Spectroscopy of the Gaseous Inner Disk

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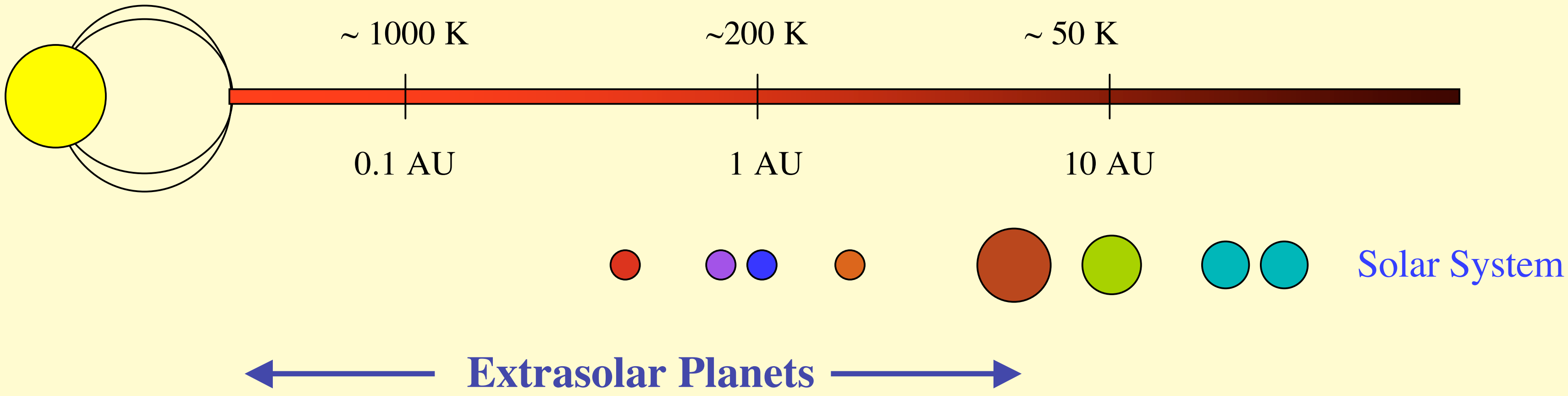
Protoplanetary Disks and Planetary Systems

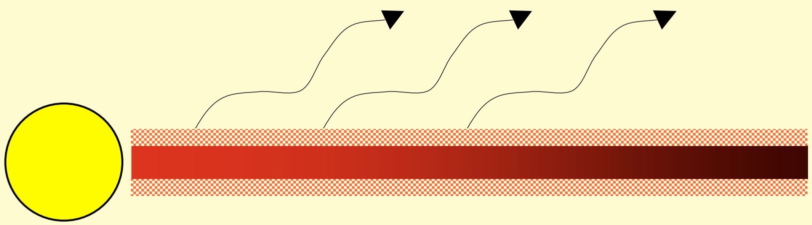


Inner disk temperatures ⇒

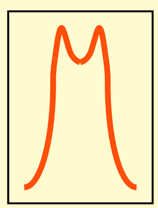
- **gas is mostly molecular**
- **no desorption onto grains**
- **rotational and ro-vibrational levels excited**
- **transitions in near- and mid-infrared**

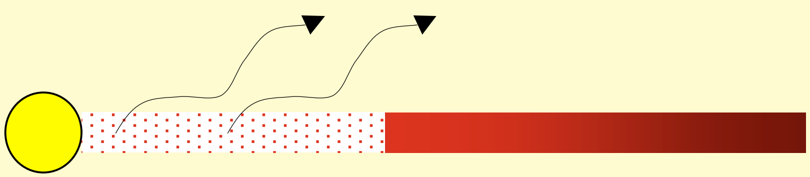
Disk Spectral Lines

Emission Lines



Temperature Inversion in
Optically Thick Disk

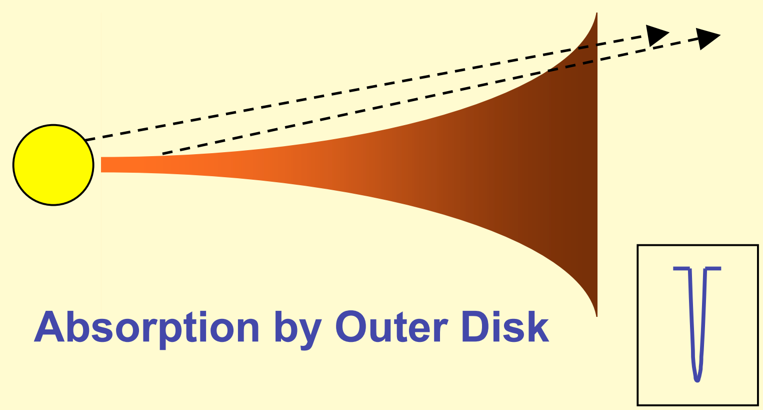




Optically Thin Disk, Hole or Gap

Absorption Lines

Optically Thick, High M_{acc}
e.g., FU Ori object



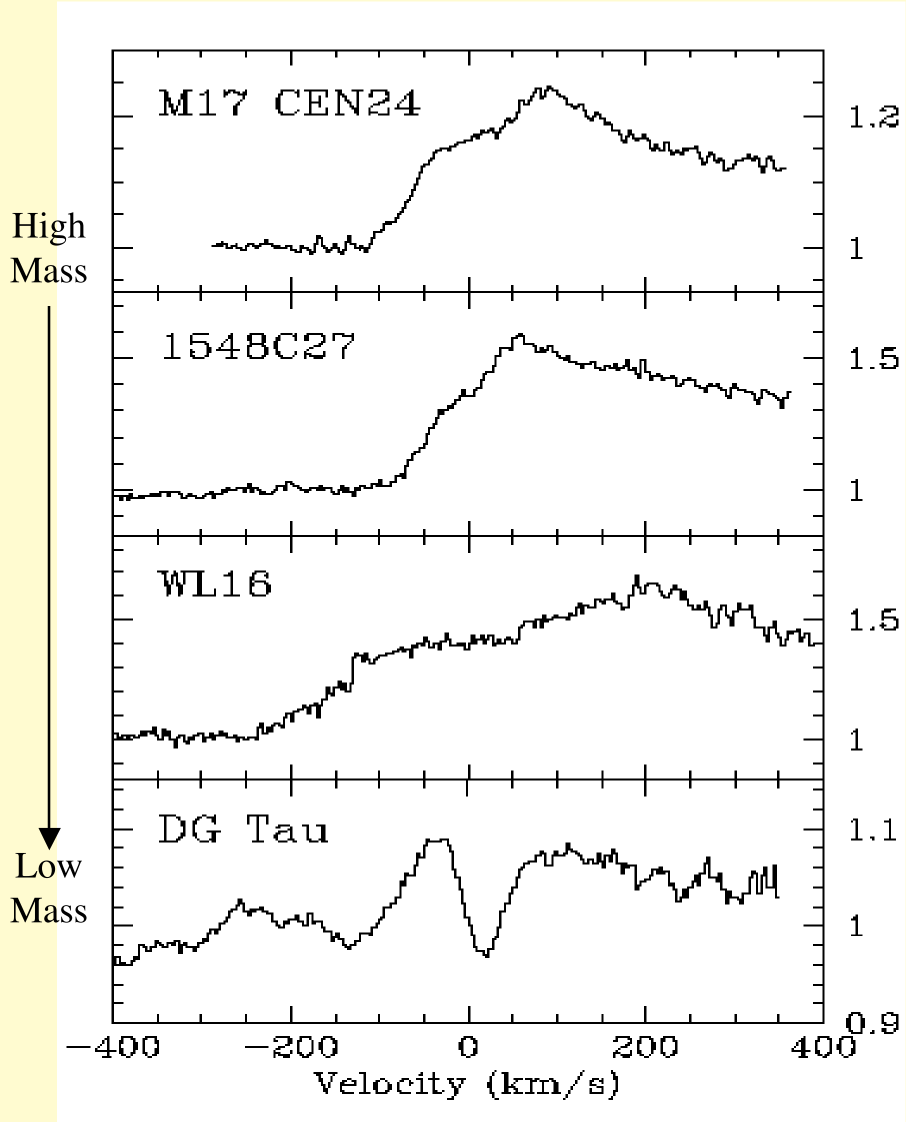
Absorption by Outer Disk

High Resolution Spectroscopy

- Study Gas in the inner disk
- Individual transitions → T, Column density
- *Line profiles*→ kinematics and radial structure
- Detection of weak lines, trace species
- Can hope to study:
  - Gas content and Dissipation timescales
  - Radial and vertical disk structure
  - Abundances and Chemistry
  - Gas dynamics

