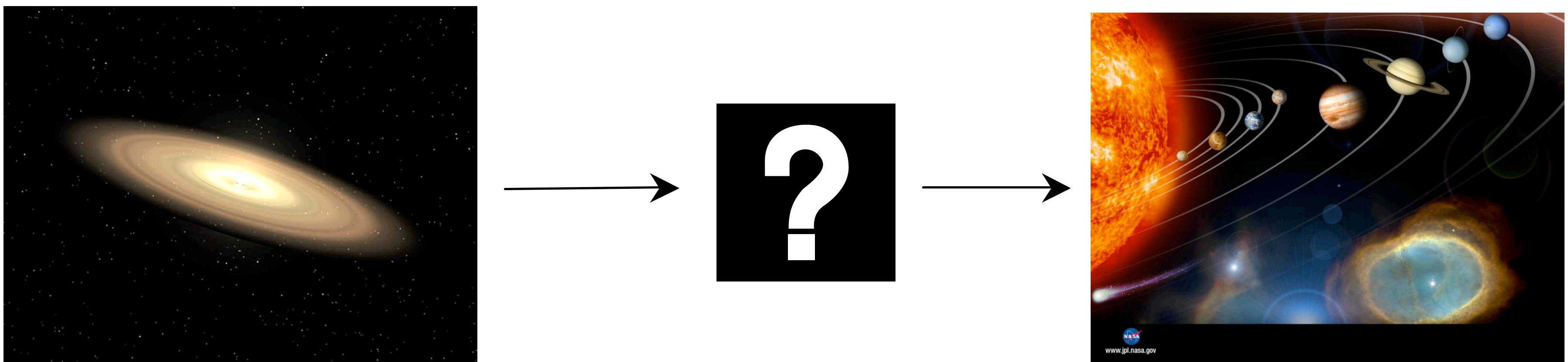
What Can Spectroscopy of Gas Tell Us about Stellar Evolution and Planet Formation?

Sean Brittain
Michelson Postdoctoral Fellow
National Optical Astronomy Observatory



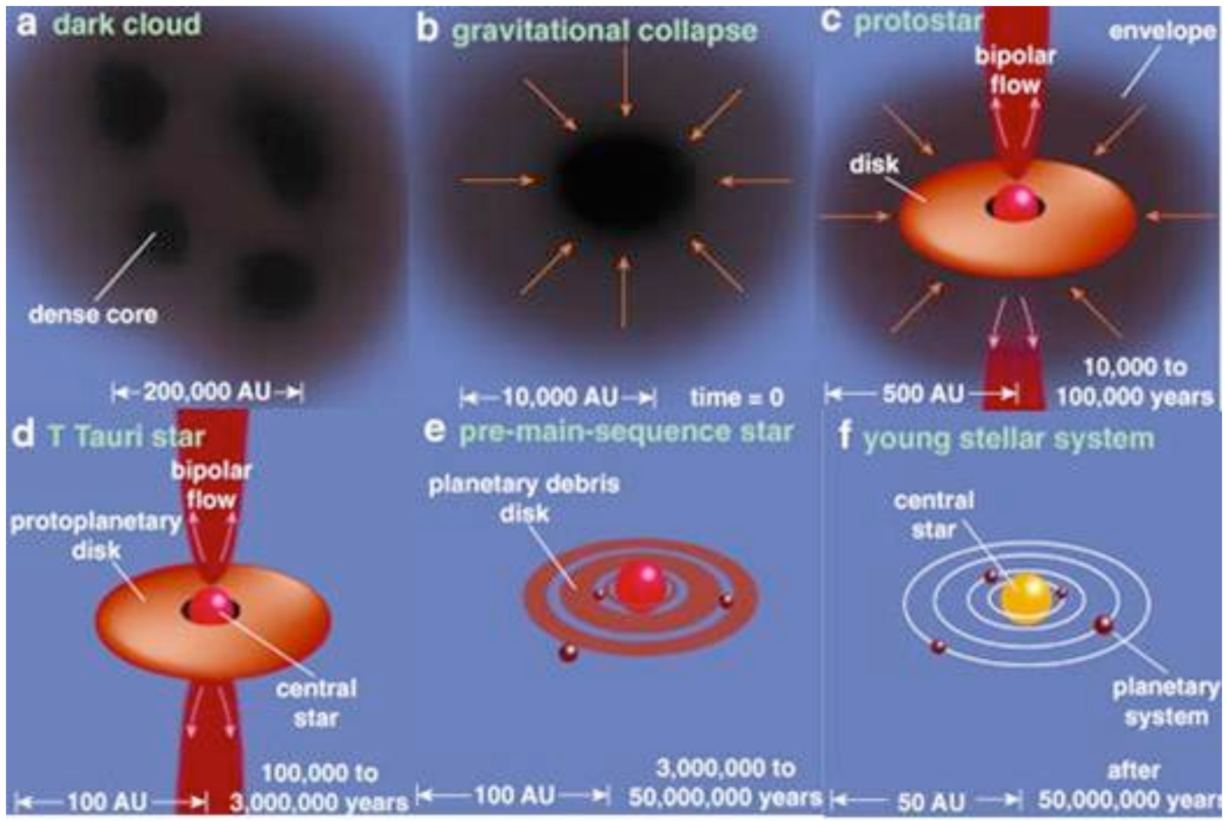
Courtesy NASA/JPL-Caltech

Courtesy NASA/JPL-Caltech

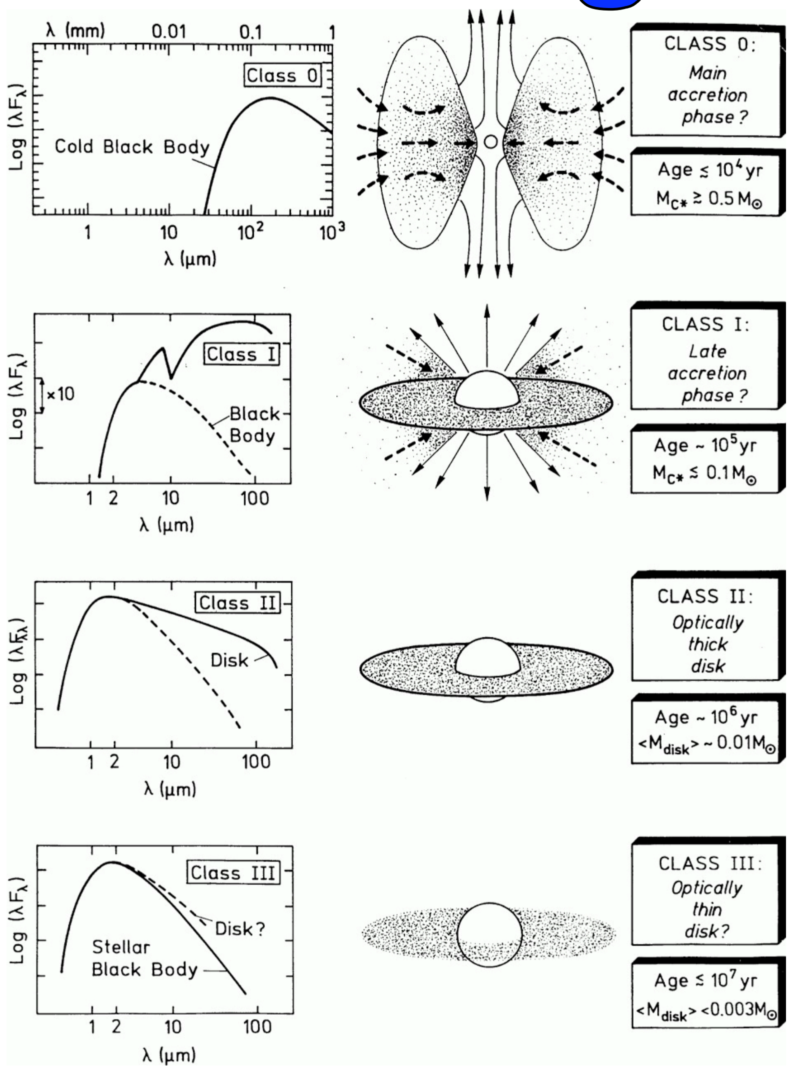
Collaborators: J. Najita (*NOAO*), T. Rettig (ND)

T. Simon (U. of HI), & C. Kulesa (U. of AZ)

2005 Michelson Fellows Symposium, October 2005

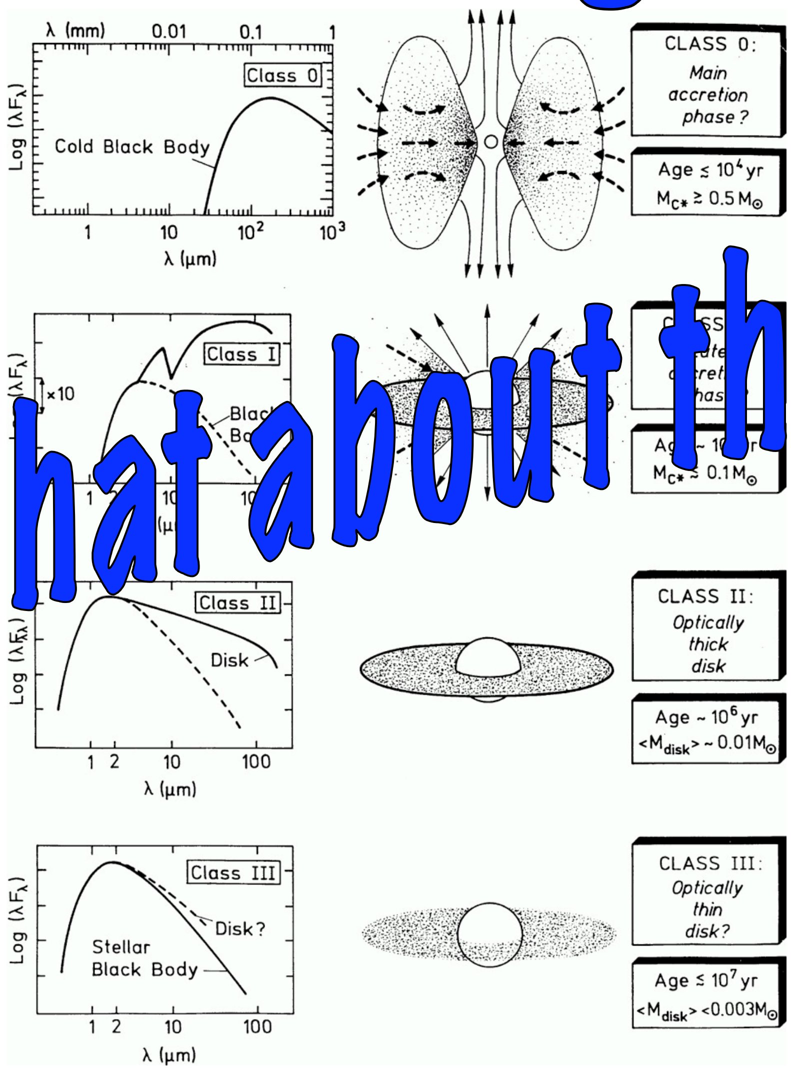

a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
envelope
bipolar flow
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years

The Evolution of Dust around Young Stars



Bachiller ARA&A **34**: 111 (1996)

The Evolution of Dust around Young Stars



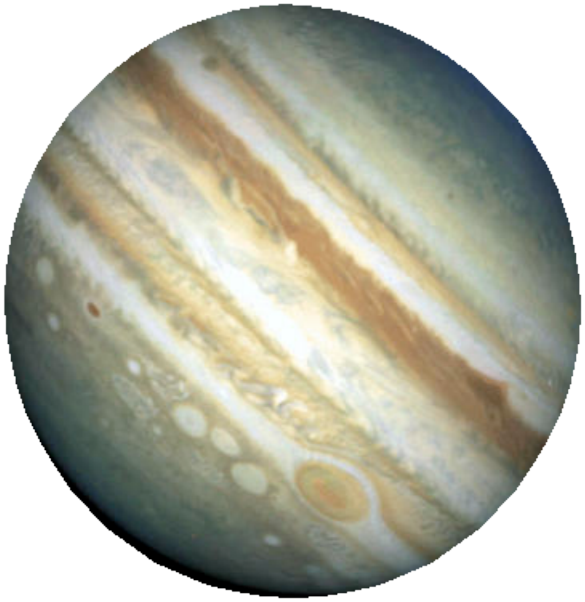
But what about the gas?

