Spitzer and Studies of Gas in the Planet Formation Region of Disks

Joan Najita (NOAO)

John Carr (Naval Research Laboratory)

With input from:

Andres Carmona

Ilaria Pascucci

Spitzer Highlights

Molecular hydrogen is a challenging diagnostic.

- Likely carries most of the mass, but...

Spitzer suggests exciting alternatives!

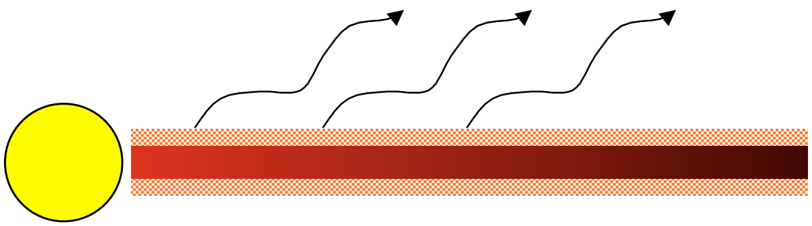
- **NeII** commonly detected…from the ionized disk surface?
- **Organic molecules, OH, and water** detected commonly from the terrestrial planet region of disks

Transition object spectra can differ from CTTS spectra.

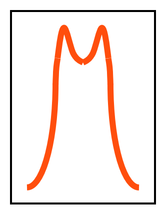
- What is the nature of transition objects?

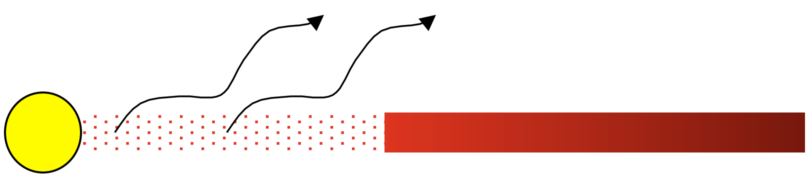
Disk Spectral Lines

Emission Lines



Temperature Inversion in
Optically Thick Disk

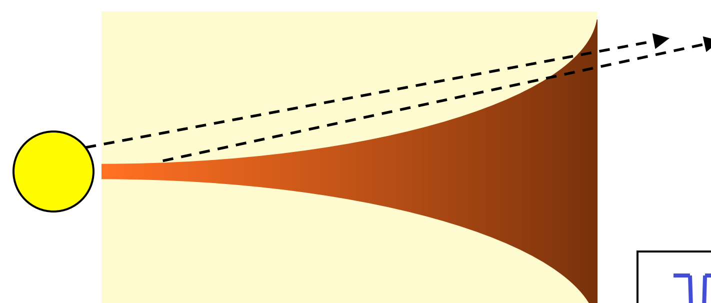


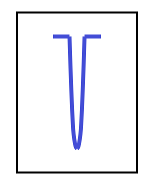


Optically Thin Disk, Hole or Gap

Absorption Lines

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





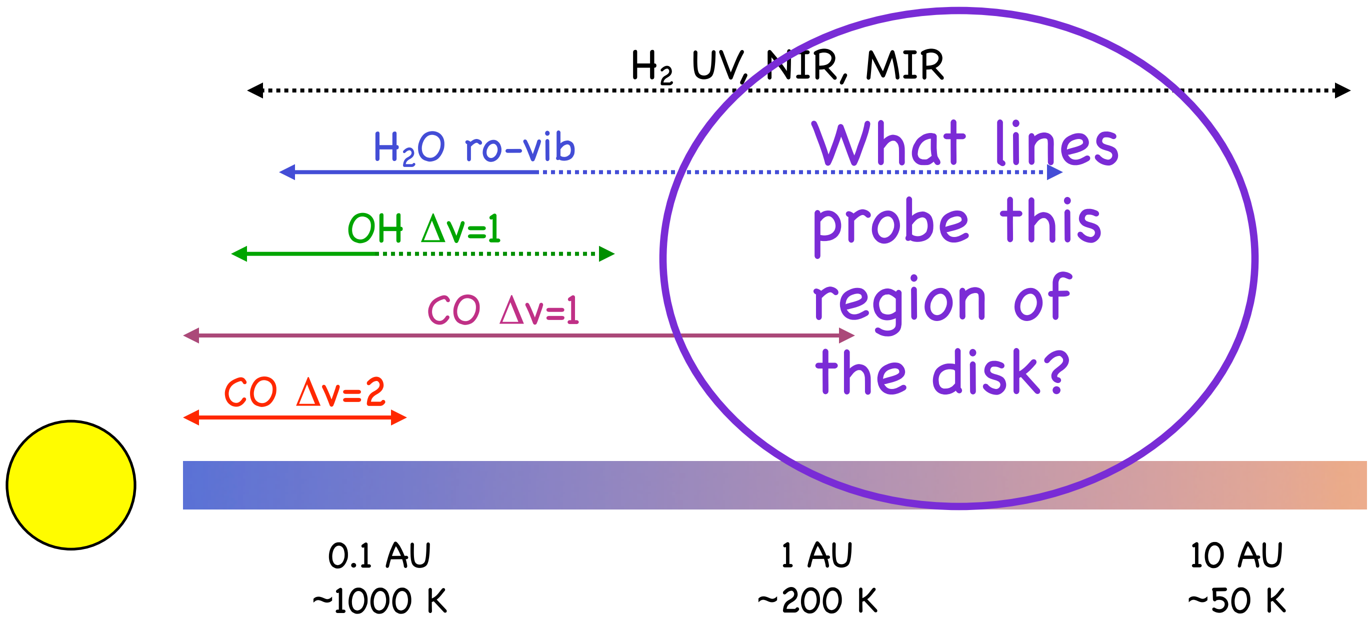
Absorption by Outer Disk

Gaseous Probes of Inner Disks
(Pre-Spitzer)

When	New Diagnostic	Temp	Comment
80s	FU Ori disk atmospheres		Rare!
80s	CO overtone disk emission	>2000	Less rare
1994+	H_2O 2μm disk em. (CSHELL)	~2000	CO overtone sources
1995+	CO 4.7μm disk em. (CSHELL)	~1500	**All** TTS
1995	OH 3μm disk em. (CSHELL)		SVS-13
2000+	H_2 NIR disk em. (Phoenix)	1000?	CTTS, 1 WTTS
2001	H_2 UV disk em. (HST/STIS)	~2000	TW Hya+
2001	H_2 MIR em. (ISO)	150?	TTS & older stars

ISO indicated H_2 em. from 150K gas (r > 1AU) in disks is not rare! Surprising and exciting: possible contributions from diffuse ISM, shocks, jets (low critical density)?

Gaseous Probes of Inner Disks
(Pre-Spitzer)



Temperatures 100 - few 1000K, high densities

» Molecules abundant in gas phase

» Excitation of IR ro-vibrational transitions

MIR H_2 Emission is Weaker than Reported by ISO

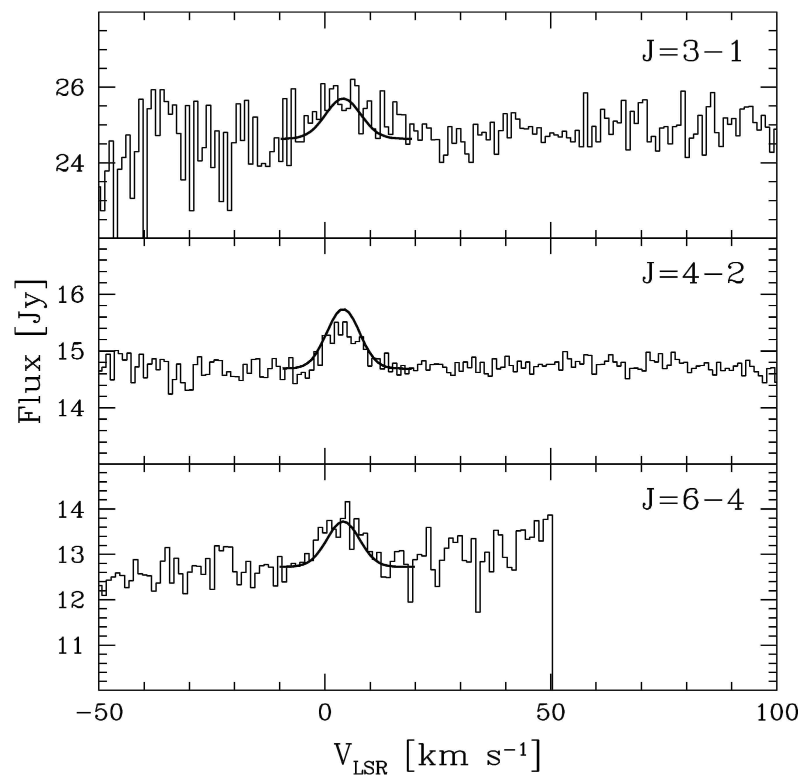
- Although H_2 is likely abundant, the conditions needed for emission (deep temperature inversion + significant dust settling or grain growth) are rarely met.
- **Spitzer:** TTS (c2d--Lahuis et al. 2007); >3Myr sources (FEPS--Hollenbach et al. 2005; Pascucci et a. 2007); Debris disks (Chen et al. 2007); others
- **Ground-based:** AB Aur (Richter et al. 2002; Sheret et al. 2003), ISO detections (Sako et al. 2005); surveys of TTS and HAB (Carmona et al. 2007; Bitner et al. 2008; Martin-Zaidi et al. 2008)

MIR H_2 Detections

Example: AB Aur

- T=670K
- Emitting $M(H_2)=0.5M_e$
- FWHM ~10 km/s

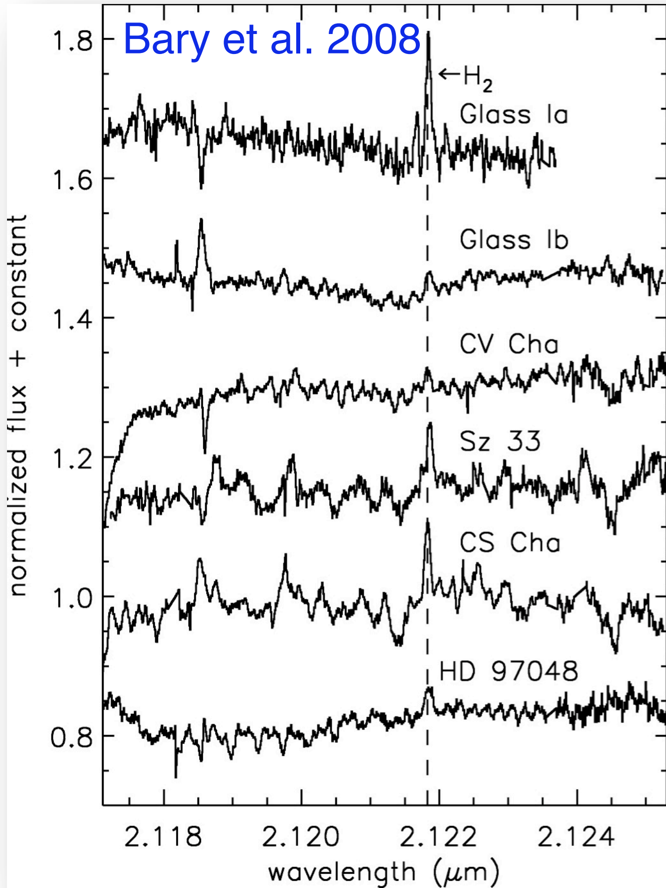
(Bitner et al. 2007; TEXES)



- FWHM ~10 km/s is typical (survey: Bitner et al. 2008).

NIR H_2

- Thermal excitation requires ~1000K
- Emission from a disk surface irradiated by UV and X-rays?



- ~15/50 detections plausibly from a disk (compact, centered on star and at stellar velocity; Bary et al. 2008 & refs therein).
- H_2 flux not well correlated with L_x; other effects significant.
- Poster #34 by Hogerheijde on DoAr21.

UV H_2

- UV H_2 detected in essentially all accreting TTS (Herczeg et al. 2002, 2004, 2005; Walter et al. 2003; Calvet et a. 2004; bergin et al. 2004; Gizis et al. 2005; archival).
- From warm (1000-3000K) gas pumped by stellar Lya. Temp similar to that needed for NIR H_2 and predicted surface temps of disks irradiated by UV and X-rays (e.g., Glassgold et al. 2004, Kamp & Dullemond 2004; Nomura & Millar 2005).
- Arises from **outflows** (blueshifted, extended) or **disks** (centered on star and at stellar velocity, compact: within few AU) (Herczeg et al. 2006)
- Poster #46 by Laura Ingleby

H_2 and CO

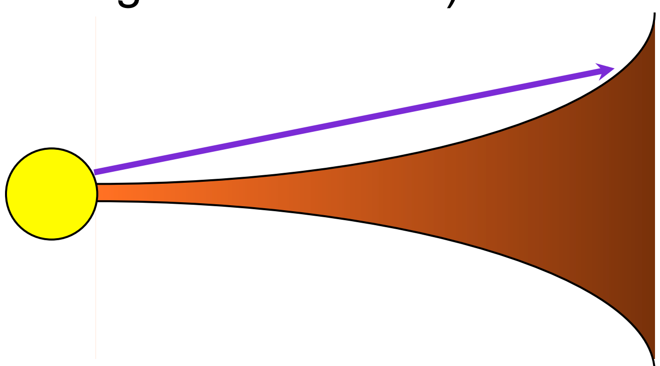
- CO fundamental emission selectively probes higher densities than H_2
- If widths indicate disk rotation, they suggest an ordering in radius of CO < UV H_2 < NIR H_2 < MIR H_2

Diagnostic	FWHM	R (AU)	References
CO fund.	~80	< 1	Najita et al. 2003
UV H2	20-50	< few	Herczeg et al. 2006; Ardila et al. 2002
NIR H2	10-20	2-10s	Bary et al. 2008
MIR H2	~10	10-50	Bitner et al. 2008

