Introduction to Young Stellar Objects

1. Nearby Star Formation
2. Scenario for Low-Mass Star Formation
3. T Tauri Stars
4. Herbig Stars

References

Adams, Lizano and Shu, ARAA 25 23 1987
Lada OSPS (Crete 1999)
Stahler and Palla, Chs. 17 & 18
Protostars and Planets IV & V

1. Nearby Star Formation

- YSOs are studied in detail in nearby GMCs; some of the usual suspects are shown in the next few slides.
- Being in or near molecular clouds, the observations are affected by extinction, which decreases with wavelength.
- Empirically, we speak of

  embedded sources - visible only from the NIR to mm and believed to be very young

  revealed sources - visible at optical-NIR wavelengths, and believed to be older (~ Myr)
- YSOs are stars under construction. They are active, with dynamic circumstellar material such: disks, outflows, and an in-falling cloud core (illustrations follow).

Local Star Forming Regions

Much of our knowledge of star formation comes from a few nearby regions

<u>Taurus-Auriga & Perseus</u>

– 150 pc

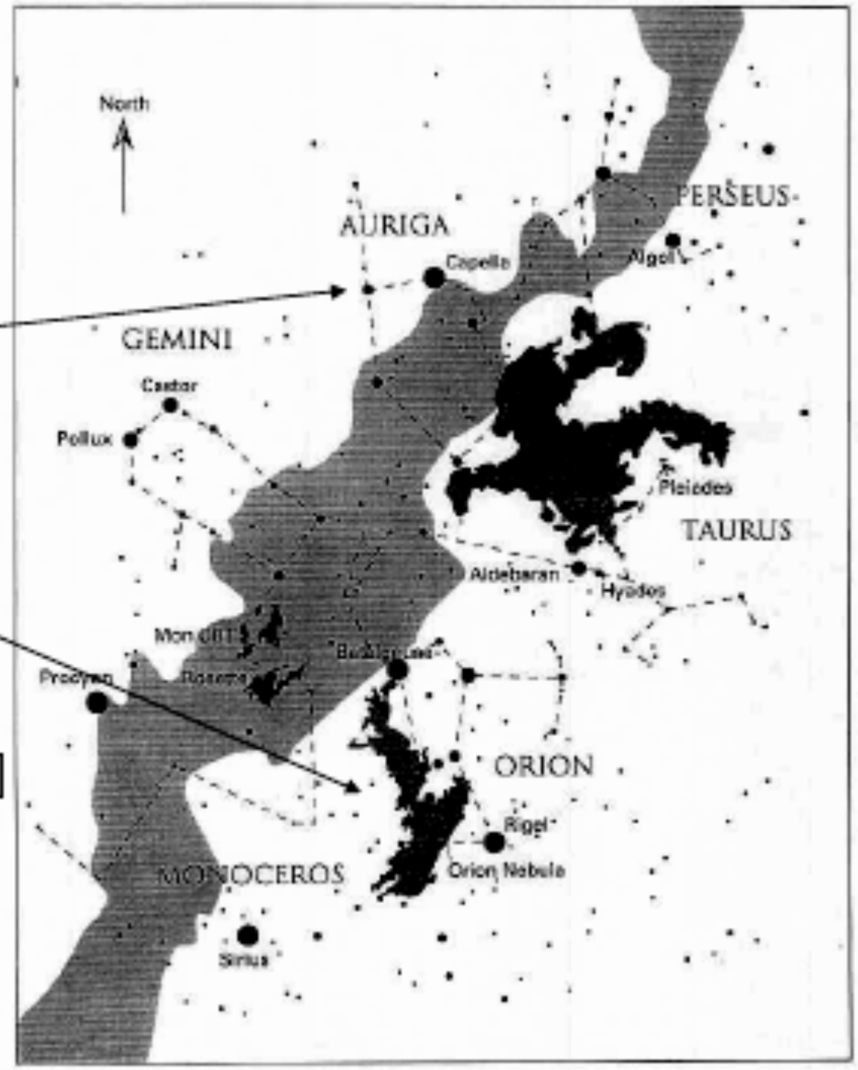
low mass (sun-like) stars

<u>Orion</u> – 450 pc

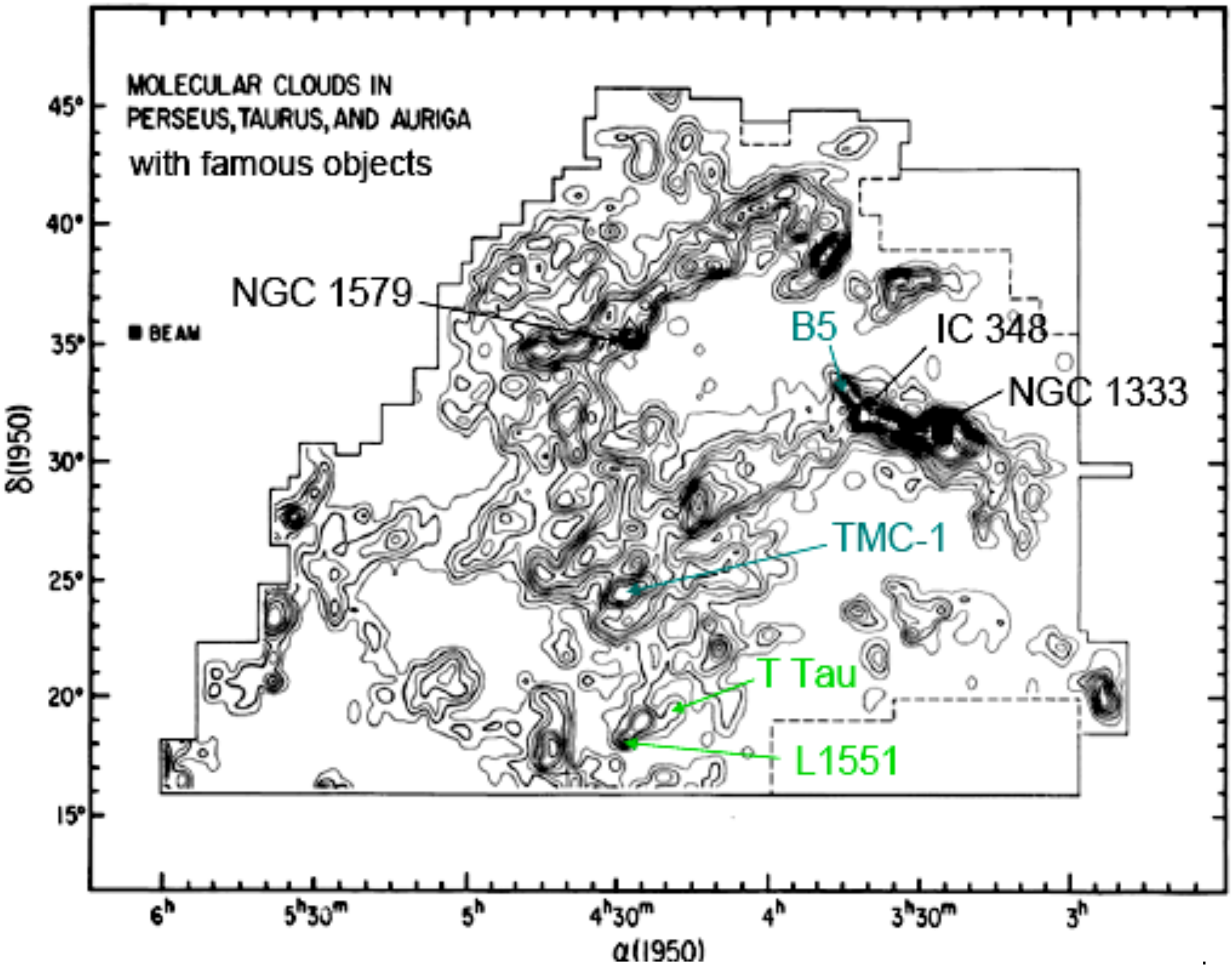
high & low mass stars

[Grey – Milky Way
Black – Molecular clouds]

Representative for the Galaxy as a whole?

