

Protoplanetary gas disks -

Accretion disks I

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Formation of a disk

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

$$R = \frac{j^2}{GM}$$

$$(mv^2/R = GM/R^2 \Rightarrow v^2 = GM/R \Rightarrow$$

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

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

Let us assume that material comes from r_0 in a cloud core with uniform rotation $\Omega_0 \Rightarrow$

$$j = \Omega_0 r_0^2 \sin \theta \quad (\theta - \text{angle from rot. axis})$$

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

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

$$R_c = \frac{\Omega_0^2 r_0^4}{GM}$$

Shu's similarity solution:

$$M = m_0 c s^3 \cdot t / G \quad \text{in region with}$$

$$r_0 = (m_0 / 2) c s \cdot t$$

$$(r_0^4 = \frac{m_0^4}{16} c^4 \cdot t^4)$$

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

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

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

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 ($\sim 100 \text{ AU}$) @ 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

- ALMA Long Baselines (2015): $0.025''$ at $870 \mu\text{m}$
- VLT SPHERE (2015): $0.027''$ at $1 \mu\text{m}$
(IWA) $\rightarrow 0.093''$

What do we see:

- long $\lambda \rightarrow$ Thermal emission from dust
- short $\lambda \rightarrow$ Scattered light from dust particles

Historically (1990)

- Shoum & Shoum (1989) \rightarrow Detection of IR excess
- Beckwith et al. (1990) \rightarrow Detection of mm emission

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

(Emission at long wavelength is optically thin)

$$I(\nu) \sim \mathcal{Z}(\nu) \sim \lambda^{-\beta} \quad \beta \approx 2$$

Emission in sphere would be optically thick in the visible, but star is visible \Rightarrow

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 & $M_{\text{gas}} / M_{\text{dust}}$)
- 100 AU with spread
- few Myrs from disk frequency

Analysis of spectral energy distributions (flat disk)

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

($\theta = 0^\circ$ - 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

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

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

Raj. 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 disks: $T(r) \sim r^{-3/4}$

(cannot be distinguished by SED)

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

Scale height of a disk:

Event, grav \approx E thermal

$$h/r \approx G M_* / r \approx h^2 T(r)$$

Let us assume $T(r) \sim r^{-3/4}$

$$h \sim h^2 / G M_* \sim r^{5/4}$$

Radiative transfer models of disks in hydrostatic equilibrium:

$$\text{Stellar radiation } (dR) + \text{Disk surface } (2R) + \text{Infrared } (2\pi \lambda)$$

Addition:

a) grain sedimentation

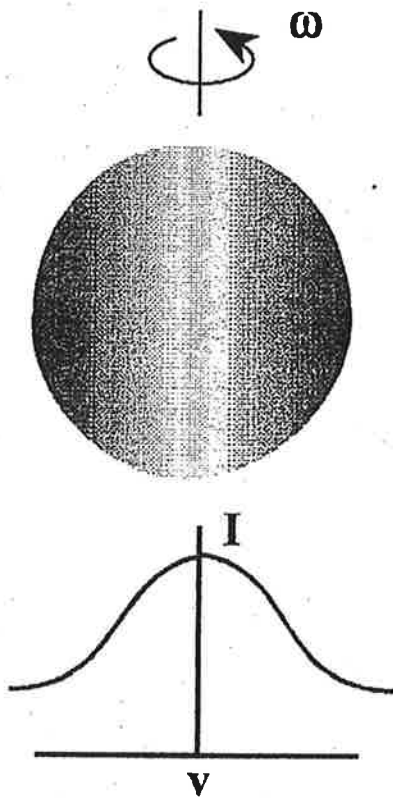
b) gap formation \rightarrow disk flaring