Bachiller ARA&A **34**: 111 (1996)

Why do we care about the gas?

The Planet Connection

1. Primary building block of giant planets

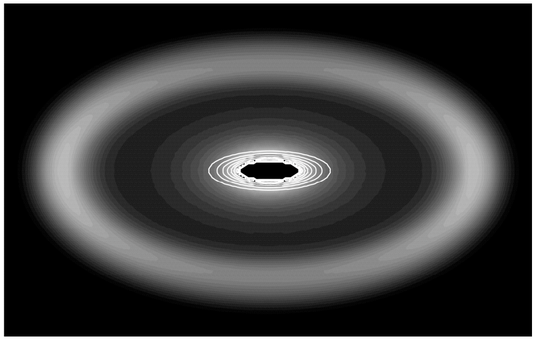


Why do we care about the gas?

The Planet Connection

1. Primary building block of giant planets
2. Interactions with dust lead to interesting morphologies

HST image taken with NICMOS by Brad Smith (University of Hawaii) & Glenn Schneider (University of Arizona)



Takeuchi, T. & Artymowicz, P. 2001, ApJ, 557, 990

Why do we care about the gas?

The Planet Connection

1. Primary building block of giant planets
2. Interactions with dust lead to interesting morphologies
3. Circularizes the orbit of terrestrial planets

Why do we care about the gas?

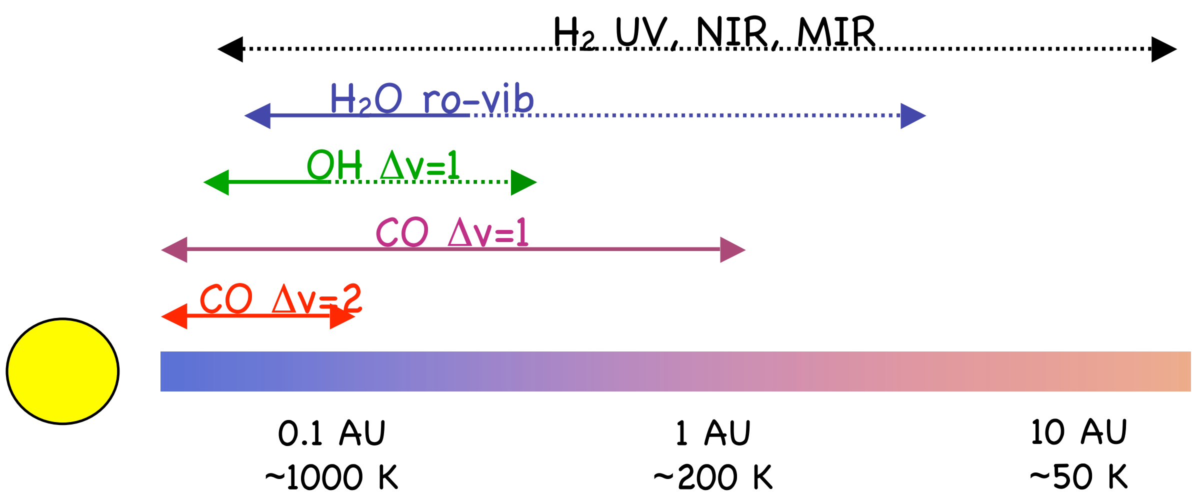
The Planet Connection

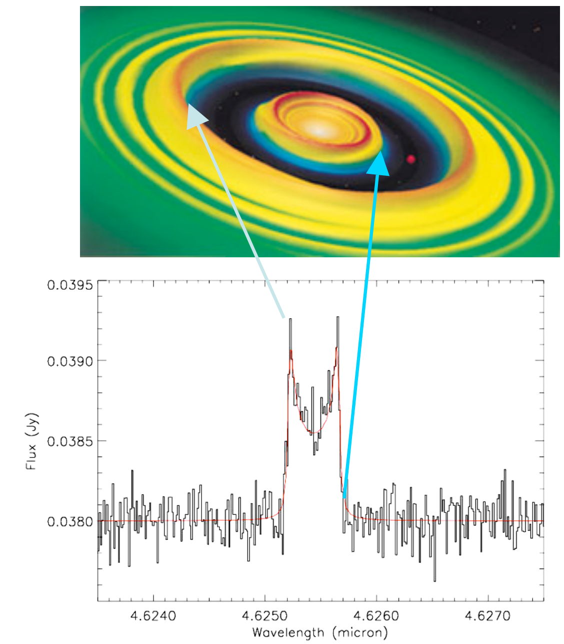
1. Primary building block of giant planets
2. Interactions with dust lead to interesting morphologies
3. Circularizes the orbit of terrestrial planets

The Stellar Connection

1. The truncation radius of the gas disk provides a measure of the magnetic field strength of the HAe star

Molecular Probes of Inner Disks





Courtesy of J. Najita (*NOAO*)

Temperatures 100 - few 1000K, high densities

» Molecules abundant in gas phase

» Excitation of IR ro-vibrational transitions

Richter et al. poster: H_2 in MIR

Lahuis + C2D poster: possible additional probes of inner disks

Gas in Circumstellar Disks

I. The Planet Connection

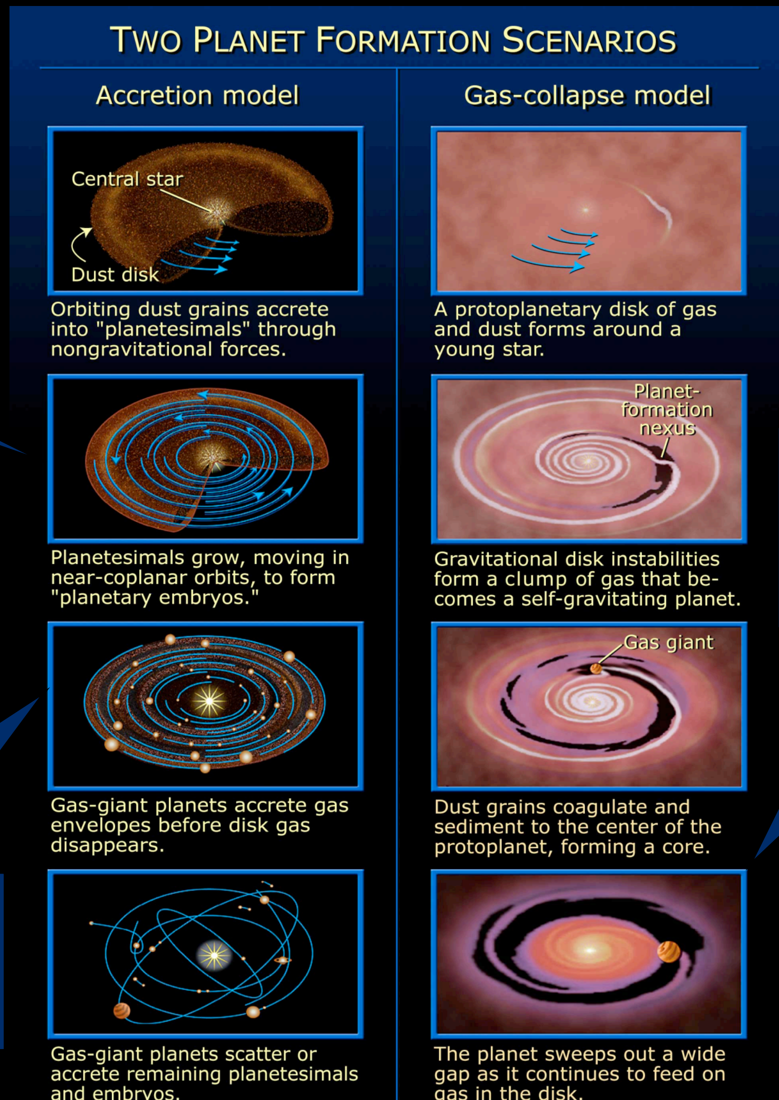
The lifetime of circumstellar gas defines the timescale for giant planet formation, so how does the evolution of gas compare to dust?

II. The Stellar Connection

A stars are generally not expected to harbor kG magnetic fields, however there are several lines of evidence to the contrary. How can we measure the presence and strength of stellar magnetic fields?

Planet Formation Timescale

~1 Myr to form 10 M_{Earth} Core



A. Field (STScI)

Jovian planets form ~1000 yrs. Dust and gas co-depleted

~10 Myr to accumulate 1 $M_{Jupiter}$ gas - disk is dust poor and gas rich

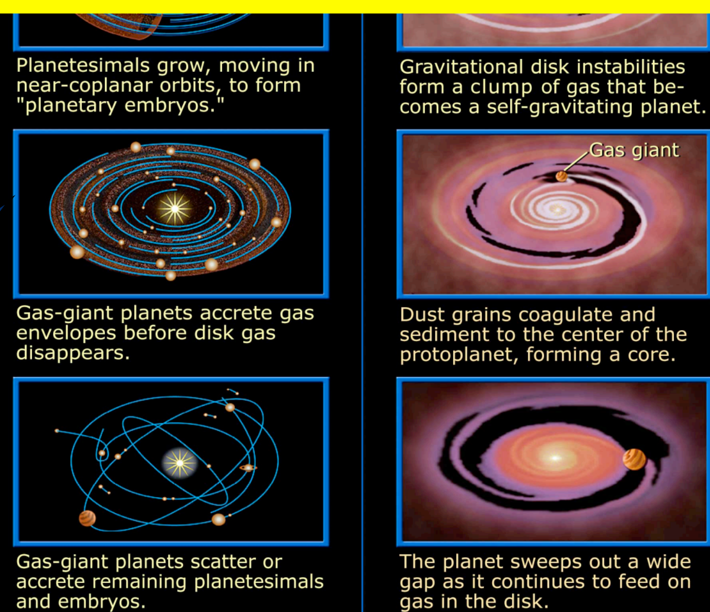
Planet Formation Timescale

Core Accretion: A substantial population of circumstellar disks that are dust poor and gas rich

Gas Instability: Dust and gas should dissipate on the same timescale.