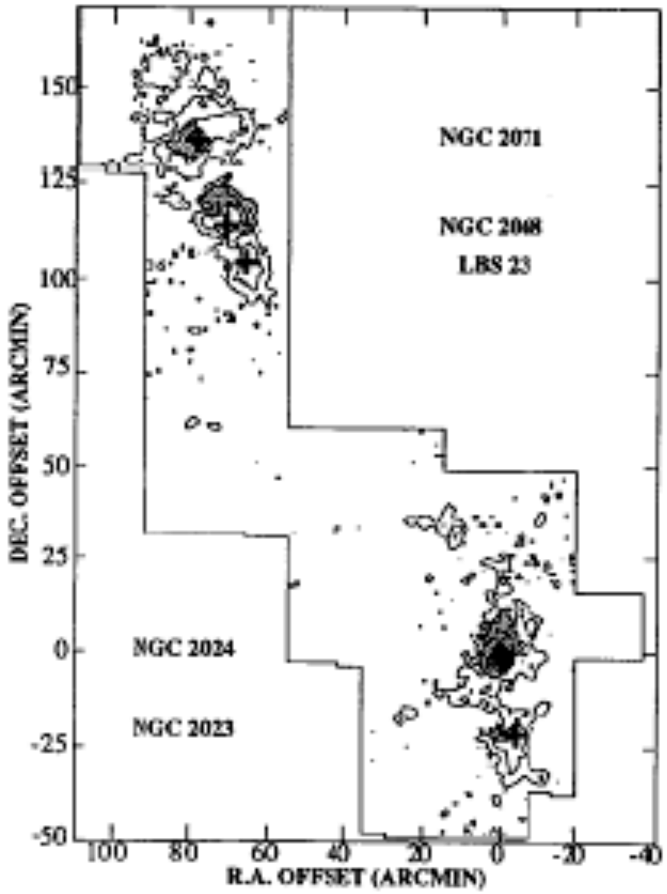


Stahler & Palla Fig 1.1


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
with famous objects
NGC 1579
BEAM
B5
IC 348
NGC 1333
TMC-1
T Tau
L1551
45°
40°
35°
30°
25°
20°
15°
δ(1950)
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)

Star Clusters in Lynds 1630

(Orion B Molecular Cloud)

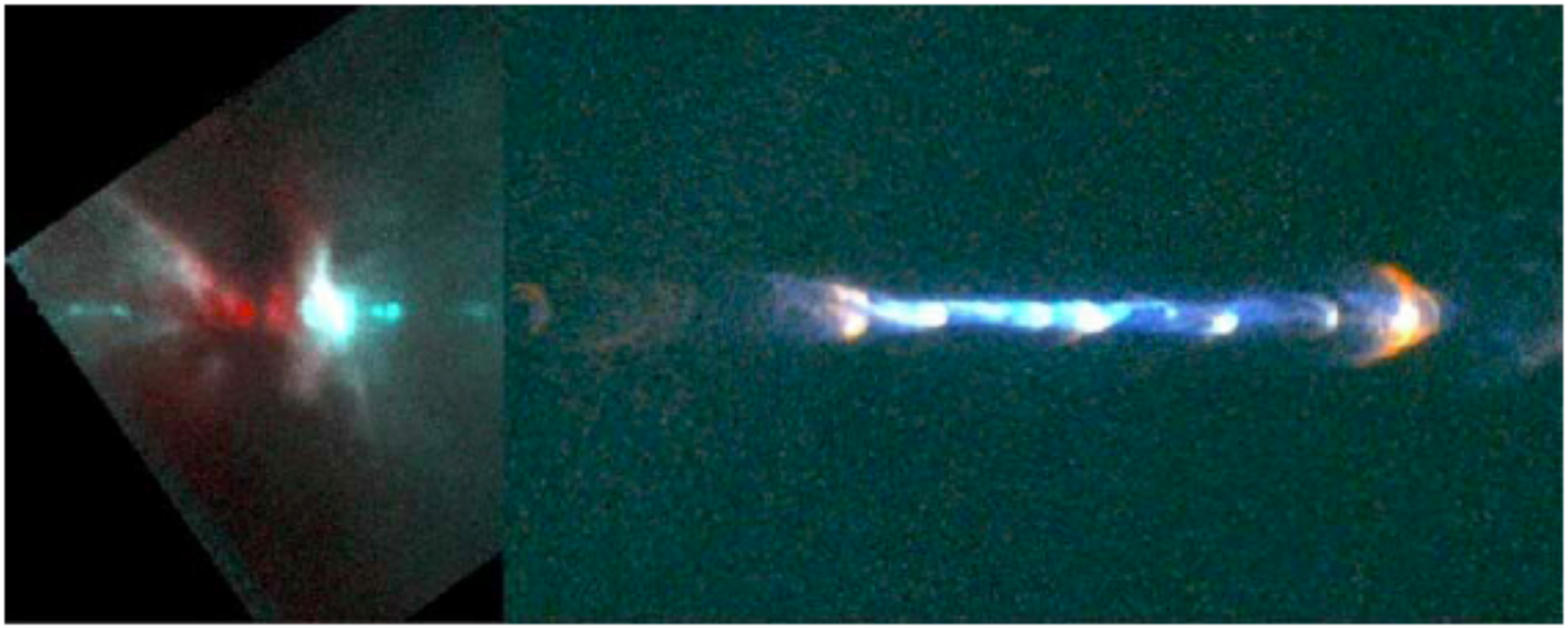


NIR star clusters on CS(2-1) map
E Lada, ApJ 393 25 1992

M(L1630) ~ 8x10^4 M_{sun}

5 massive cores (~ 200 Msun) associated with NIR star clusters

HH 111 Jet in Orion B



NICMOS WFPC2

Picture from Bo Reipurth

SMA Observations of HH 212

C.-F. Lee et al. (2008)

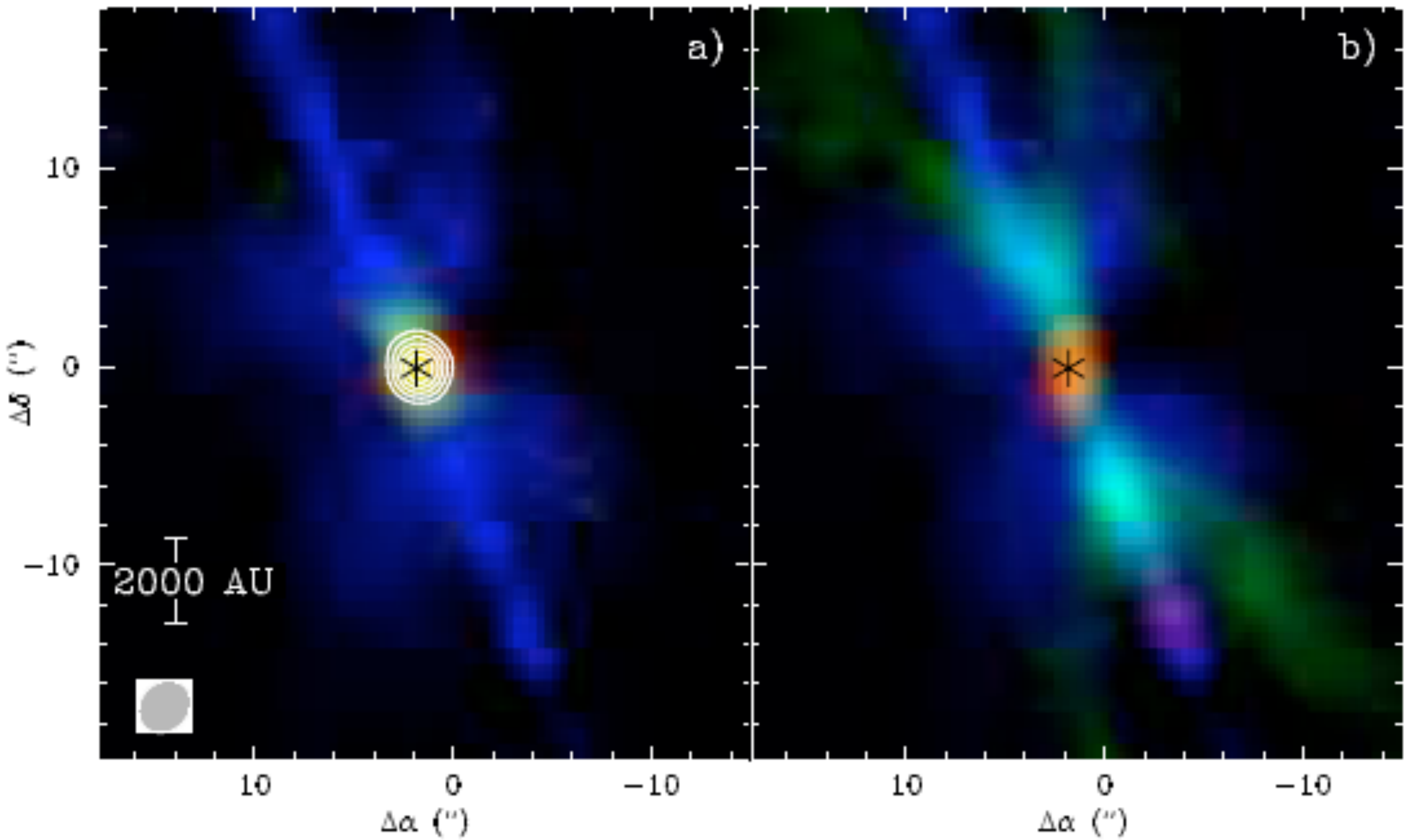
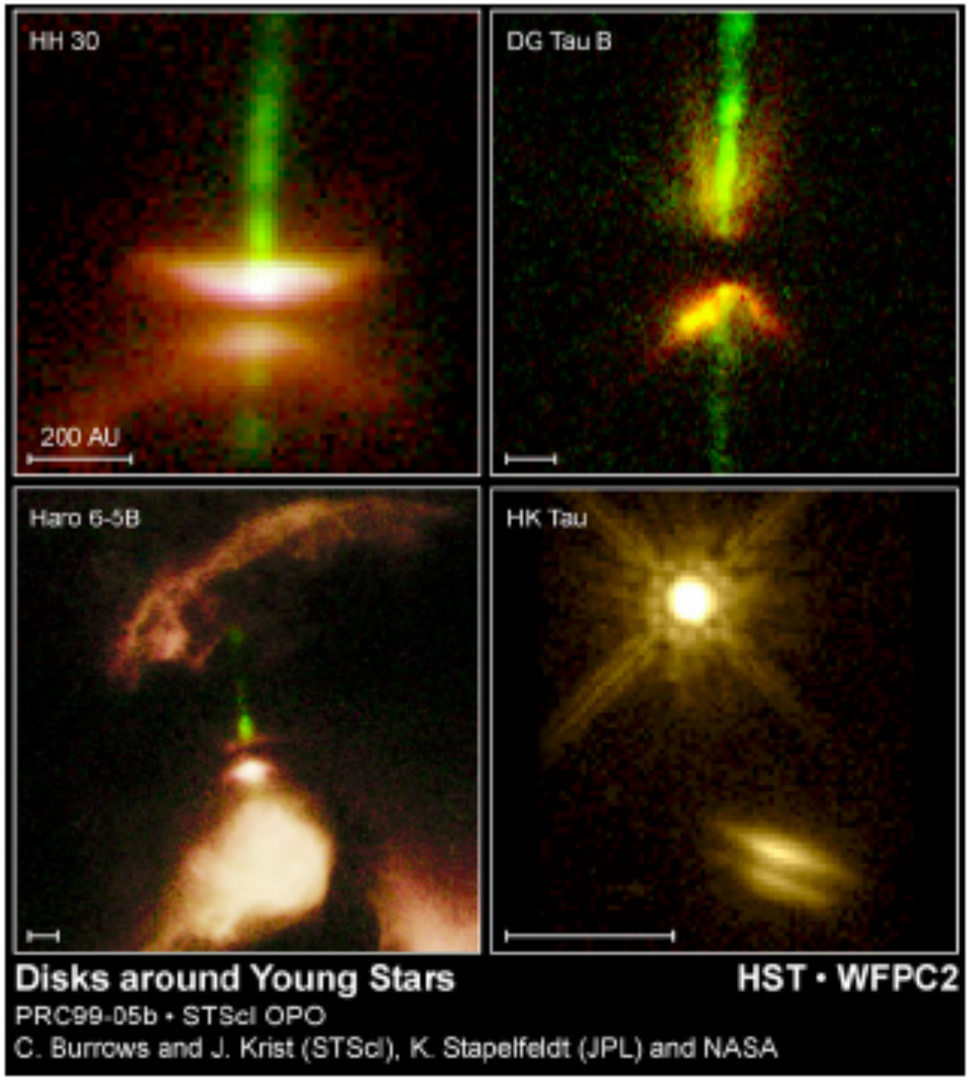


