Cores and Disks

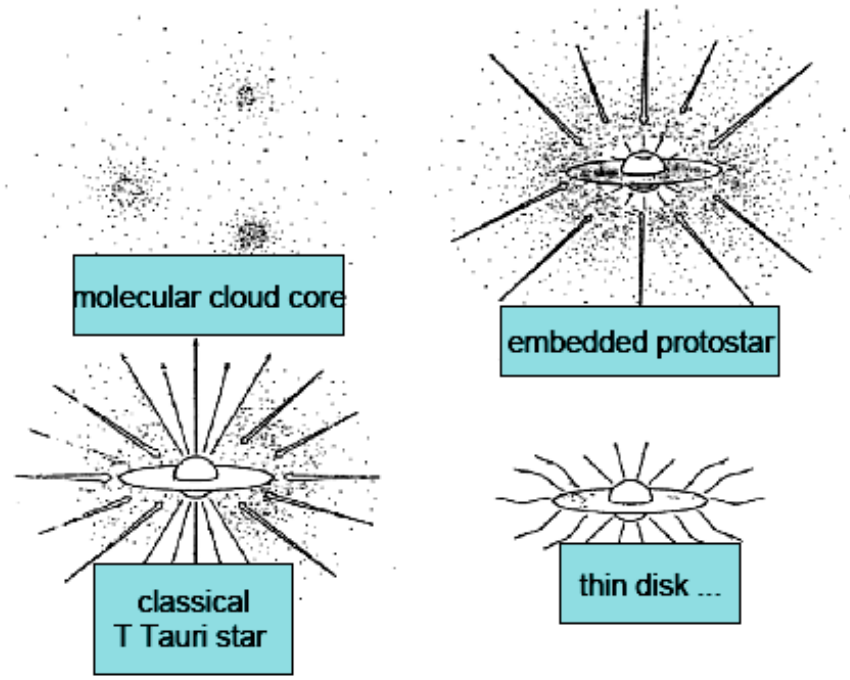
1. Overview of Low-Mass Star formation
2. Observed Properties of Disks
3. Initial Mass Functions

References

Section VI of PPV on disks
”The IMF 50 Years Later”, Corbelli et al. (Springer 2005)
Alves et al. A&A 462 L17 2007

1. Overview of Low-Mass Star Formation

Star formation scenario
emphasizing disks and winds
Shu, Adams & Lizano
ARAA 25 23 1987



- These observed stages are a likely evolutionary sequence.
- Each raises innumerable dynamical questions that relate to
    - core formation and collapse
    - disk formation and wind generation
    - role of magnetic fields and turbulence
    - the initial mass function

(much of which we can only mention without further discussion)

Disk Lifetimes in Young Clusters

(2.5 - 30 Myr)