CO Overtone Emission

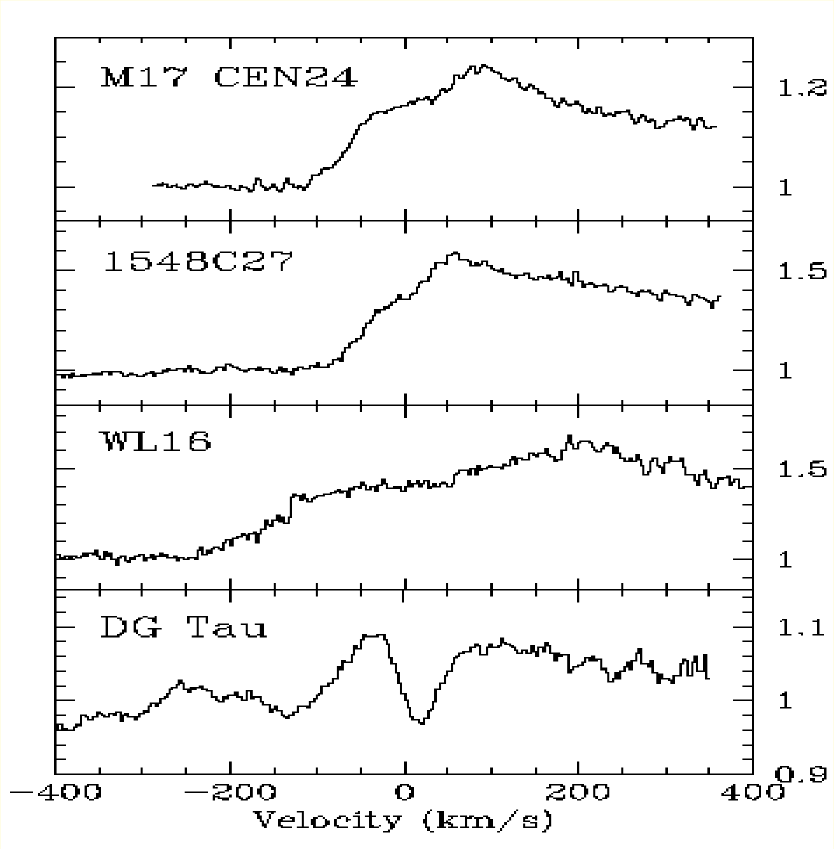
- Δv=2 Bandheads $\lambda \geq 2.3\ \mu m$
- Hot dense gas, T ~ 3000 K
- Most active stars
- Low to High-mass YSOs

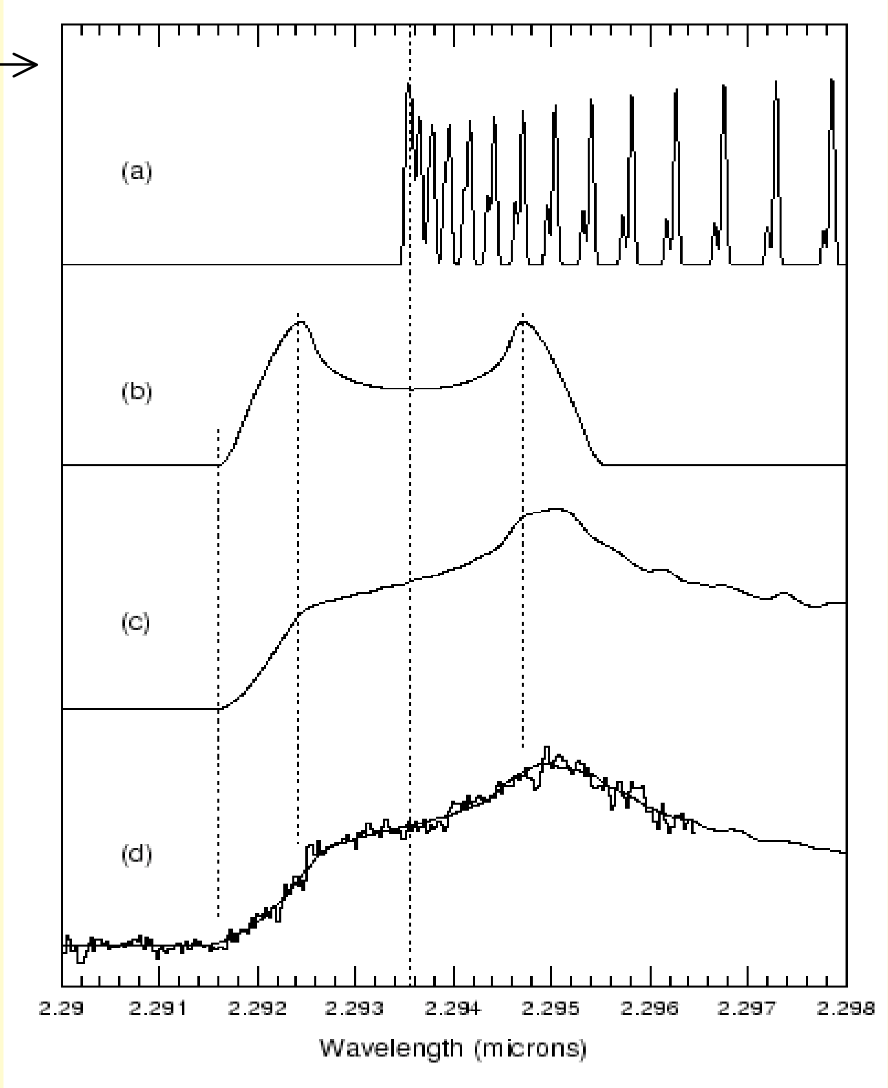


CO 2–0 Bandheads (Najita et al. 2000)

CO Overtone Emission

- Disk Rotation Profiles:
- Radii ~ few 0.1 AU
  (in lower mass stars)