FIG. 10.— (a) Composite image of continuum (white contours), $C^{18}O$ (red), ^{13}CO (green), and H_2 (blue) emission. (b) Composite image of SO (red), ^{12}CO (green), and H_2 (blue) emission.

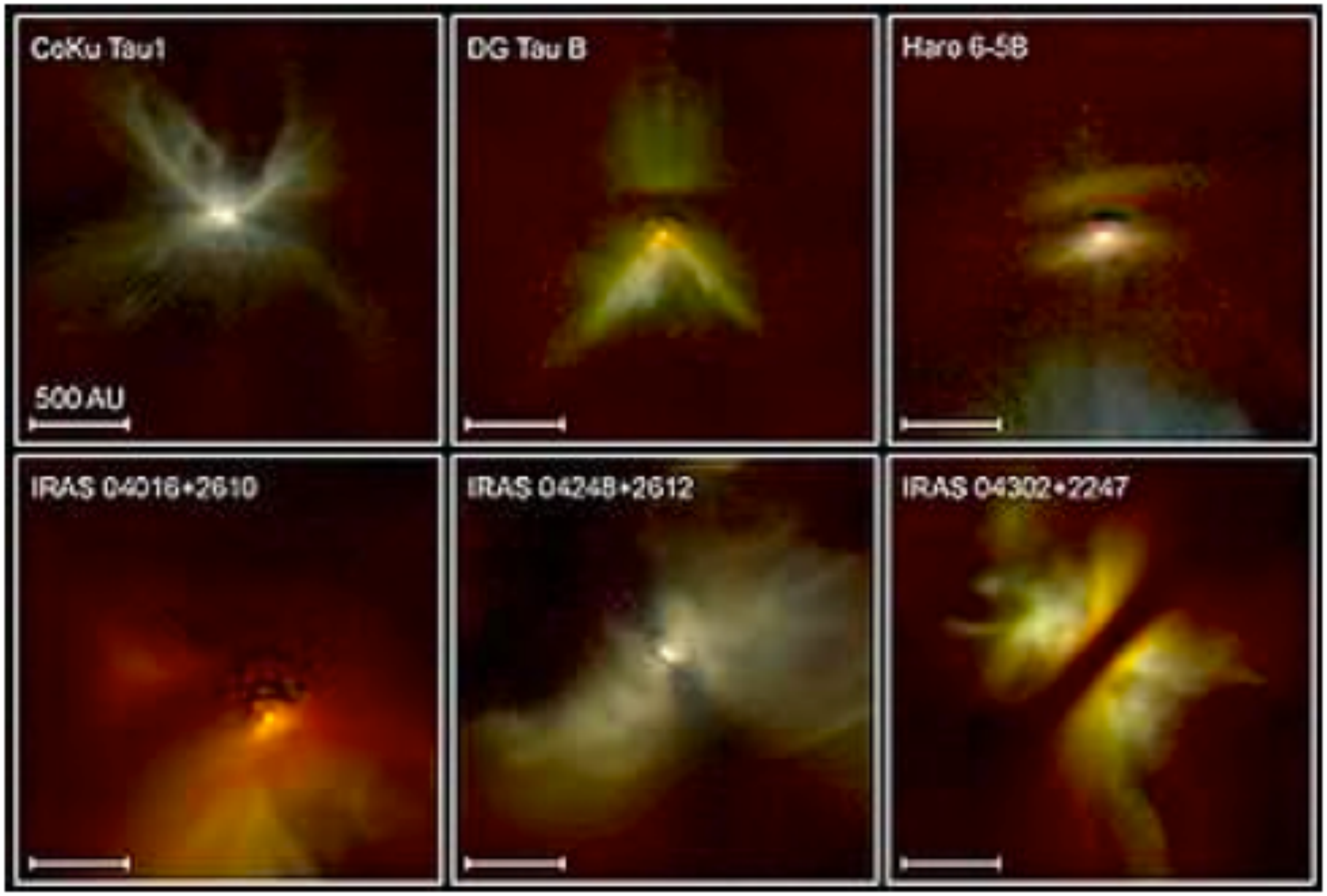
Embedded Class 0 source in L 1630

1.3 mm continuum, 3 CO isotopes SO shown with H_2(v=1-0).

Star/Disk Systems (3 with Jets)



Infrared Images
Dusty Wide-Angle Winds?



NASA/Padgett, Brandner, & Stapelfeldt (1999)

2. Properties of YSOs

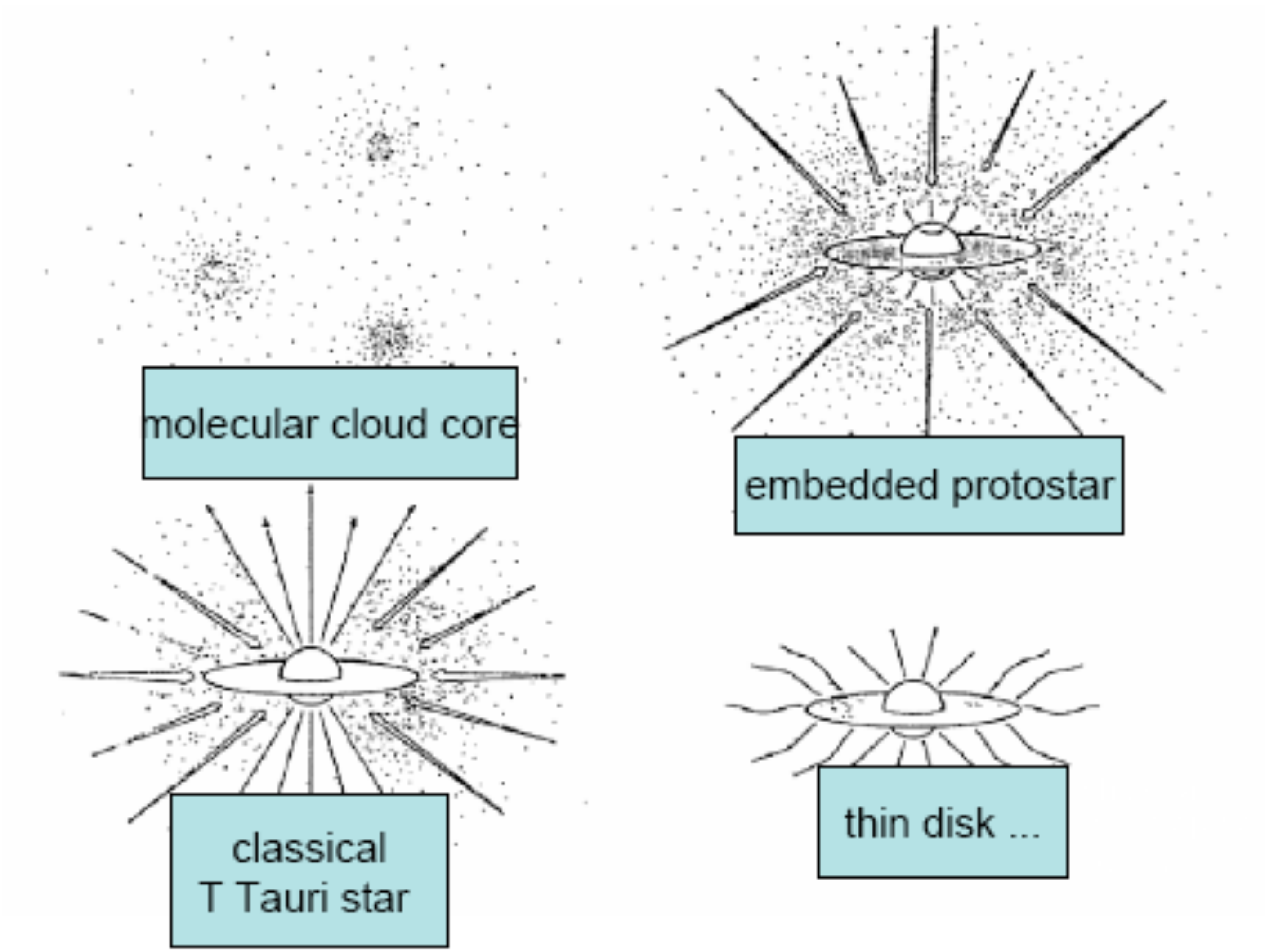
Some signposts of star formation:

- GMCs and young stellar clusters
- Dark clouds and dense cores
- Embedded IR sources
- Disks
- Outflows: jets and swept out molecular cavities

- YSOs are composed of several components, e.g. cloud, core, disk, accreting stars, outflows.
- They are small: the components vary in size from 10^{11}-10^{17} cm, i.e., from a few solar radii to 10,000 AU.
- Spatially resolved observations at 140 pc (distance to Taurus etc,) require arcmin down to milli-arcsec spatial resolution
- The components are observed from optical to mm wavelengths.

Scenario for Low-Mass Star Formation

Shu, Adams, & Lizano ARAA 25 23 1987



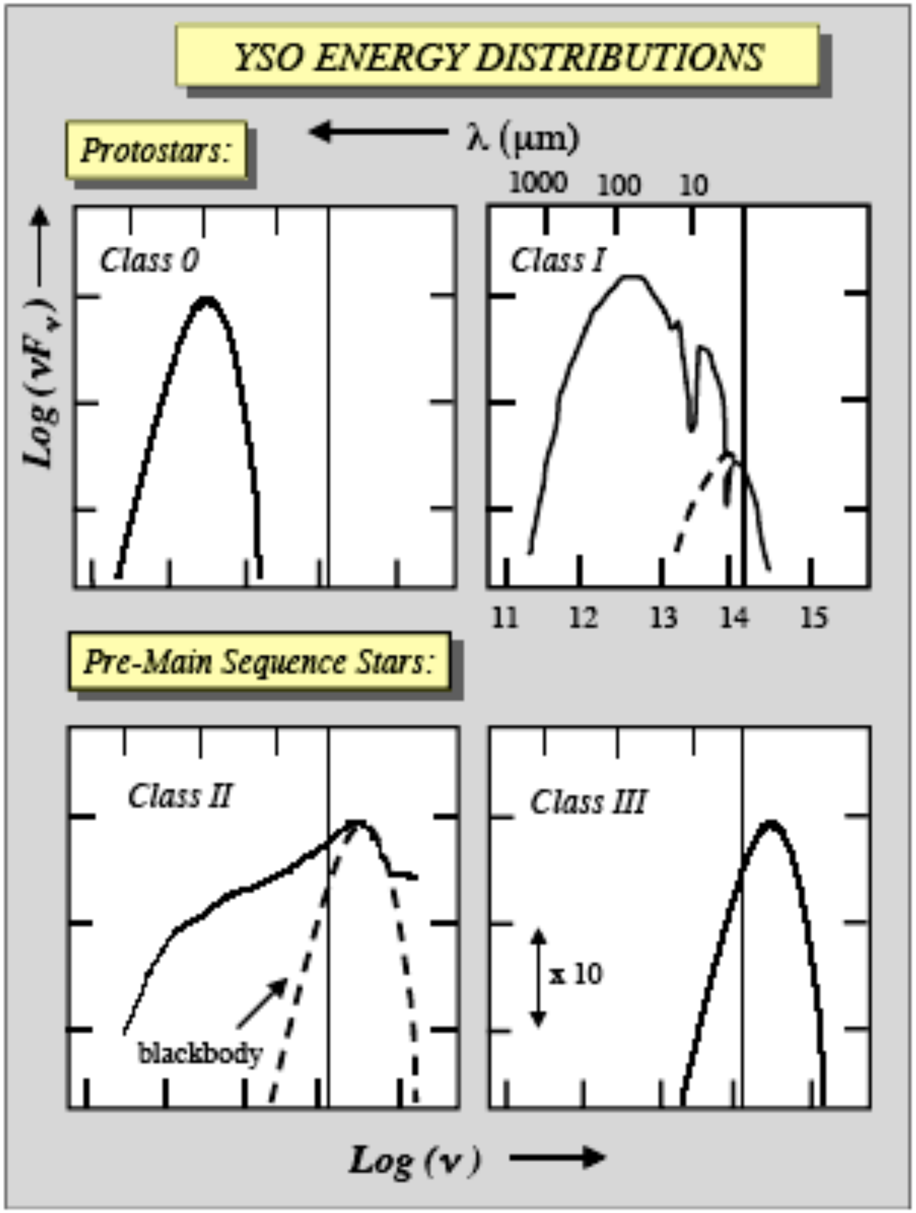
Spectral Energy Distributions

- Pioneered by Lada and Wilking (ApJ 287 610 1984) and Adams, Lada and Shu (ApJ 312 781 1987).
- Based on the fact that YSOs are obscured by circum-stellar material that reradiates stellar radiation in the IR
- The reprocessing agent is a circumstellar disk
- YSOs are classified into classes:

  Class 1 - deeply embedded sources, with positive IR spectral index, emitting in the mm an submm
  Class 2 - revealed sources with NIR and MIR excess
  Class 3 - small NIR excess
  Class 0 - earliest phase of Class 1 - just after collapse

- This classification is based on the continuum (dust) spectrum; various gas lines are of course observable but their dependence on IR class is not yet known.

YSO CLASSES



Lada (1999, OSPS)

Vertical line marks 2.2 μm.

Notice that Class 0 and Class III are near BBs.

Class II and III spectra are broader.