Haisch et al.
ApJ 553 L153 2001
JHKL excesses

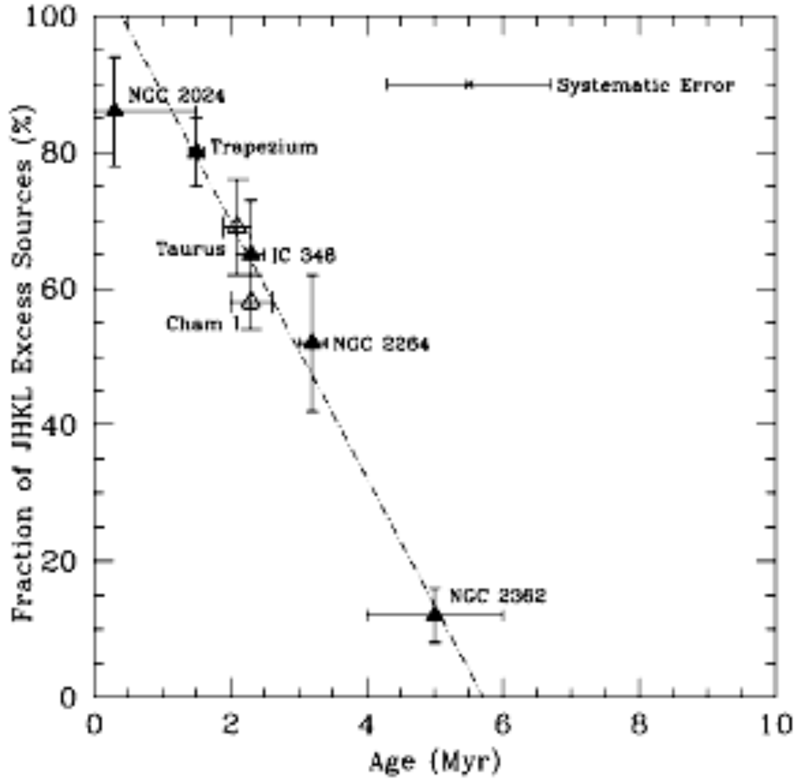


FIG. 1.—*JHKL* excess/disk fraction as a function of mean cluster age. Vertical error bars represent the statistical $\sqrt{N}$ errors in our derived excess/disk fractions. For all star-forming regions except NGC 2024 and NGC 2362, the horizontal error bars represent the error in the mean of the individual source ages derived from a single set of PMS tracks. The age error for NGC 2362 was adopted from the literature. Our estimate of the overall systematic uncertainty introduced in using different PMS tracks is plotted in the upper right corner and is adopted for NGC 2024. The decline in the disk fraction as a function of age suggests a disk lifetime of 6 Myr.

Cluster stars lose disks in 6 Myr

2. Observations of Disks

Observations of dust:

scattered optical light or silhouettes of disks

SEDs from optical through mm wavelengths

Observations of the gas;

NIR ro-vibrational transitions of molecules

mm rotational transitions of of molecules

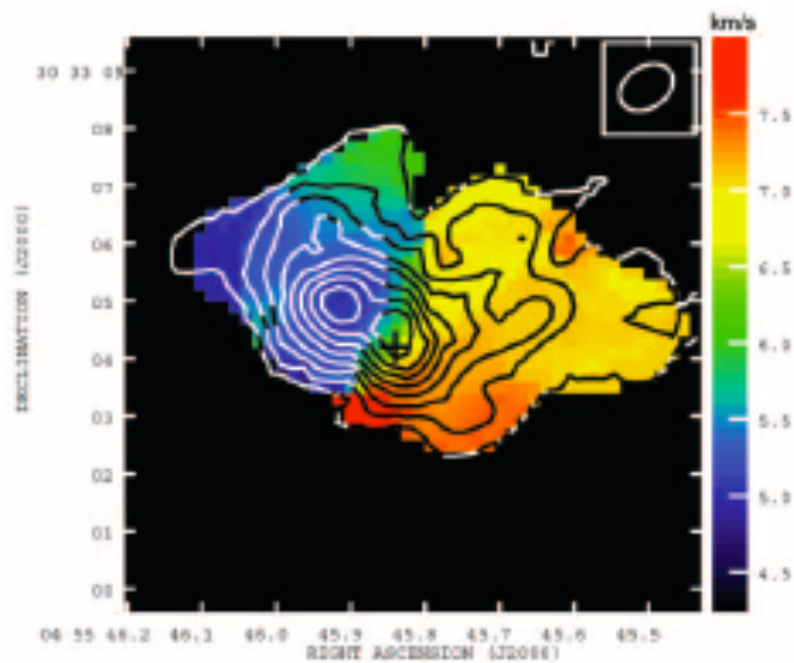
- The dust is easier and more frequently observed.
- The gas and dust are not always co-spatial.
- The focus is now on the gas.
- SPITZER IRS adds a new dimension in MIR

A sample of recent observations are shown below.
Consult the articles in Sec. VI of PPV for more.

