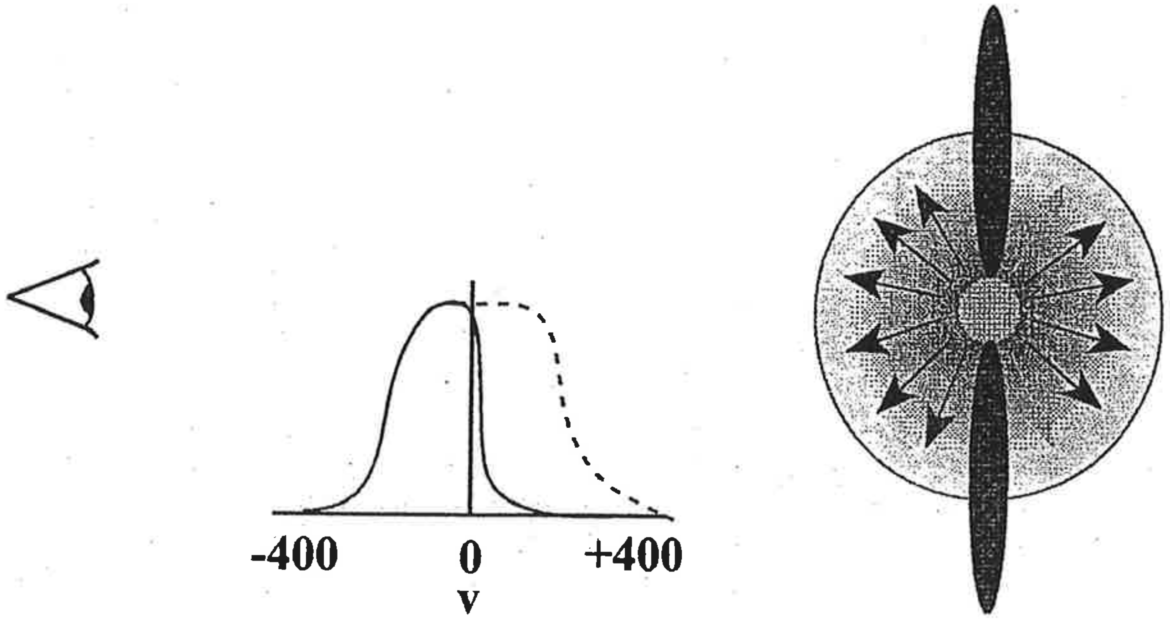
a) Optical "double" profiles (Hartman & Kenyon)

b) Profiles of forbidden lines, e.g. [OI]

Red part is blocked (Appenzeller & Edwards)