gas disks

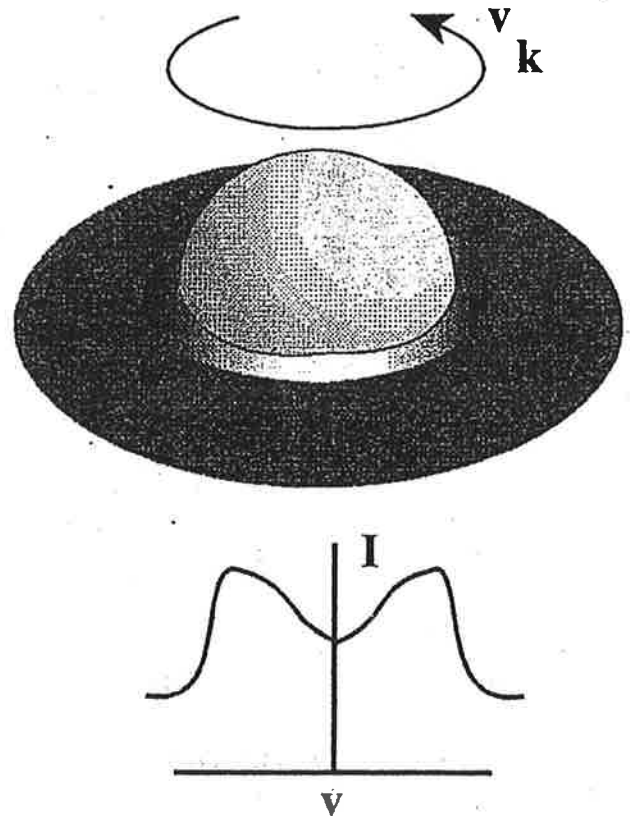
- a) Optical "double" profiles (Hartman & Kenyon)
- b) Profiles of forbidden lines, e.g. [O I]
Red part is blocked (Appenzeller & Edmonds)
- c) Millimeter astronomy \rightarrow Keplerian velocity profiles