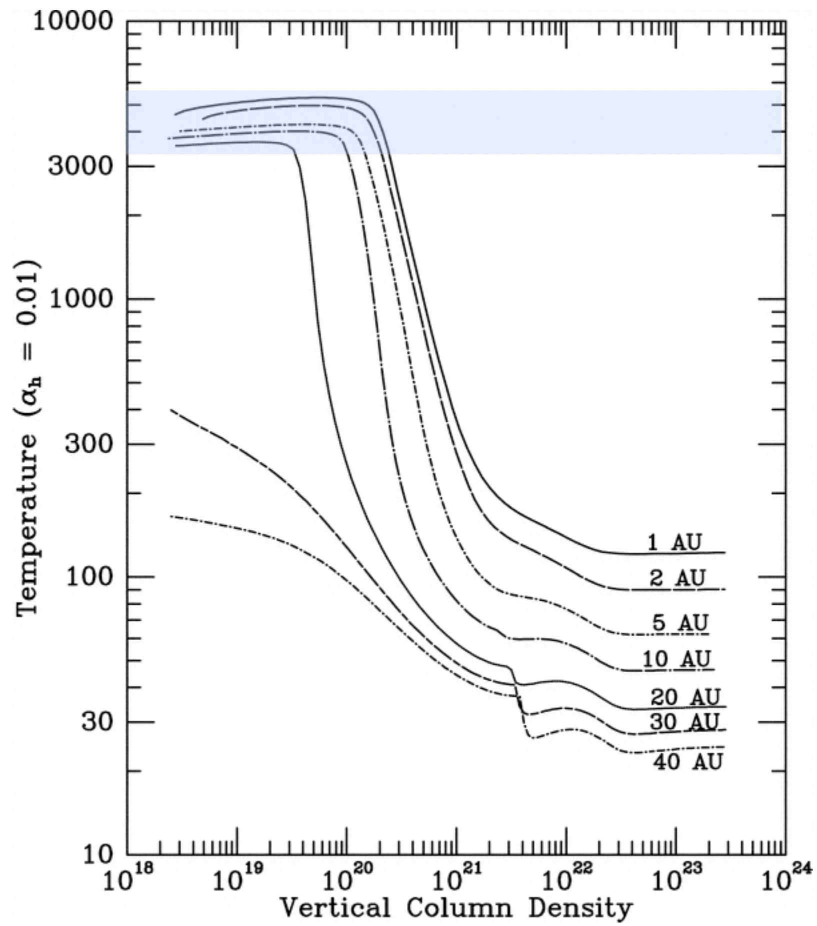
NeII From X-ray Irradiated Disks

X-ray irradiated disks predicted to produce [NeII] emission that is detectable with Spitzer

(Glassgold et al. 2007)



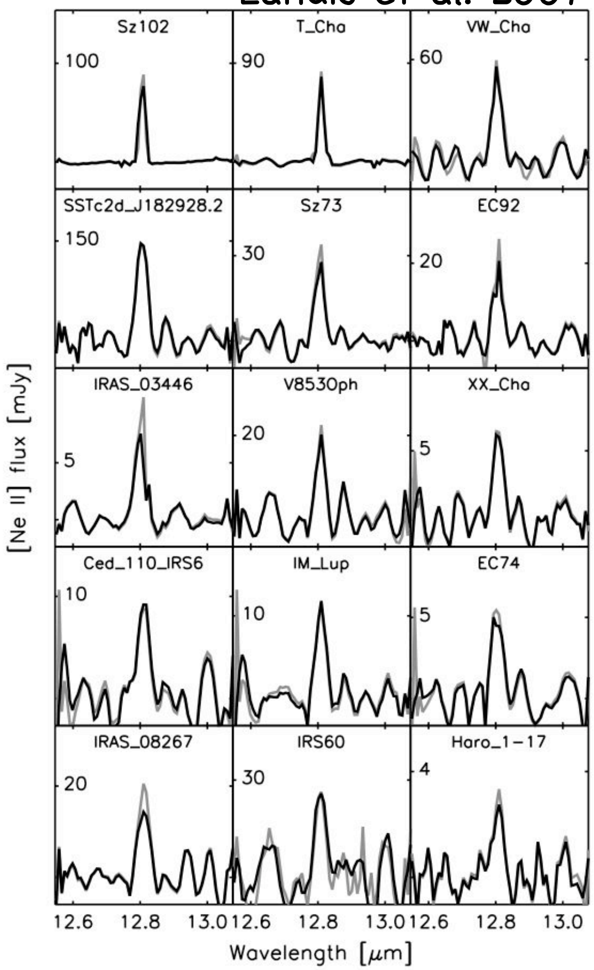
X-rays ionize and heat the disk surface…

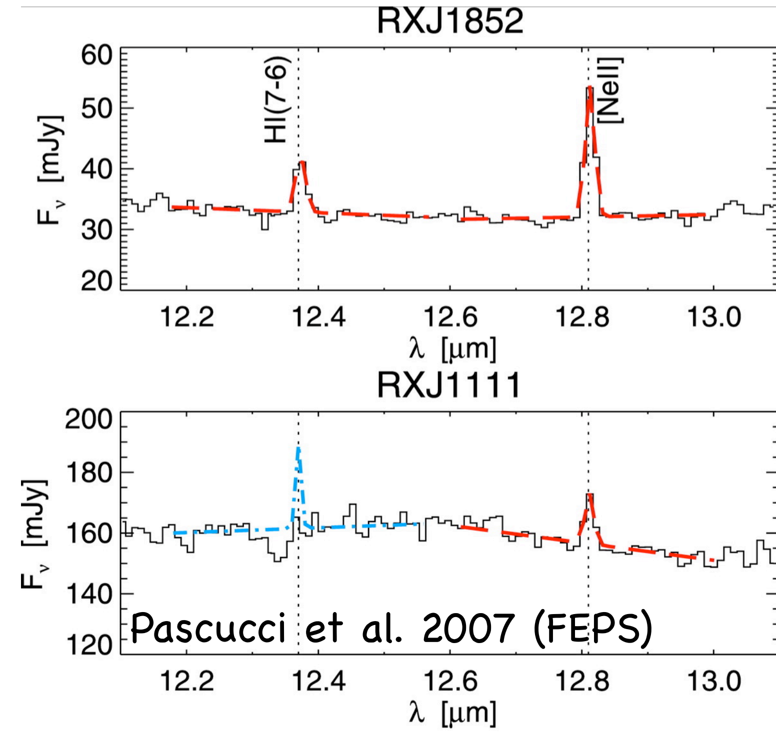


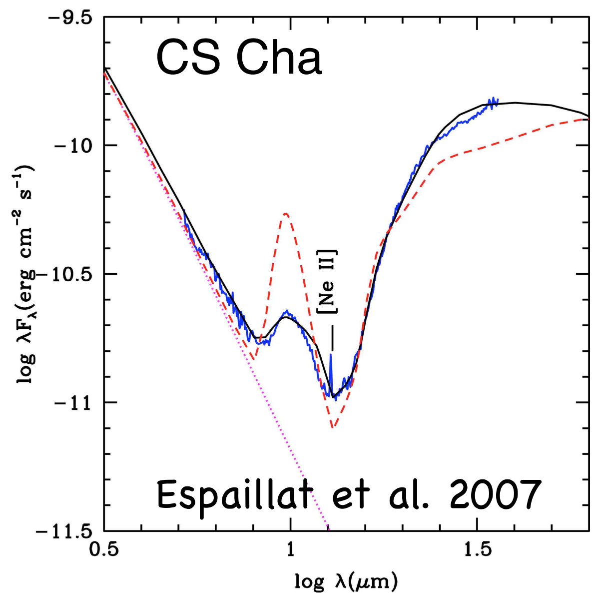
… producing bright [NeII] emission from 4000K surface extending over $\Sigma = 10^{19}\text{-}10^{20}$ cm^{-2} and out to 20 AU

TTS NeII Emission

Lahuis et al. 2007

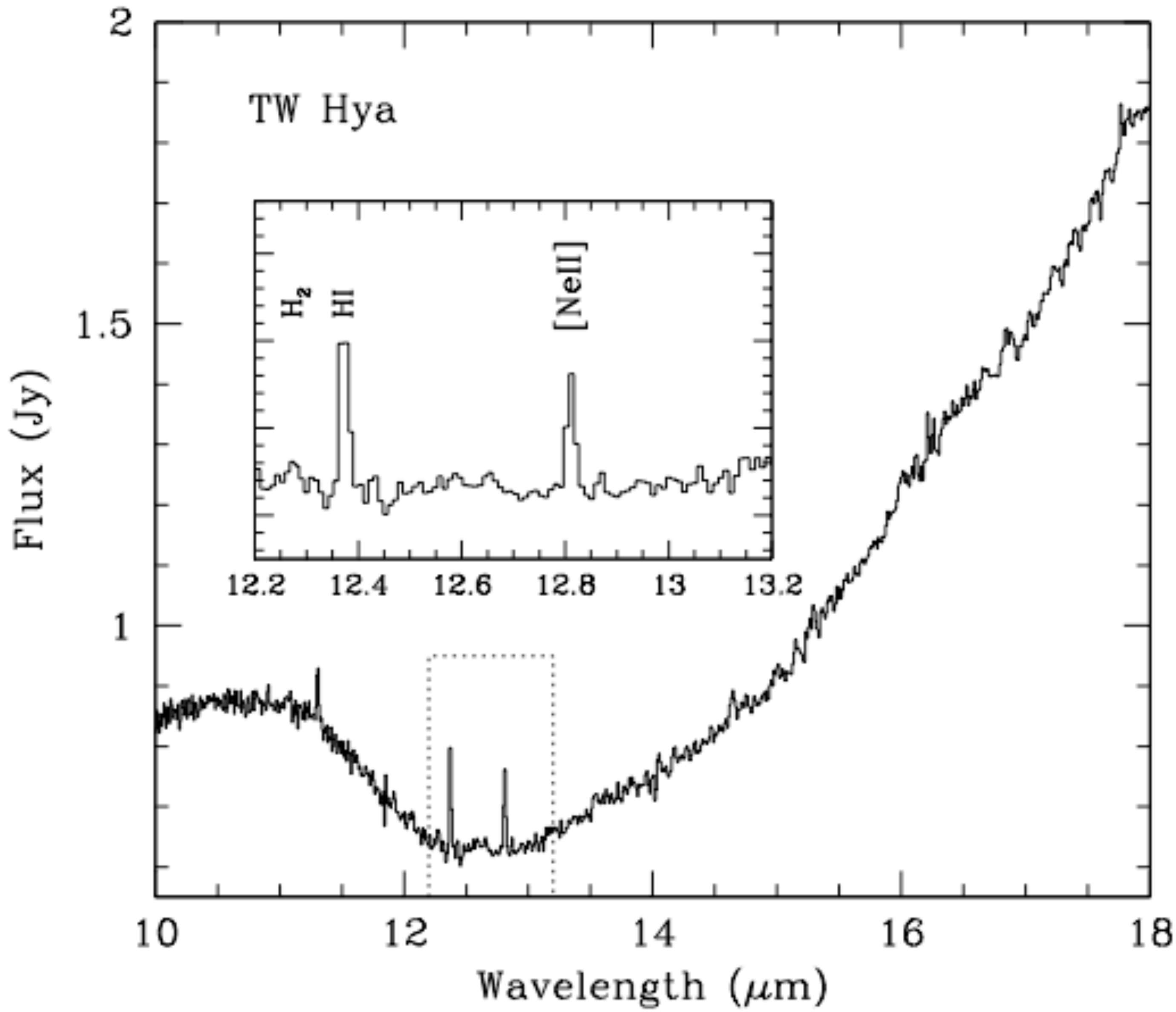






Observed line strengths similar to predicted values.

NeII Emission from TW Hya



Transition object

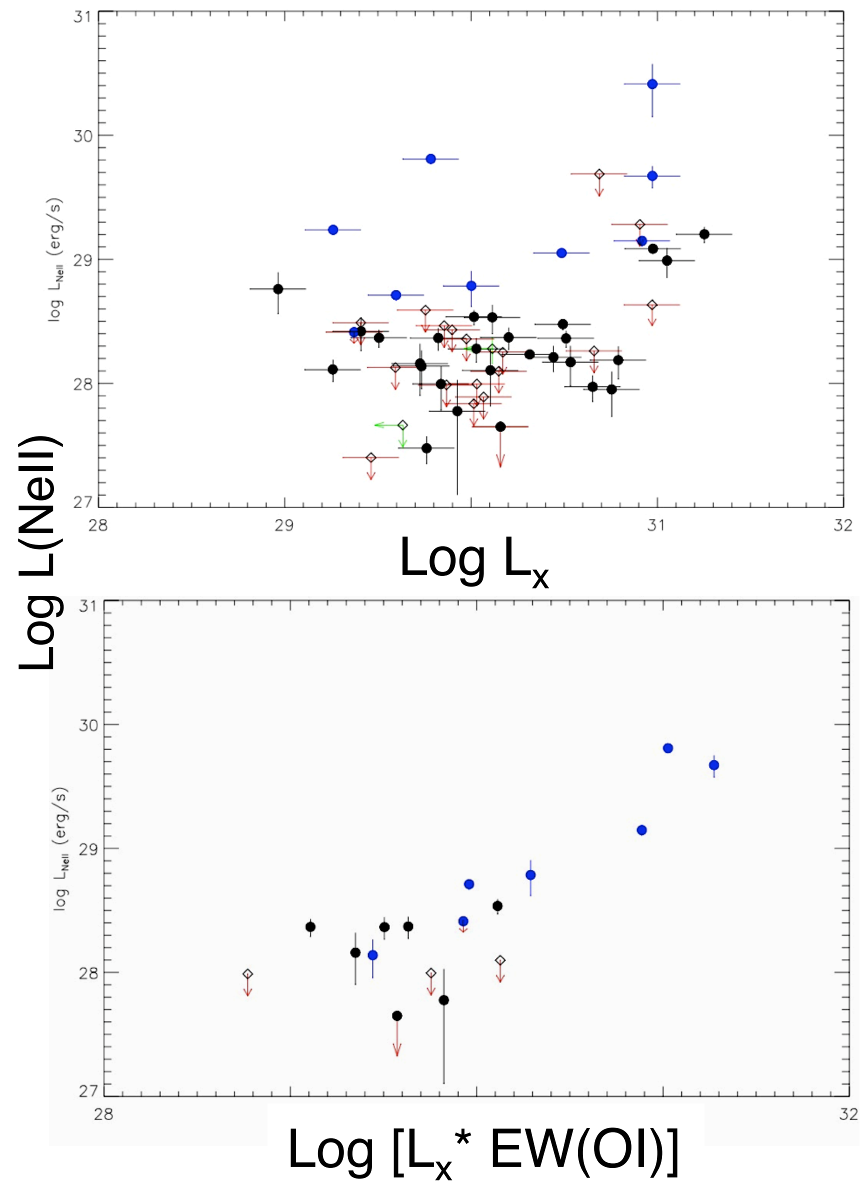
[NeII]12.8mm is one of the strongest lines