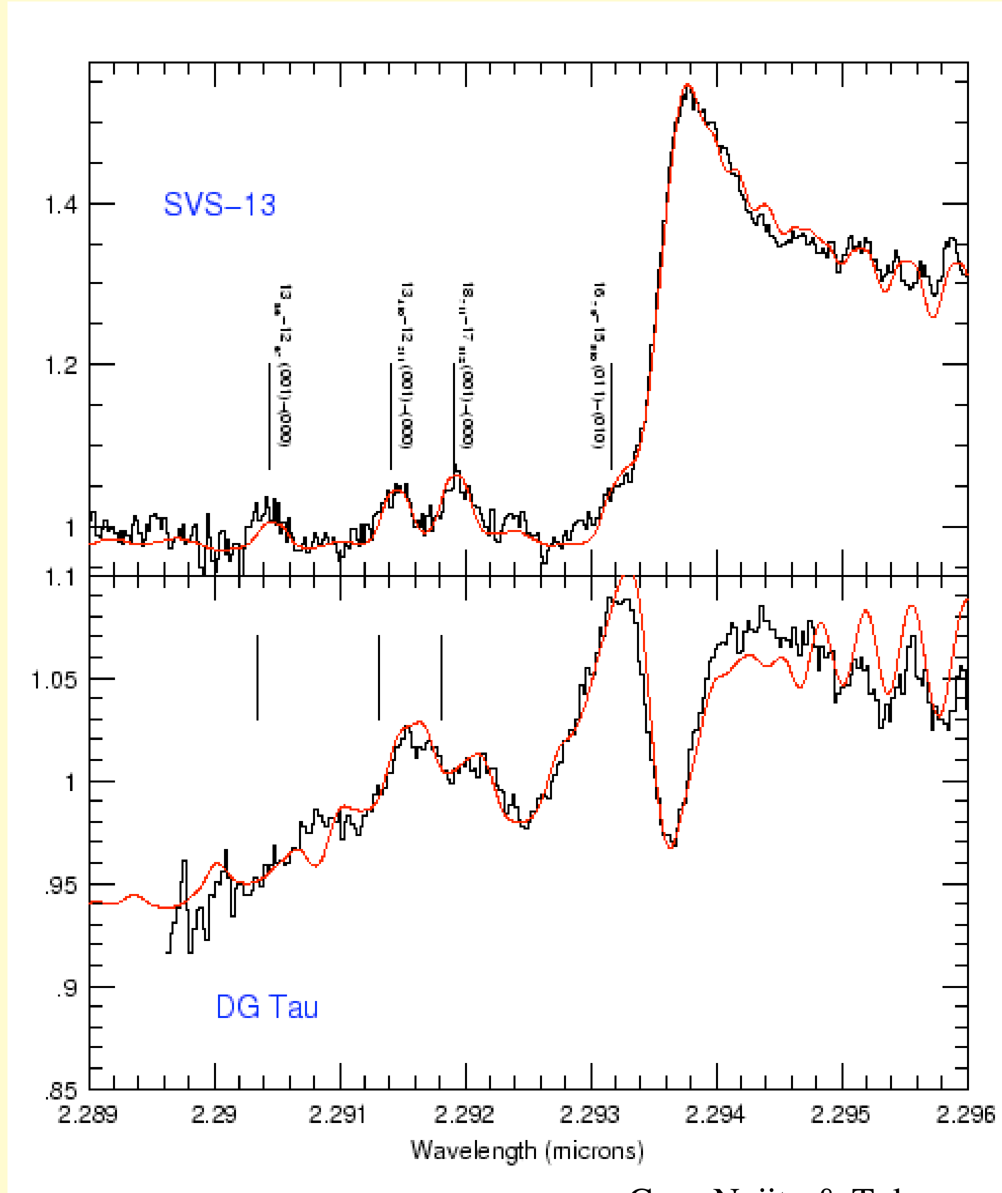




H_2O Ro-Vibrational Emission

- Near-IR (2-4 μm) ro-vibrational transitions
- T ~ 1500–2000 K
- $T_{H_2O} < T_{CO}$
- $\Delta V_{H_2O} < \Delta V_{CO}$

