Signatures of accretion and MRI in protostellar disks

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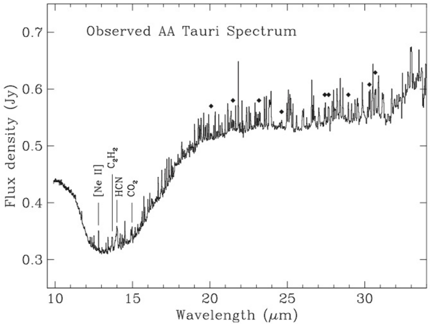
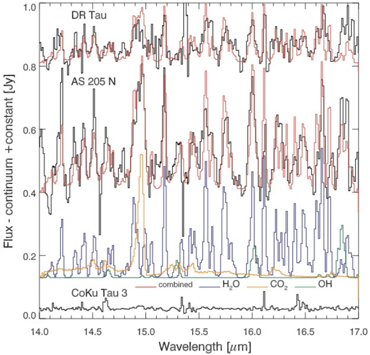
Bohr Institute
4 August 2014

Protoplanetary disks in hot water



Carr & Najita (2008)



Salyk et al. (2008)

Collaborators & Thanks

Brandon Hensley

Johannes Rothe

This work made heavy use of the ProDiMo code, written by

- P. Woitke
- I. Kamp
- W. Thi

... and was supported by NASA-OSS grant NNX10AH37G

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$$L_{\rm wind} \approx \underbrace{\tfrac{1}{2}\dot{M}_{\rm acc}\Phi_*}_{L_{MRI}} - \underbrace{\tfrac{1}{2}\dot{M}_{\rm wind}\,V_\infty^2}_{\rm mechanical}$$

Energetics of viscous-disk accretion

$$L_{\mathrm{acc}} = \frac{GM_* \dot{M}}{R_*} \approx \; 0.3\,\mathrm{L}_\odot \times \frac{M_* /\, \mathrm{M}_\odot}{R_* /\, \mathrm{R}_\odot} \, \frac{\dot{M}}{10^{-8}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}$$

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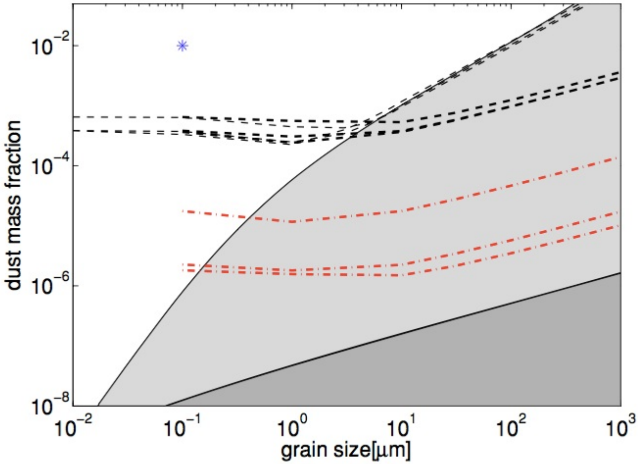
Bai & Goodman (2009)



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$$a_d \equiv \text{dust grain radius} \lesssim 1\,\mu\rm m$$

$$n_d \equiv \text{grains/volume} = f_{\rm dust-to-gas}\frac{\rho_{\rm gas}}{m_{\rm grain}}$$