H_2 **much** weaker

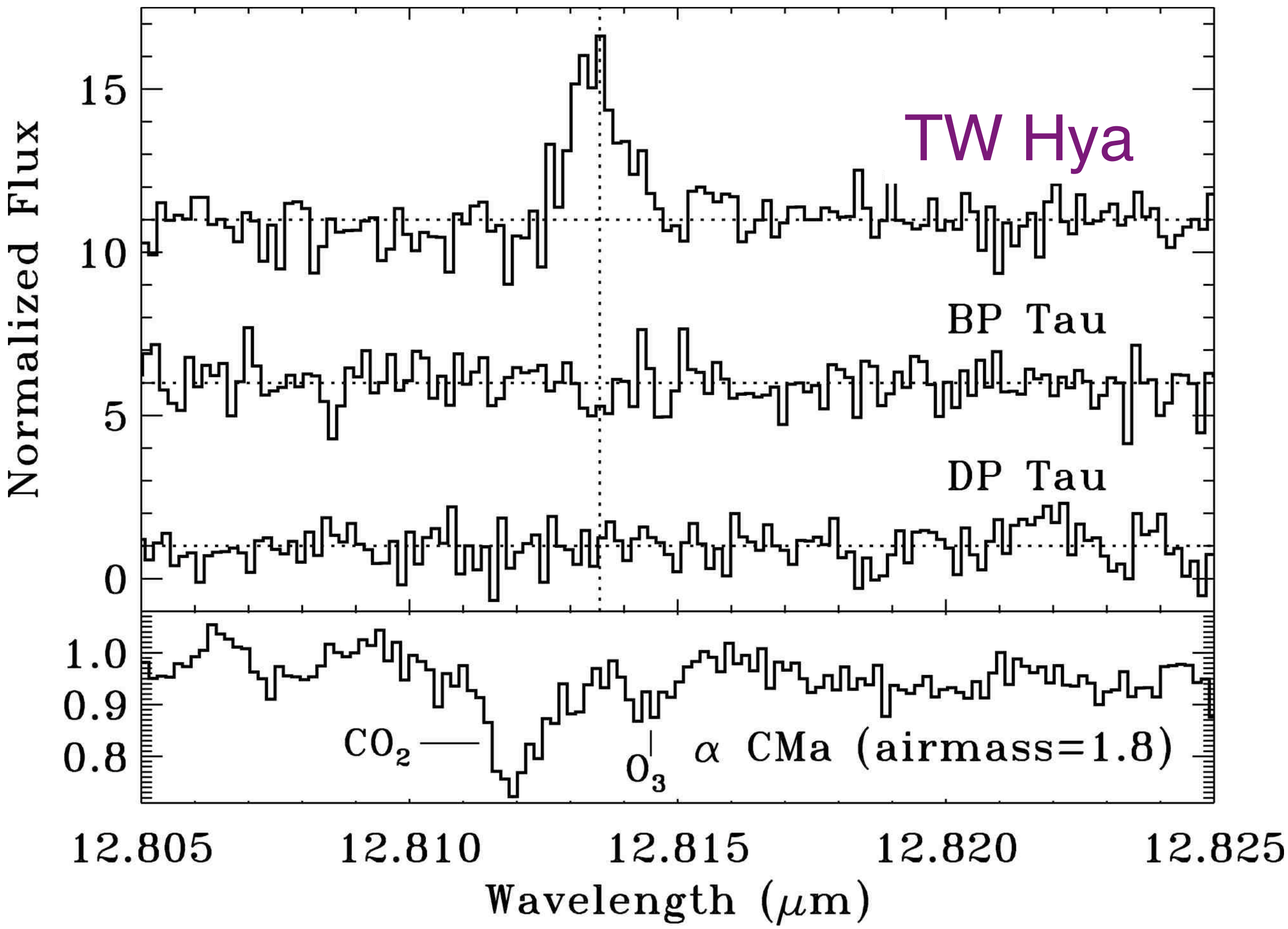
Origin of NeII: Demographics

- Early relation between NeII and L_X, Mdot (Pascucci et al. 2007, Espaillat et al. 2007)
- More extensive recent study (talk by M. Guedel):
  - L_X plays a role, but other parameters also matter.
  - Possible contributions from outflows, disks, and…
- Variability of NeII

  (Poster #60 by Leisenring)



NeII Emission at High Resolution: TW Hya



Herczeg et al. (2007)
Gemini/MICHELLE
R ~ 30,000

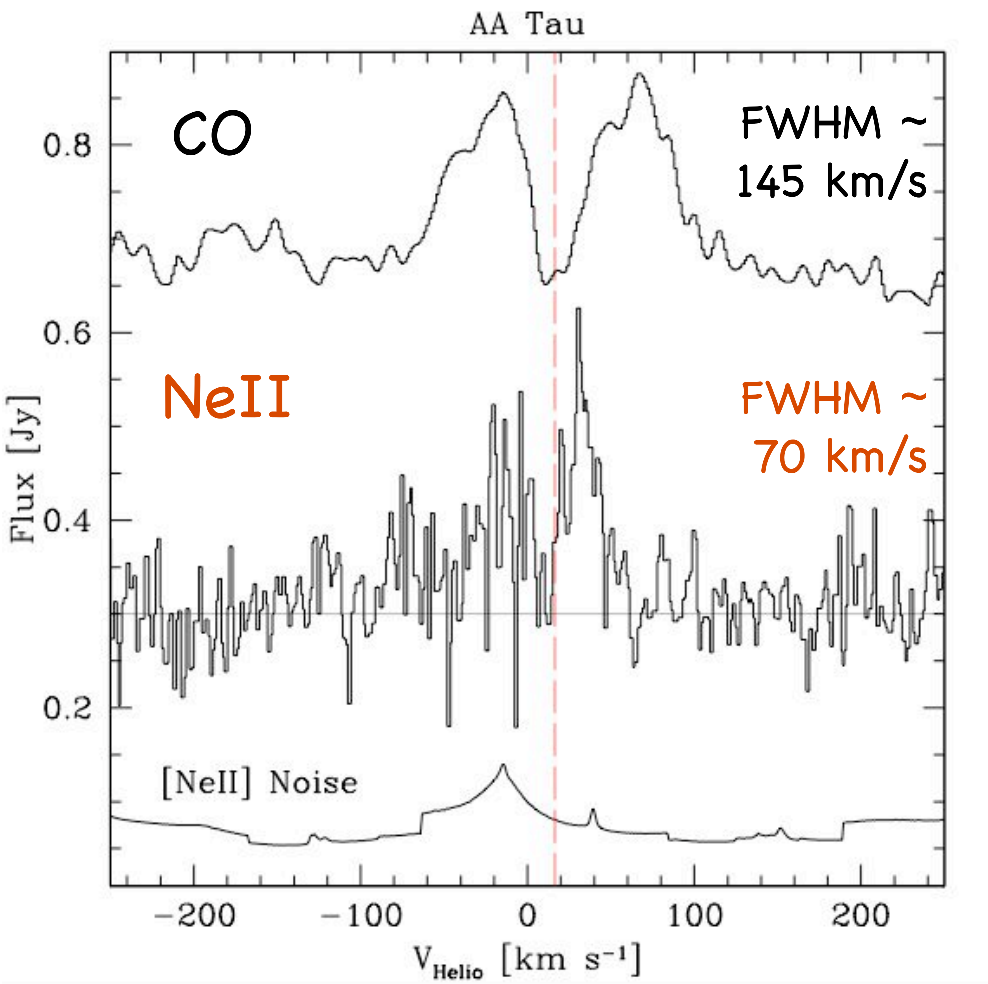
Line is symmetric, approximately at RV of star

- FWHM (21 km/s) is broader than expected for i=3.
- Formation at 0.1 AU, turbulence, or photoevaporation.

NeII Line Profiles vs. Inclination

Scenario for NeII line width	At larger i, line profile is...
Rotation	Broader
Turbulence	Unchanged
Photoevaporation	Lower velocity; blueshifted

NeII Emission at High Resolution: AA Tau



Najita, Bitner, Herczeg, Richter, Lacy et al., in prep

Gemini/TEXES

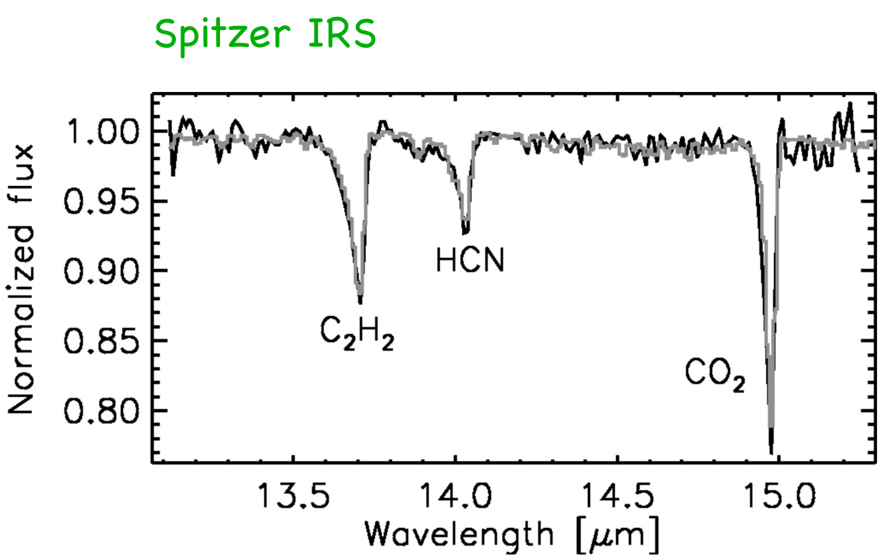
R ~ 50,000

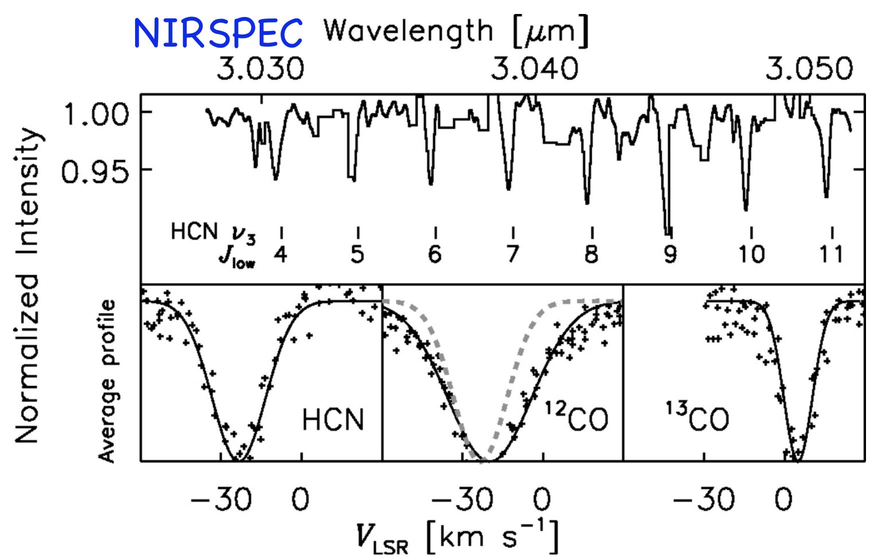
- Line is approx. symmetric and at RV of star
- Profile is consistent with double-peaked
- Narrower than CO fundamental emission

Broader NeII for higher i=75 of AA Tau consistent with disk origin. But need larger sample, better profiles.

Organic Molecules in Absorption: IRS 46

Lahuis et al. 2006

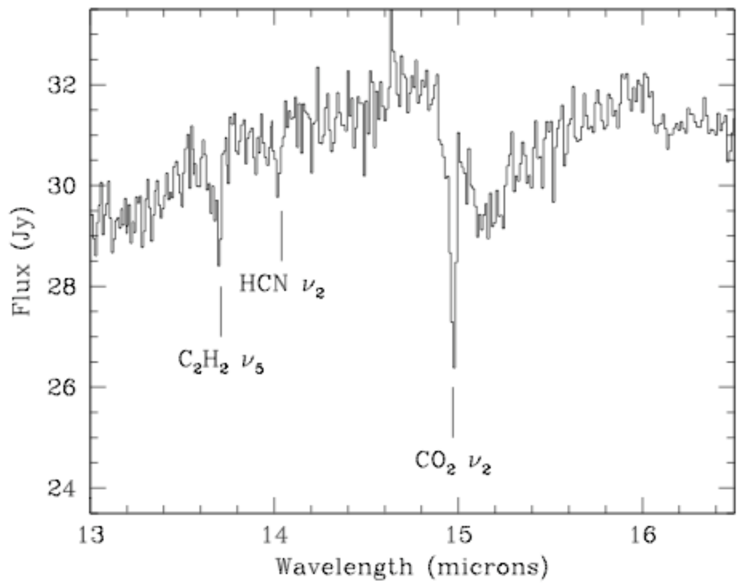




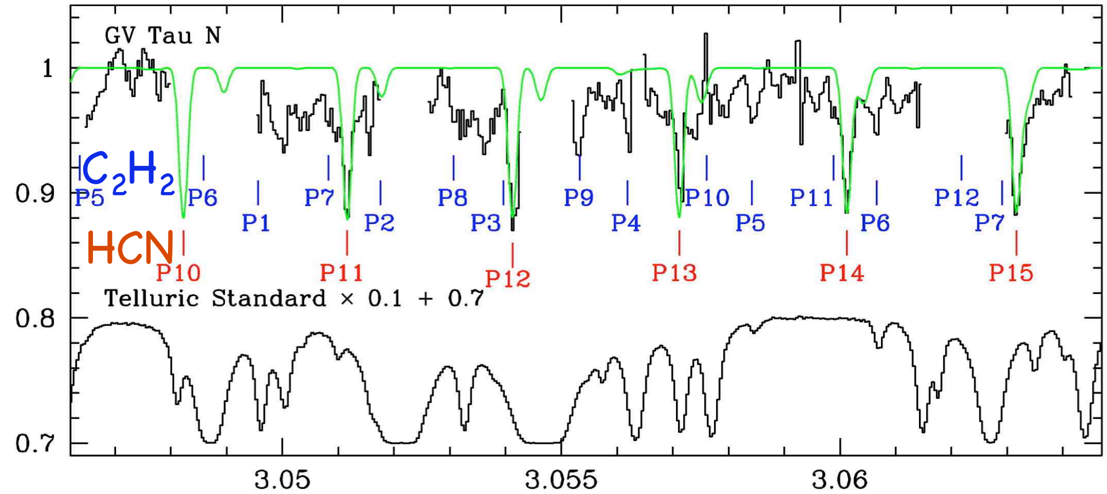
- C_2H_2, HCN, CO_2 detected in absorption (700-300K).
- NIR CO and HCN is blueshifted from cloud -20 km/s. Origin in a disk atmosphere or disk wind?
- Such absorption is rare; ~1/100 sources in c2d.