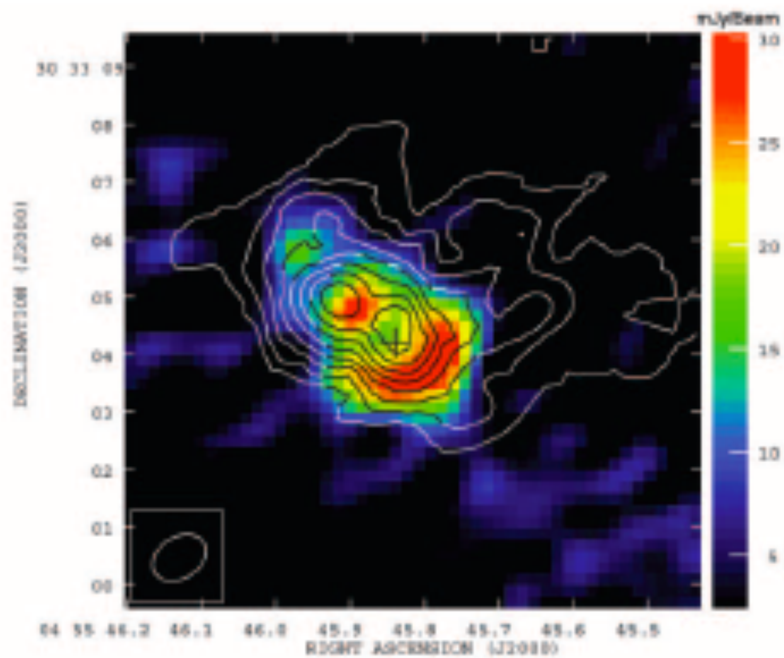
The Potential of Sub-mm Observations

S.-Y. Lin et al, ApJ 845 1297 2006

SMA gas map of the disk of the Herbig star AB Aur in the CO J=3-2 transition at a resolution of 1” (150 AU).



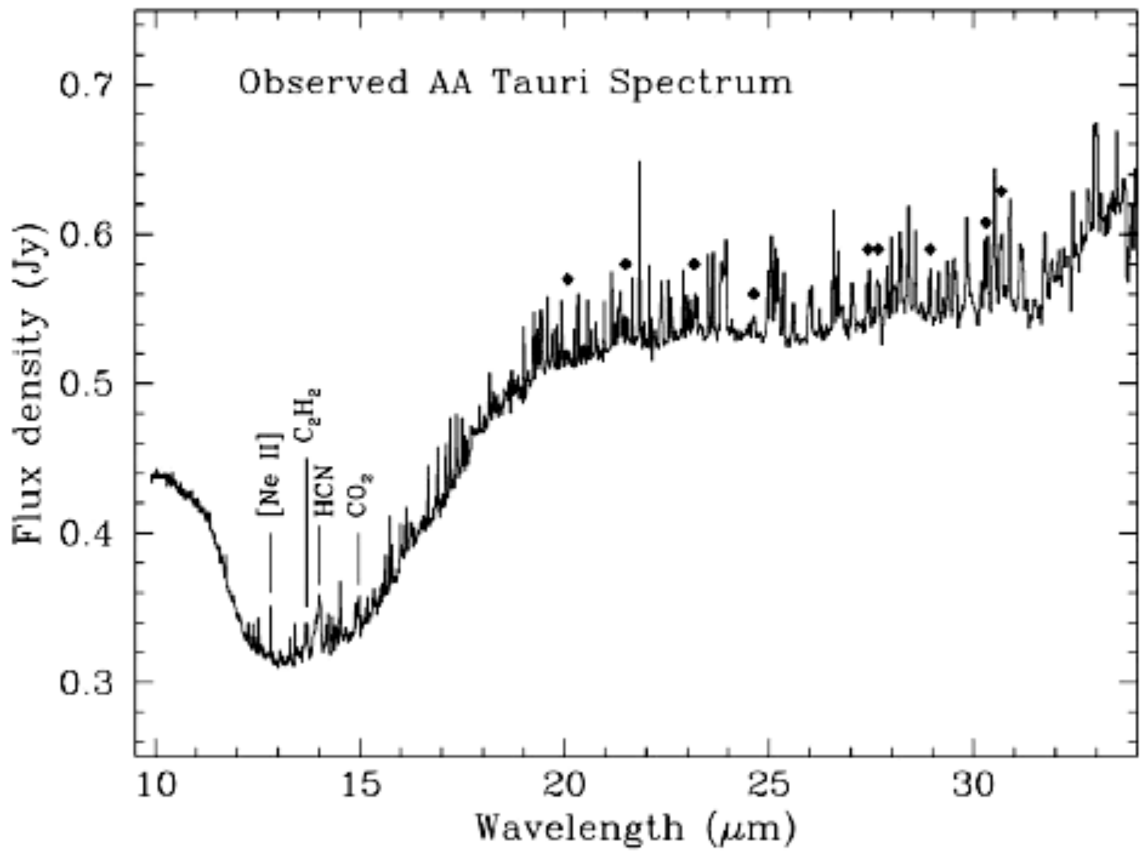
Integrated CO intensity contours plus velocity (color) from 4.2-8.0 km/s