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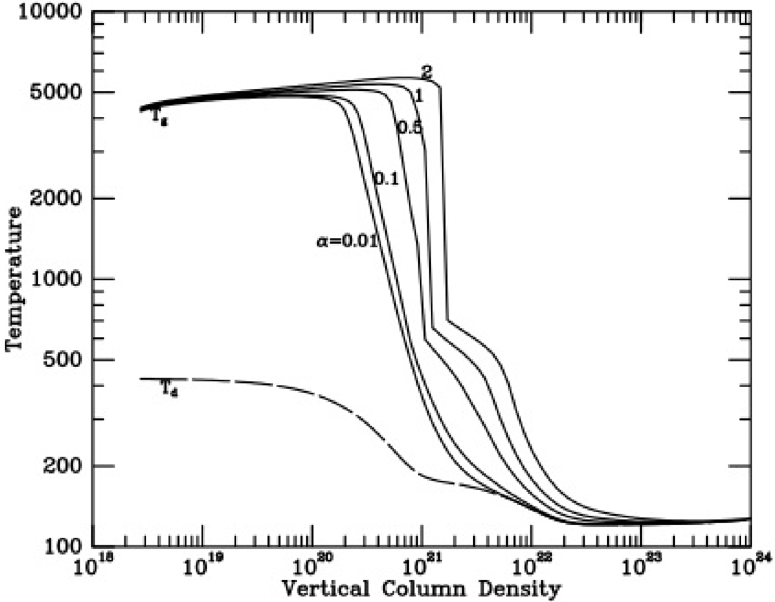
$$\rho_{\rm crit}(t_{\rm cool} = t_{\rm heat}) \sim \alpha f^{-1}\frac{a_d}{H}\rho_{\rm solid} \sim 2\times 10^{-14}\,\rm g\,cm^{-3}$$

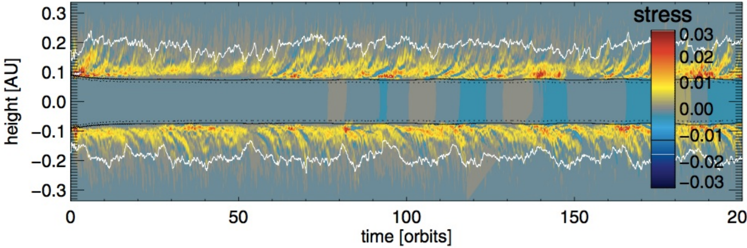
$$n_{\rm H,crit} \sim 10^{10}\,\rm cm^{-3} \;\Rightarrow\; N_{\rm H,crit} \sim n_{\rm H,crit} H \sim 10^{22}\,\rm cm^{-2}$$

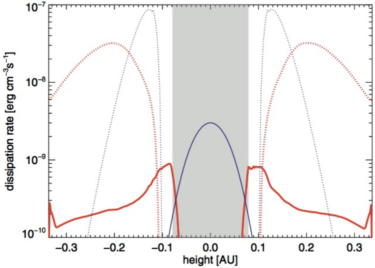
...for $\alpha = 0.1$, $f = 10^{-3}$, $a_d = 1\,\mu\rm m$, $H = 0.1\,\rm AU$, $\rho_{\rm s} = 3\,\rm g\,cm^{-3}$

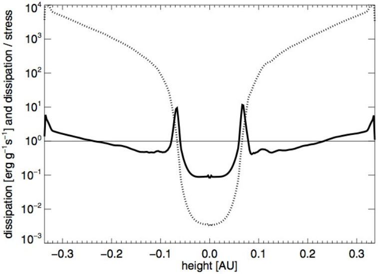
Glassgold, Najita, & Igea (2004)



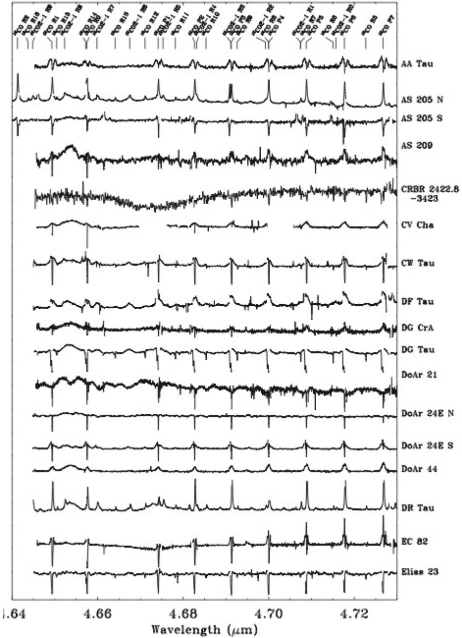
Hirose & Turner (2011)