Organic Molecules in Absorption: GV Tau

Spitzer Courtesy IRS GTOs

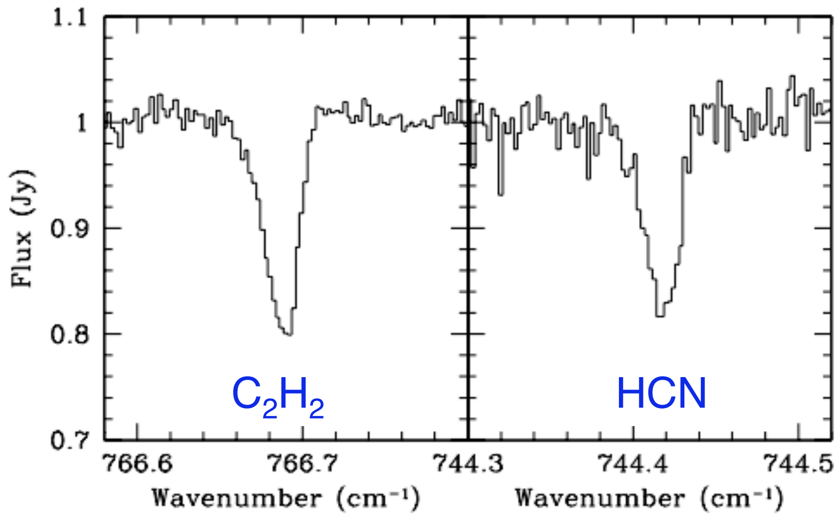


NIRSPEC 3μm: Doppmann et al. 2008; see also Gibb et al. 2007



- C_2H_2, HCN, CO_2 detected in absorption (T=550 for HCN)
- 3μm HCN ~at cloud velocity; absorption in a disk atmosphere?
- Source is very bright in MIR; enables study of other molecules

MIR Molecular Absorption at High Spectral Resolution

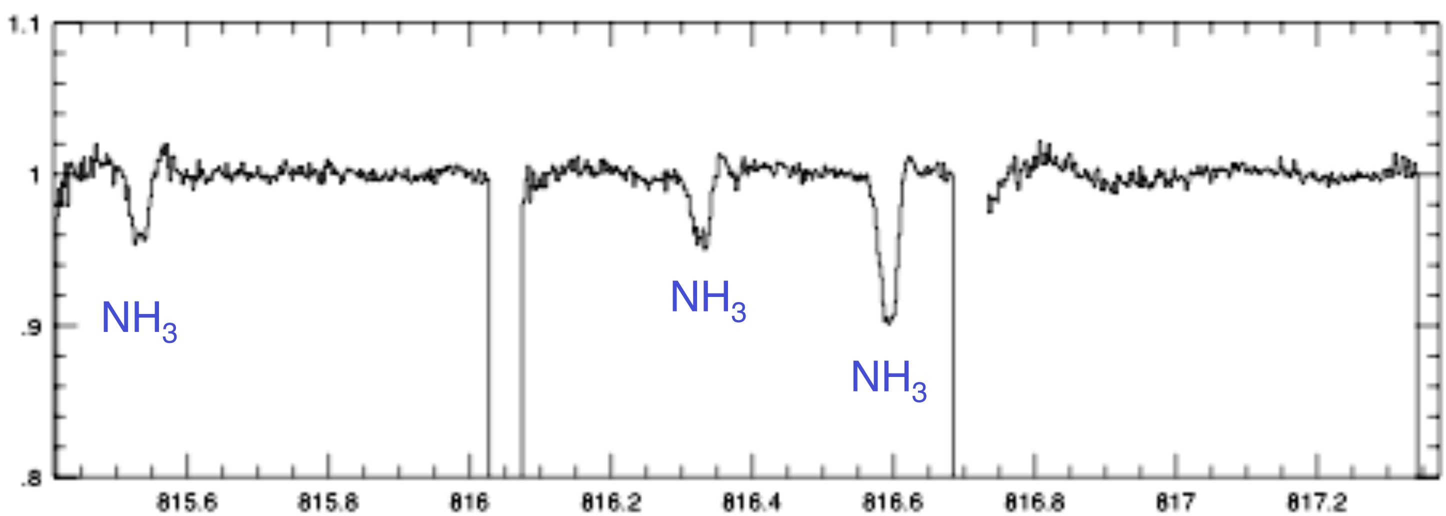


Gemini/TEXES (R=100,000)

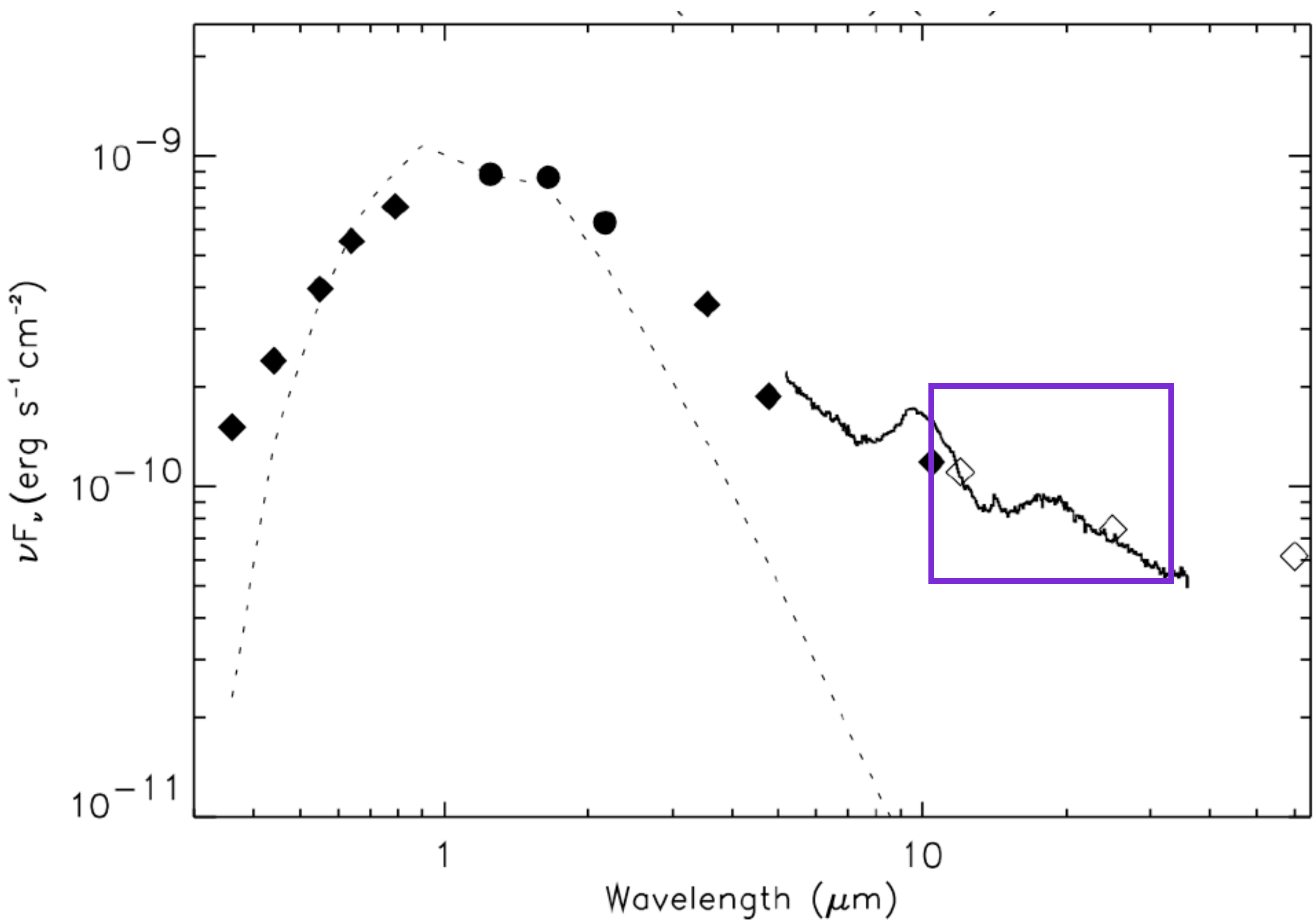
FWZI ~ 20 km/s

Can detect molecules w/o strong bands that Spitzer does not detect.

Study relative abundances in disk atmospheres.