CO contours overlain on the 850 micron dust continuum

Spitzer MIR Spectroscopy of T Tauri Disks

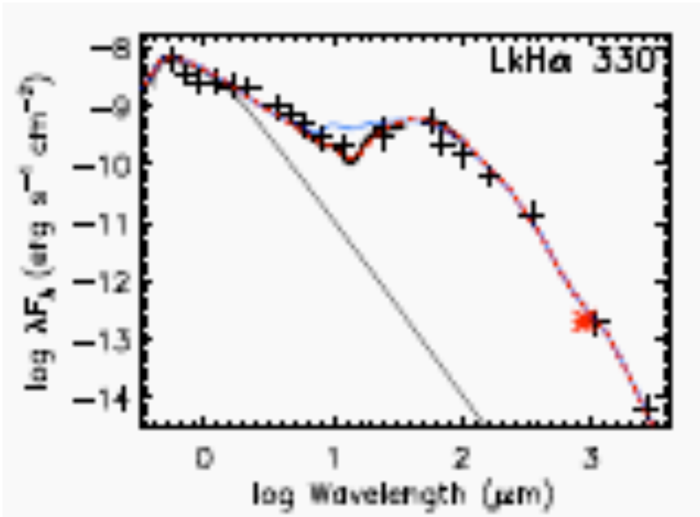
Carr & Najita, Science 319 1504 2008



Most features are lines of H_2O, unless marked. The solid diamonds are from OH rotational bands. The data supplement higher excitation ro-vibrational transitions of CO and simple complex molecules.

Dust Hole in a Transition Disk

Brown et al. ApJ 675 L109 2008

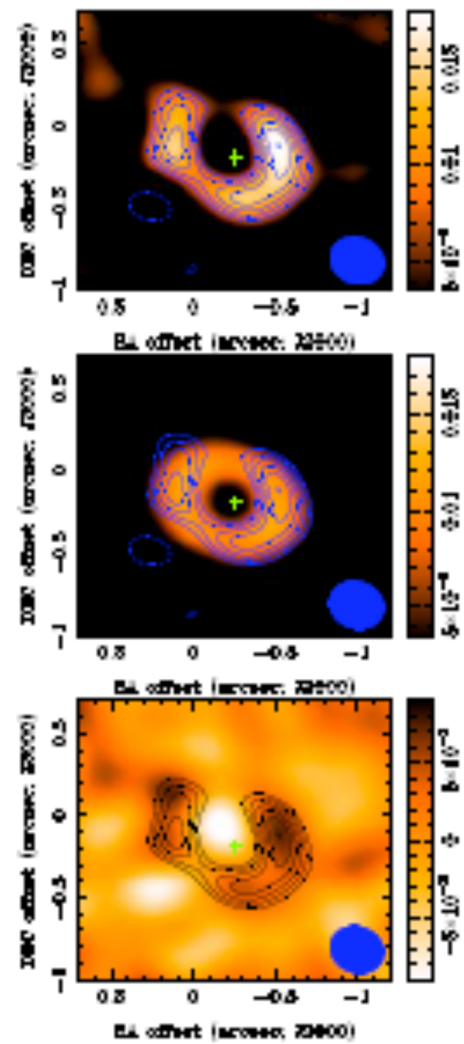


- Small IR excess and a minimum indicate a disk with an inner hole
- Solid curve and middle panel on right use a 40 AU inner hole
- Hole is confirmed by interferometry (angular resolution of 0.33”), but fit is imperfect
- Speculations abound for the origin of the hole, e.g., an unseen planet
- CO is detected inside the hole