c) Mm interferometry → Keplerian velocity profiles

Circumstellar Emission Lines



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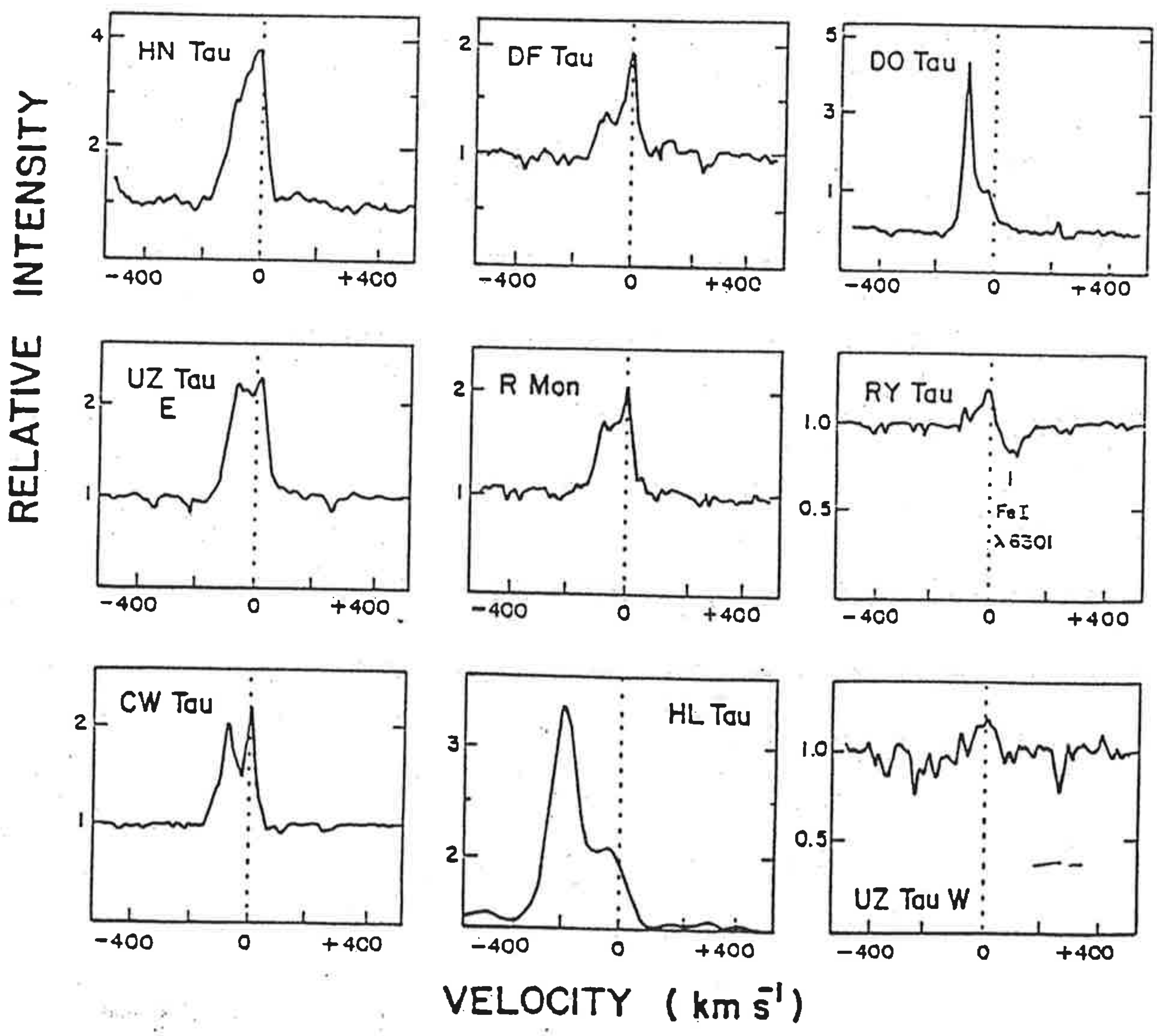
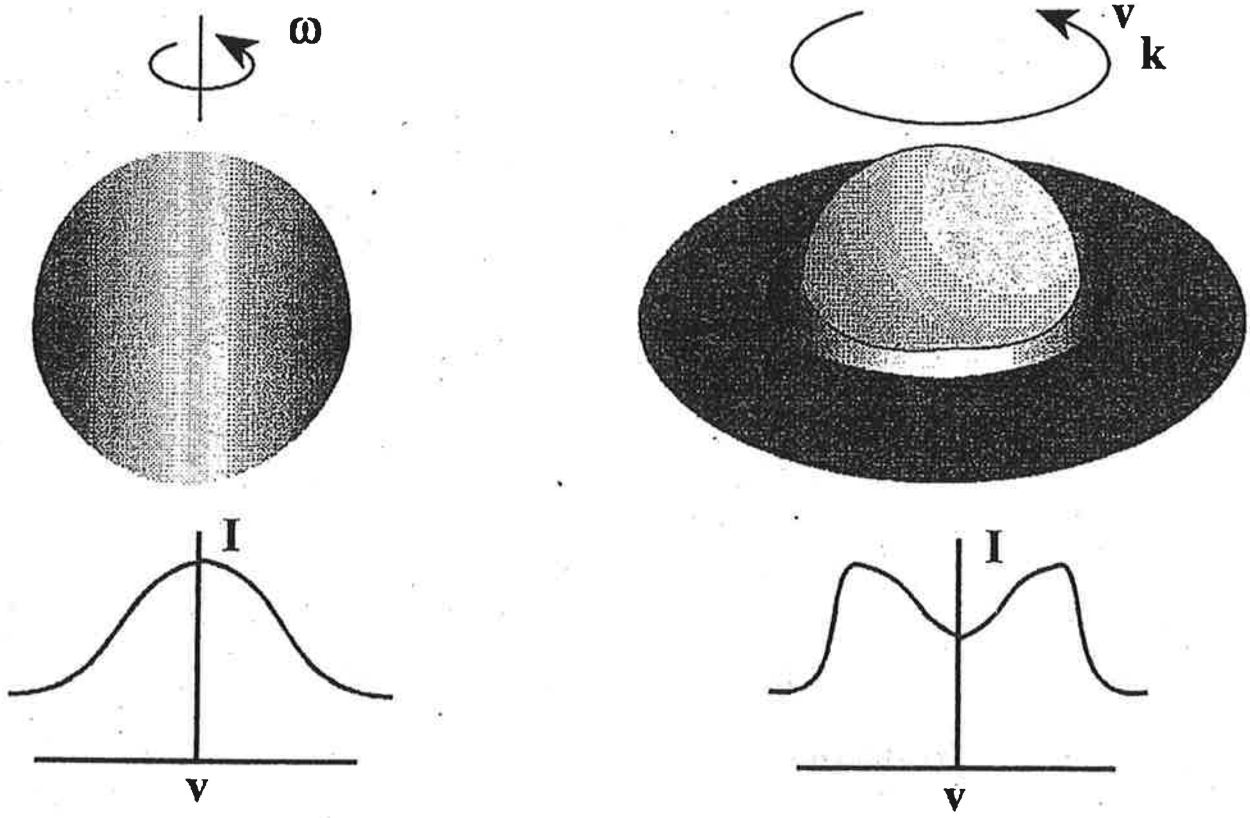