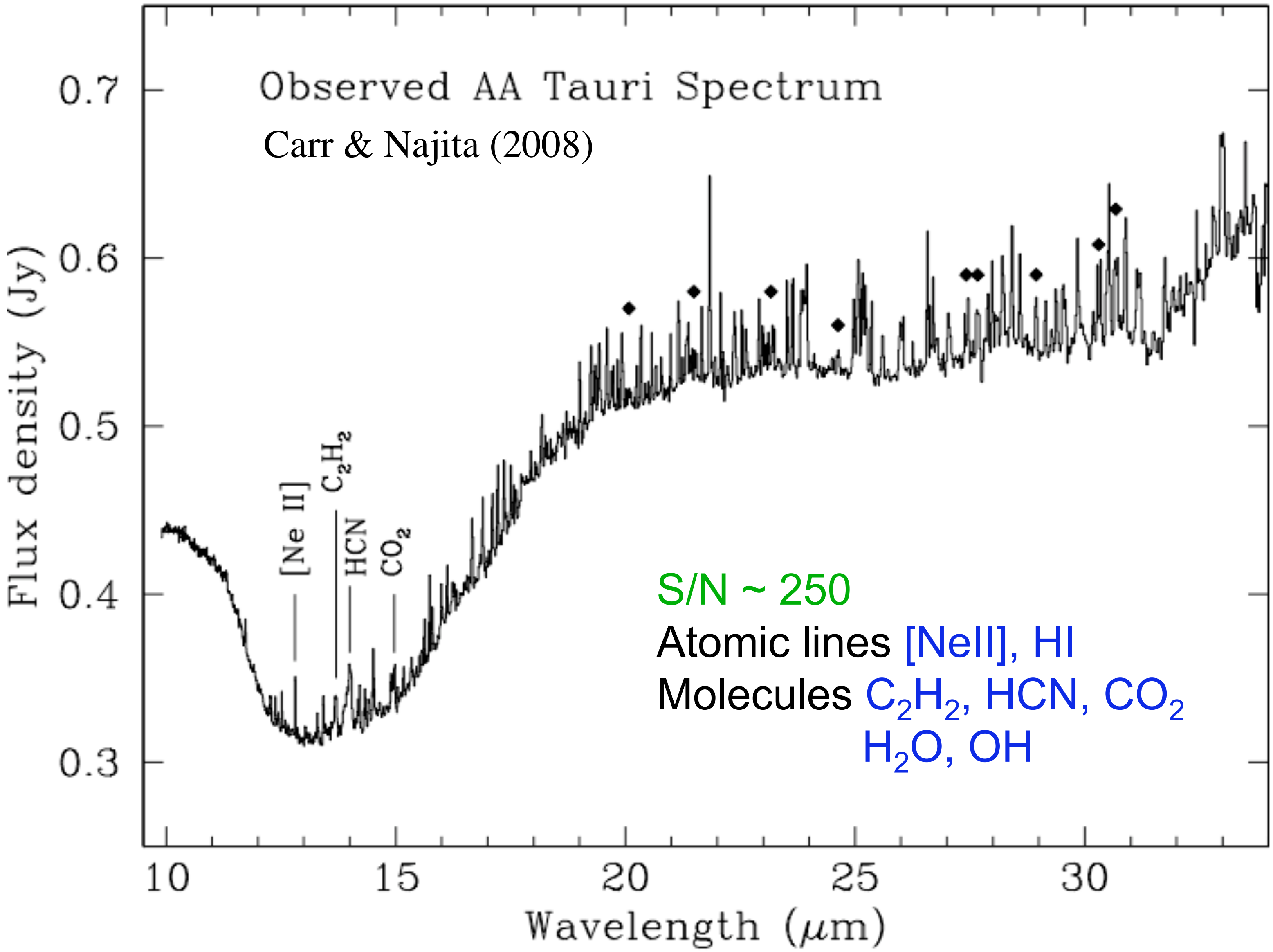


Spitzer IRS Spectrum of a Typical T Tauri Star

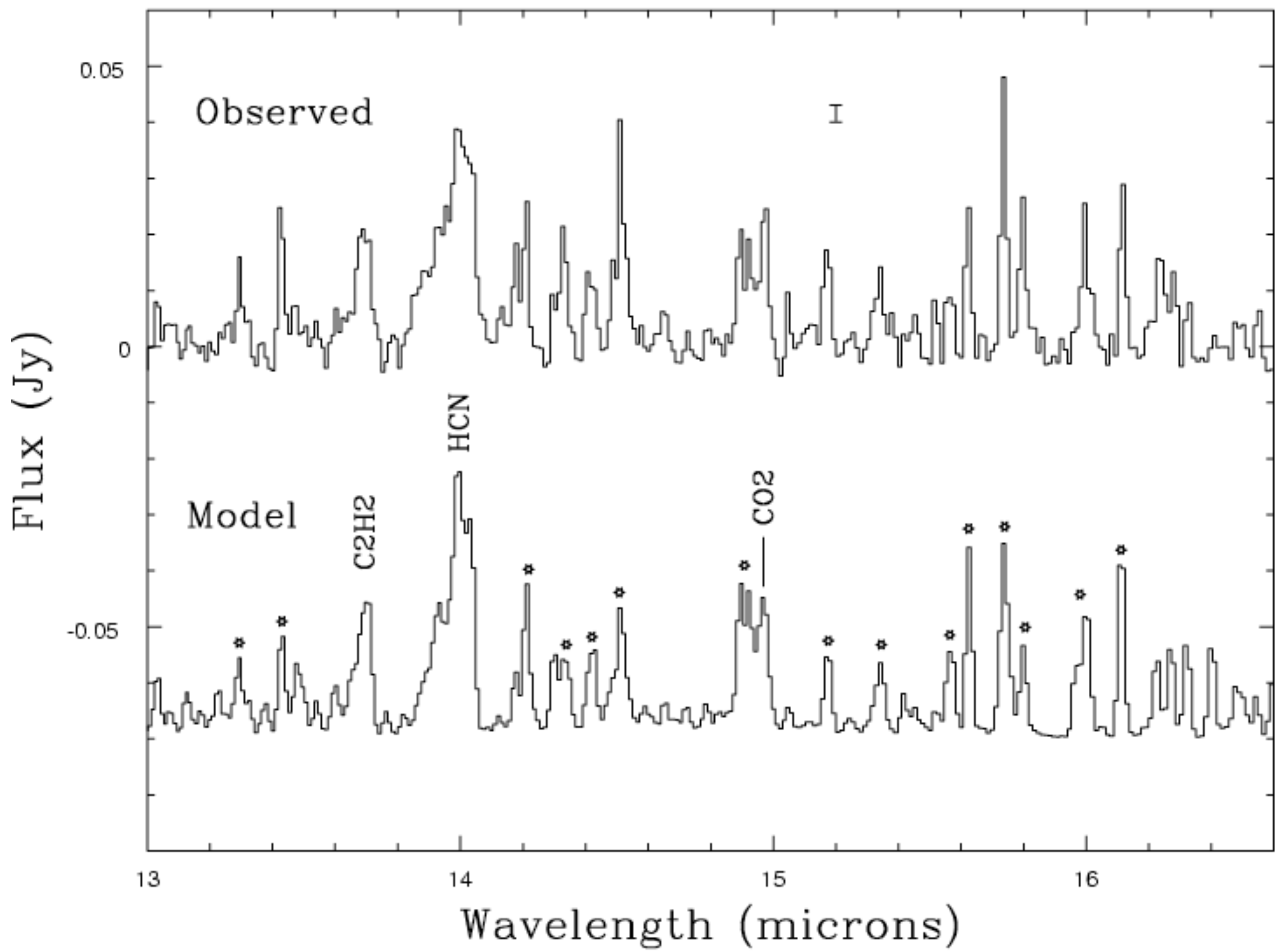


Low resolution, modest s/n

Spitzer IRS Spectrum of a Typical T Tauri Star



Continuum-subtracted T Tauri Star Spectrum



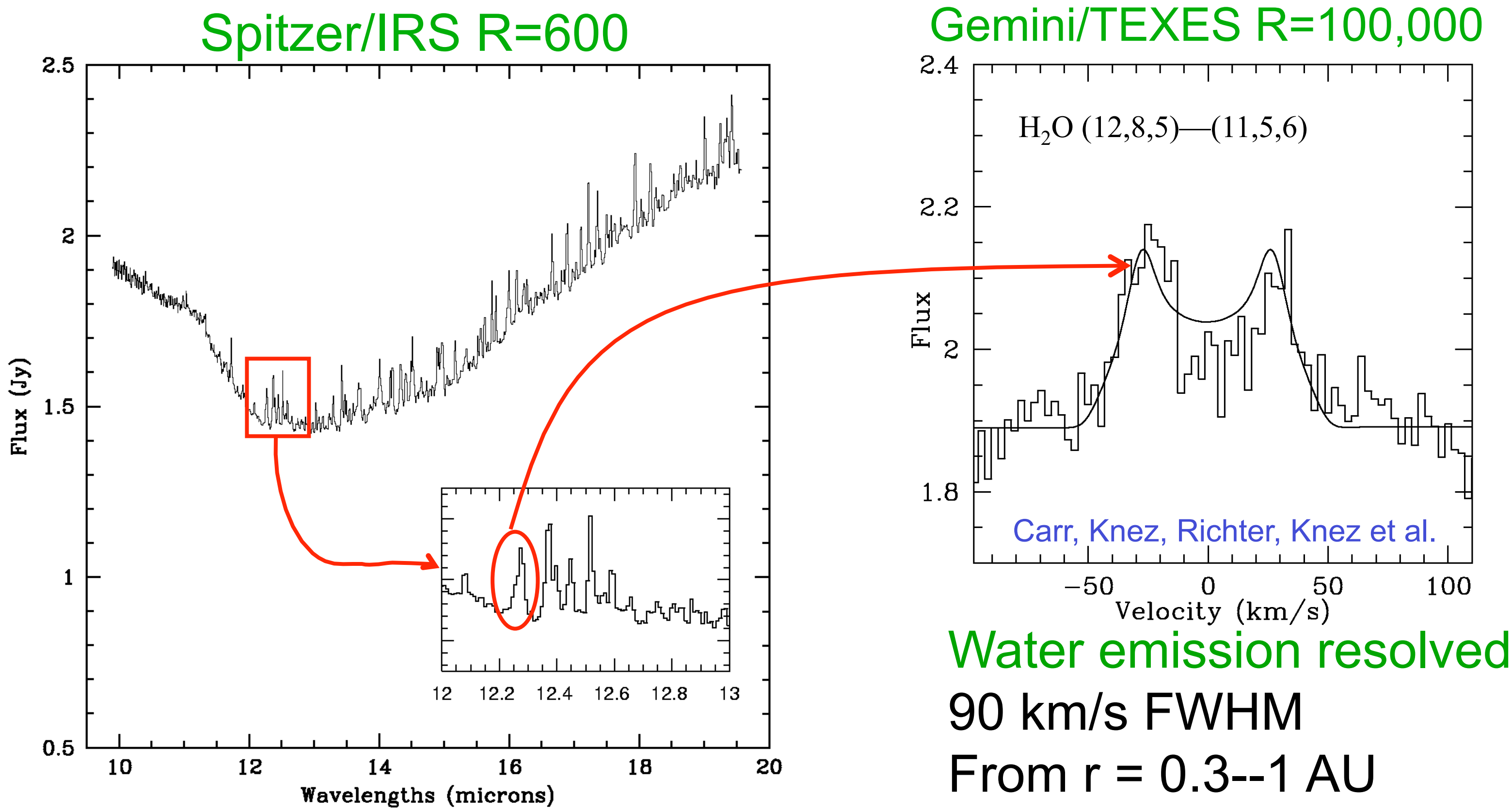
Lines of water throughout (*)

Molecular Emission Properties

Molecule	T (K)	N (10^{16}cm^{-2})	R (AU)
H_2O	575	65	2.1
OH	525	8.1	2.2
HCN	650	6.5	0.6
C_2H_2	650	0.81	0.6
CO_2	350	0.2–13	1.2
CO	900	49	0.7

Temperatures and emitting areas consistent with an origin in the terrestrial planet region of the disk

H_2O Rotational Emission Line Resolved



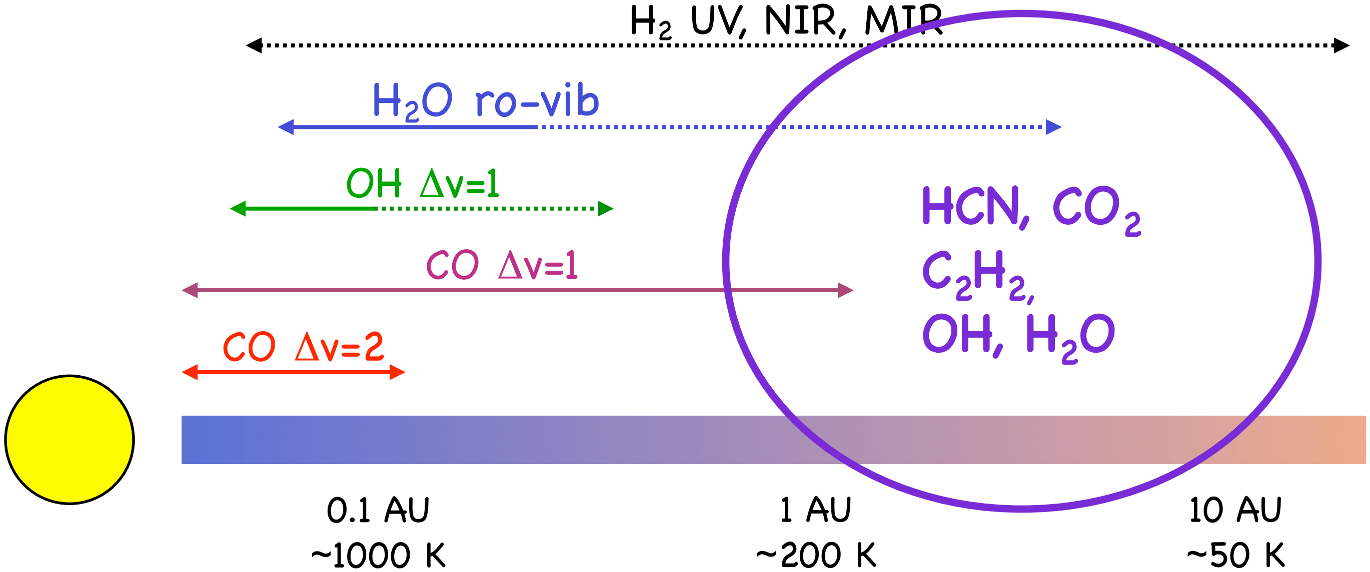
Water emission resolved:

90 km/s FWHM

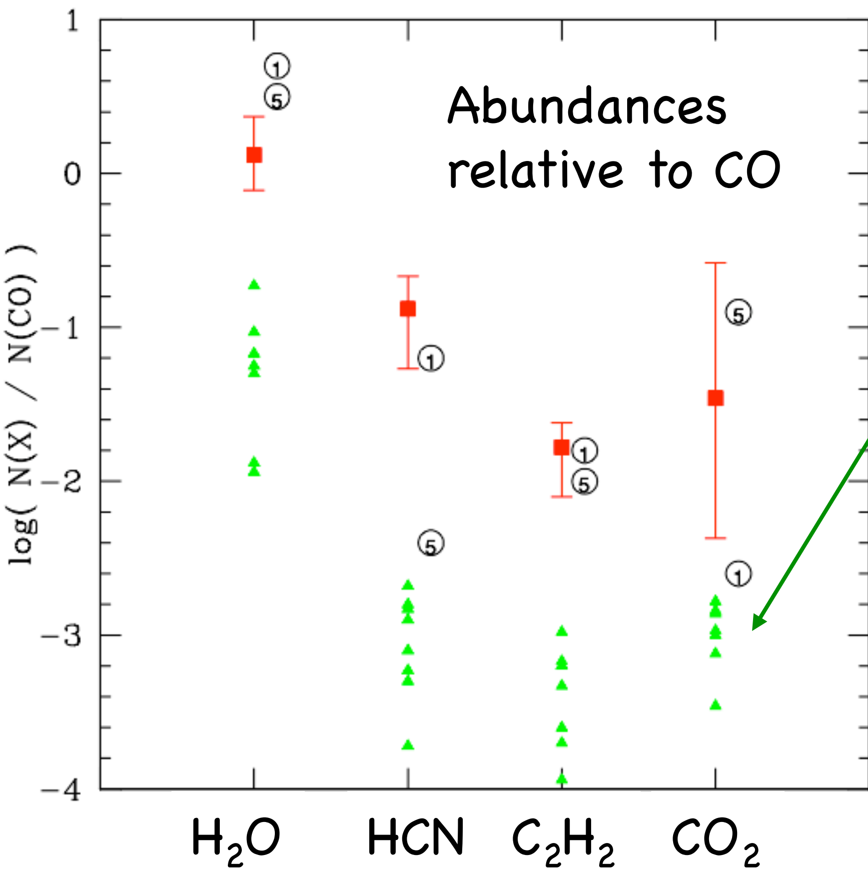
From r = 0.3--1 AU

Line profiles, temperatures, and emitting areas indicate origin in planet formation region of disk

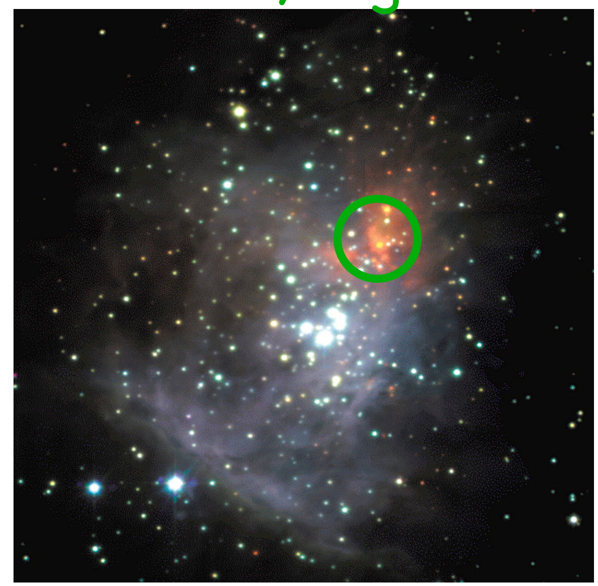
Molecular Probes of Inner Disks

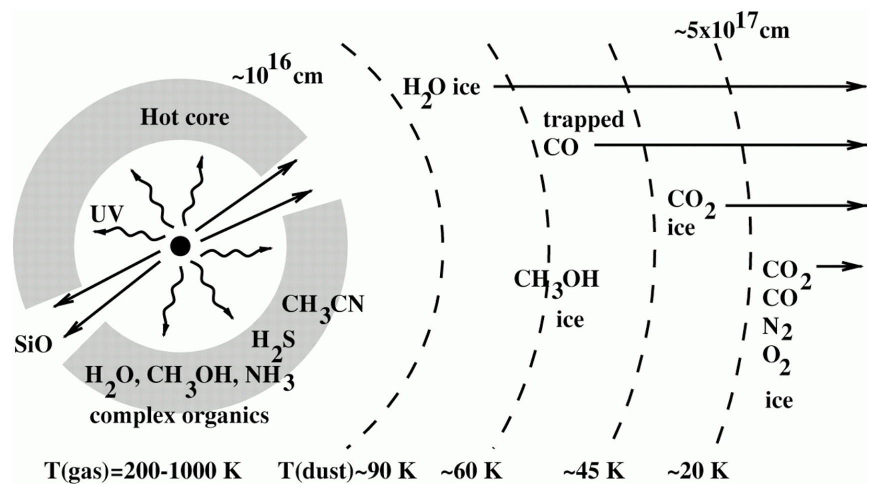


AA Tau Molecular Abundances



"Hot core", e.g. Orion





Higher abundances than hot cores
→Molecular synthesis in disks
→Similar chemistry to hot cores?

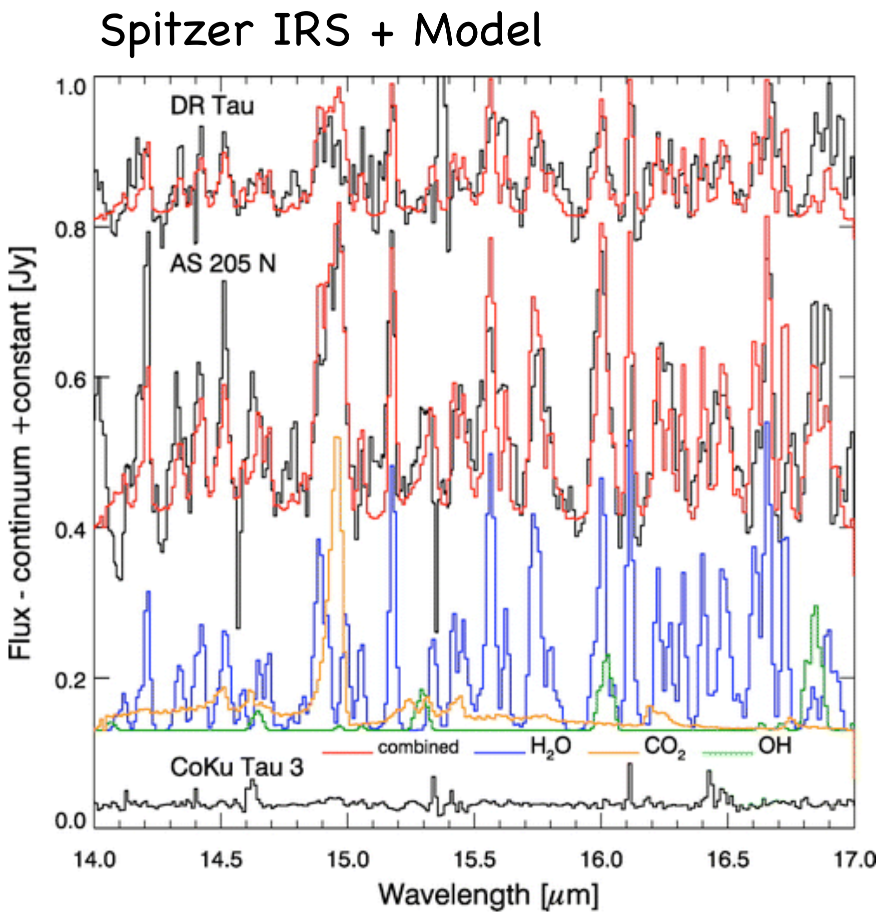
Molecular Inventories

Starting to probe molecular processing in disks!