~10 Myr to accumulate 1 $M_{Jupiter}$ gas - disk is dust poor and gas rich

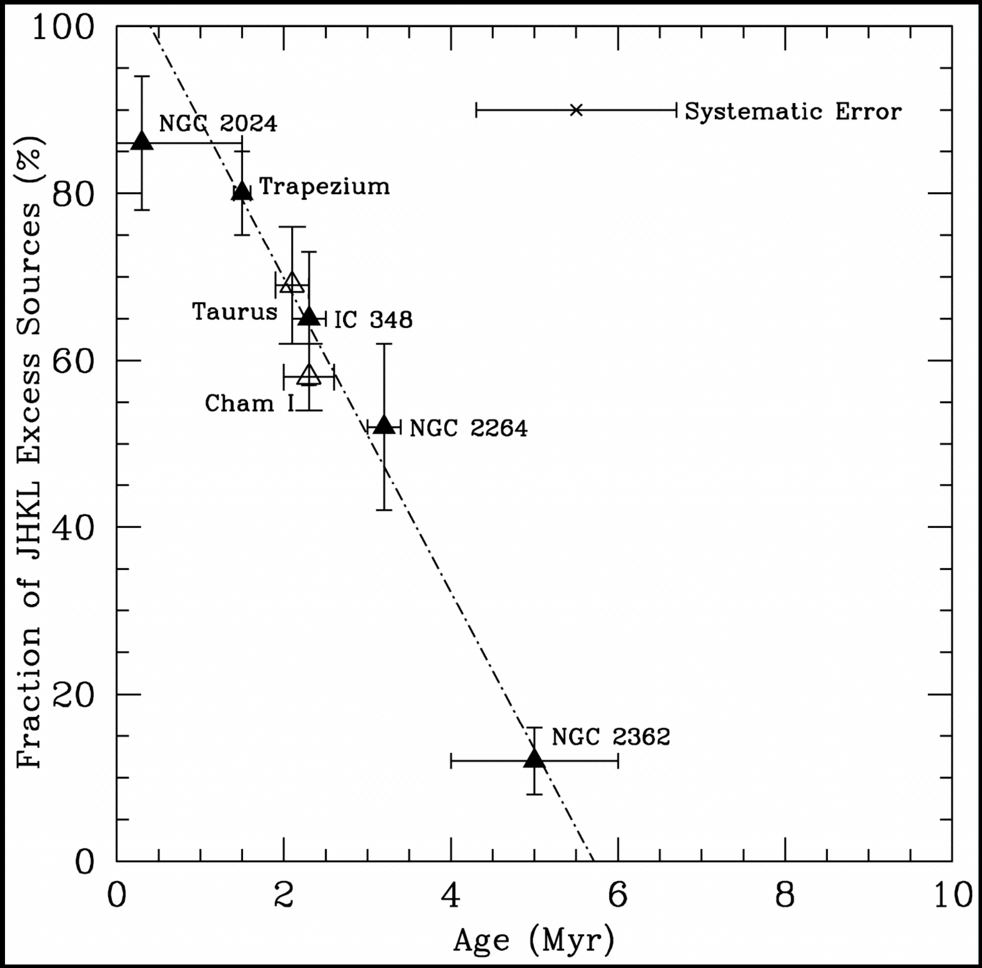
m ~1000 yrs. Dust and gas co-depleted



A. Field (STScI)

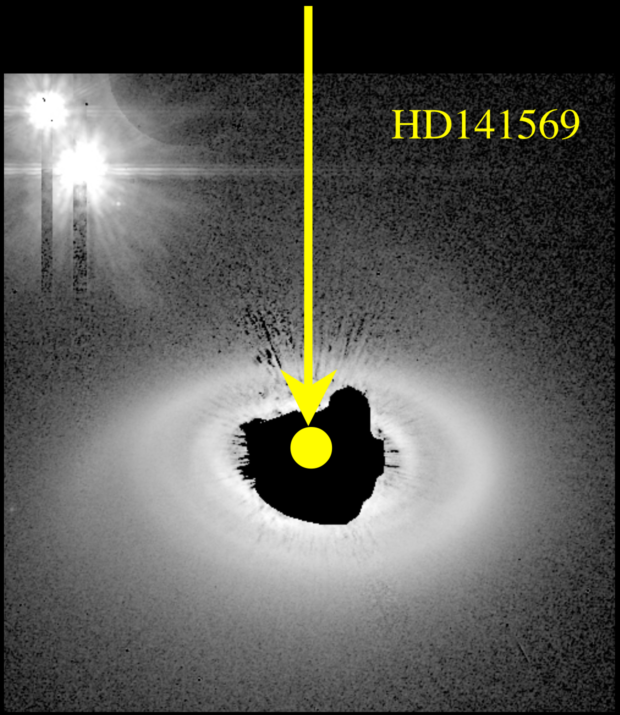
Radial Evolution of Circumstellar Gas

Disks take ~5 Myr to become optically thin. How does this compare to the dissipation rate of the gas in the inner 50 AU?



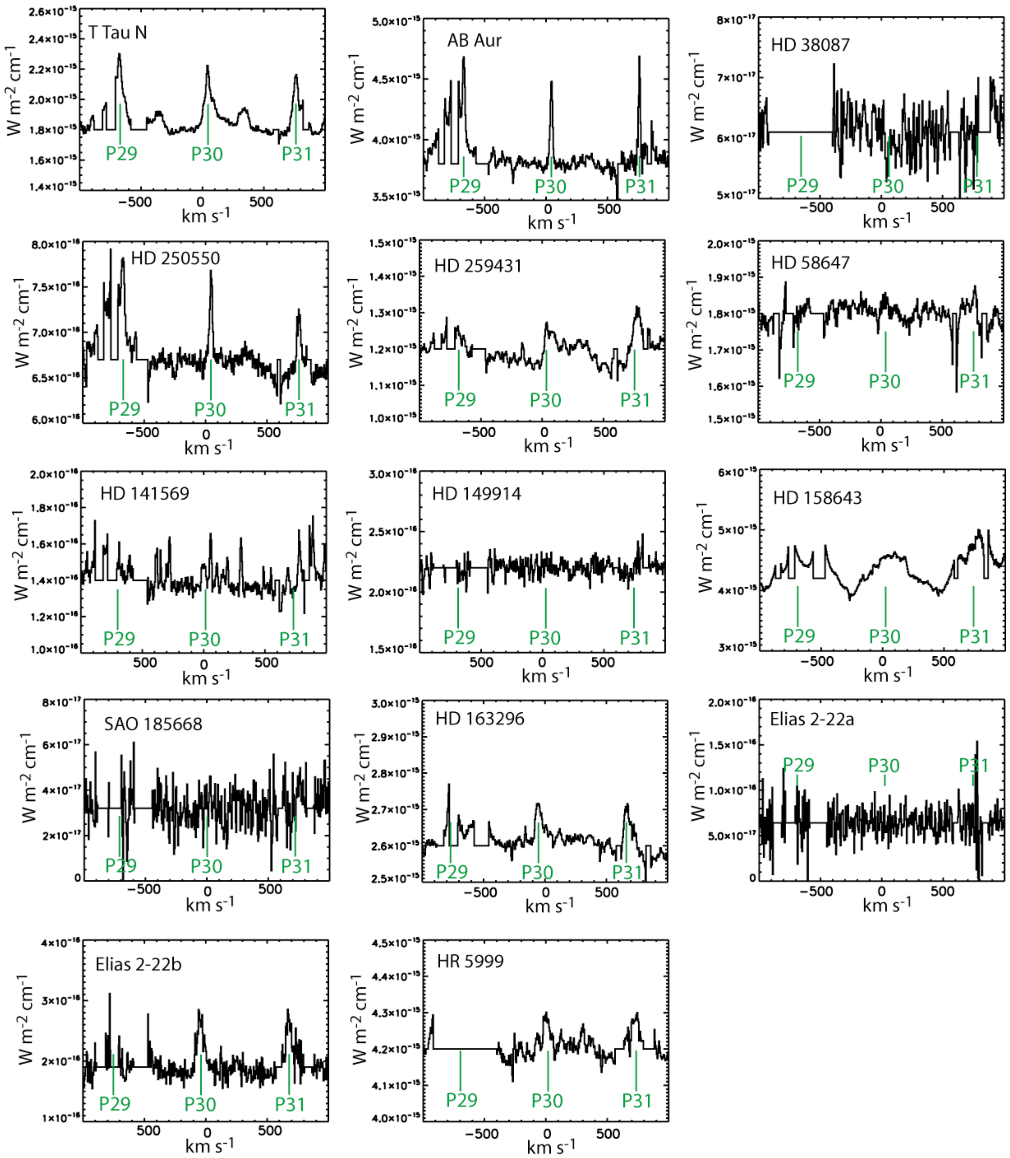
Haisch, et al. 2001, ApJ, 553, L153

Region of interest



Clampin, et al. 2003, AJ 126, 385

CO emission from Herbig Ae/Be stars



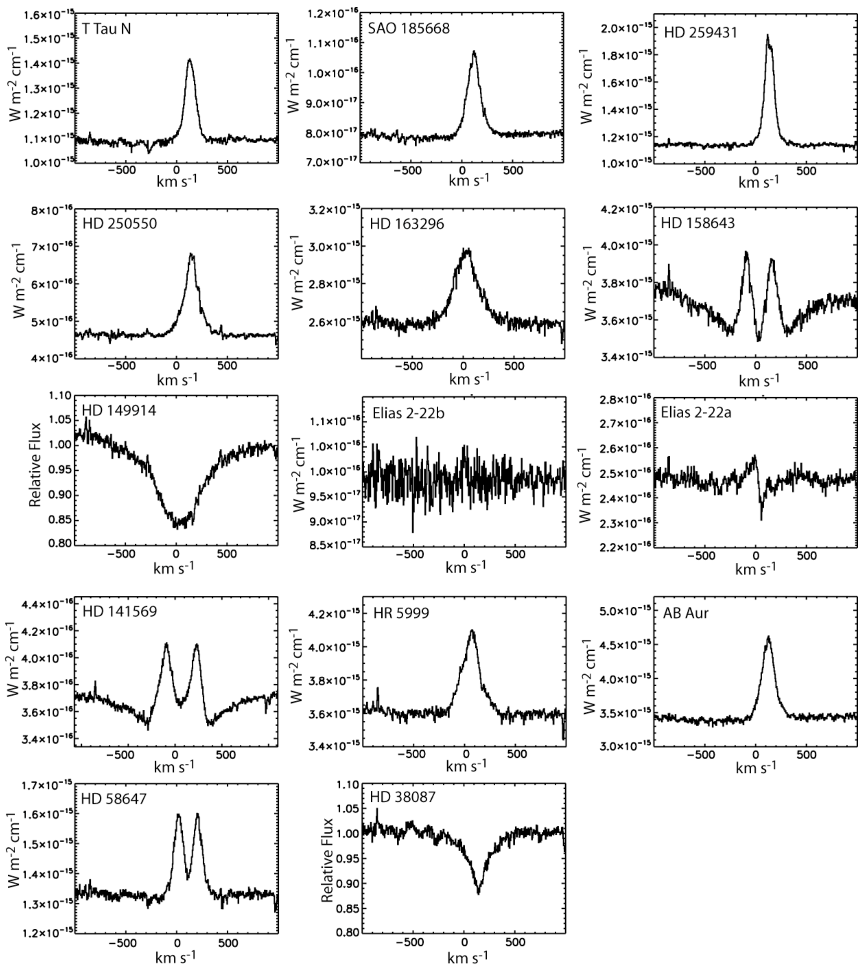
2 IMMTS

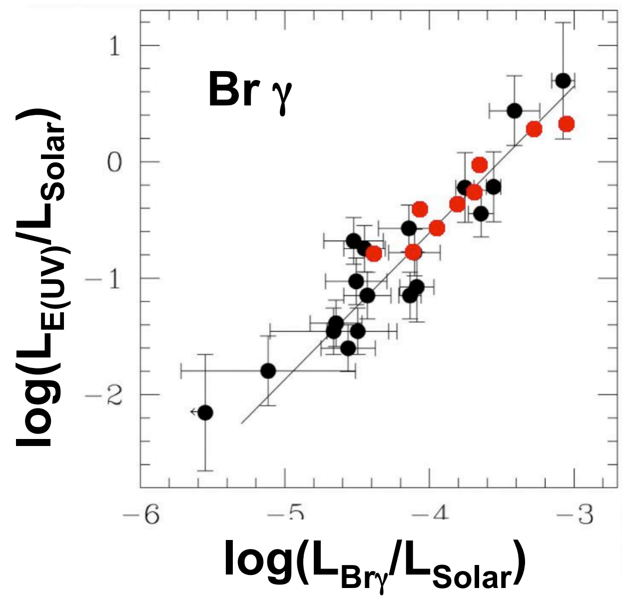
7 HAeBe (A7-B2)