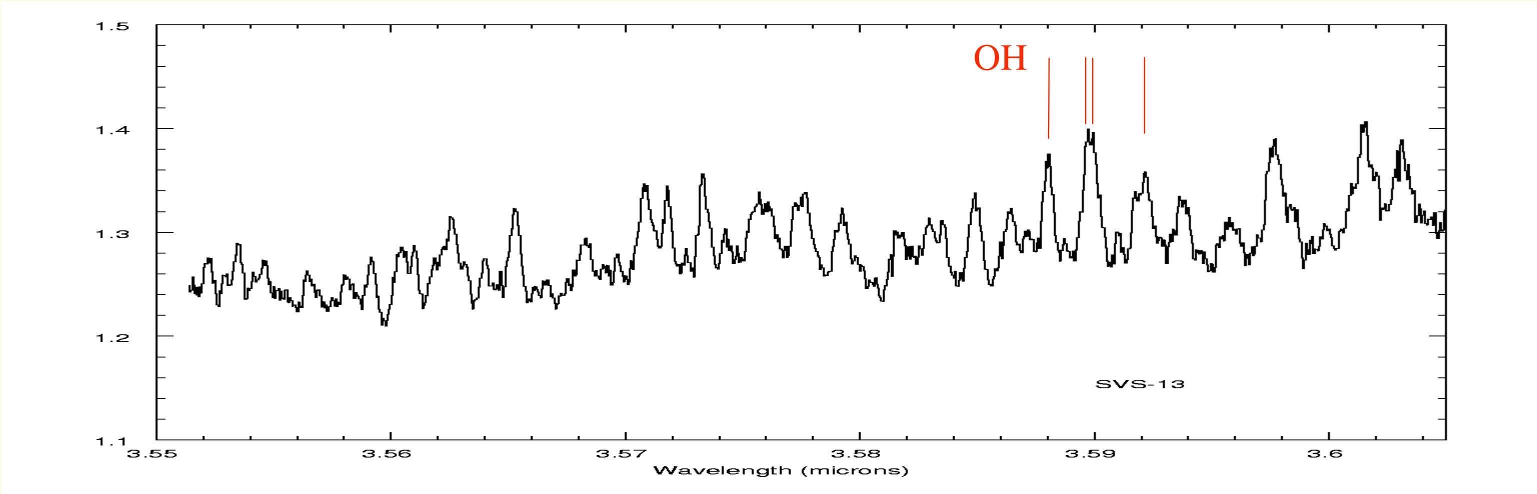
=> Differential Rotation

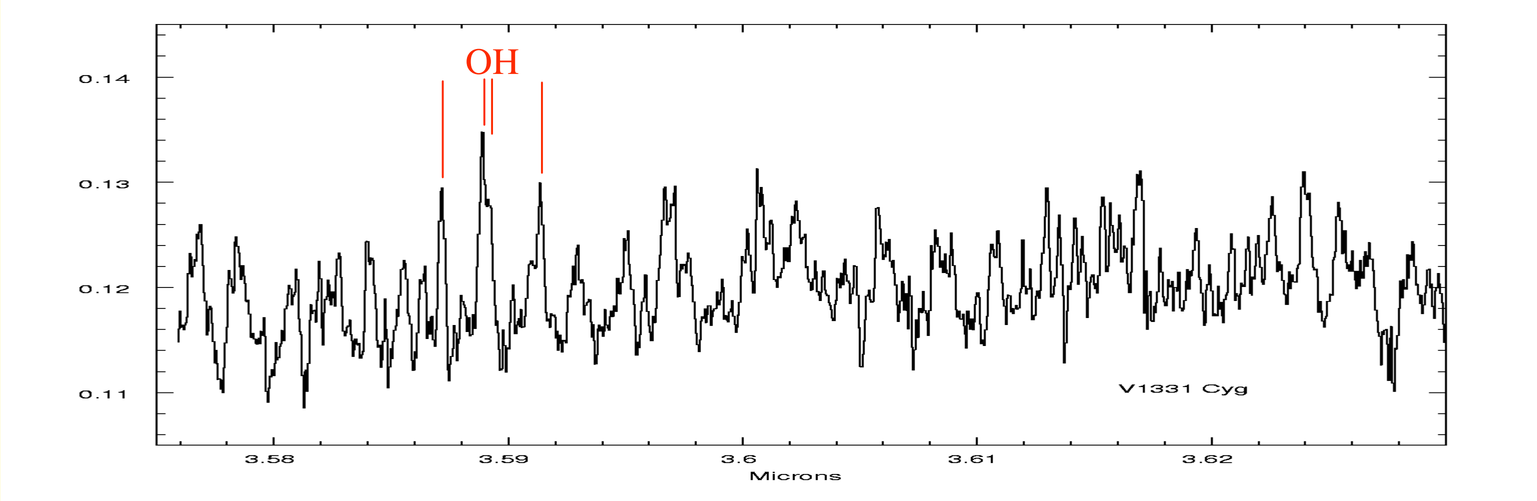


Carr, Najita & Tokunaga

OH and H_2O Emission

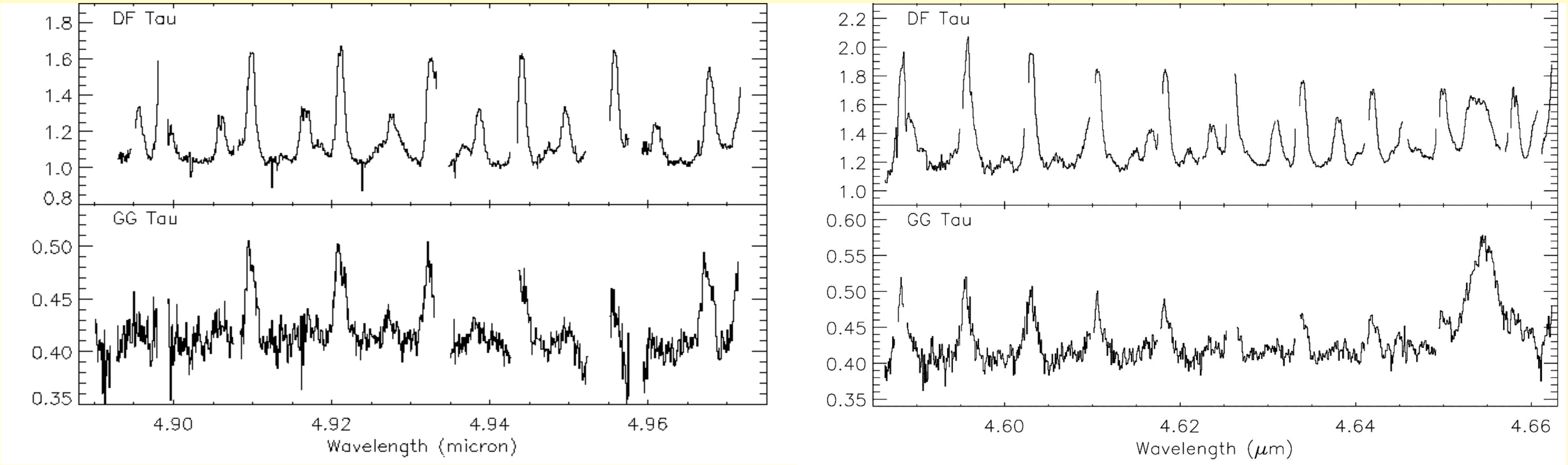
- OH Δv=1 fundamental transitions





CO Fundamental Emission

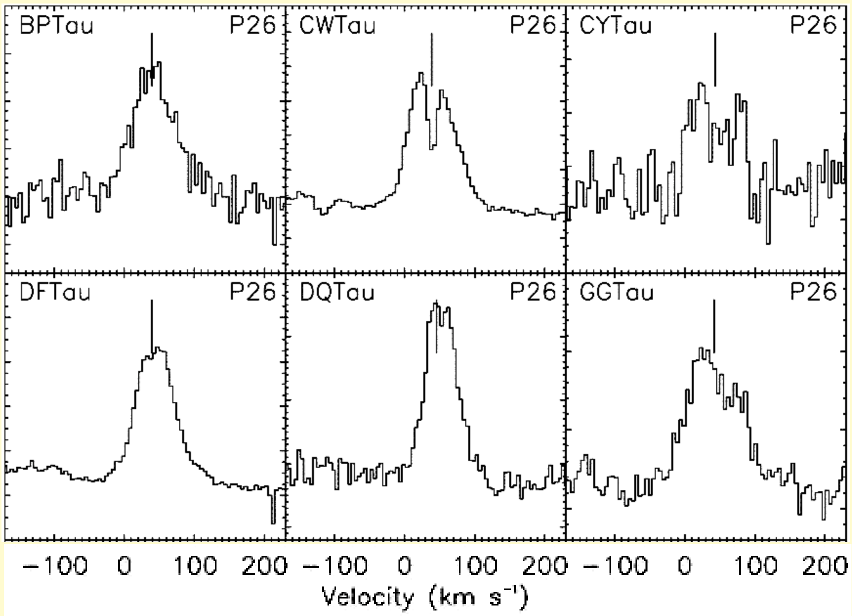
- CO Δv=1 transitions near 4.9 μm
- $A_{\Delta v=1} \approx 10^2 A_{\Delta v=2}$
- Temperatures 600 – 1800 K, up to 3500 K
- v = 1–0, 2–1 common; also v=3–2, ^{13}CO, etc.
- some cases of UV excitation



T Tauri Stars (Najita et al. 2003)

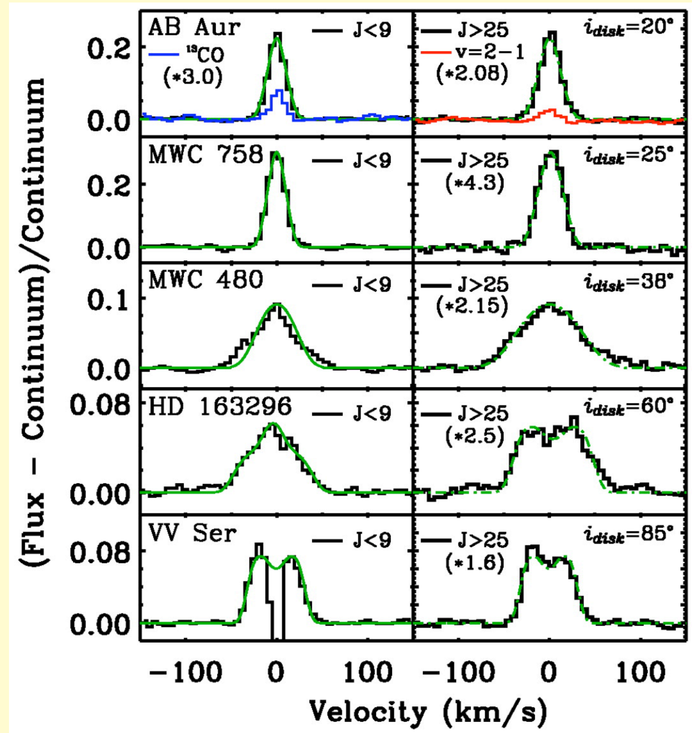
CO Fundamental Emission

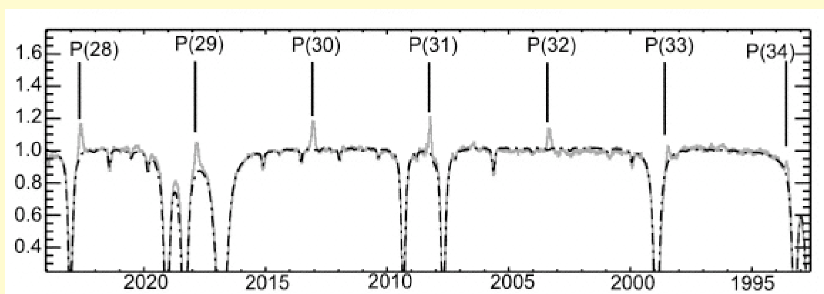
- Emission from T Tauri stars and Herbig AeBe stars



T Tauri Stars

Najita et al. 2003





Herbig Ae/Be stars

Brittain & Rettig 2003

Blake & Boogert 2004

Molecular Hydrogen

- Major component of disk gas is H_2
- MIR rotational, NIR ro-vibrational, FUV electronic transitions
  - IR quadrupole transitions are weak
  - Easily excited in shocks or by UV
  - Spatially extended emission possible

- Near-IR ro-vibrational transitions
  - Thermal emission (e.g., shocks) T > 1000 K
  - UV or X-ray Excitation possible
  - 1-0 S(1) detected in some CTTs and WTTs (e.g., Bary et al. 2003)
    - Lines $\leq$ 10 km s^{-1} wide $\Rightarrow$ $\gtrsim$ 10 AU if in disk
    - Excitation by UV or X-rays likely

Molecular Hydrogen

- Mid-IR pure rotational transitions
  - Directly measure thermal emission (T ≥ 100) from gas
  - Ground-based: 8, 12, 17 μm lines: S(4), S(2), S(1)
  - Measurements/limits towards some young stars
    (Richter et al. 2002; Sheret et al. 2003; Sako et al. 2004)
  - Narrow lines, ≤ 10 km s^{-1}
  - Most detections by ISO not confirm! Why? Extended?

- FUV electronic transitions
  - Ly α pumped H_2 fluorescence
  - Observed in several CTTs
    (Herczeg et al. 2001,2004; Adila et al 2003)
  - Originates in hot gas, ~2500 K

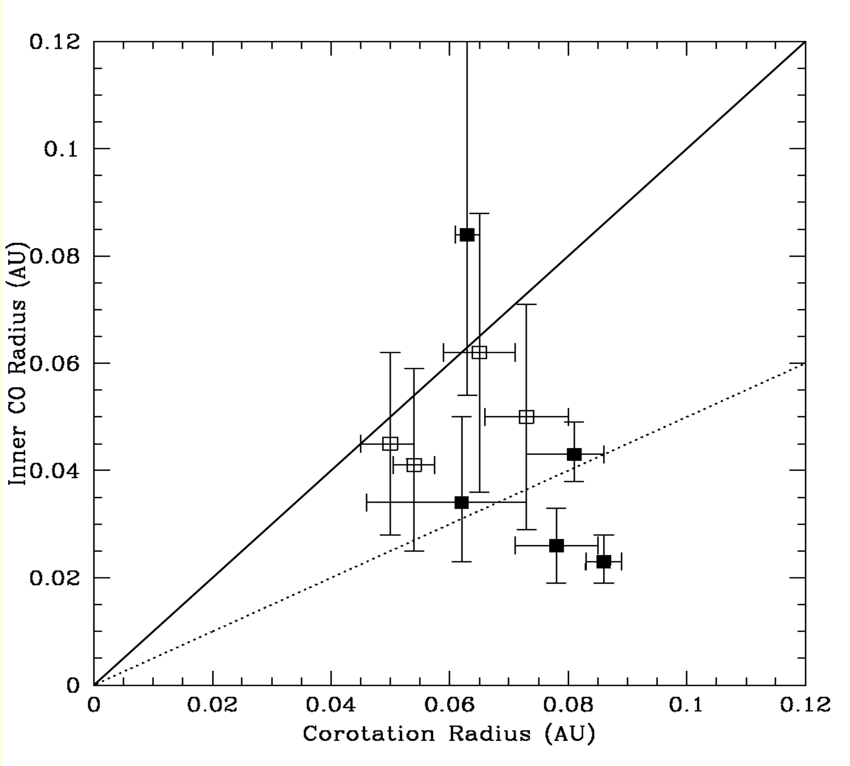
CO Fundamental Emission in Classical T Tauri Stars