Inner Disk Optical Lines

Rotating star   Orbiting disk



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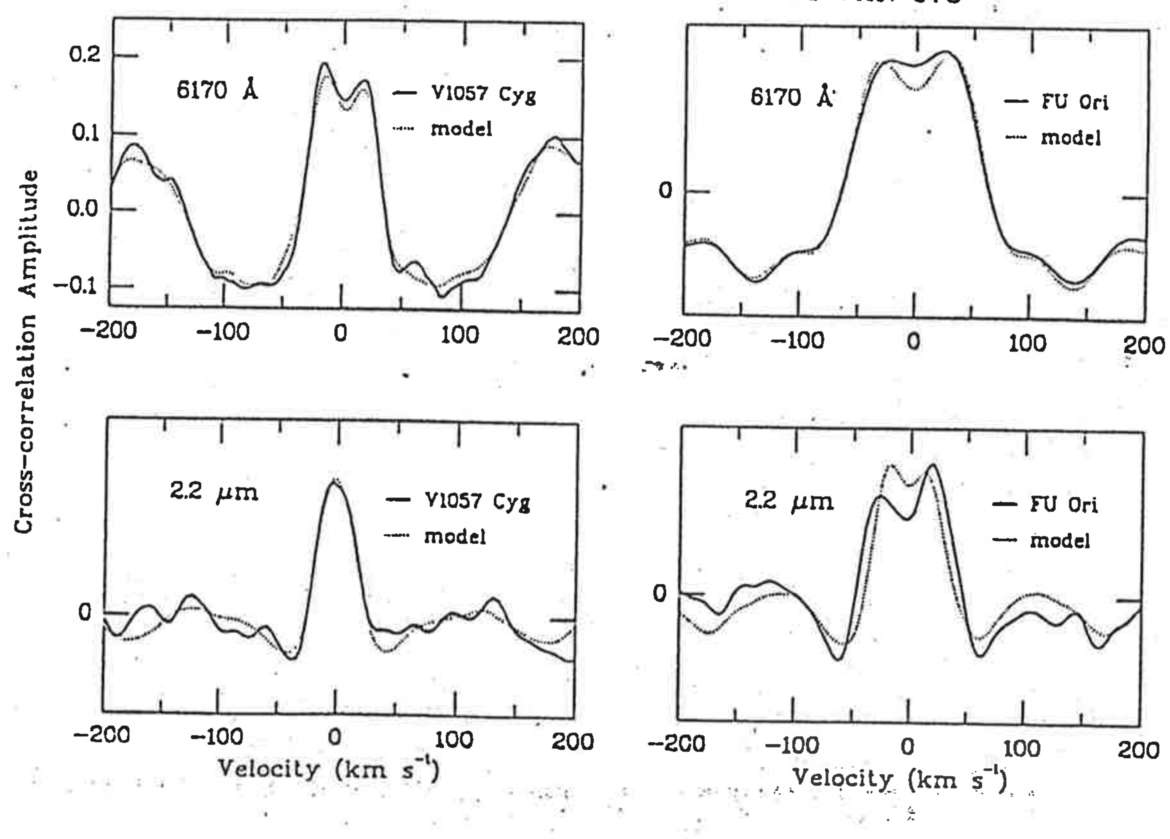