5 Transitional Stars

1 Embedded Source

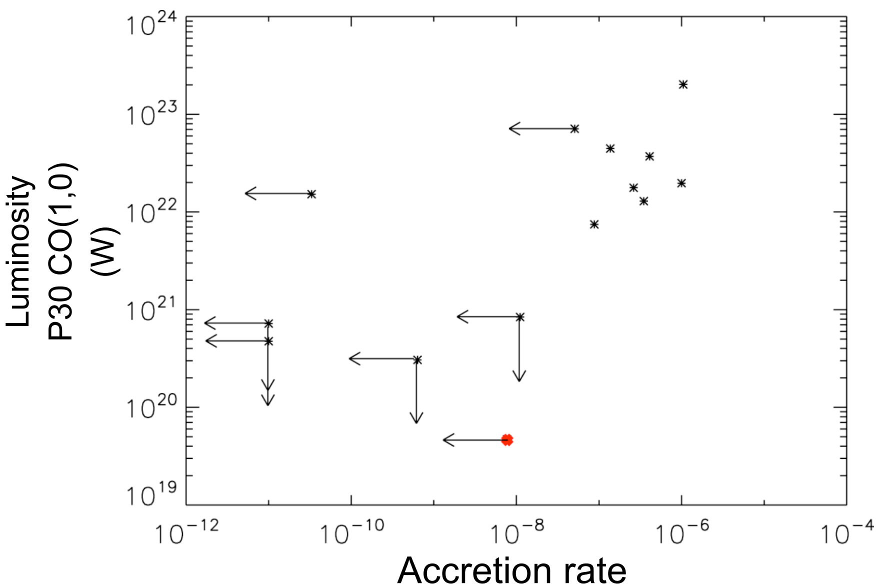
Br-gamma emission from Herbig Ae/Be stars





van den Ancker 2003 astro-ph/0403034

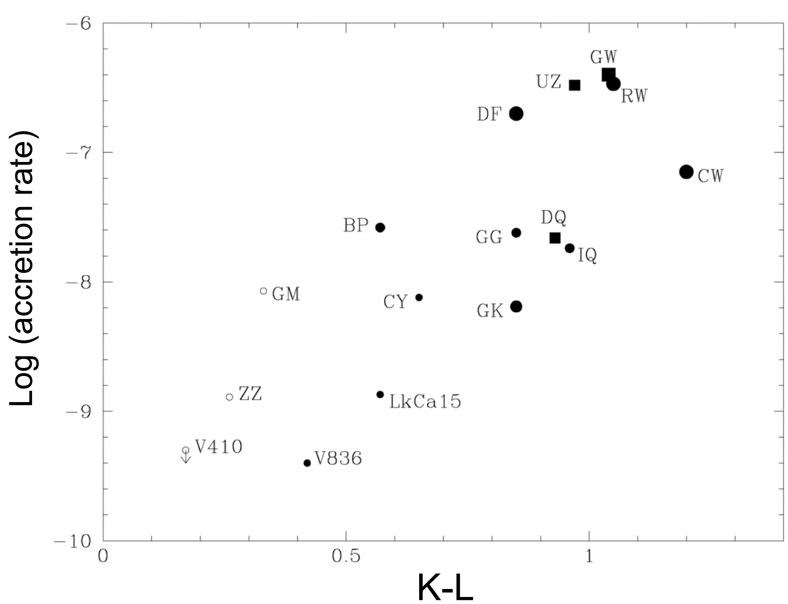
Muzerolle et al. 1998



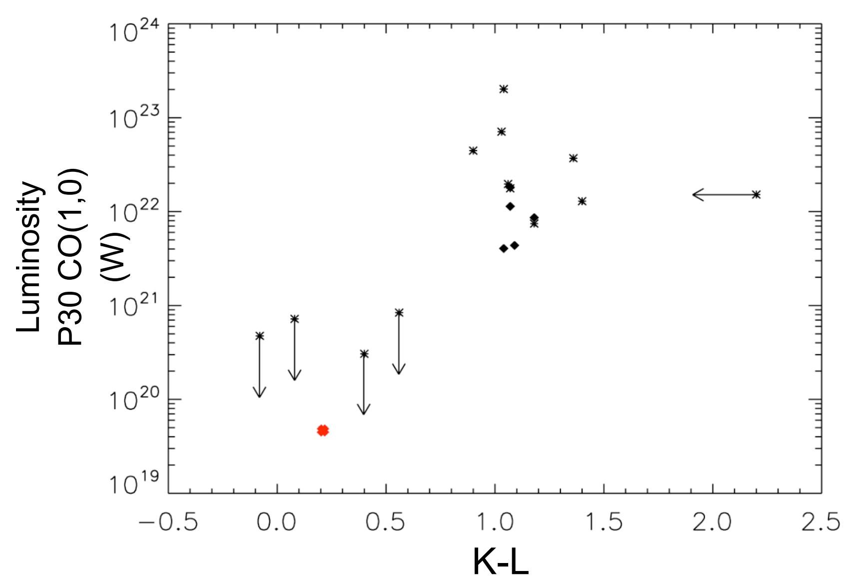
•Detect CO emission in 10/14 sources

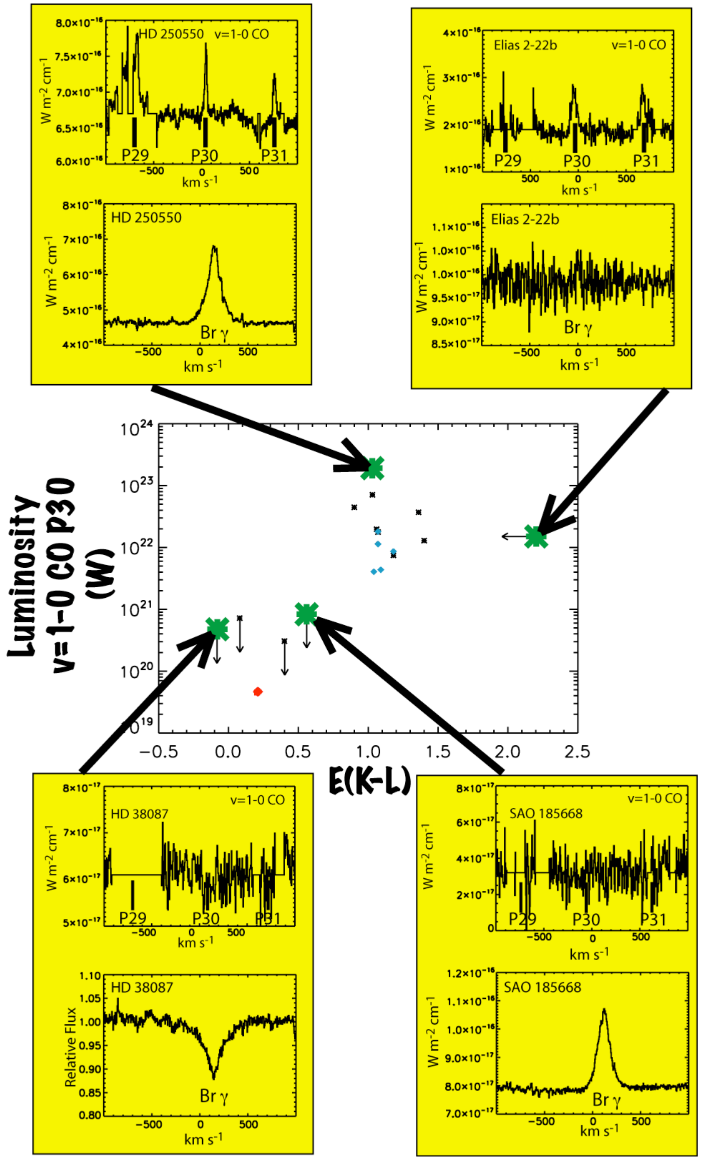
•CO always observed from systems with optically thick inner disks

•CO always observed from accreting systems

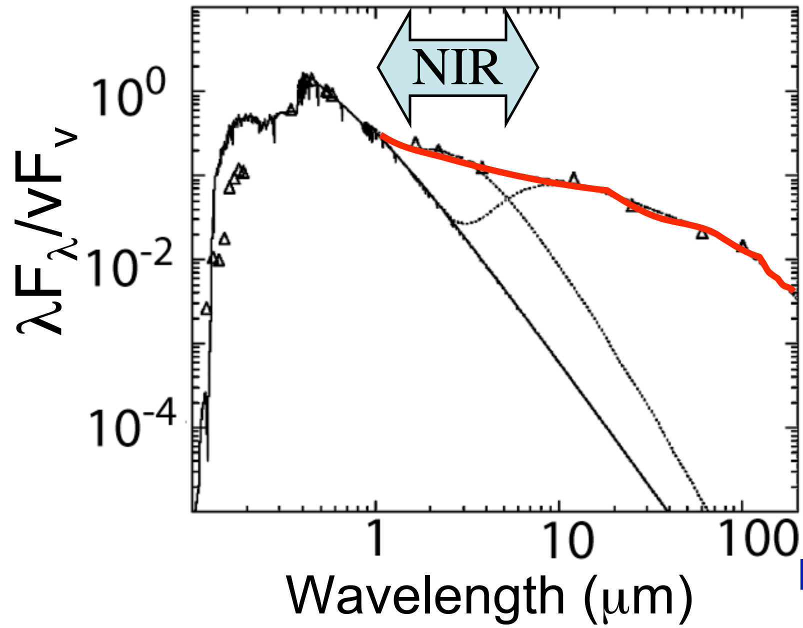


Najita, Carr & Mathieu 2003, ApJ, 589, 931





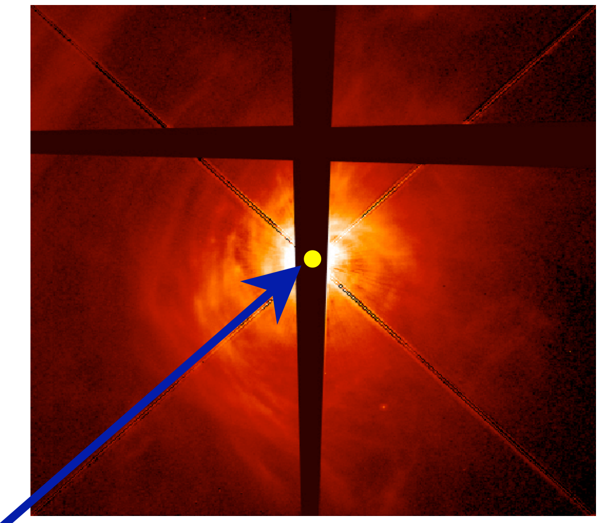
Interpretation of detections and non-detections of CO emission requires an excitation model of the gas