- Common; detection rate ~ 80 %
- Correlated with accretion indicators
- Disk radii ~ 0.04 to ≥ 1 AU, based on line profiles
- Emission from:
  - disk atmospheres
  - *gaps* in Spectroscopic binaries
  - optically thin holes in “transitional” T Tauri stars

Inner Gas Radius in Classical T Tauri Stars

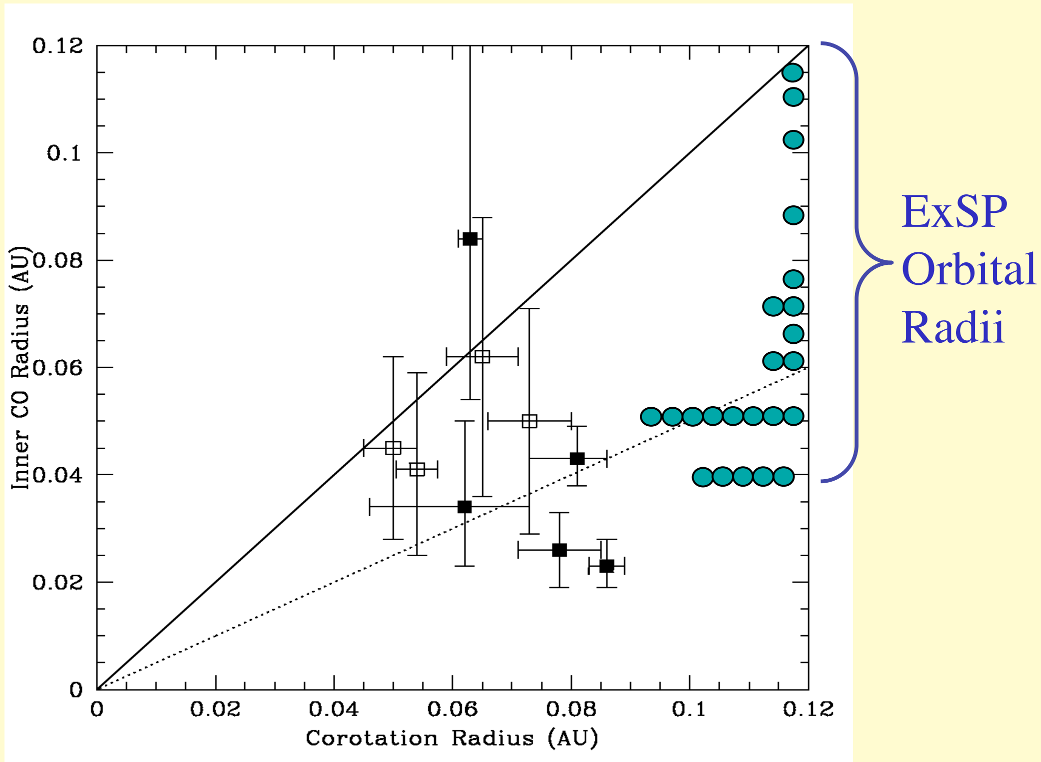
- Innermost CO Radius, R_{CO} follows from M_* and sin i and max. CO velocity

$\Downarrow$



- R_{CO} < Co-rotation Radius
- Actual disk truncation radius?
- R_{CO} < Dust radii from IR interferometry $\Rightarrow$ gaseous disk extends inward of dust sublimation radius

Inner Gas Radius in Classical T Tauri Stars



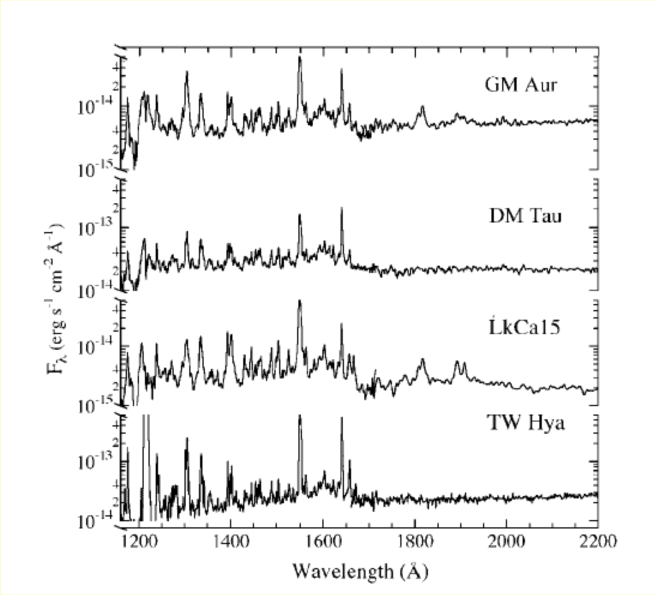
➢ R_{CO} = same as minimum Orbital Radii of Short-period Extra-Solar Planets ⇒ role of disk in forming "hot Jupiters"

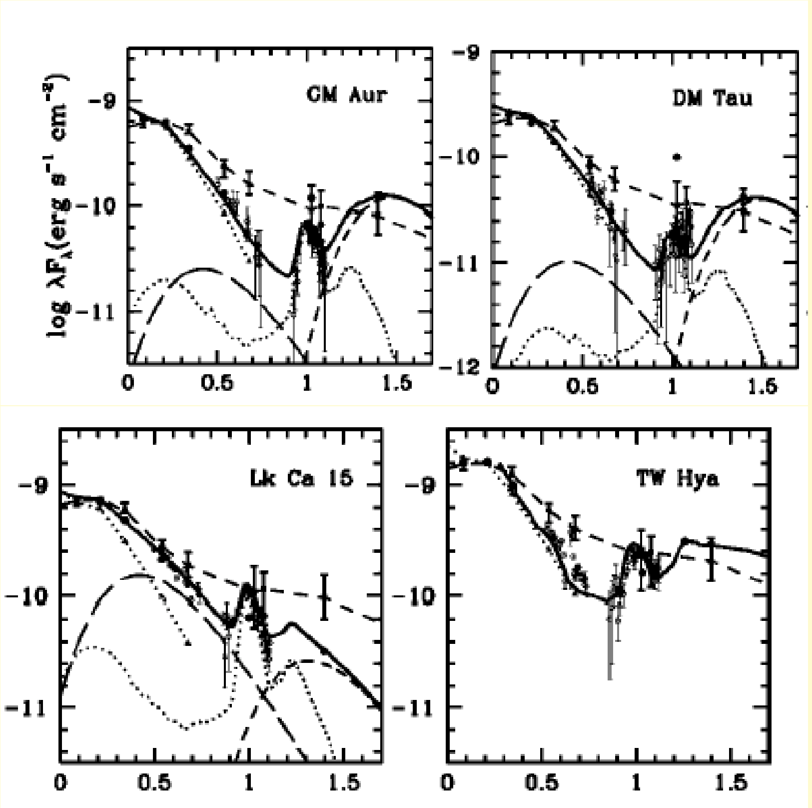
Inner Disk Holes or "Transitional" T Tauri stars

- Systems whose SED's require a large inner hole that is optically thin in the continuum
- Is hole due to:
  - Dust growth into larger bodies?
  - Inside-out disk clearing?
  - Planetary companion?
- Is the inner hole:
  - Devoid of gas?
  - Gas-rich and dust-poor?
  - Totally cleared of material?
- What is content and evolution of the gas?