The Classes can also be defined by the spectral index beyond the NIR

$$s = \frac{d(\log \nu F_\nu)}{d\nu}$$

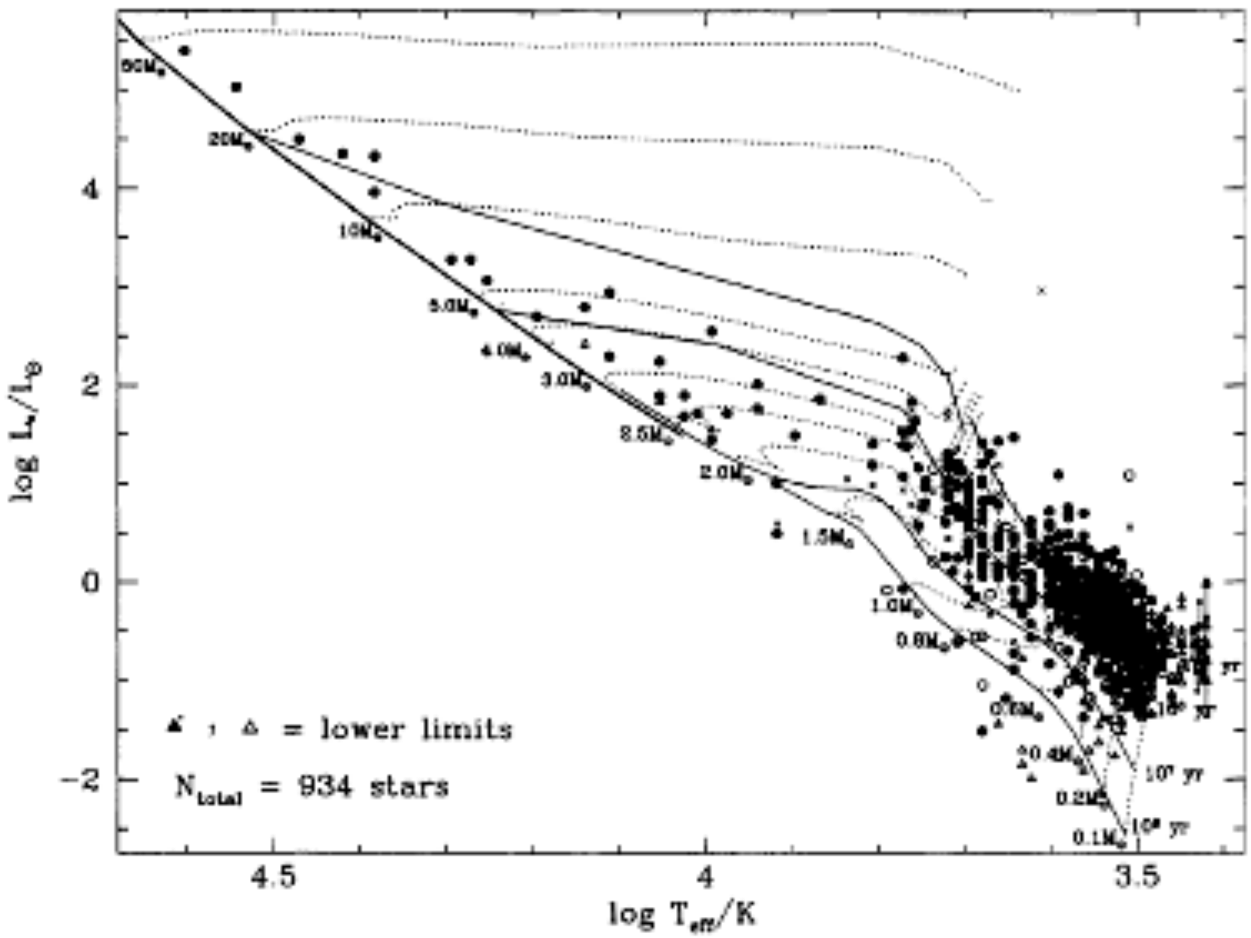
3. T Tauri Stars

- Optical detection of young stars or pre-main-sequence stars (YSOs) by AH Joy (ApJ 102 168 1945)
  - The class of T Tauri stars was defined after the prototype T Tau
    - **Irregular variability by as much as 3 magnitudes**
    - **Spectral types F5 to G5, with strong Ca II H & K emission lines as well as H Balmer lines**
    - **Low luminosity**
    - **Association with either bright or dark nebulosity**
    - **Later extend to allow any type later than F5, and requiring strong Li 6707 A absorption (as an age indicator)**
  - It was recognized from the start that the emission line patterns resemble those of the solar chromosphere, but much stronger compared to the stellar photospheric emission
    - **Ambartsumian proposed that T Tauri stars were young stellar objects (YSOs) (~1957)**

Hα is a primary line diagnostic. It is used to discriminate between “classical” T Tauri stars (EW(Hα) > 5Å) and “weak-lined” T Tauri stars (EW(Hα) < 5Å).

HR Diagram for the Orion Nebula Cluster

Hillenbrand, AJ 113 1733 1997



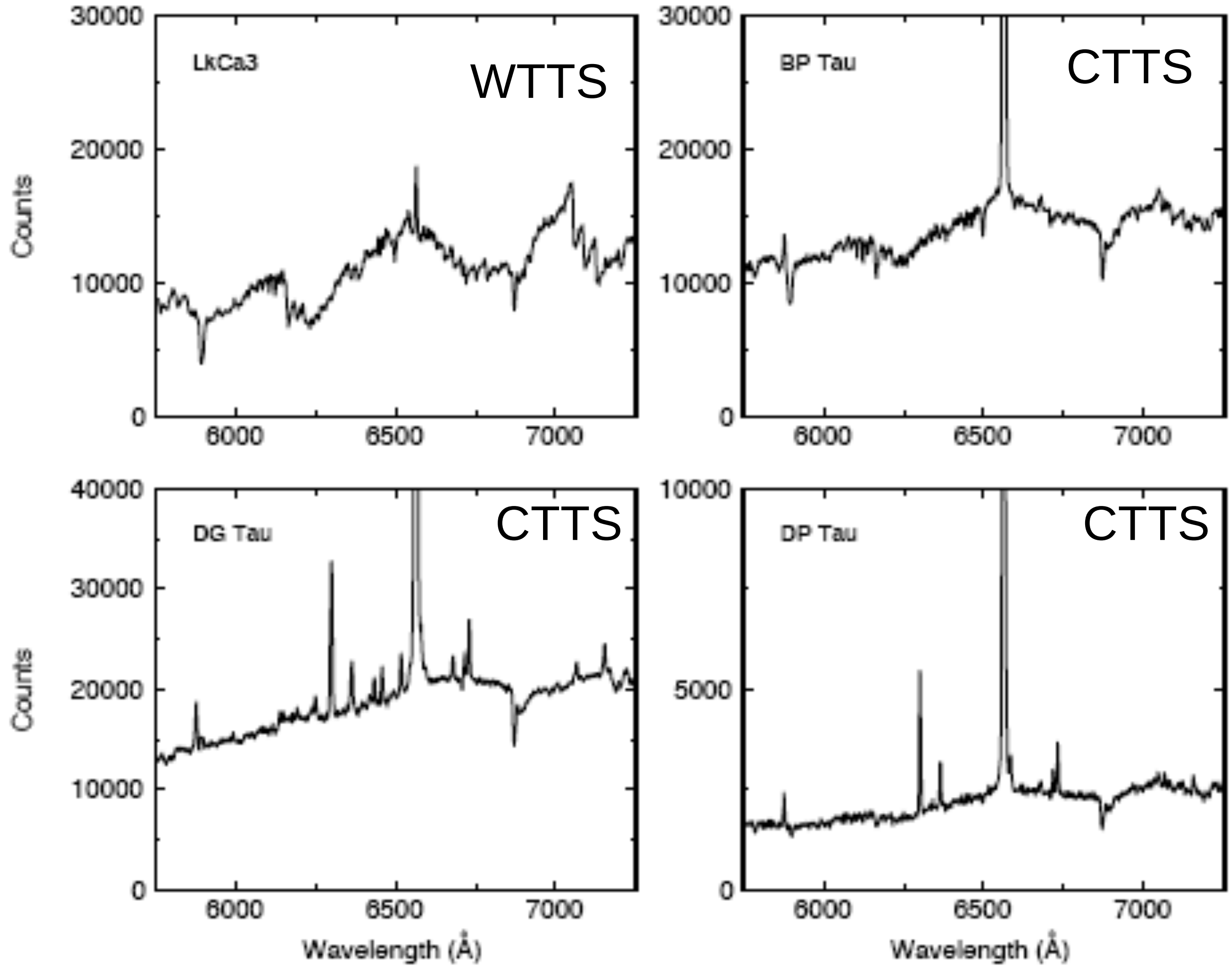
Curves of constant mass are shown as well as the main sequence. The stars can be dated with pre main sequence evolutionary tracks

T Tauri Stars without Accretion

- By definition, weak-lined T Tauri stars (WTTS) have little or no line emission and are not accreting
- Prior to IR observations, line emission was thought to be vigorous chromospheric activity
  - YSOs must (and do) have very strong magnetic fields
  - YSO magnetic fields are probably not strong enough to directly produce the line emission without a disk or outflows
- Even though WTTS are not now accreting, it does not mean that always was the case
  - Accretion is episodic, as evidenced by the structure of jets
  - WTTS probably still have disks around them