AB Aurigae

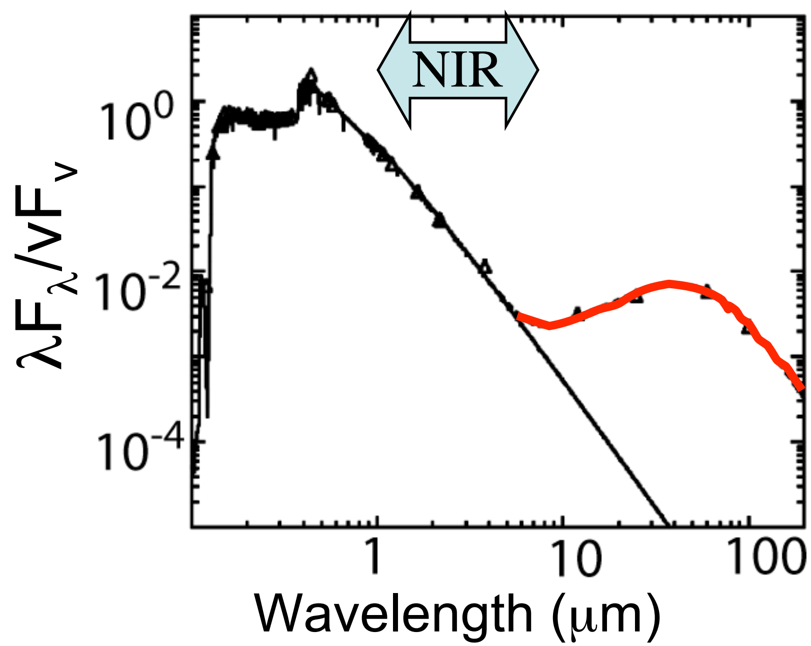
A0 star

Age ~ 4 Myr



C. Grady, et al. 2003, ApJ, 683, 151

Regions of interest

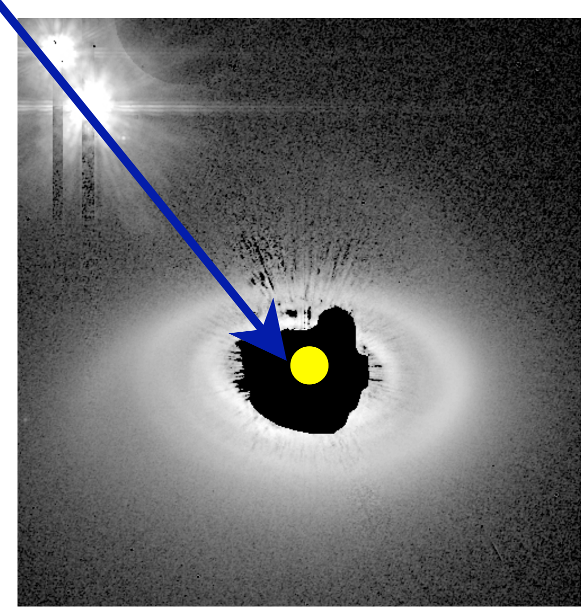


Malfait et. al. A&A **331**: 221 (1998)

HD 141569

A0 star

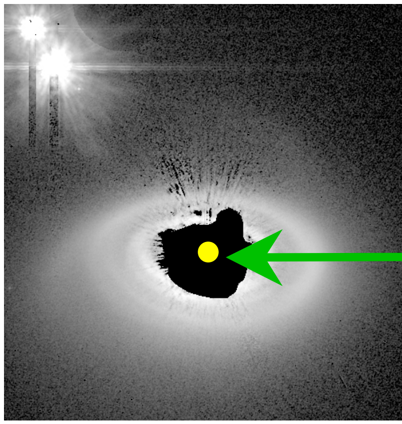
Age ~ 6-8 Myr

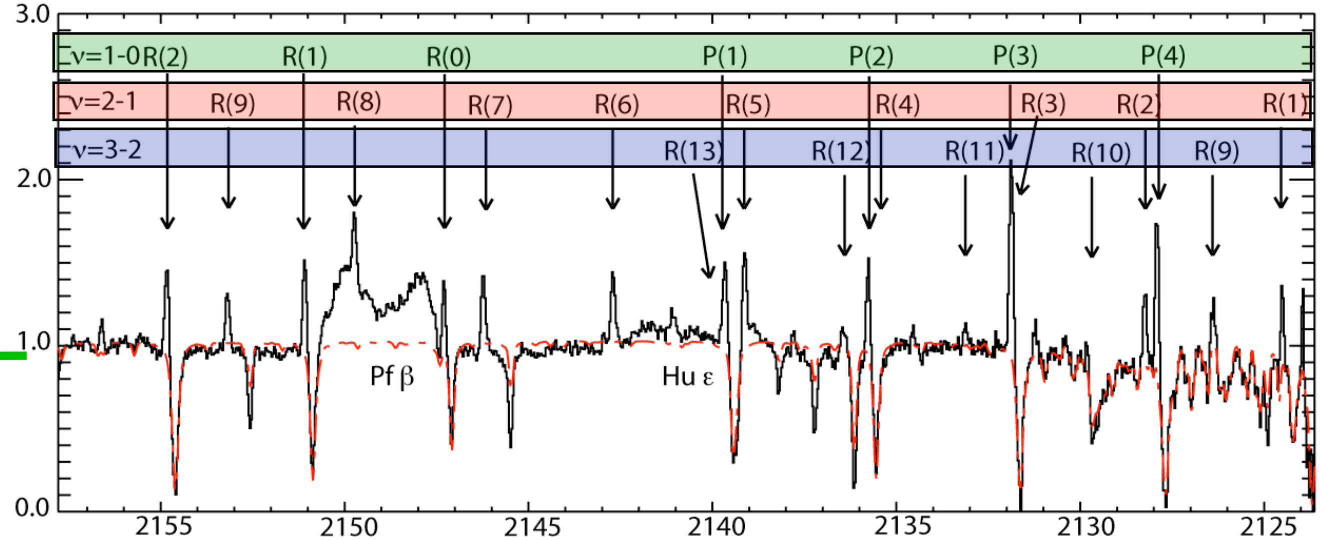


Clampin, et al. 2003, AJ 126, 385

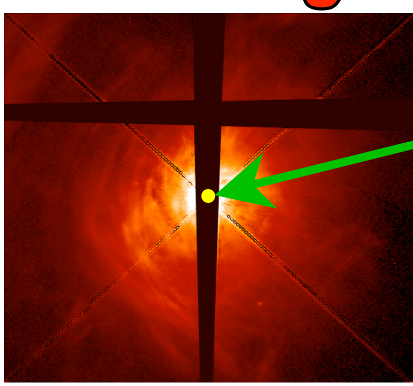
Using NIR Spectroscopy to probe the inner disk: CO