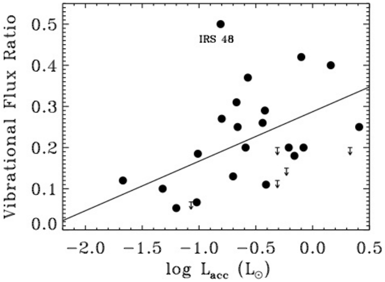






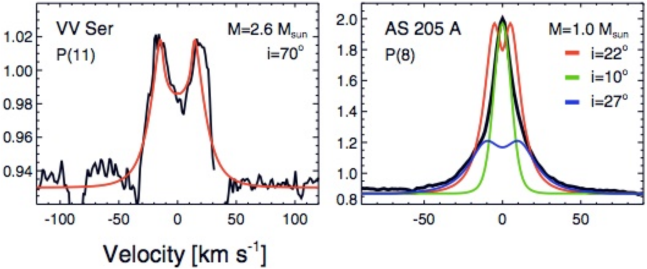
CO rovibrational spectra of disks at $4 - 5\,\mu m$





Brown et al. (2013)

CO line shapes @ resolution $\Delta v \approx 3\,\mathrm{km\,s^{-1}}$



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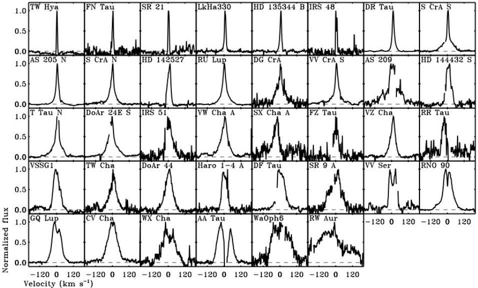

CO & its rovibrational spectrum

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\begin{aligned}
E(v, J) &\approx E_{\mathrm{vib}}(v) + E_{\mathrm{rot}}(J), \\
E_{\mathrm{vib}}(v) &= 3122\left(v + \tfrac{1}{2}\right) k_{\mathrm{B}}\,\mathrm{K}, && v \in \{0, 1, 2, \ldots\} \\
E_{\mathrm{rot}}(v) k_{\mathrm{B}}^{-1} &= 2.779 J(J+1) k_{\mathrm{B}}\,\mathrm{K}, && J \in \{0, 1, 2, \ldots\}
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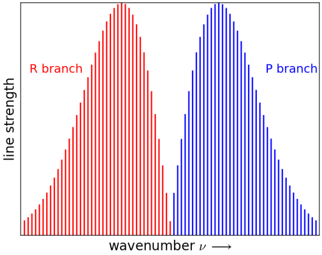
$$
E(v,J) \to E(v-1,\ J\pm 1)
$$

$$
\frac{hc}{3122k_{\mathrm{B}}\,\mathrm{K}} \approx 4.61\,\mu\mathrm{m}
$$



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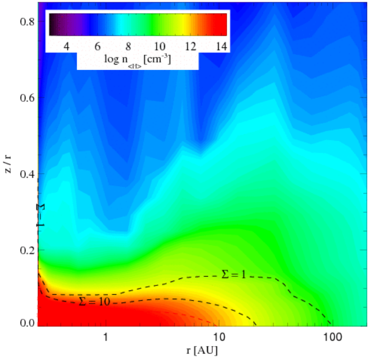
- Physics:
  - Non-LTE atomic & molecular level populations
  - Non-LTE heating, cooling, & ionization
  - Frequency-dependent continuuum radiation transfer (axisymmetric)
  - Lines via escape-probability approximation
  - UV photochemistry
  - X-rays
  - Vertical hydrostatic equilibrium
  - **Iterates toward equilibrium**

Density and temperature structure: $\dot{M} = dex(-10)$



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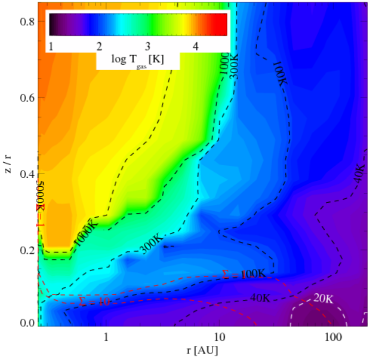