Spectra of T Tauri Stars

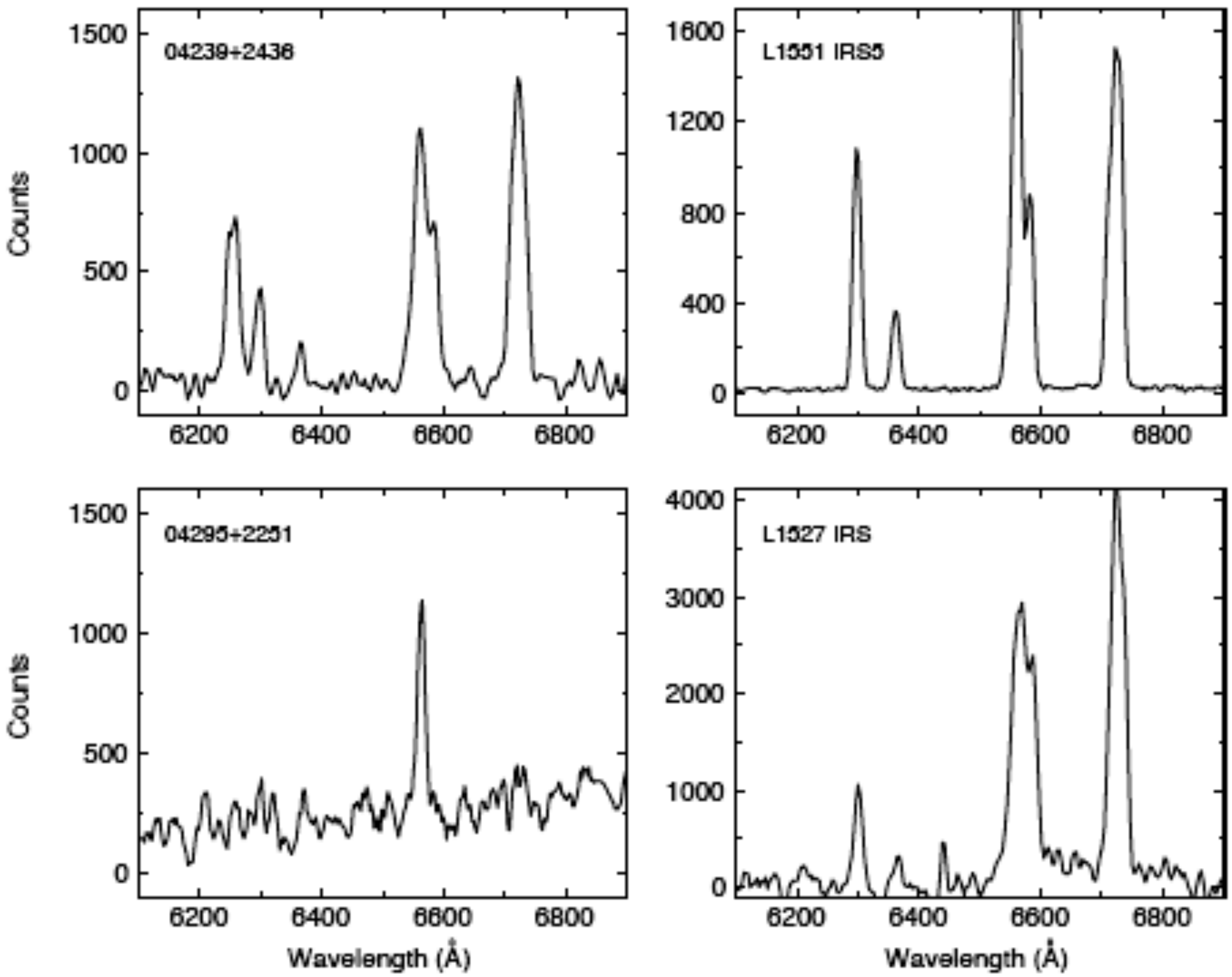
Kenyon et al. AJ 115 2491 1998



The strongest lines are usually OI,Hα and SII

Spectra of Extreme Class I TTSs

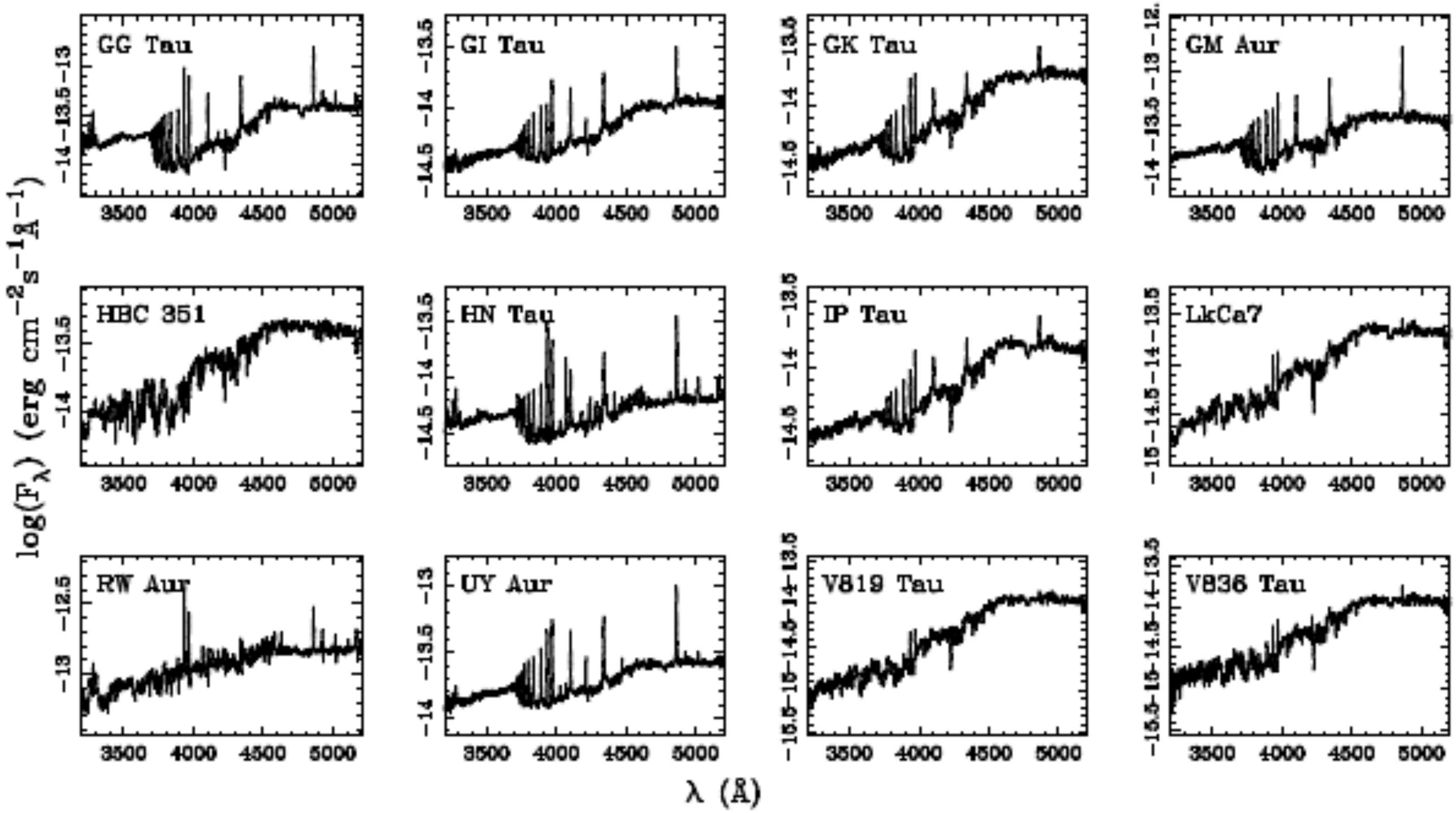
Kenyon et al. AJ 115 2491 1998



Lines dominate the continuum. The Hα line is very broad with a has a lineshape indicative of strong flows (accretion and winds).

UV Spectra of TTTs

Gullbring et al. ApJ 492 323 1998



TTSs are cool stars with spectral types K4-M3. CTTS are also strong emitters of UV and display a Balmer continuum jump at 3647 Å. The UV is believed to arise from an “accretion shock” onto the stellar surface.

The Accretion Rate

If a newly born star gains mass at the rate $(dM/dt)_{acc}$, the accreted material carries liberated gravitational energy at the equivalent luminosity,

$$L_{acc} \approx \frac{GM_* \dot{M}}{R_*}$$

Some fraction of this power may be liberated in UV generated on impact (through an accretion shock at the stellar surface . The accretion rate can be estimated from the “veiling” of stellar UV absorption lines, I.e., the filling in of the lines characteristic of the spectral type of the TTS.

Estimates by Gullbring et al. (ApJ 492 323 1998) give values in the range 10^{-9} - 10^{-7} M_{sun}/yr for TTSs (next slide).

Estimated Accretion Rates for TTS

Gullbring et al. ApJ 492 323 1998

STELLAR PARAMETERS FOR THE CTTSs

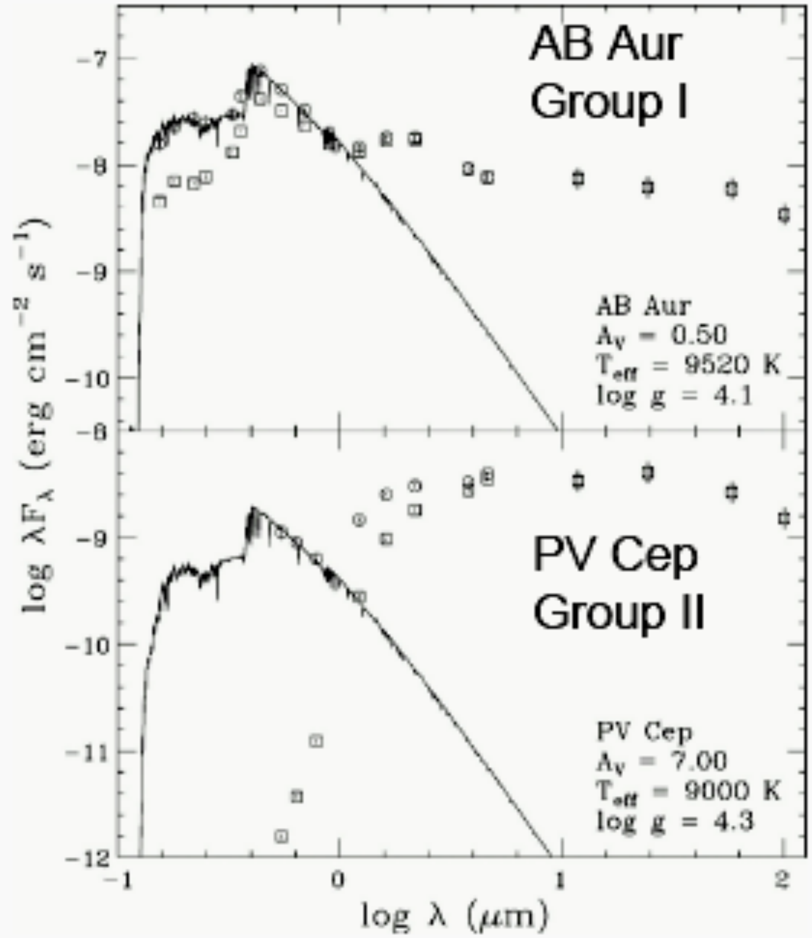
Object	L_* ($L_\odot$)	log (age) (yr)	M ($M_\odot$)	R_* ($R_\odot$)	A_V	L_{acc} ($L_\odot$)	$\dot{M}$ ($\times 10^{-7}$ $M_\odot$ yr $^{-1}$)
BP Tau	0.925	5.79	0.490	1.99	0.51	0.179	0.288
DN Tau	0.87	5.69	0.382	2.09	0.25	0.016	0.035
DF Tau	1.97	3.59	0.27	3.37	0.45	0.358	1.769
DE Tau	0.87	5.01	0.259	2.45	0.62	0.071	0.264
DK Tau	1.45	5.56	0.431	2.49	1.42	0.166	0.379
AA Tau	0.71	5.98	0.530	1.74	0.74	0.025	0.033
GG Tau	1.25	5.63	0.442	2.31	0.60	0.084	0.175
DQ Tau	0.635	5.88	0.439	1.785	0.71	0.004	0.006
HN Tau	0.19	7.49	0.81	0.76	0.65	0.035	0.013
GM Aur	0.74	5.95	0.524	1.78	0.31	0.071	0.096
UY Aur	1.585	5.52	0.421	2.60	1.26	0.268	0.656
GI Tau	0.85	6.09	0.668	1.735	1.34	0.094	0.096
DS Tau	0.57	6.58	0.870	1.36	0.34	0.209	0.129
IP Tau	0.41	6.23	0.522	1.44	0.32	0.007	0.008
GK Tau	1.08	5.70	0.461	2.15	0.94	0.035	0.064
DO Tau[a]......	1.01	5.625	0.369	2.25	2.27	0.600	1.442
CY Tau	0.46	6.32	0.424	1.63	0.32	0.041	0.075