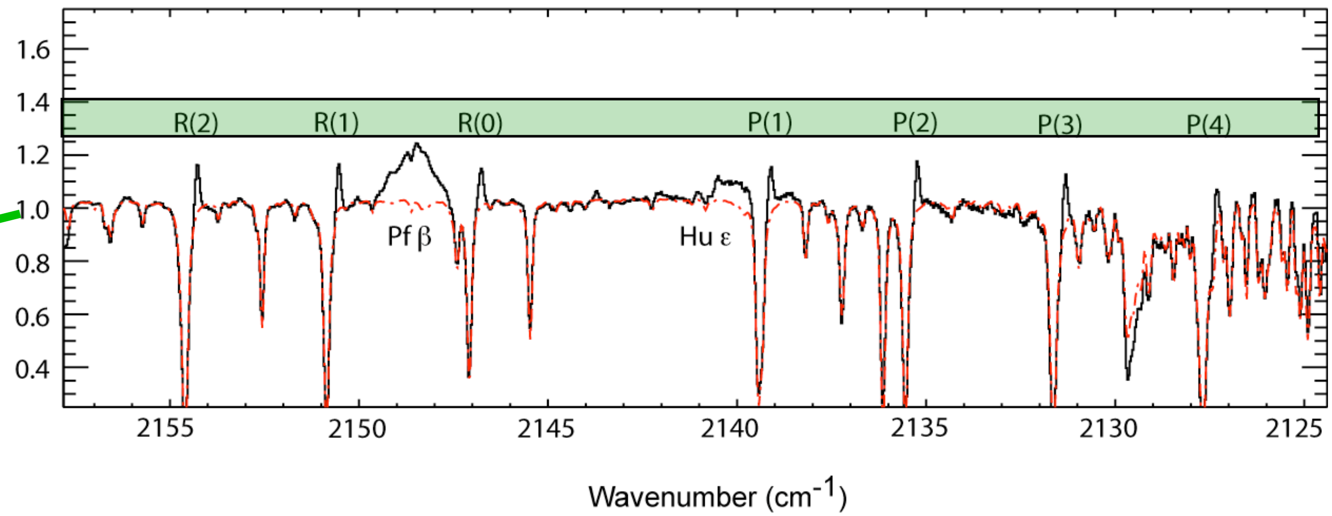
HD 141569





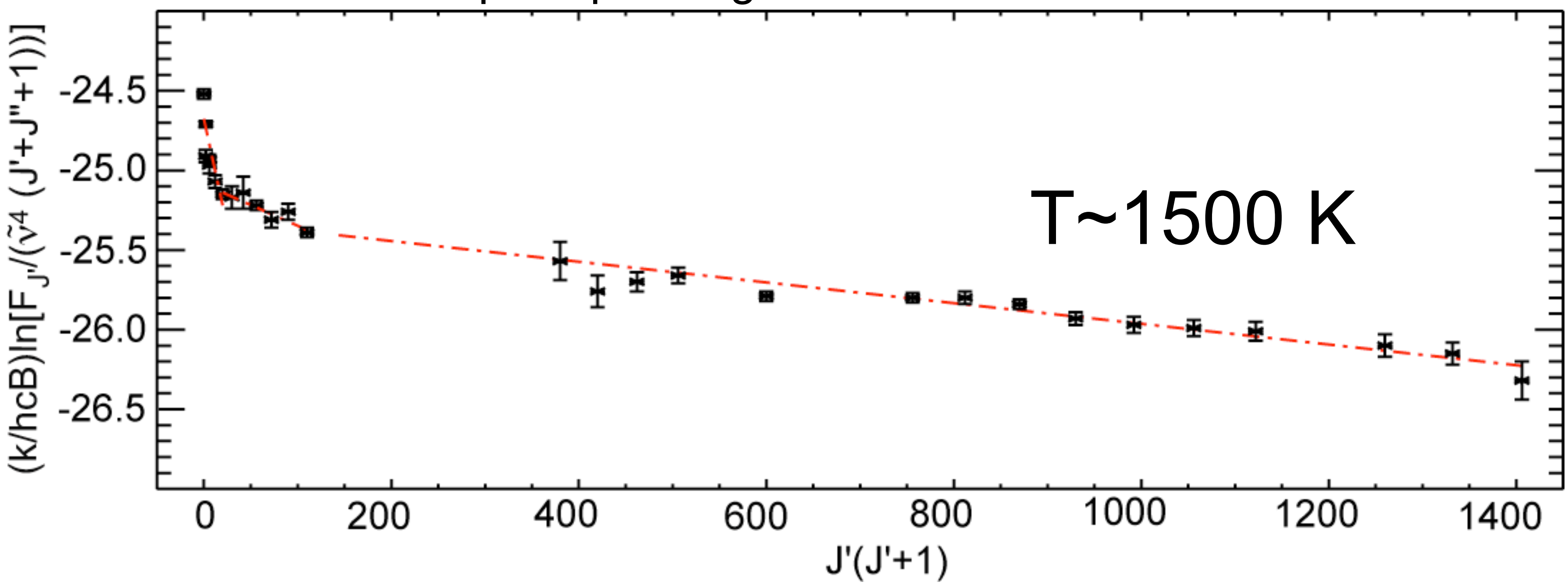
AB Aurigae



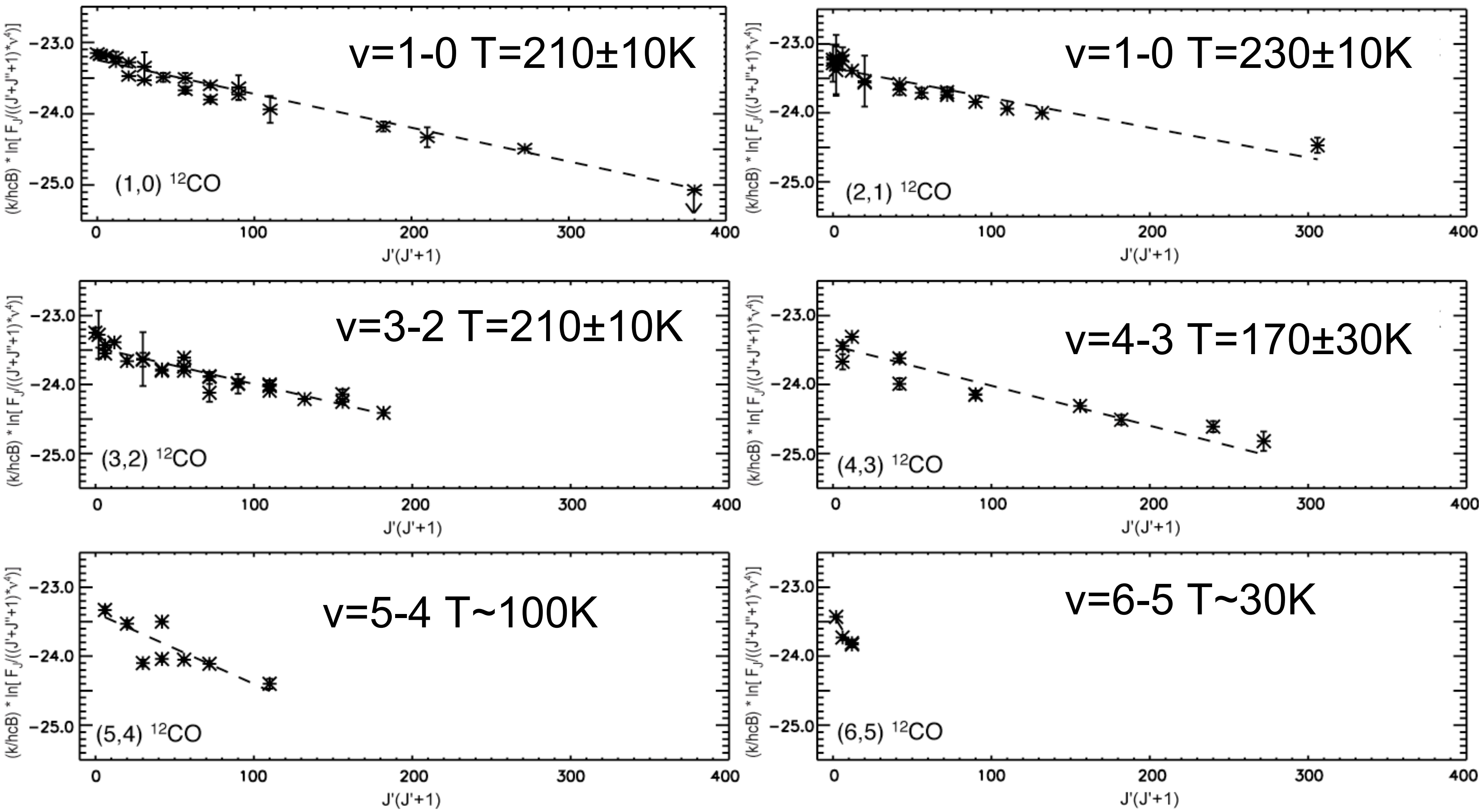


AB Aurigae

CO Excitation plot spanning J'=0-37

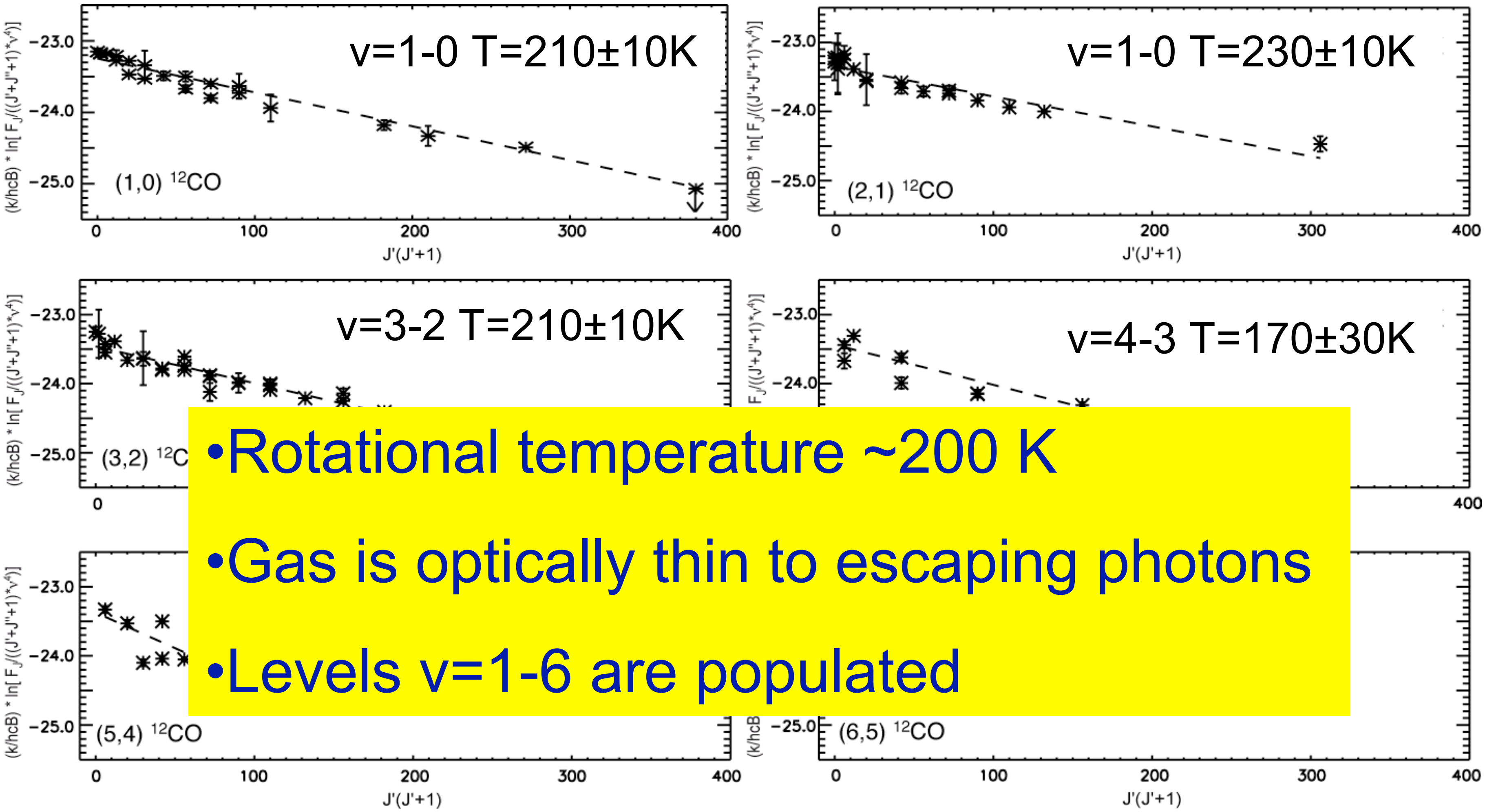


HD 141569



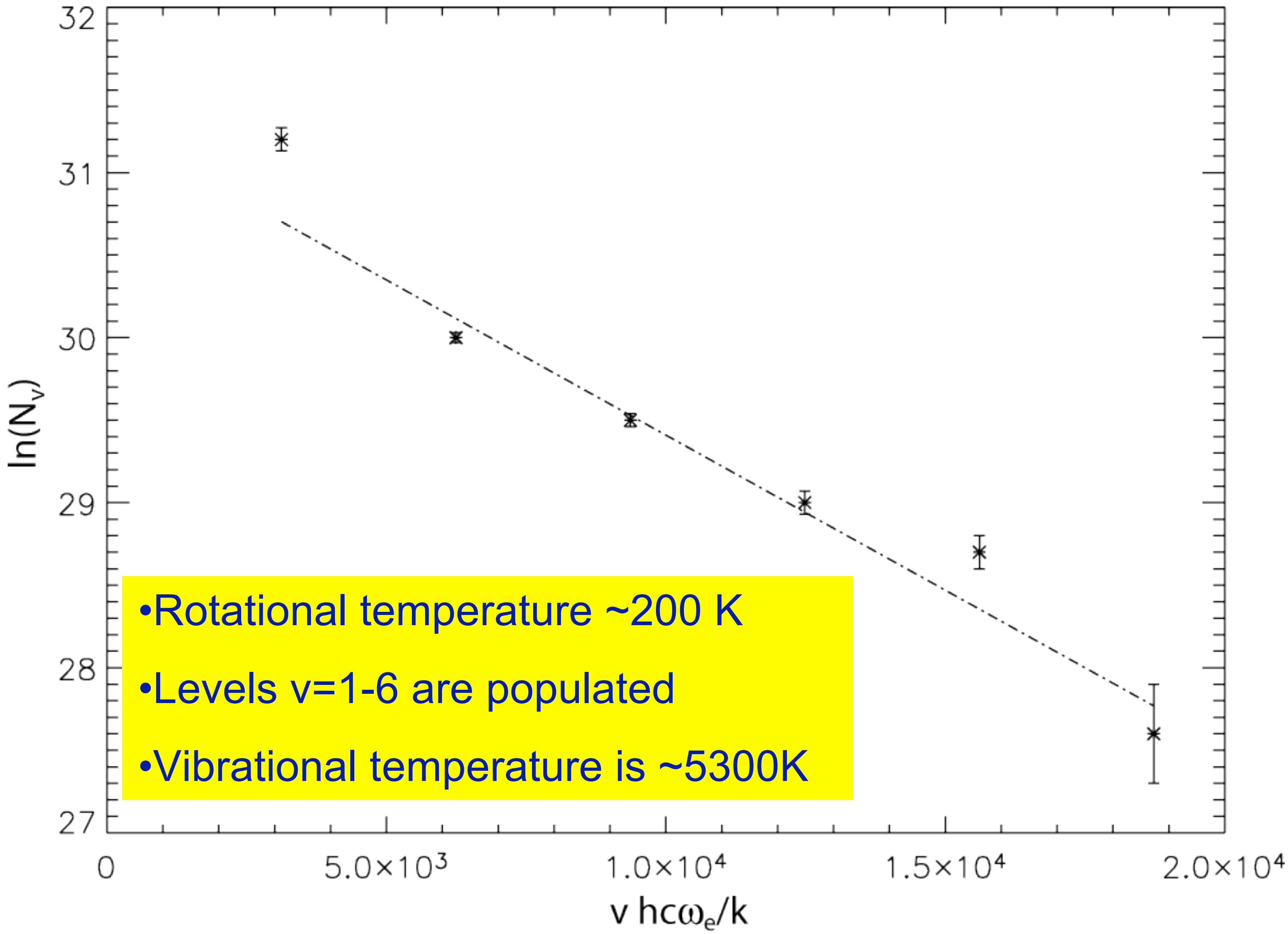
v=1-0 T=210±10K
(1,0) 12CO
v=1-0 T=230±10K
(2,1) 12CO
v=3-2 T=210±10K
(3,2) 12CO
v=4-3 T=170±30K
(4,3) 12CO
v=5-4 T~100K
(5,4) 12CO
v=6-5 T~30K
(6,5) 12CO
J'(J'+1)
(k/hcB) * ln[F_J/((J'+J''+1)*ν^4)]
-23.0
-24.0
-25.0
0
100
200
300
400