Inner Disk Optical Lines

Rotating star



Orbiting disk



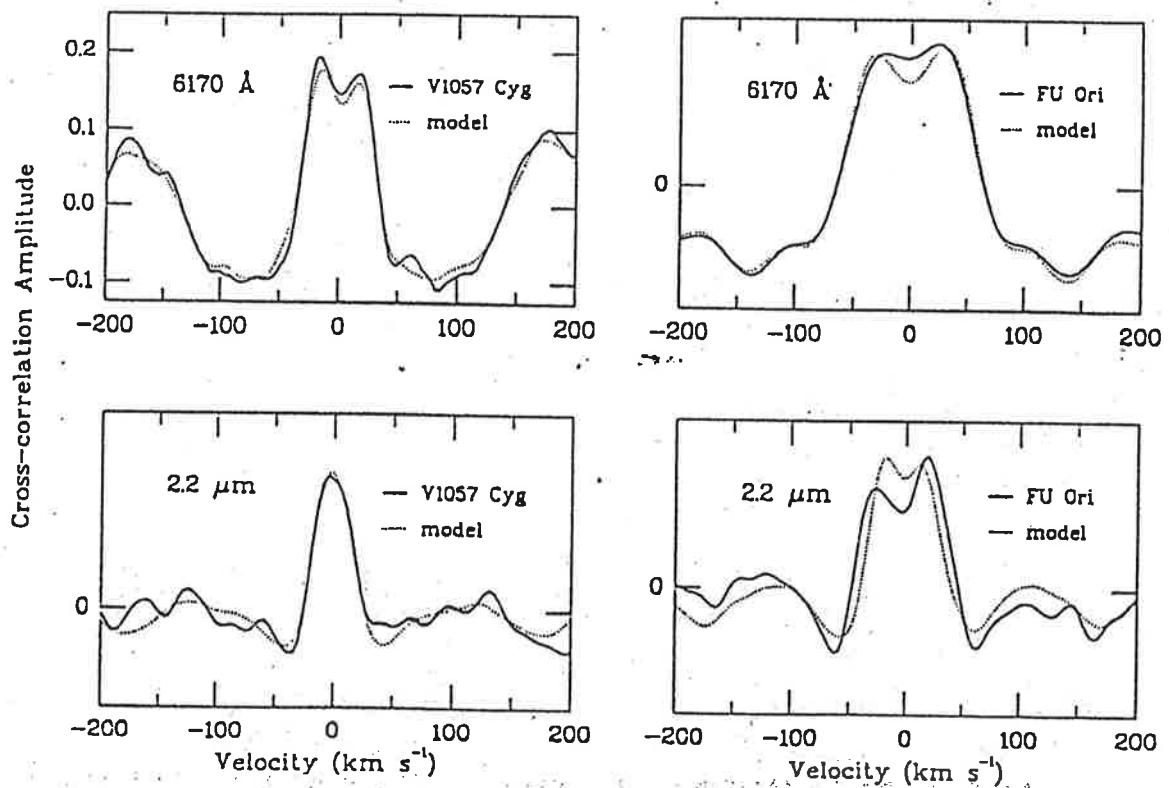
KENYON, HARTMANN, AND HEWETT

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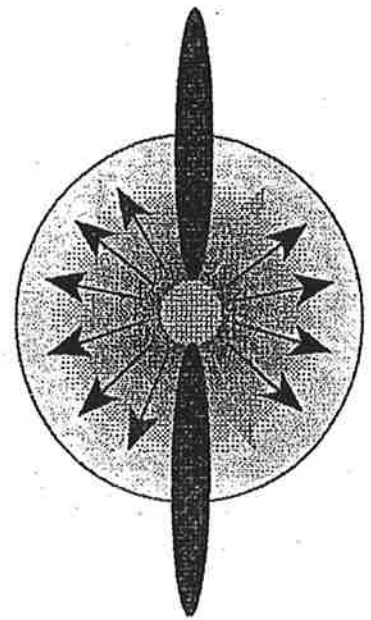
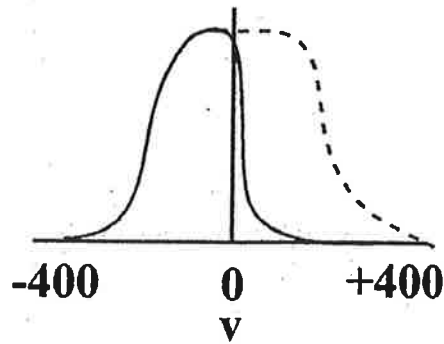
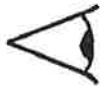
No. 1, 1988

ACCRETION DISK MODELS FOR FU ORI AND V1057 CYG

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Circumstellar Emission Lines