4. Herbig Ae/Be Stars

Herbig (1960) searched for these more massive analogs of TTS. Comprehensive studies of the SEDs by Hillenbrand et al. (ApJ 397 613 1992 etc.).

The IR excess starts already at 1-2 μm.

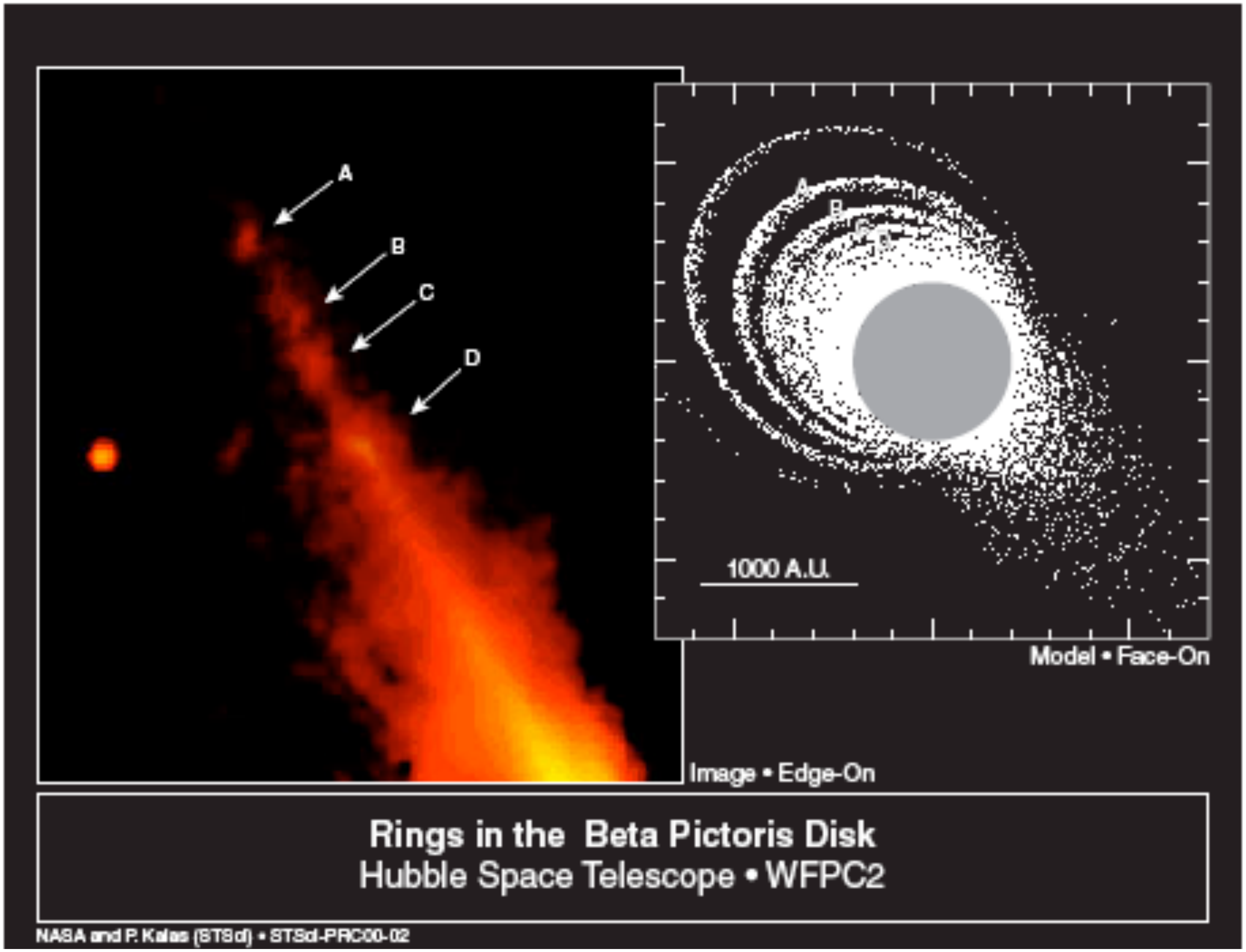
Hillenbrand's classification (I - declining & II – rising) is the opposite of the accepted Classes I,II,III for TTSs.



Squares: observed fluxes
Circles: extinction corrected

The strong MIR-FIR emission indicates one difference with the lower mass TTSs, I.e., the presence of a quasi-spherical dust shell.

Herbig Stars and Debris Disks



Debris disks have their dust replenished by erosion of planetesimals.
The prototypes ***former Herbig Ae stars***: β Pic, Vega, & Fomalhaut.
Planets can affect the distribution of dust.

SEDs of Herbig Stars

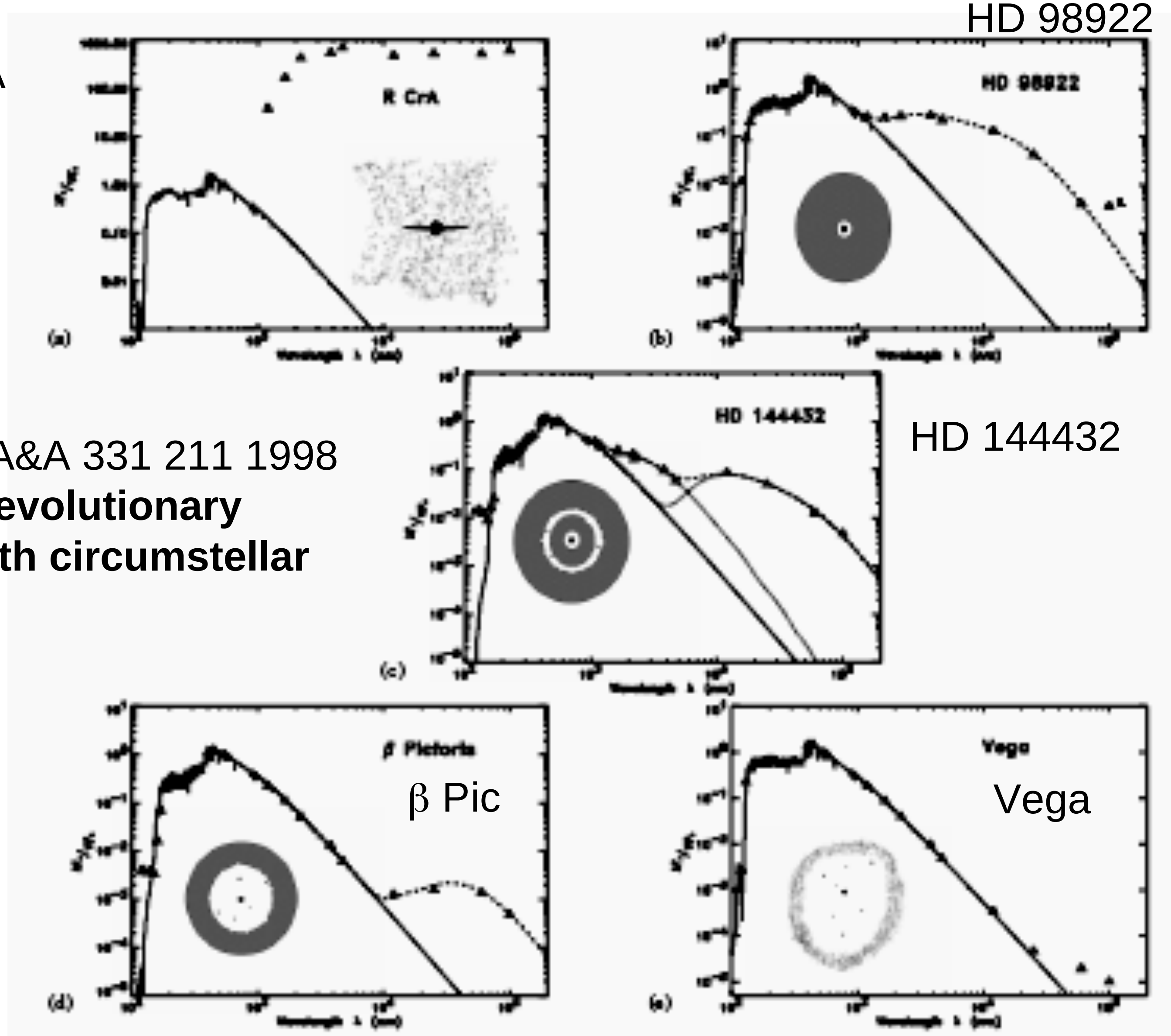
(2-8 Msun Analaogs of TTSs)