HD 141569



- Rotational temperature ~200 K
- Gas is optically thin to escaping photons
- Levels v=1-6 are populated

HD 141569

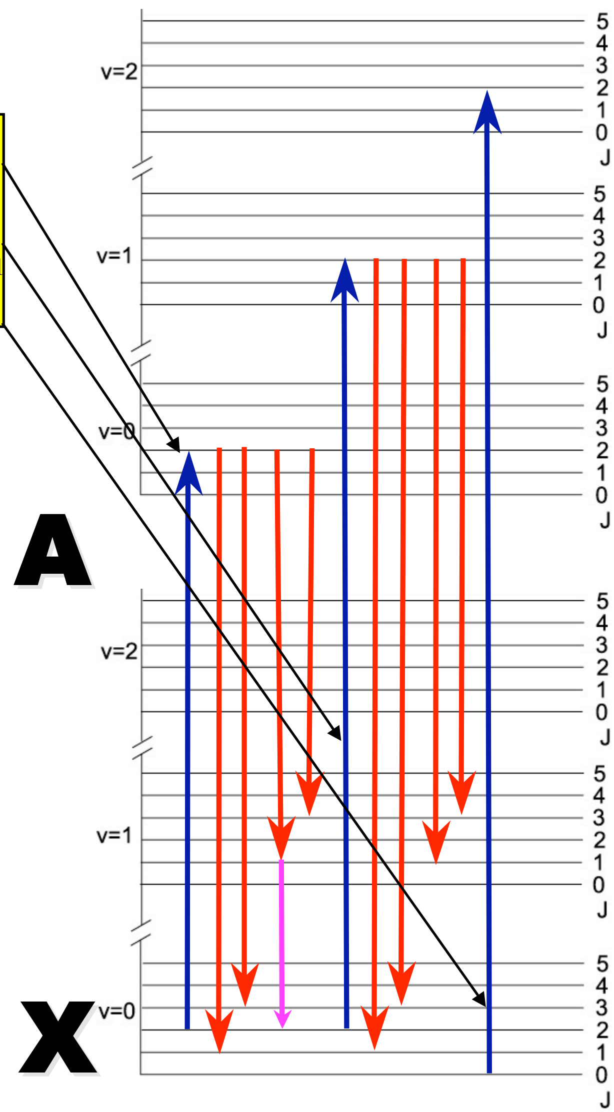


32
31
30
29
28
27
ln(N_v)
0
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
v hcω_e/k
•Rotational temperature ~200 K
•Levels v=1-6 are populated
•Vibrational temperature is ~5300K

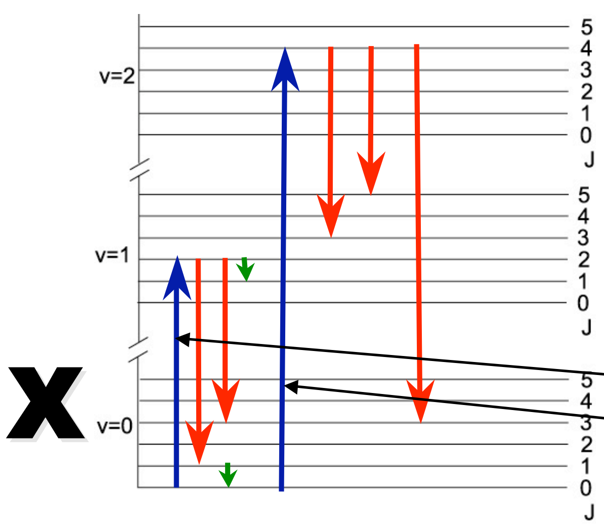
Excitation of CO

UV Fluorescence

$$g_{X-A}^{v=0-0} = 1x10^{6}\ photons\ s^{-1}\ mol^{-1}$$
$$g_{X-A}^{v=0-1} = 3x10^{6}\ photons\ s^{-1}\ mol^{-1}$$
$$g_{X-A}^{v=0-2} = 3x10^{6}\ photons\ s^{-1}\ mol^{-1}$$

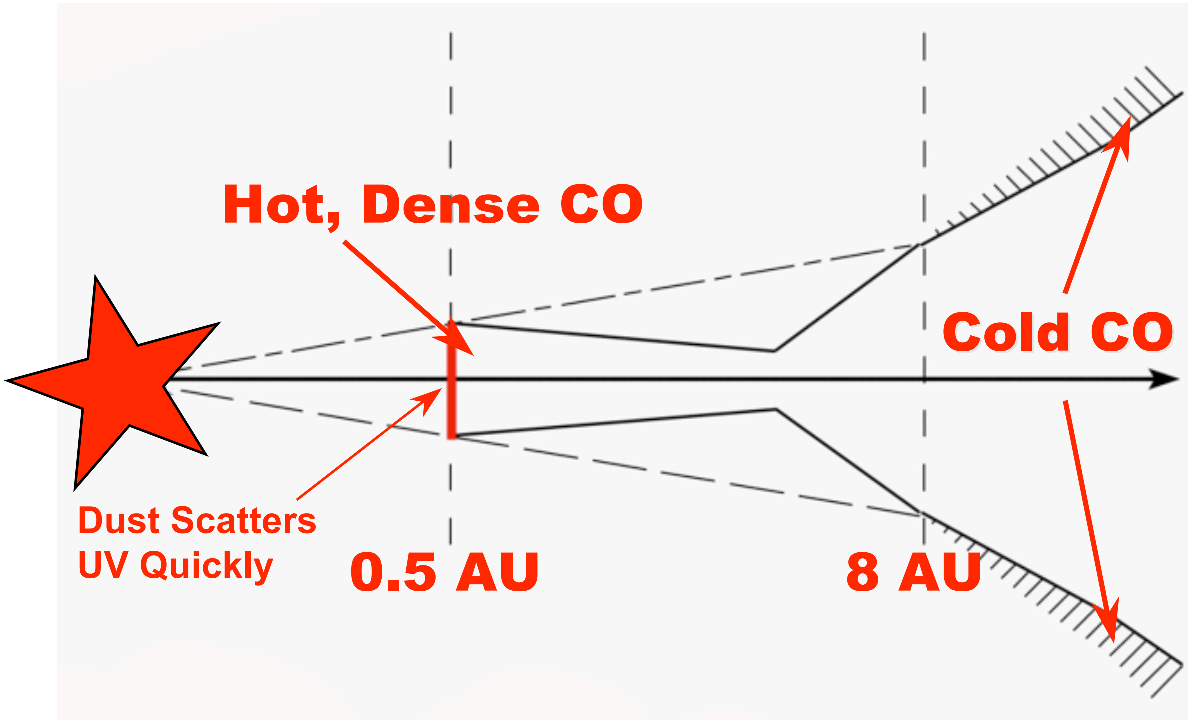


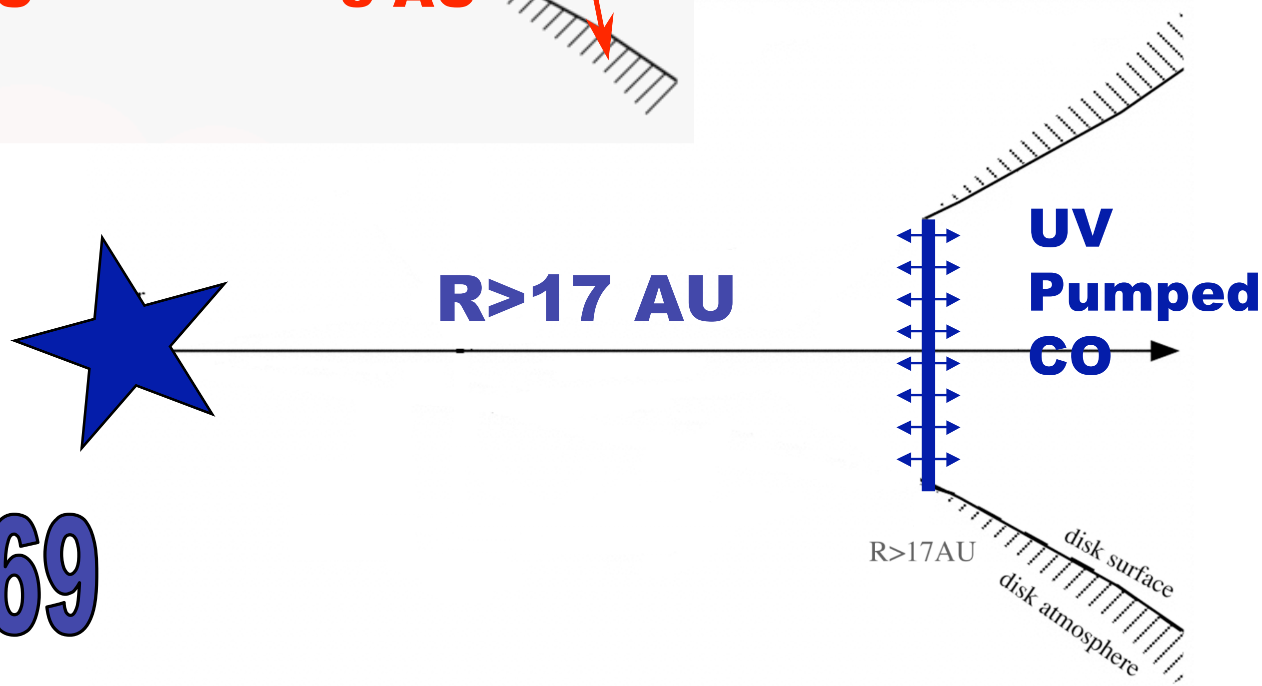
IR Fluorescence & Collisional Excitation



$$g_{X-X}^{v=0-1} \sim 10^{-5}\ photons\ s^{-1}\ mol^{-1}$$
$$g_{X-X}^{v=0-2} \sim 10^{-7}\ photons\ s^{-1}\ mol^{-1}$$
$$g_{X-X}^{v=0-3} \sim 10^{-10}\ photons\ s^{-1}\ mol^{-1}$$