Relative Abundances	Comets			Disks	Pre-Infall
	Halley	Hyakutake	Hale-Bopp	Inner Disk Atmospheres	Orion Hot Core
H_2O	100	100	100	100	>100
CO	15	6-30	20	200-1000	1000
CO_2	3	2-4	6-20	0.1-3	2-10
C_2H_2	-	0.5	0.1	0.01-1	3-10
HCN	0.1	0.1	0.25	0.1-10	4
NH_3	0.1-2	0.5	0.7-2	<1	8

Related Result

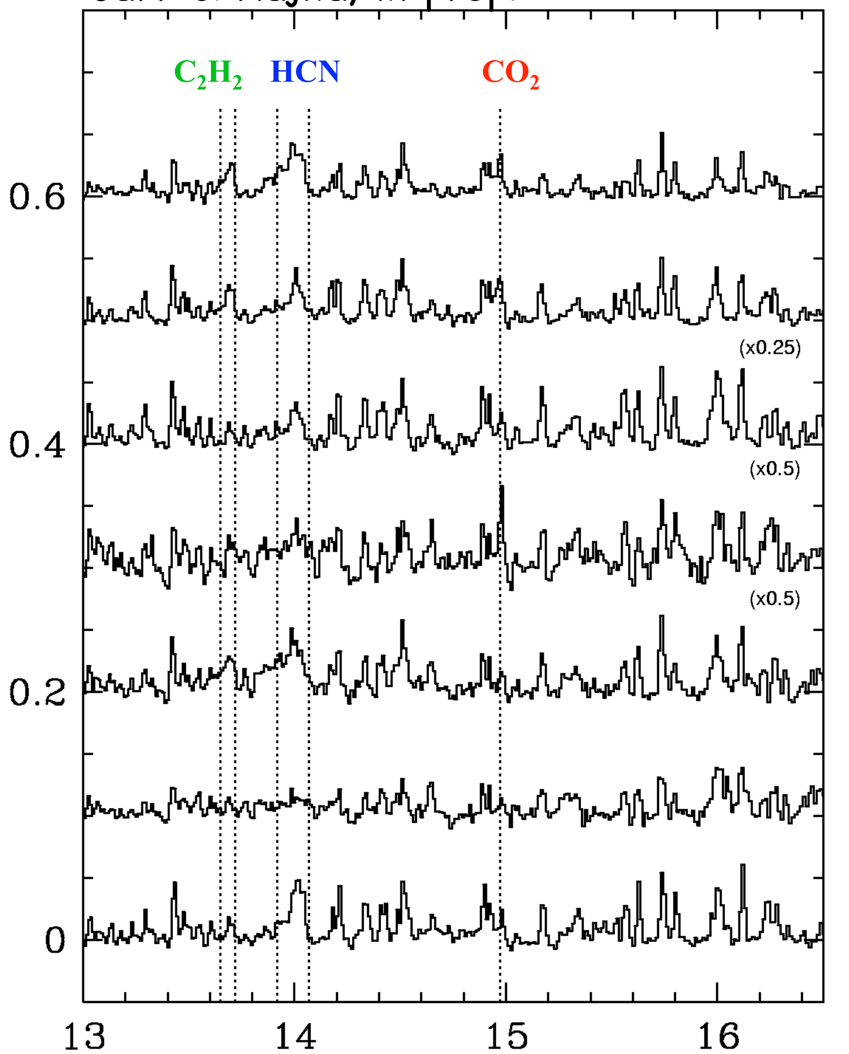
Salyk et al. (2008)



- H_2O, CO_2, OH emission from T Tauri stars DR Tau and AS 205 N
- From warm ~1000 K inner disk?
- Complementary high resolution NIR spectroscopy of CO, H_2O, OH

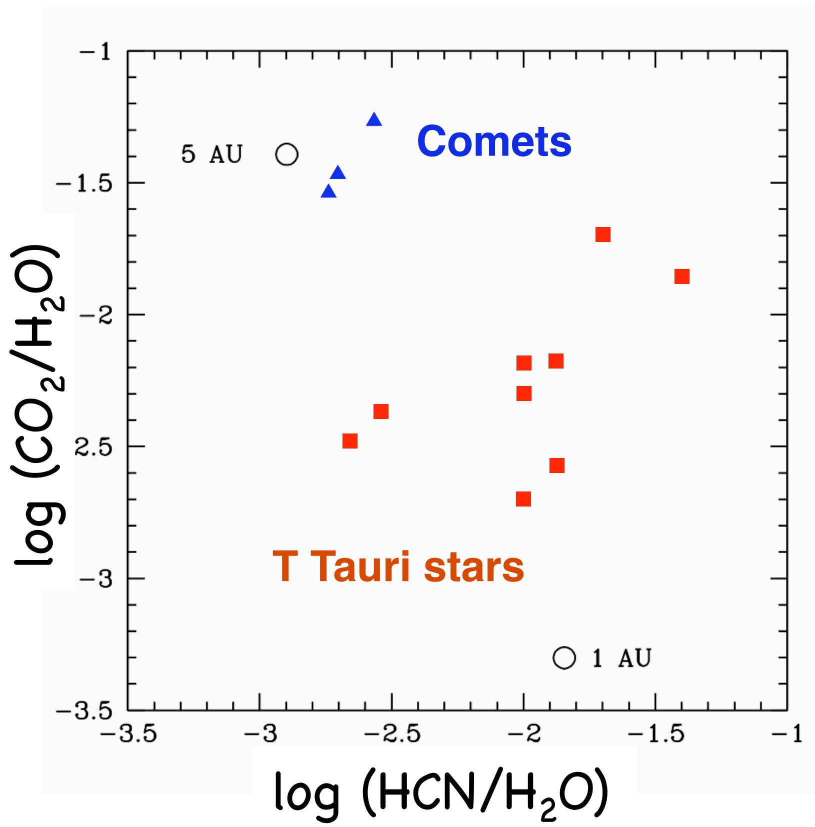
Molecular Emission is Common, Diverse

Carr & Najita, in prep.



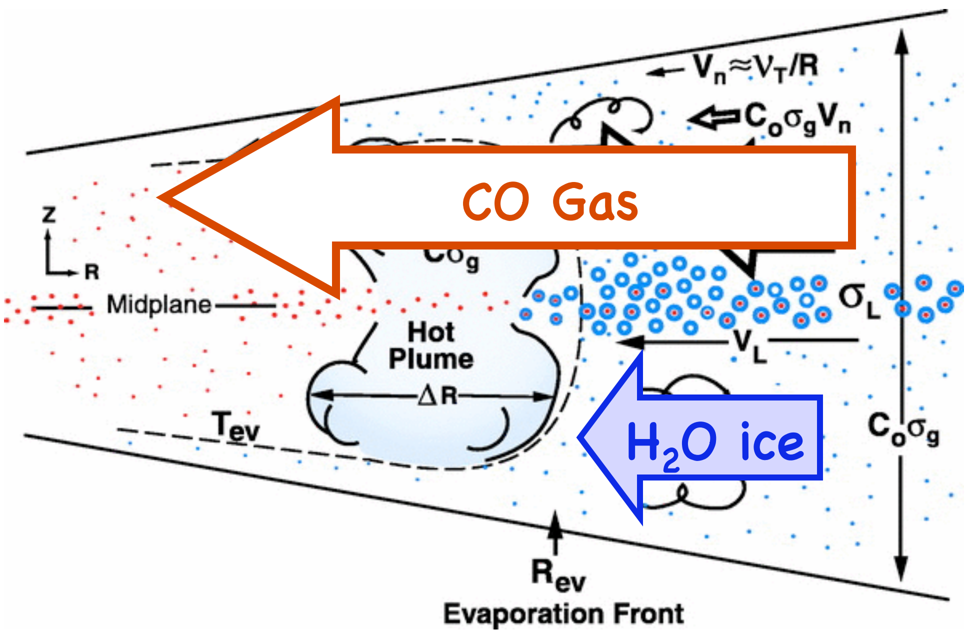
What other species are present?

- Relative strengths of molecular features vary.
- Abundances are diverse.



Can Abundances Probe Icy Bodies?

Problem: planetesimals (~1 km) and protoplanets (~M_{Mars}) are too small to open gaps. How to detect them?



Cuzzi & Zahnle 2004
Ciesla & Cuzzi 2007

Large (> 1km), non-migrating bodies dehydrate inner disk (low H_2O); increases C/O; enhances organic molecules?

What Can We Learn from Surface Abundances?

May be affected by:

Irradiation (UV, X-rays)

Radial & vertical mixing

Accretion

Grain growth & settling

Planetesimal migration

etc.

Measurable demographics:

L_X, L_{UV}

Mdot

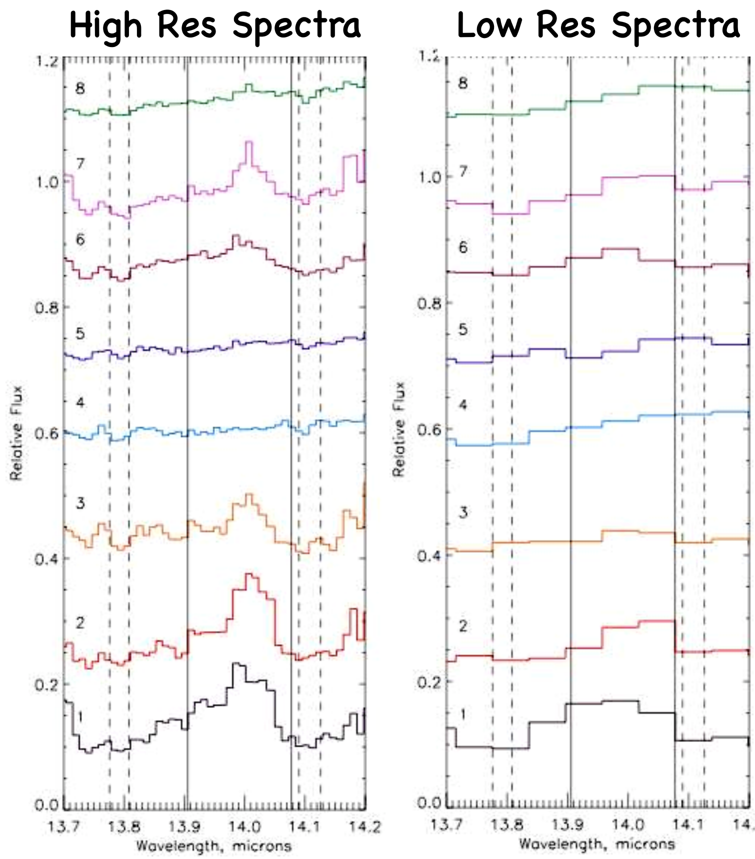
SED shape

Silicate feature morphology

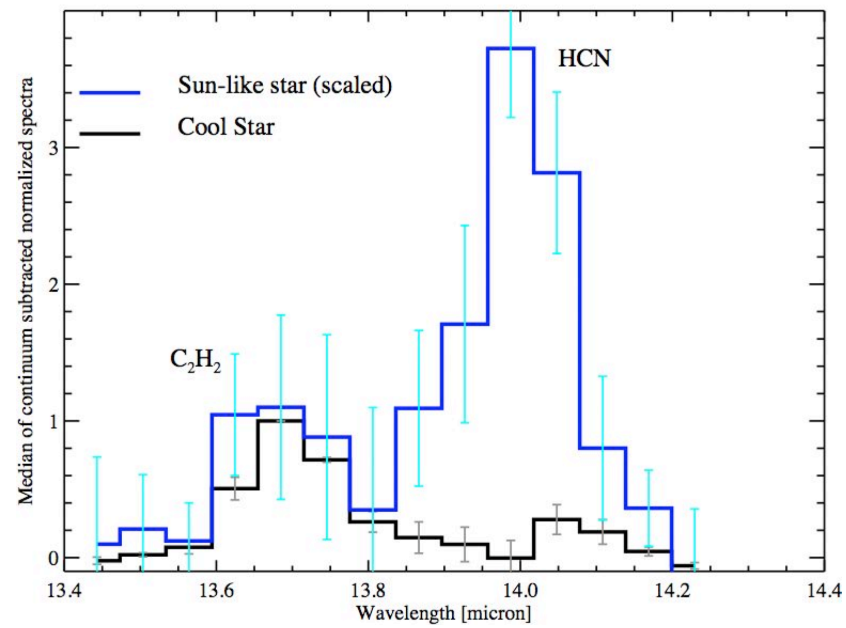
Crystallinity

Need a big survey: Carr, Blake, van Dishoeck, Pontoppidan, Salyk, Lahuis, & Najita (GO5)

Probing Organic Molecules with Low Res IRS data



Pascucci et al. 2008



Can detect and recover trends in relative strengths of strong molecular bands in low res IRS spectra
(Teske et al. poster).