30° from face-on

DM Tau

Guilloteau, S., Dutrey, A.: 1994, AA 291, L23.

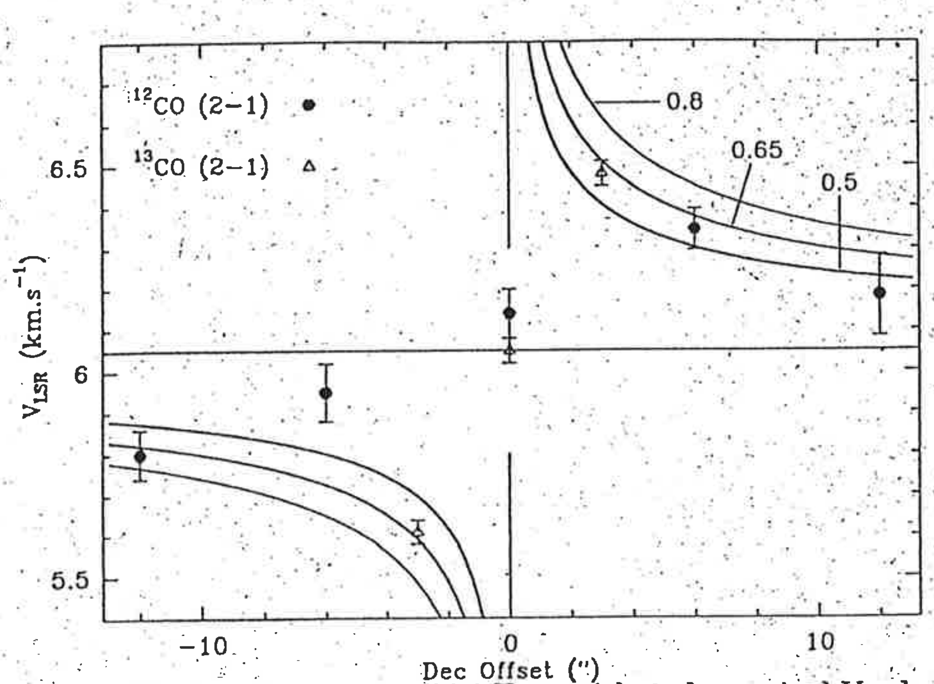

Fig. 3. Velocity diagram for DM Tau, with 3 theoretical Keplerian rotation curves superimposed. The open triangles indicate velocities derived from the ^{13}CO $J = 2 \rightarrow 1$ spectrum toward DM Tau, and were assigned to offsets $\pm 3''$ since for Keplerian rotation the two peaks represent emission from the outer edge of the disk.