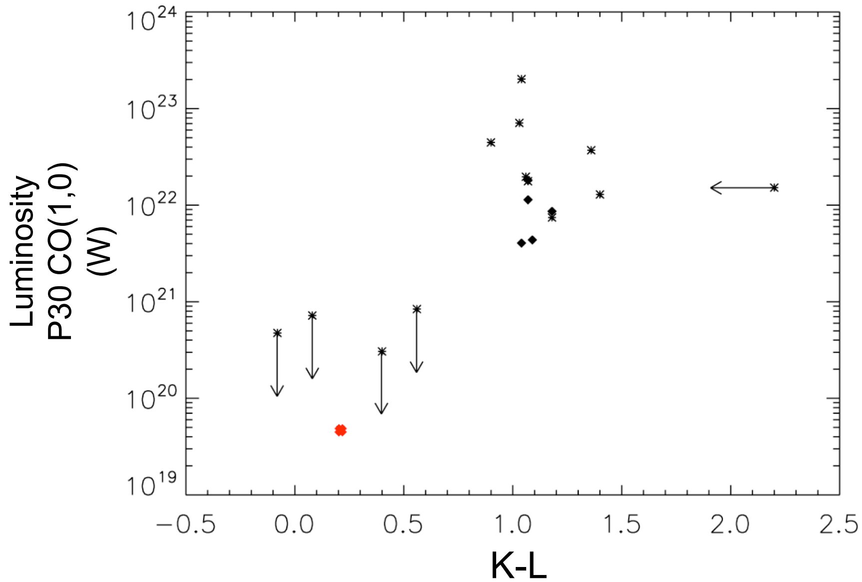
AB Aurigae

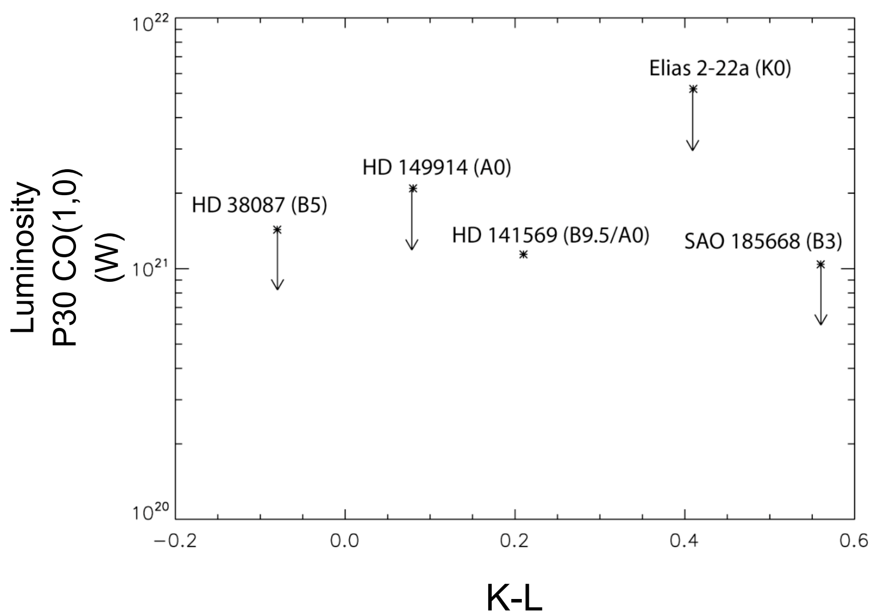




HD 141569

Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957





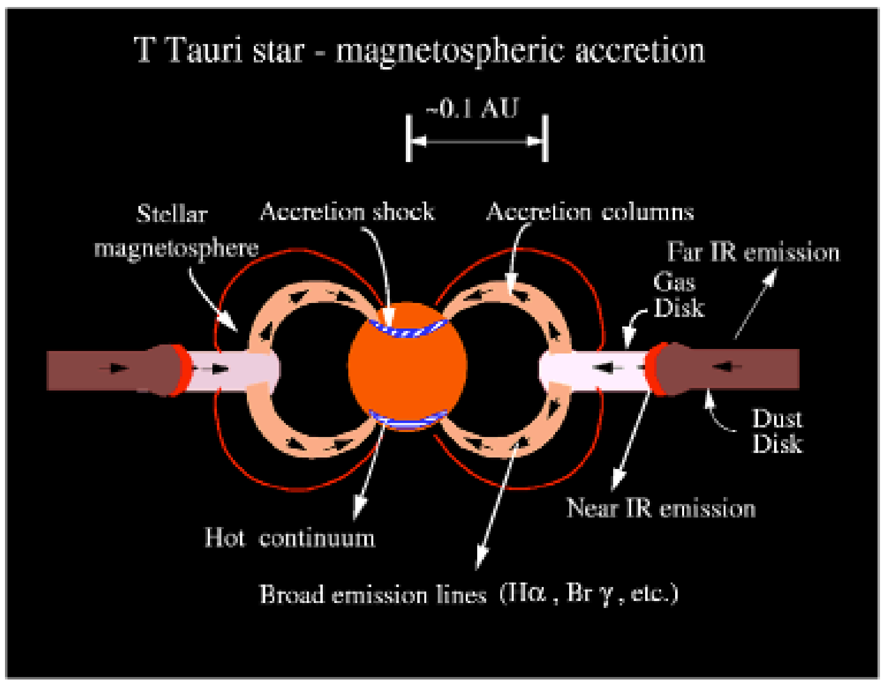
- Detect CO emission in 10/14 sources
- CO always observed from systems with optically thick inner disks
- CO always observed from accreting systems
- Higher signal/noise observations needed to rule out UV fluorescence in observed transitional HAeBe stars
- Expanded observations planned to fill in E(K-L) distribution from 0.0-1.0
- Quantitative UV fluorescence model of CO in circumstellar disks

Tracing the Magnetic Field Strength of Herbig Ae Stars

Do Herbig Ae stars have strong B-fields?

>The rotation properties of A/B stars provide evidence of disk locking (Wolff et al. 2004)

>Muzerolle et al. (2004) find evidence of magnetically mediated accretion in A stars



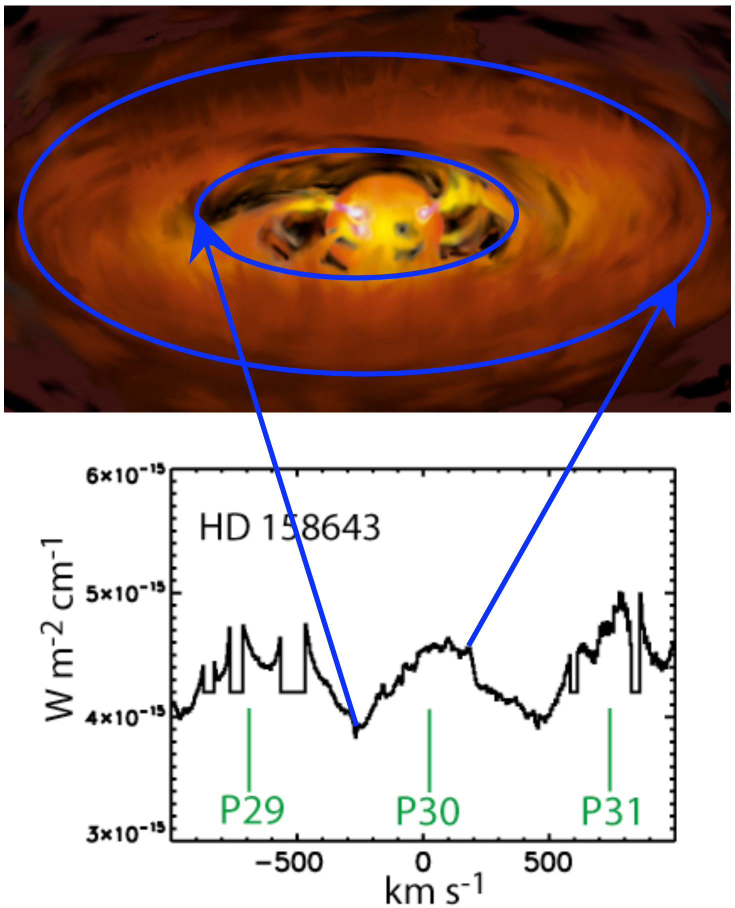
Hartmann, L., From Disks to Planets, Pasadena, 2003

Tracing the Magnetic Field Strength of Herbig Ae Stars

How can we measure the magnetic field strength of Herbig Ae/Be stars?

1. The stars tend to be rapid rotators, so Zeeman splitting is blurred.
2. Circular polarization measurements are inconclusive because of the possibility of polarization cancellation (Valenti & Johns-Krull 2004)

Tracing the Magnetic Field Strength of Herbig Ae Stars



Courtesy of P. Hartigan (Rice U.)

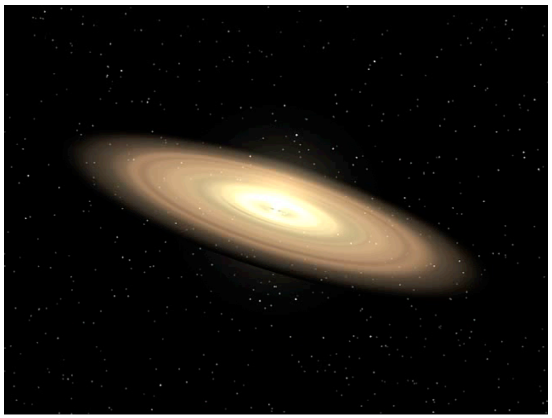
$$R_T \approx B^{4/7} R_*^{5/7} M_*^{-1/7} \dot{M}^{-2/7}$$

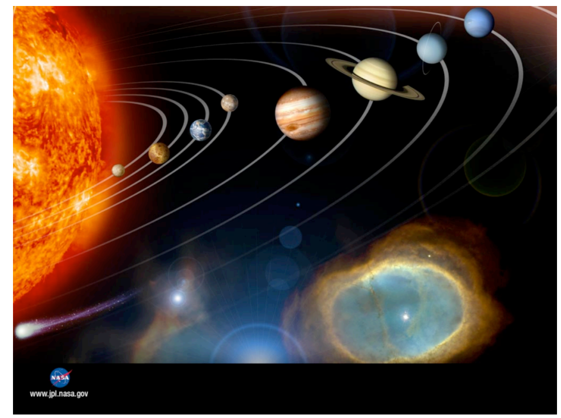
Stellar parameters for AB Aur

M_star	2.8M_\sol	Corder et al. 2005
R_star	2.7R_\sol	Hillenbrand et al. 1992
Mdot	3.00E-07	This Work
HWZI	40km/s	This Work
inclination	12±4	Eisner et al. 2004

$B=2.9^{+4.8}_{-2.2}$ kG

Summary of Results





- **Gas/Dust evolution of circumstellar disks:**
  - CO robust tracer of gas
  - Initial results indicate that gas co-evolves with dust
- **Measuring B-fields of Herbig Ae stars:**
  - Herbig Ae stars may have kG B-fields
  - Expanded observations planned

What's Next?

- Increase sample of transitional Herbig Ae/Be stars that exhibit CO emission
- Fill in E(K-L) to see when P30 goes away
- Develop UV flu. model to make detailed predictions of emission signature given stellar type and gas content
- Explore markers of gas disk around B stars to use to measure their B-field (e.g. OI)