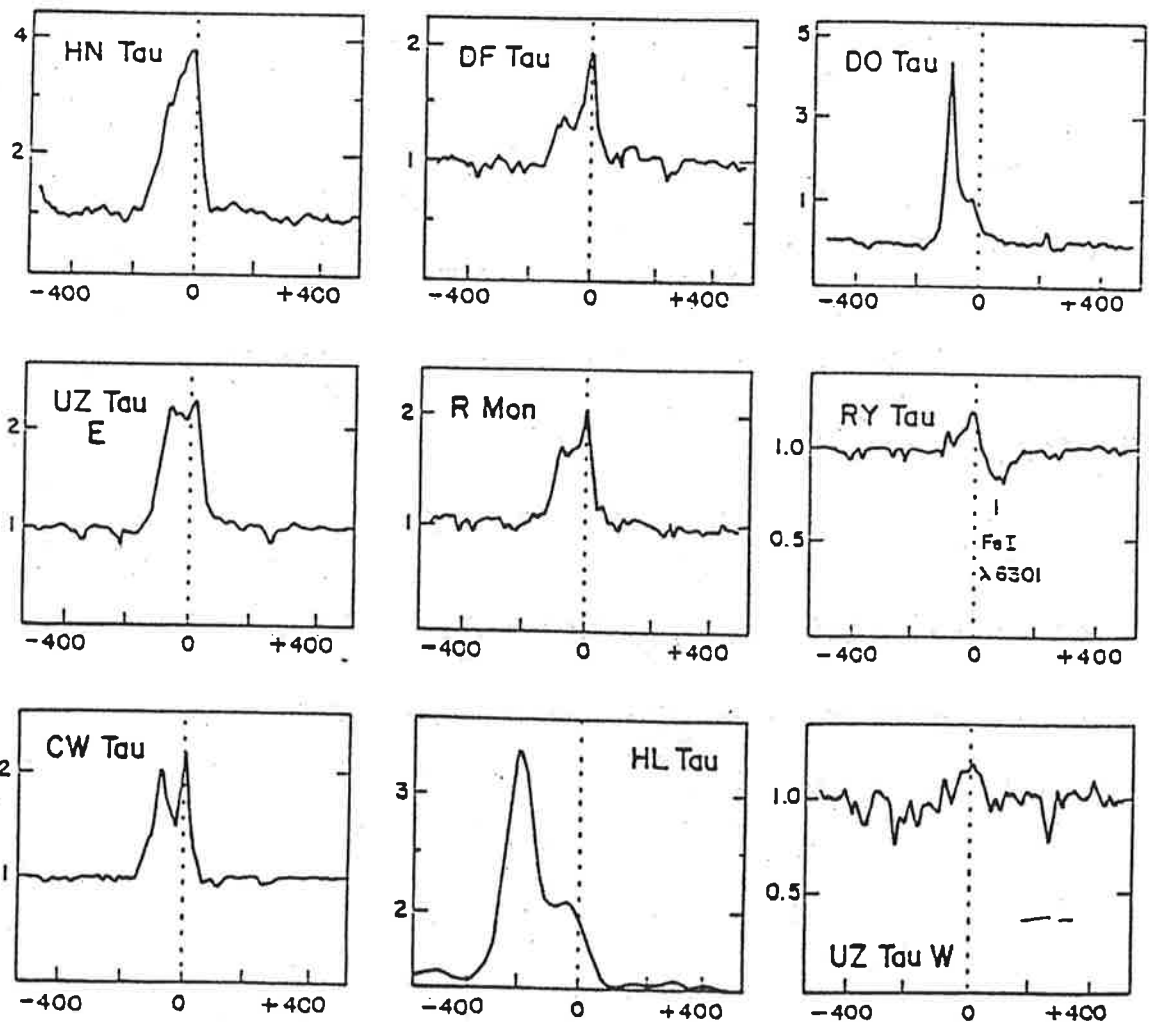


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RELATIVE INTENSITY



VELOCITY (km s⁻¹)

30° from face-on

DM Tau

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

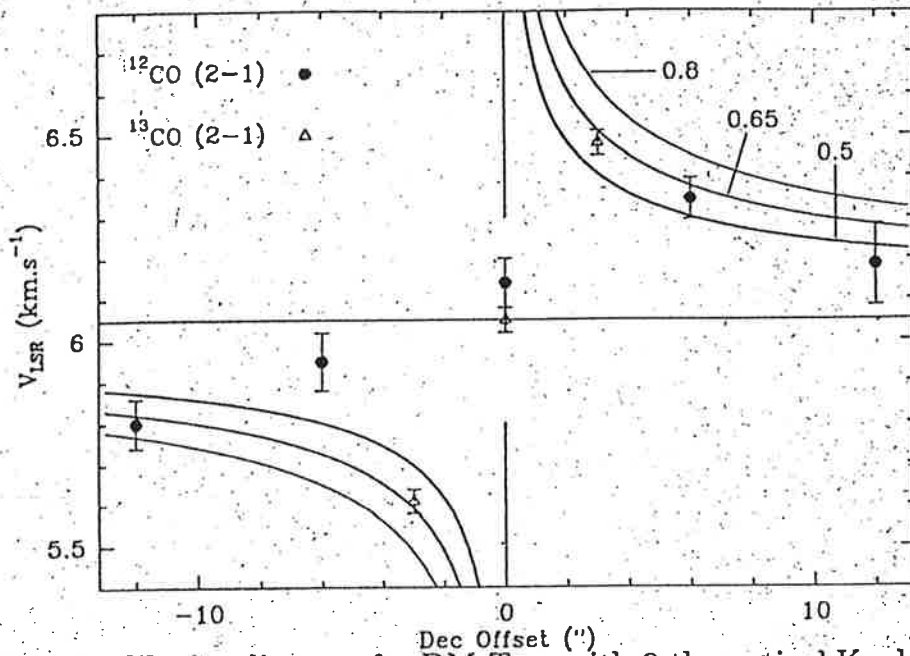


Fig. 3. Velocity diagram for DM Tau, with 3 theoretical Keplerian rotation curves superimposed. The open triangles indicate velocities derived from the ¹³CO $J = 2 \rightarrow 1$ spectrum toward DM Tau, and were assigned to offsets $\pm 3''$ since for Keplerian rotation the two peaks represent emission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