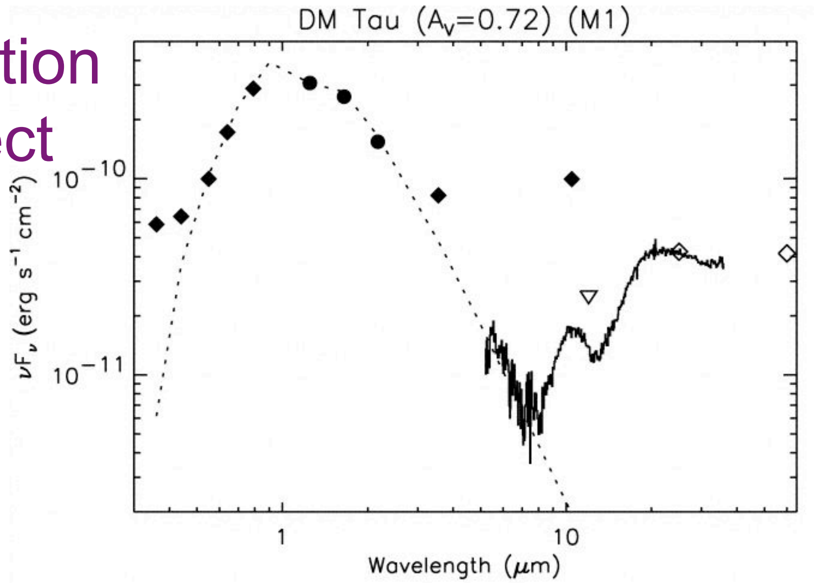
HCN/C_2H_2 strength differs in

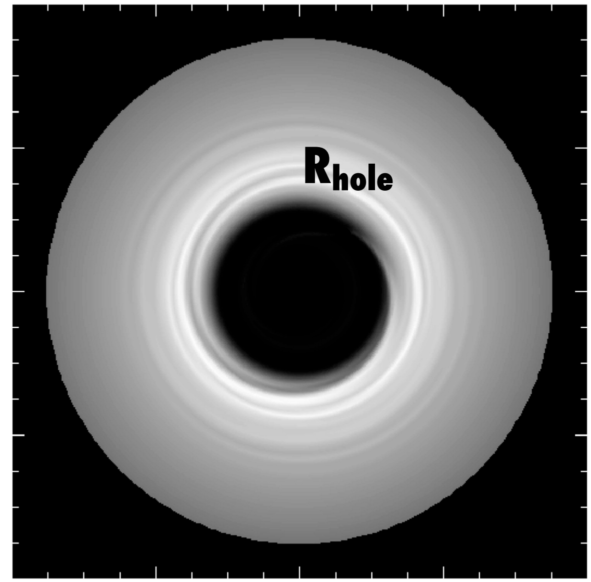
- CTTS (>1)
- Brown dwarfs (<1)

(Pascucci et al. poster)

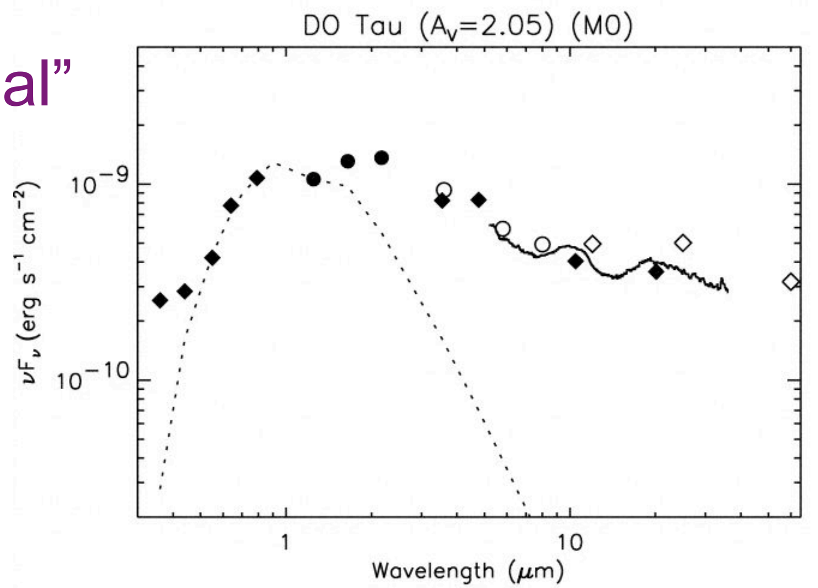
Transition Object SEDs imply evolution

Transition Object





"Normal"



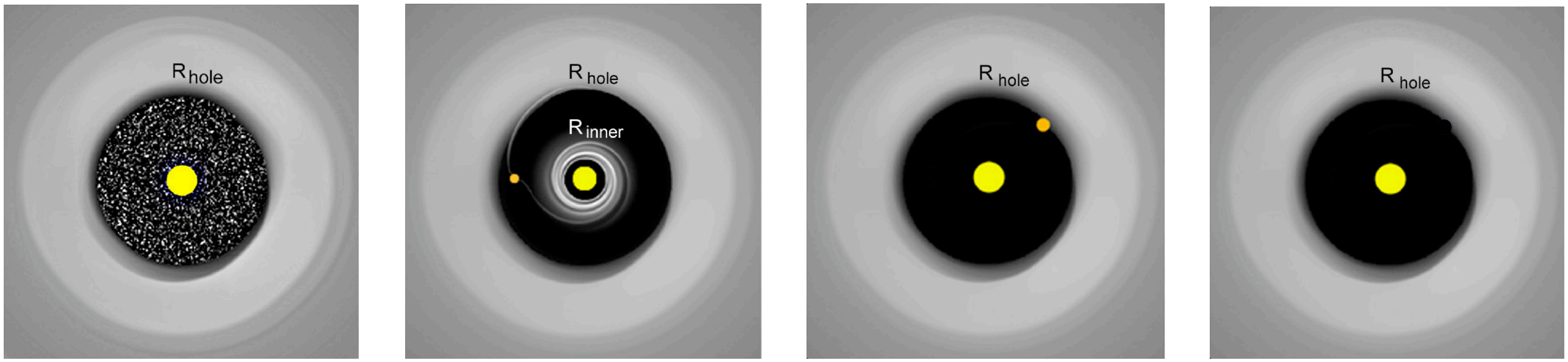
Optically thin inner region

(< R_{hole} = 1-50 AU)

Optically thick outer disk

(> R_{hole})

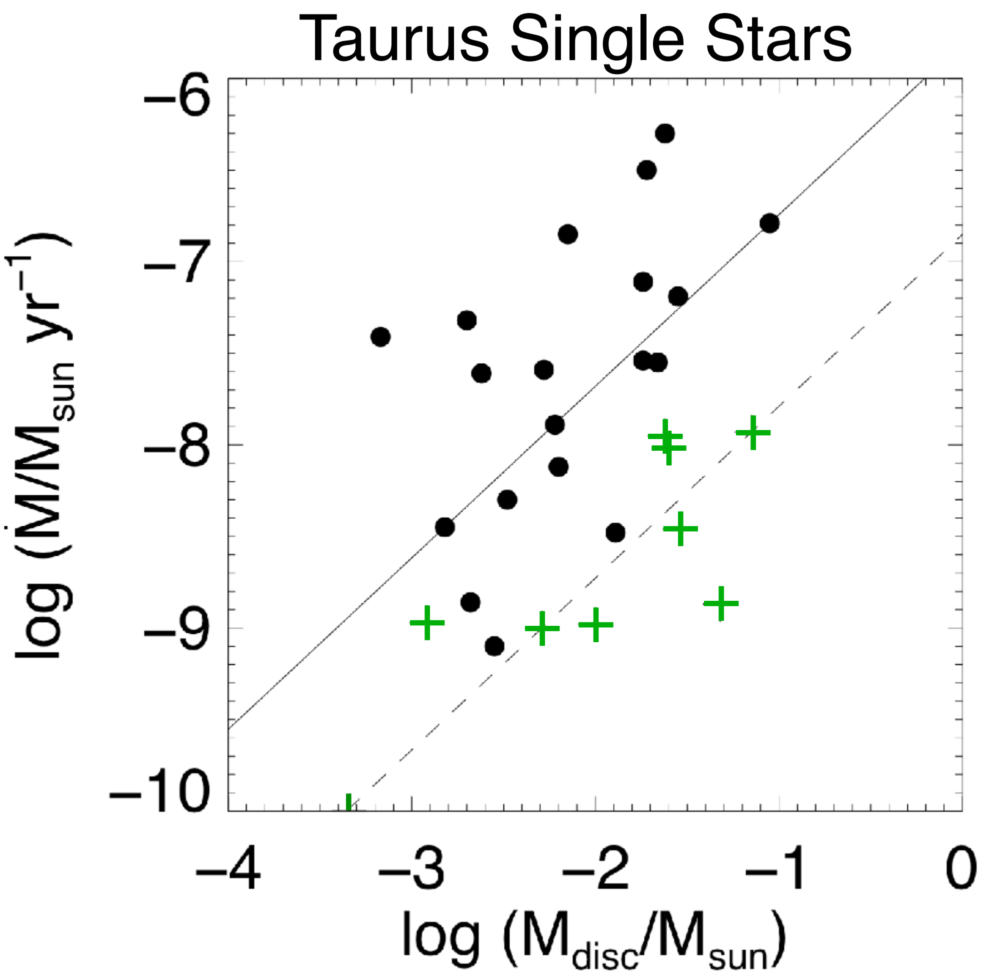
Planetesimal | ~1M_J Planet | ~5M_J Planet | Photoevaporating



Stage	Outer Disk Mass	Stellar Mdot	Gas w/in R_{hole}
Grain Growth	Any	CTTS	Fills R_{hole}
~1 M_J Planet	High	~0.1 CTTS	$R < R_{inner}$
~5 M_J Planet	Very High	None	None
Photo-evaporation*	Low	None	None

* Poster #86 (Cieza) discusses evidence for this scenario.

Demographics: M_{disk} vs. Stellar Mdot



Najita, Strom & Muzerolle (2007)

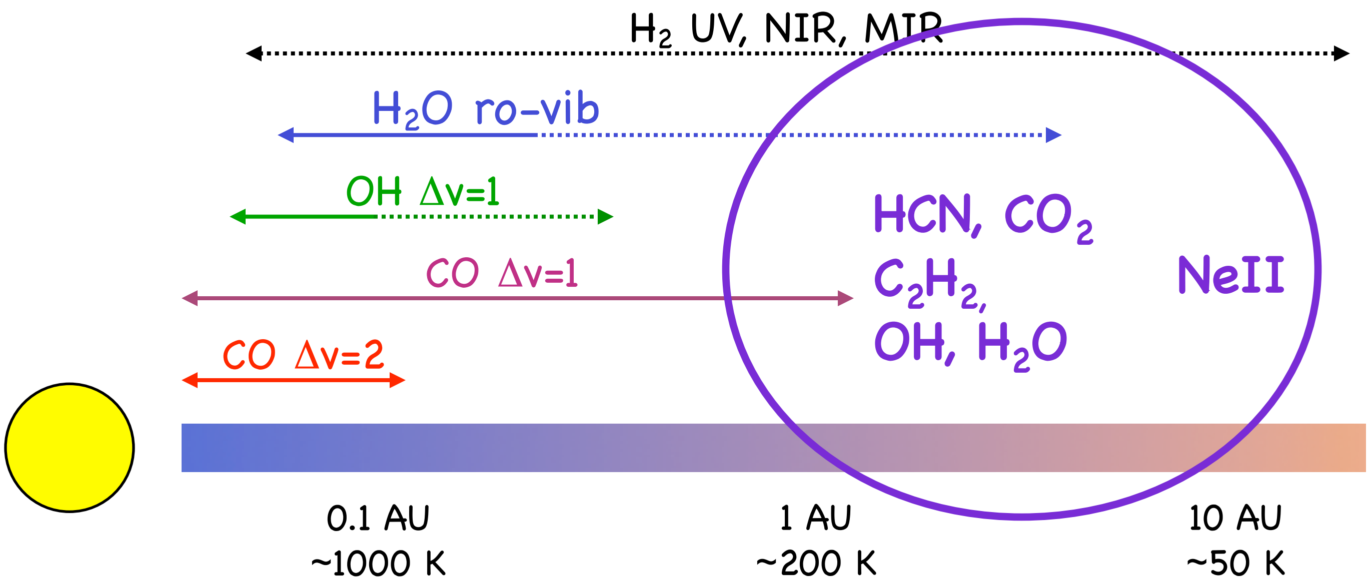
Transition objects:

- 10 x lower accretion rates for their disk masses.
- 4 x higher disk masses

Black = non-transition

Crosses = transition

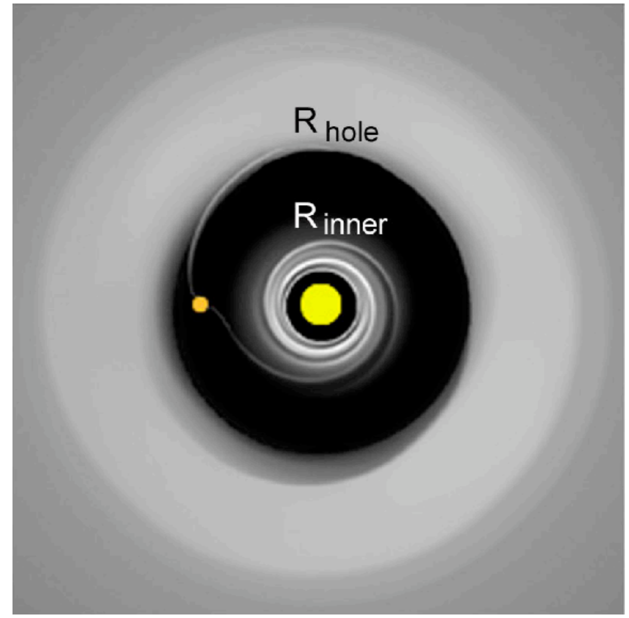
Gaseous Probes of Inner Disks



New diagnostics from Spitzer

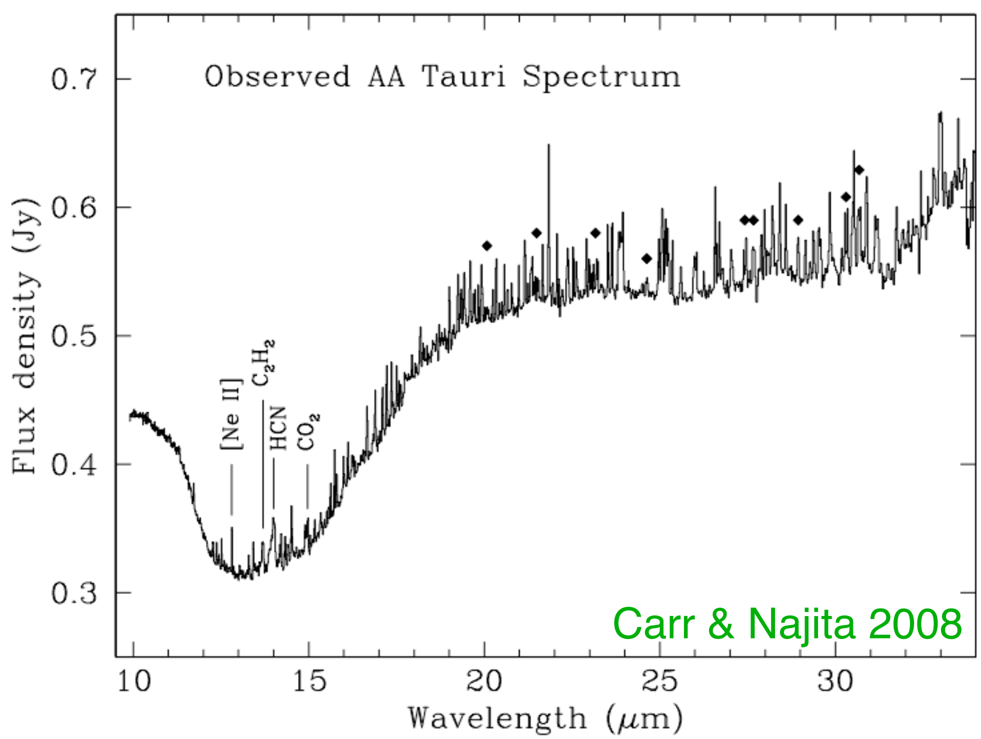
Gas in Transitional Disks

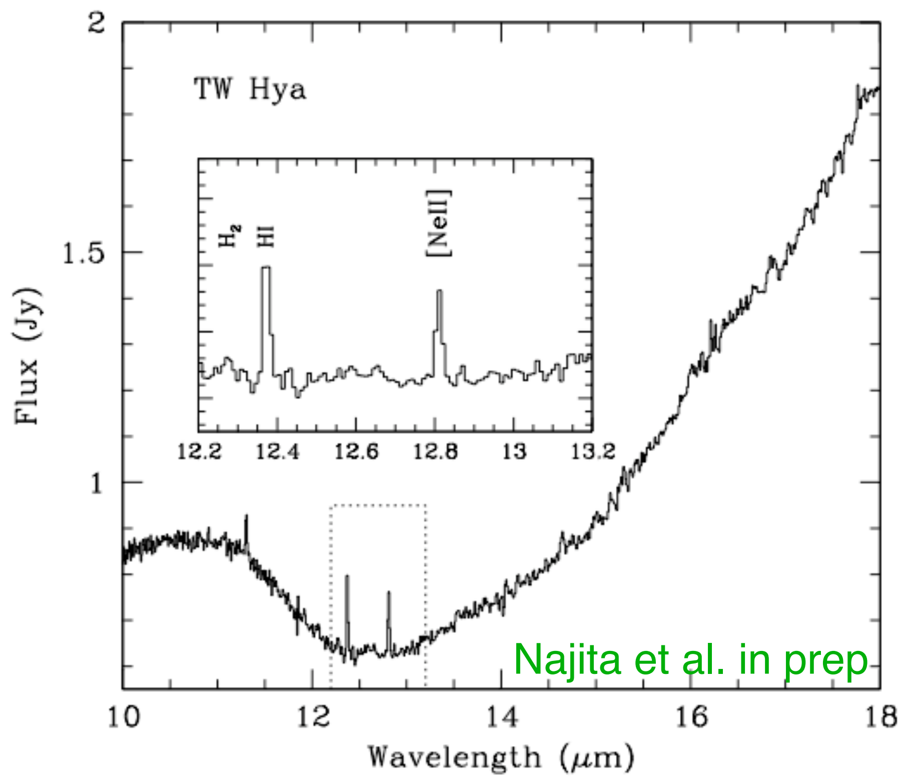
	R_{hole}	Tracer	FWHM	Ref
TW Hya	4	CO	8.3	Salyk07
		H2 UV	14	Herczeg06
		H2 NIR	<13.6	Weintr.00
		NeII	22	Herczeg07
DM Tau	3	H2 UV	--	Bergin04
		NeII	--	Espaillat07
GM Aur	24	CO	50	Salyk07
		H2 UV	--	Bergin04
		H2 NIR	~10?	Bary08?
		NeII	~15	Najita08
LkCa 15	46	CO	80	Najita03
		H2 UV	--	Bergin04
		H2 NIR	~10	Bary03
CS Cha	43	H2 NIR	13	Bary08
		NeII	--	Espaillat07



- CO: gas in the inner (accretion) disk;
- Where do other tracers arise?

A typical CTTS and a Transition Object





Transition Objects lack strong molecular emission in SH

- Missing gas at a few AU?
- Or low excitation due to low accretion?

Need theory…or try empirical approach?

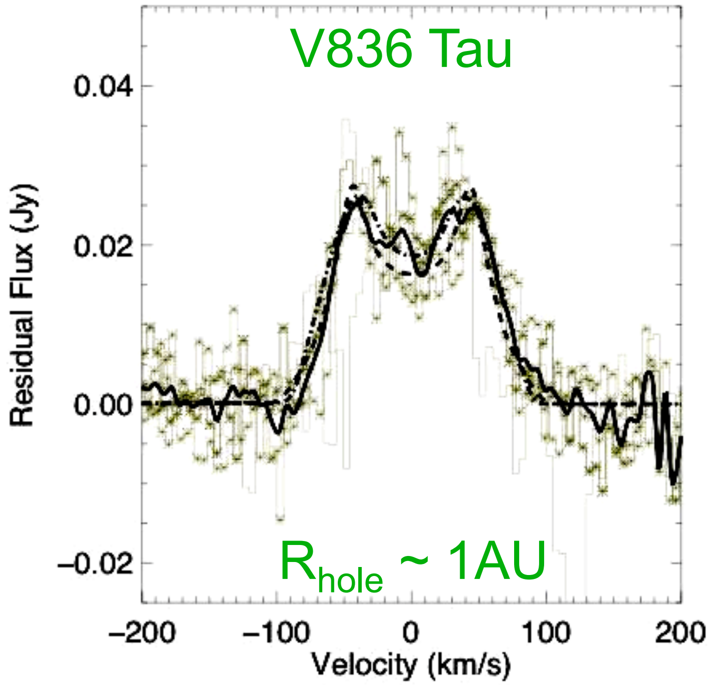
Theories of Gaseous Disk Atmospheres

Species	Studies
Atomic, H_2, CO, H_2O	Glassgold et al. 2004, 2007, Meijerink et al. 2007+poster
	Kamp & Dullemond 2004+ Jonkheid et al. 2004+
	Gorti & Hollenbach 2008 + posters
Focus on H_2	Nomura & Millar 2005, Nomura et al. 2007 + poster
Focus on Atomic	Ercolano et al. 2008 + poster
Water and Organics	Markwick et al. 2002 Agundez et al. 2008 Woods & Willacy 2008 Poster by #31 M. Kress

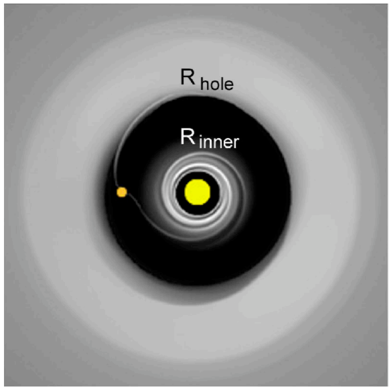
Note: different assumptions about heating processes, chemistry, gaseous hydrostatic equilibrium.

CO Line Profile of V836 Tau

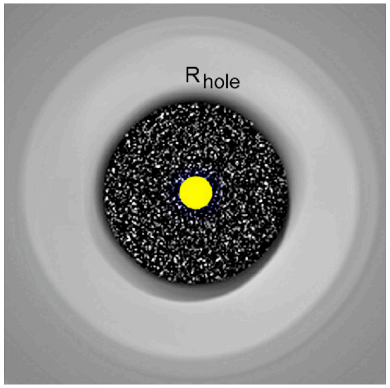
Najita, Crockett, Carr 2008



Line profile indicates CO emission from 0.06-0.4 AU Even after correcting for stellar CO absorption.



Truncated disk?

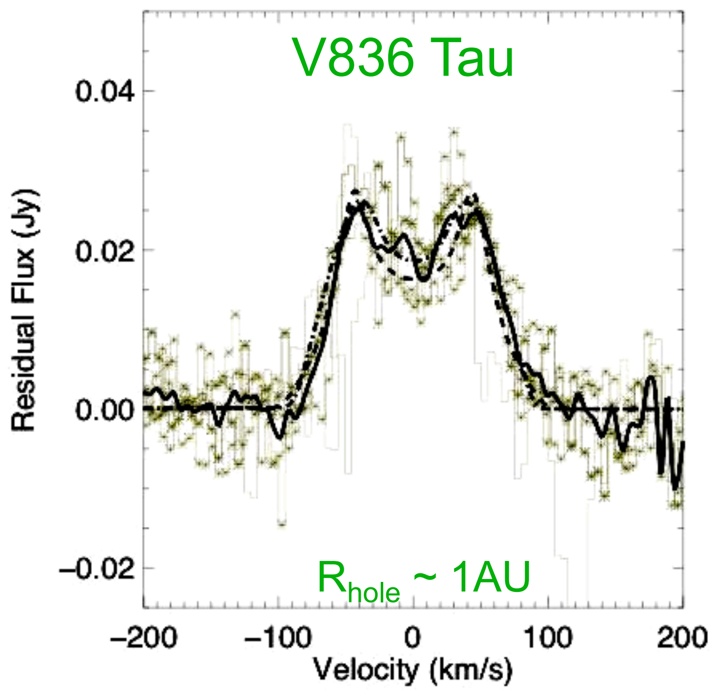


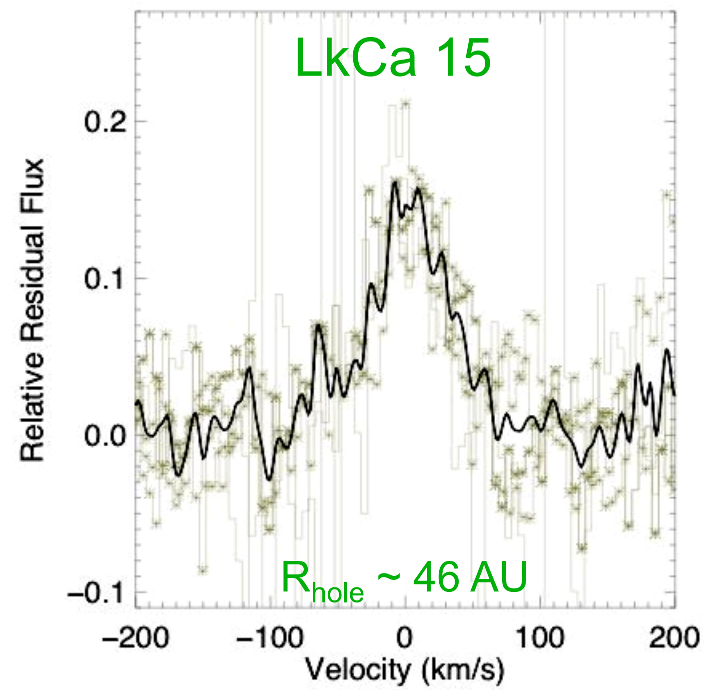
Low excitation due to low accretion rate?

CO Profiles of TOs V836 Tau and LkCa 15

Najita, Crockett, Carr 2008

Both have low accretion rates (~10^{-9} M_{sun}/yr) and weak NIR excesses.



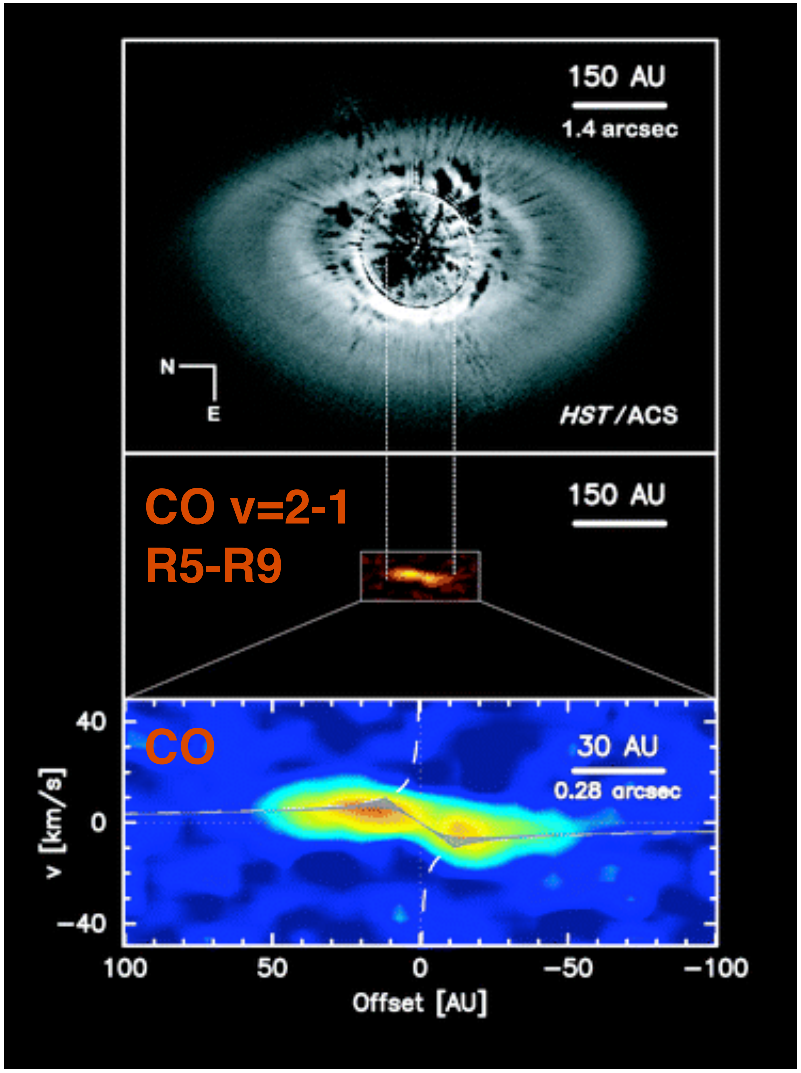


CO from 0.06-0.4 AU
Look at other diagnostics for corroborating evidence -- expect an emission deficit at 25-40 km/s

CO emission to >1-2 AU.
(Similar to other CTTS.)

Probing Disk Structure with UV Fluorescent CO Emission

- UV fluorescence can light up even cool gas and reveal its presence.
- Spatially resolved CO in HD141569 shows lack of emission within 10 AU (Goto et al. 2006).
- Lack of high velocity wings in UV fluorescent CO emission from HD141569 indicates a true CO inner hole (Brittain et al. 2007).
- Similar situation for HD100546 (talk by S. Brittain)



Goto et al. 2006

Spitzer Highlights

Molecular hydrogen is a challenging diagnostic.

✧ Likely carries most of the mass, but emission is weak.

Spitzer suggests exciting alternatives!

✧ **NeII** commonly detected.

- Line strengths similar to predictions for irradiated disks.
- Line profiles consistent with disk origin (so far).
- Profiles and demographics useful to understand origin.

✧ **Organic molecules, OH, and water** detected from the terrestrial planet region of disks.

- In absorption: rarer, can probe large column densities
- In emission: common, abundances are diverse
- Study of larger samples needed to interpret diversity

Spitzer Highlights

Transition object spectra differ from CTTS spectra.

✧ At Taurus age, transition objects have low accretion rates for their disk masses.

✧ Spectral diagnostics:

- Diagnostics of gaseous inner disks of CTTS are present.
- Spitzer spectra differ: low column density or low excitation at distances of several AU?

✧ To interpret diagnostics:

- Use improved theory
- Try empirical approach
- UV fluorescence is a useful tool.