Temperature

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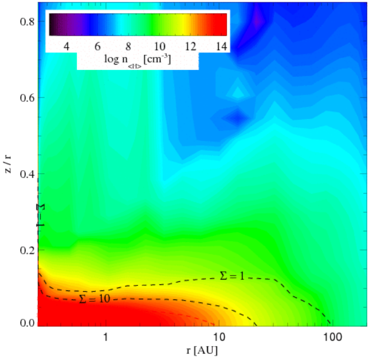
$$Q_+ = \dot{M} r^{-3} z_{\rm act}^{-1} F(z/z_{\rm act})$$

$$z_{\rm act} = 1.97 r \qquad 0.25 \leq r_{\rm AU} \leq 2$$

Density and temperature structure: $\dot{M} = dex(-8)$



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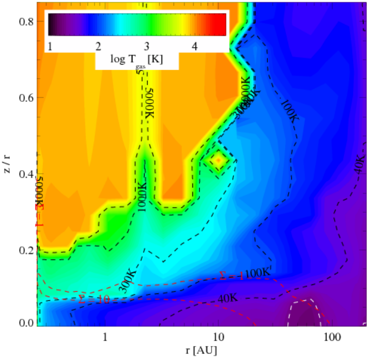

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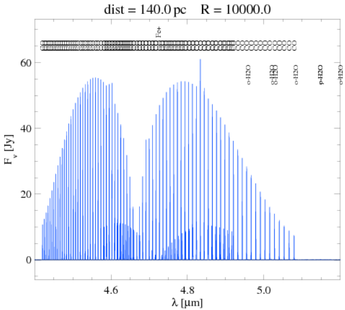
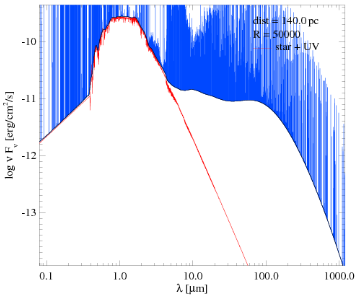
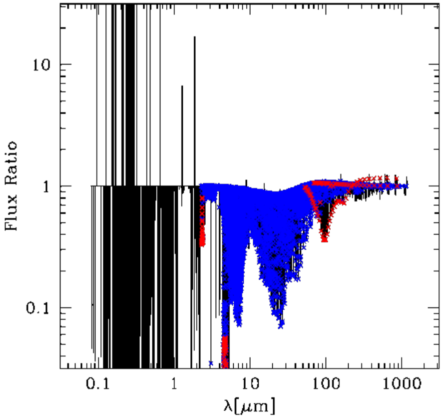
Model spectra





Spectral ratios



$$\frac{\text{dex}(-10)\ \dot{\rm M}_\odot\ {\rm yr}^{-1}}{\text{dex}(-8)\ \dot{\rm M}_\odot\ {\rm yr}^{-1}}$$

Line sums

log $\dot{M}$	4-5 μm (CO)	0.35-1.0 μm (All)	0.13-0.3 μm (All)
-10	0.92×10^{-3}	1.14×10^{-4}	3.38×10^{-5}
-9	1.08×10^{-3}	3.84×10^{-4}	1.41×10^{-4}
-8	1.76×10^{-3}	2.97×10^{-3}	1.70×10^{-3}

Table : Line luminosities $[\mathrm{L}_\odot]$ vs. accretion rate $[\dot{\mathrm{M}}_\odot\,\mathrm{yr}^{-1}]$ in several wavelength regions

$M_* = 0.7\,\mathrm{M}_\odot$, $L_* = 1\,\mathrm{L}_\odot$, $f_{UV} = 0.01$, $L_X = 10^{30}\,\mathrm{erg\,s^{-1}}$, $f_{\mathrm{dust-to-gas}} = 10^{-4}$

Summary

- Accretion via MRI or magnetocentrifugal winds would have different implications for heating the upper layers of the disk
- The MRI heating is small bolometrically compared to reprocessed star light, but potentially observable if effective at high altitudes where $T_{\rm gas} \gg T_{\rm dust}$ $(n_{\rm H} \lesssim 10^{10}\,{\rm cm}^{-3}$
- There is a wealth of data for resolved $(\Delta v \approx 3\,{\rm km\,s^{-1}})$ mid-IR CO and H_2O lines that have not been systematically compared to dynamical (MRI/wind) models
  - Line shapes are puzzling in most cases