Gas in Inner Disk Holes

Ly α induced fluorescence and continuum H_2 emission

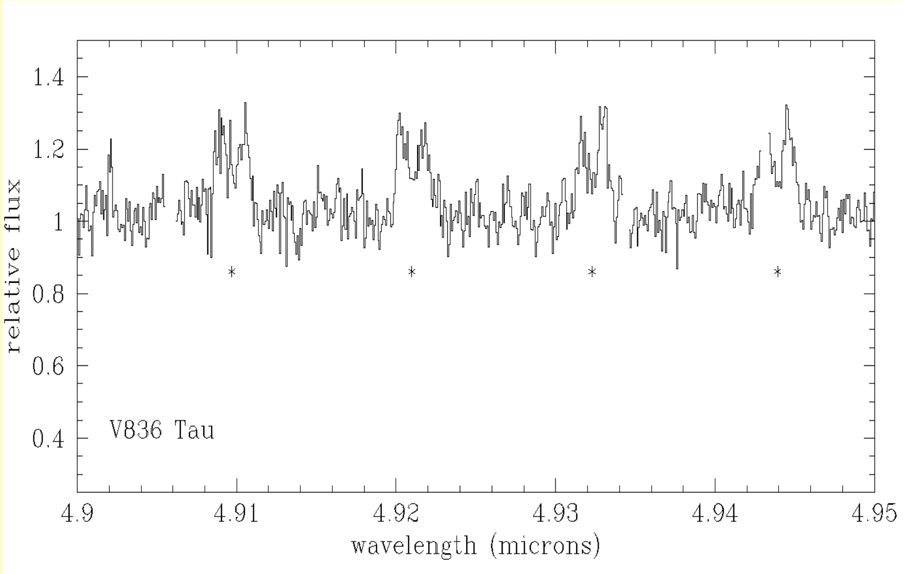


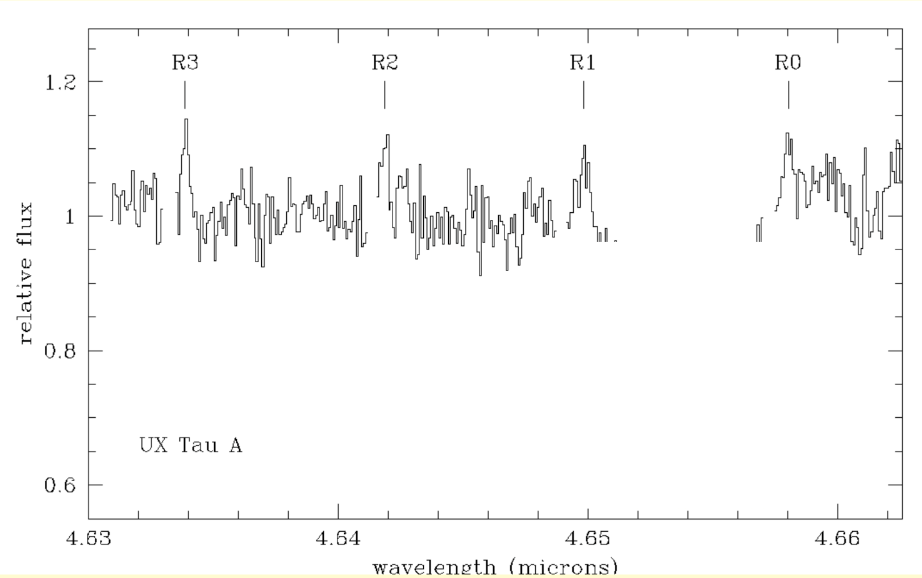


Bergin et al. 2004;
Herczeg et al. 2001,2004

Gas in Inner Disk Holes

CO fundamental emission in “transitional” TTSs

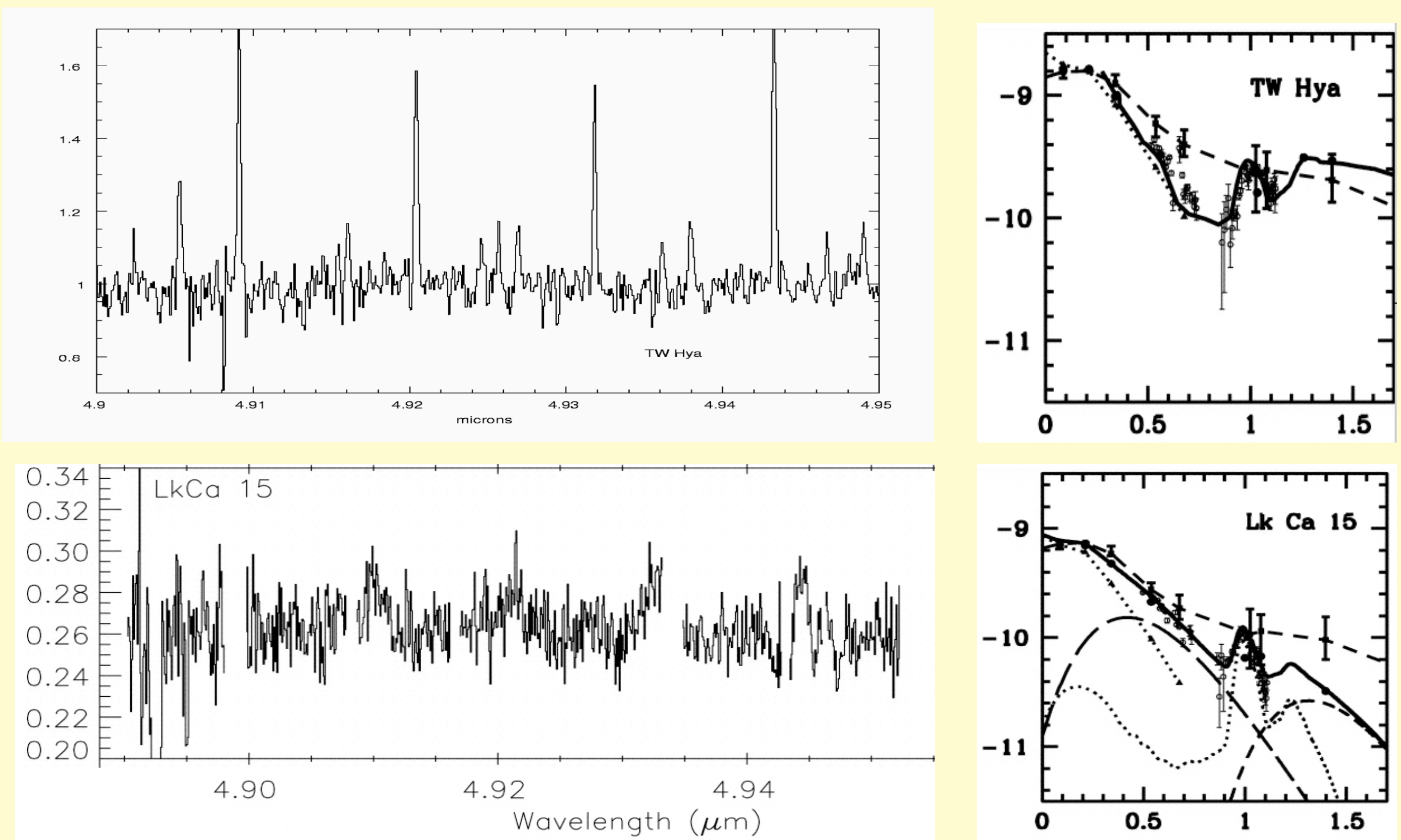




Najita & Carr

CO Gas in Inner Disk Holes

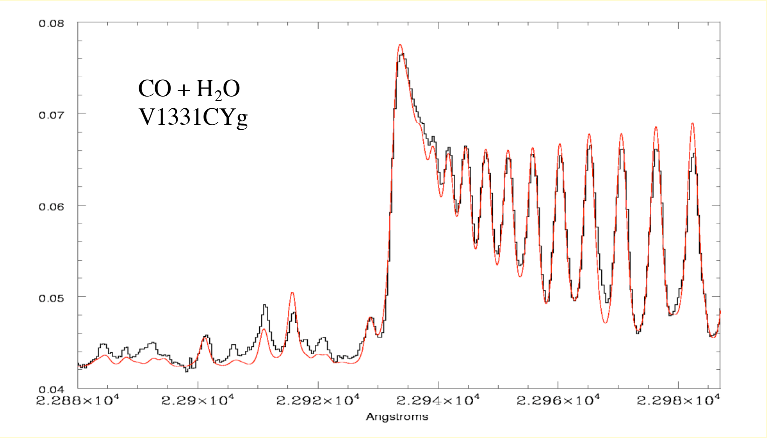
- Measure CO column, temperature, mass, radial extent from emission
- Measure dust continuum from IR veiling –> gas/dust ratio
- Need chemical model –> total gas mass!