R CrA

HD 98922

HD 144432

Malfait et al. A&A 331 211 1998
Speculative evolutionary sequence with circumstellar material

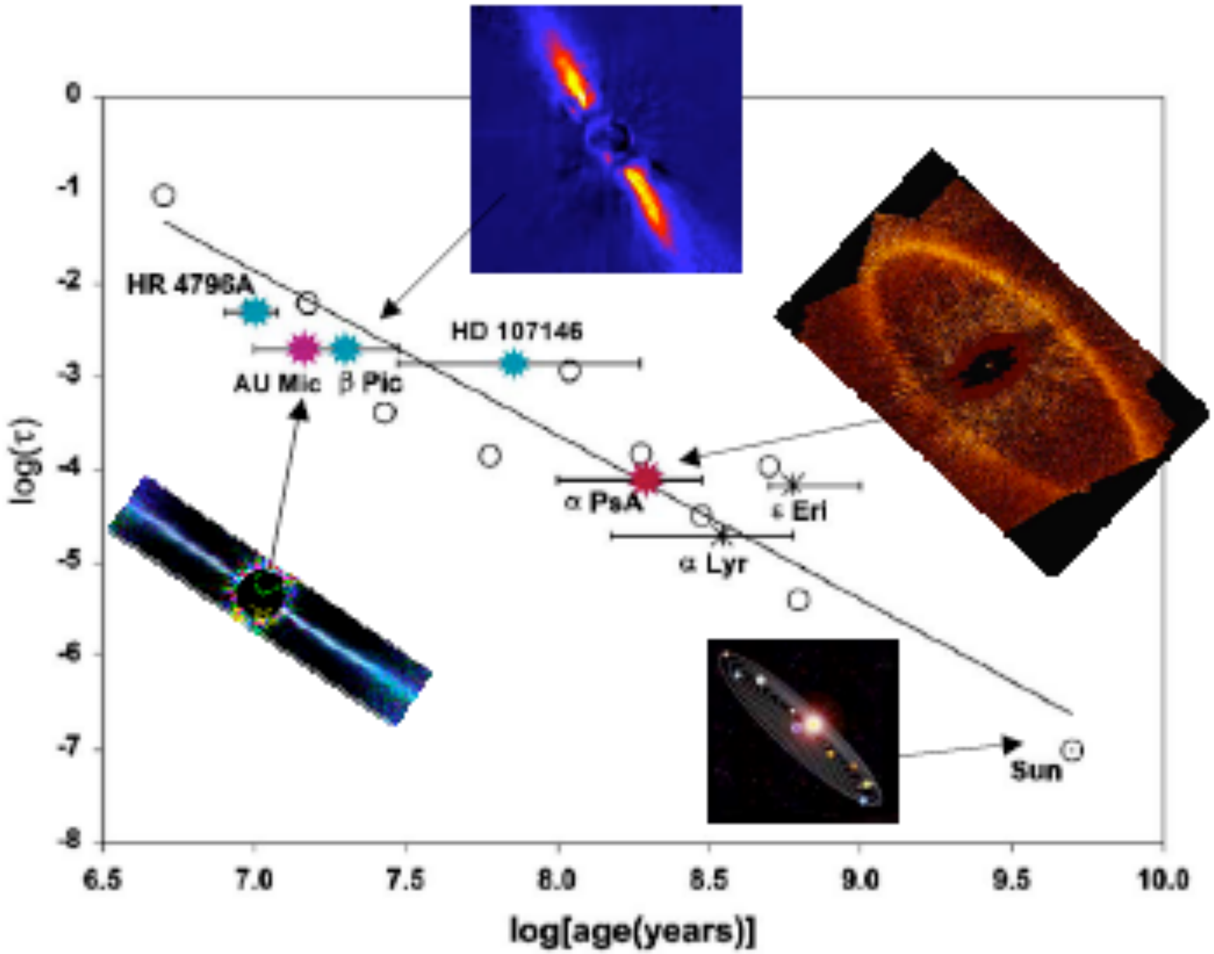


β Pic

Vega

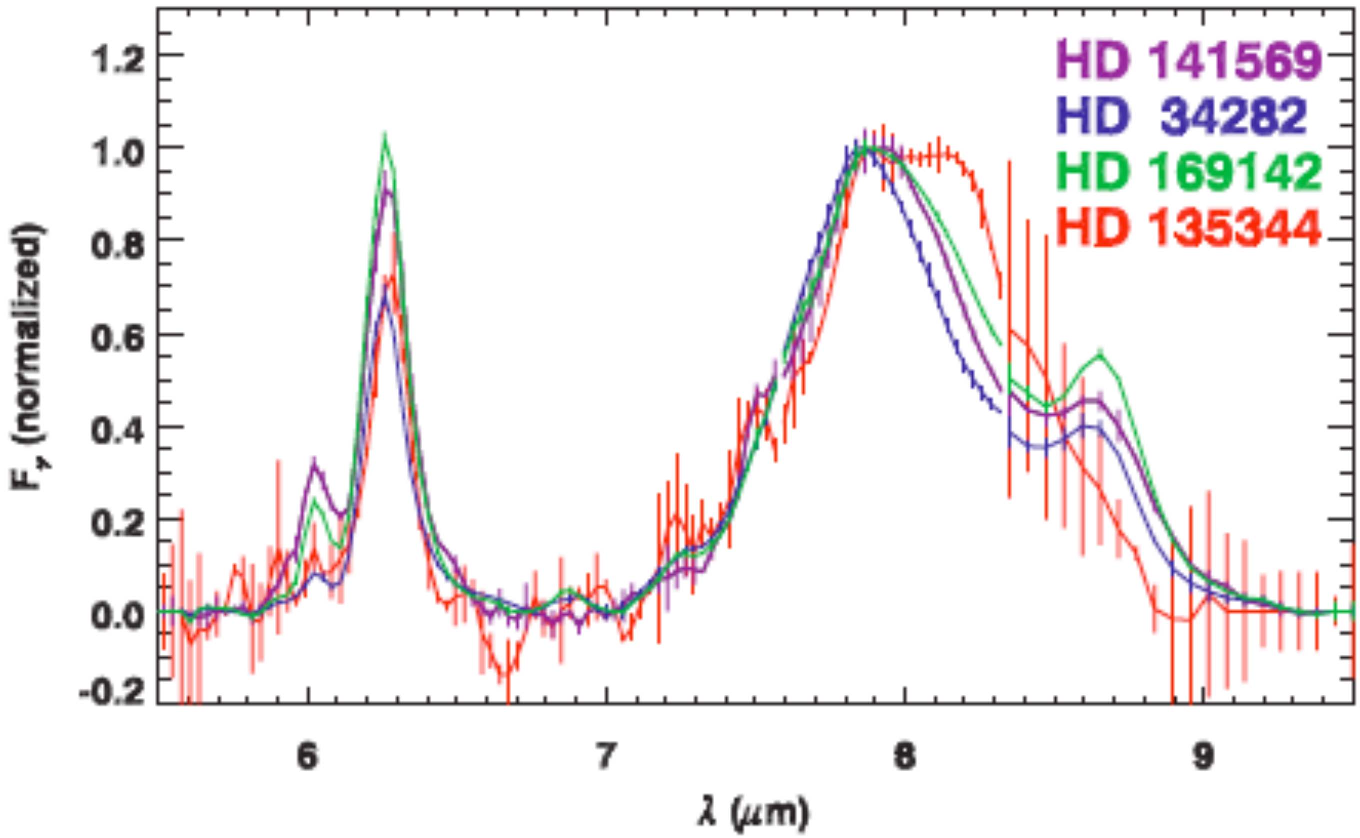
Evolving Circumstellar Environment

Debris disk studies suggest that the quantity of circumstellar material declines rapidly with age: $M \propto t^{-2}$



Spectroscopy of Herbig Stars

Being 10-100 times more luminous than TTS, Herbig stars are often the targets of IR space observations, which observations shed interesting light on the solids and large molecules near YSOs.



6.2 and 7.7 μm PAH feature in Herbig stars
(Sloan et al. ApJ 632 956 2005)