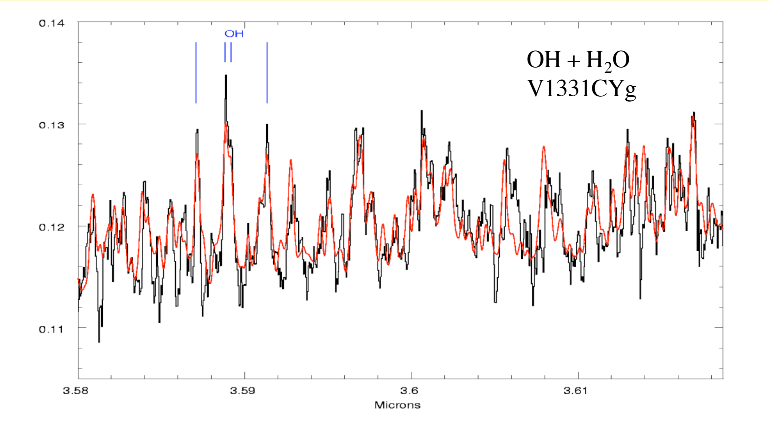


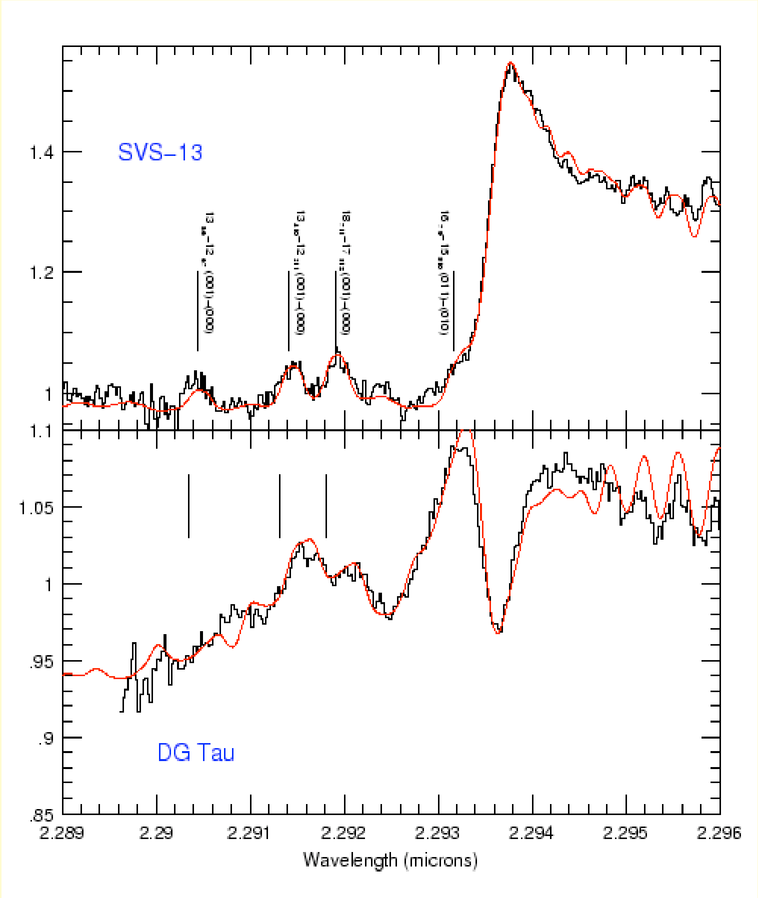
Carr & Najita
see also Rettig et al. 2004

Chemical Abundances

- Disk Modeling for CO, H_2O and OH Emission
  - ❖ heated upper atmosphere modeled as single layer with power laws in T, Σ







Chemical Abundances

- Disk models reproduce:
  - – different excitation temperatures of CO and H_2O
  - – relative linewidths of CO vs. H_2O and OH

- H_2O and OH Abundances are “Low” :

  H_2O/CO and OH/CO are low relative to chemical equilibrium values by factors of 2–10

- Model too simple:
  - –UV photodissociation
  - – X-ray driven chemistry
  - –Vertical thermal-chemical structure
  - – Grain opacity important at these temperatures?

Thermal-Chemical Structure

- Observations ⇒ surprisingly warm gas in atmosphere
  - CO fundamental: ~500 K at 1 AU (Najita et al. 2003)
  - H_2 UV emission: ~2300 K at < 1-2 AU (Herczeg et al. 2004)
- Gas temperatures > dust-temperature predicted by irradiated disk models (e.g., D'Alessio et al.)
- Gas not thermally coupled to dust in upper atmosphere

Thermal-Chemical Structure

Thermal-chemical models of inner disk atmospheres
(Glassgold & Najita 2001; Glassgold et al. 2004)

– X-ray ionization and heating

– Chemical network

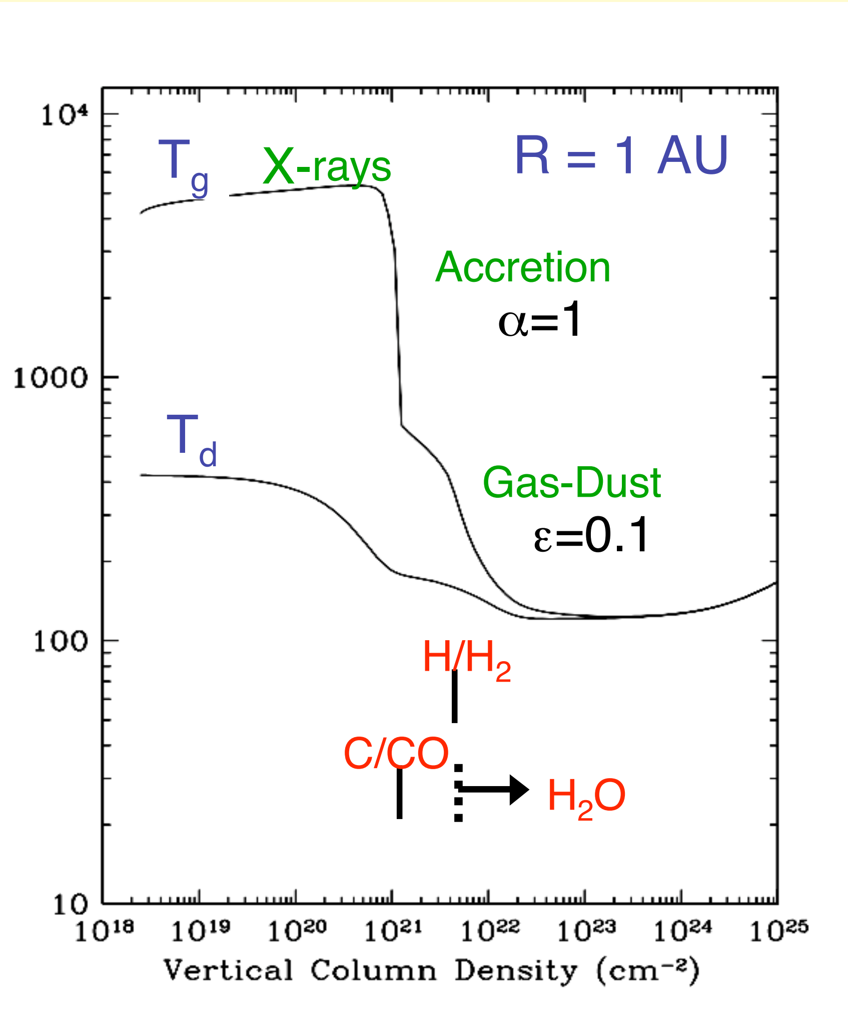
$\Longrightarrow$

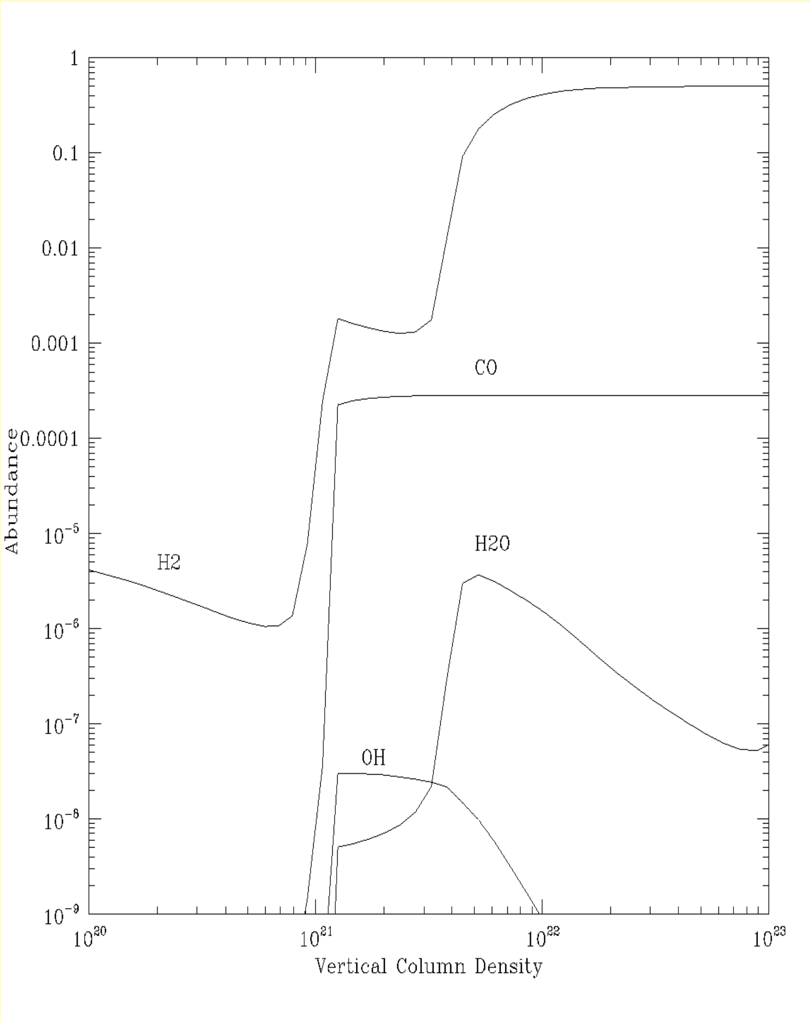
❖ X-rays produce temperature inversion in *gas*

❖ $T_{gas} > T_{dust}$

❖ Strong vertical chemical structure

Thermal-Chemical Structure

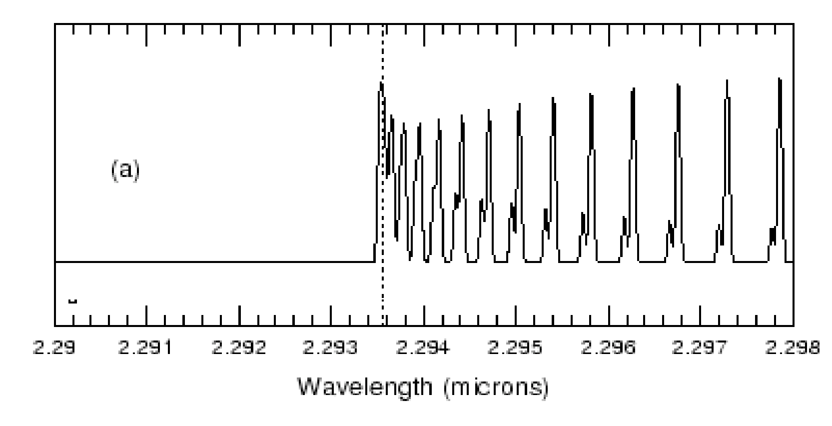


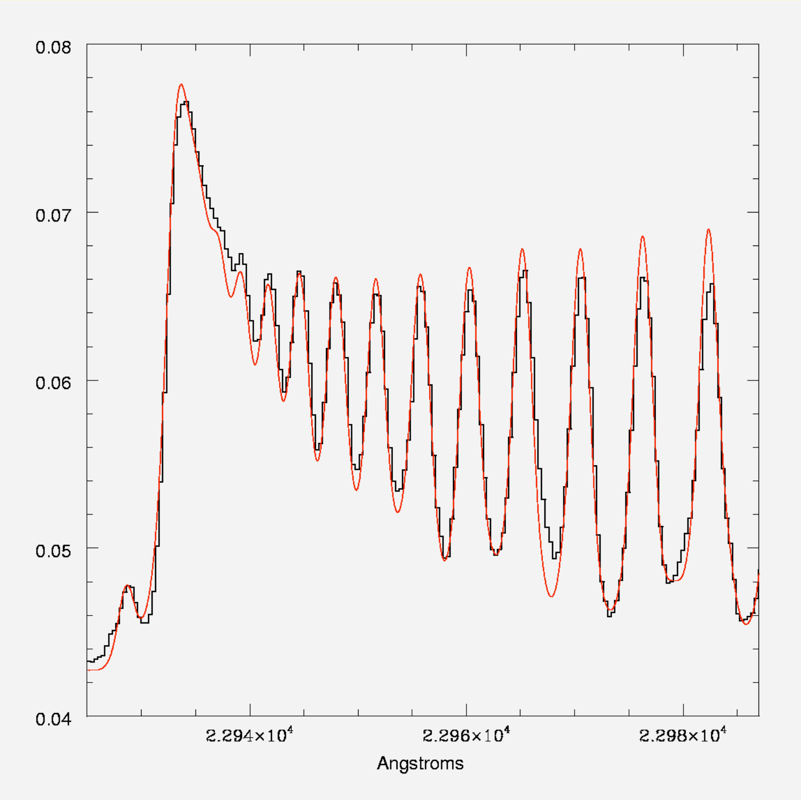


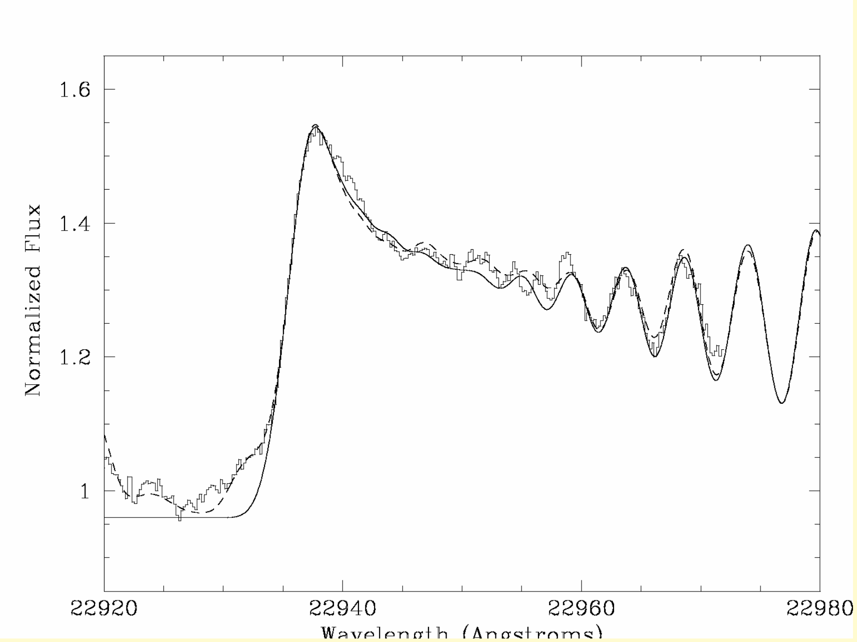
Glassgold, Najita & Igea 2004

Turbulence in Disk Atmospheres

- CO bandhead shape is sensitive to optical depth and line overlap







Turbulence in Disk Atmospheres

- Modeling of CO overtone bands
  $\Rightarrow$ large, local line broadening
- ~ transonic to supersonic velocities: 1–3 c_s
- also, transonic motions in FU Ori objects (Hartmann et al. 2004)

Turbulence due to Accretion Viscosity?

- Numerical simulations → sonic turbulence
  in upper atmosphere:
  - Magnetorotational instability – Miller & Stone 2000
  - Global baroclinic instability – Klahr & Bodenheimer 2003

A modest hope

Velocity-resolved measurements of numerous transitions from various molecular (and atomic) species, coupled with models for gas disk atmospheres and information on the dust, can be used to determine the thermal, chemical, and turbulent structure of the atmosphere, revealing the dominant heating and chemical processes.