data

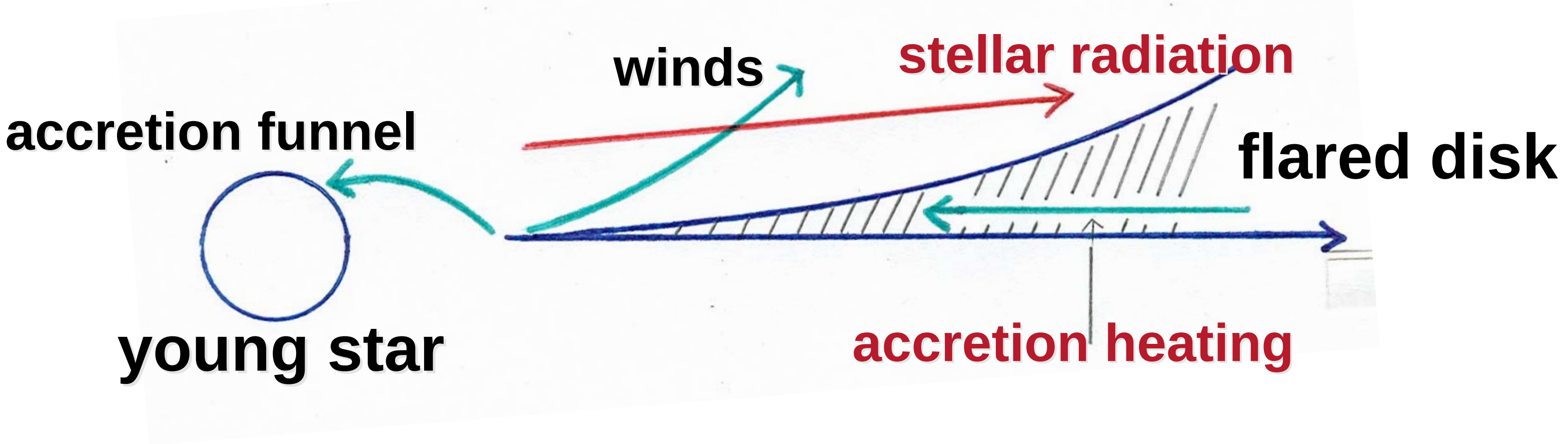
model + data

data - model



SMA 340 MHz maps

Modeling the Observations



Schematic of a disk with three main flows and two heating sources.

Among other things omitted from the diagram are:

- The feeding of the disk by the nascent cloud core
- The stellar rotation
- The disk rotation, usually assumed to be Keplerian (the disk mass is less than the stellar mass)
- Magnetic fields, especially that of the star

Semi-Empirical Disk Models

Despite a vast literature on the accretions disks of YSOs, the theory is far from complete and modeling is usually carried out with semi-empirical models. The first such model was ***The Minimum Solar Nebula*** (e.g., Hayashi et al. Protostars & Planets II, 1985).

This model uses power-law distributions for density and temperature:

$$\rho(r,z) = \rho_0 r^{-q} e^{-z^2/2H^2} \qquad T = T_0 (r/R_0)^{-p}$$

Hayashi determined the density distribution by assessing the radial distribution of the refractory elements in the present solar system, which are found in the terrestrial planets, the cores of the giant planets and in various smaller rocky bodies (asteroids, Kuiper-Edgeworth objects, comets, etc.). Adding back the volatiles that must have been present in the so-called ***primitive solar nebula***, he found that q = 2.75 and M_{disk} = 0.013 M_{sun}. He chose p=1/2 by considering heating of dust grains by the diluted stellar radiation. The Gaussian atmosphere assumes it is isothermal.

Summary of the Hayashi MSN

$$\rho(r,z) = \rho_0 r^{-2.75} e^{-z^2/2H^2} \qquad T = T_0 (r/R_0)^{-0.5}$$

$$\text{surface density}: \ \Sigma = \Sigma_0 (r/R_0)^{-1.5} \quad \text{scale height}: \ H = H_0 (r/R_0)^{1.25}$$

$$R_0 = 1\text{AU}, \quad \rho_0 = 1.4\text{x}10^{-9} \text{ g cm}^{-3}, \quad T_0 = 280 \text{ K},$$

$$\Sigma_0 = 1700 \text{ g cm}^{-2}, \ H_0 = (1/30) \text{ AU},$$

$$M(0.35\text{AU}, \ 35\text{AU}) = \ 0.013 \ M_{\text{sun}}$$

$$n_{\text{H}}(1\text{AU}) \approx 5.5\text{x}10^{14}\,\text{cm}^{-3}$$

The Gaussian atmosphere follows from balancing the vertical pressure *for constant T* against the vertical force of gravity for a thin disk, ignoring the self-gravity of the disk:

$$\frac{1}{\rho}\frac{d}{dz}\rho c^2 = -\frac{GM}{\varpi^3} z \quad \Rightarrow \quad \rho \propto e^{-z^2/2H^2} \ \ \text{with } H = c/\Omega_{\text{K}}$$

where Ω_K is the Keplerian angular velocity.

Properties and Problems of the Simple Models

- Optical/IR photons are absorbed by dust
- Power-law models help correlate SEDs and scattered light images of the dust with many free parameters, e.g., the optical properties and size distribution of the dust.
- Disk masses are unconstrained because the dust to gas ratio is unknown.
- Molecular observations of simple molecules like H_2 and CO indicate higher gas temperatures than suggested by the MSN and its generalizations.
- Disk surface layers are heated by FUV and X-rays (which couple well to the gas) and produce a temperature inversion in the upper atmosphere of disks
- Disk atmospheres are dense, inhomogeneous PDRs

Modeling of mm lines is reviewed by Dutrey et al. in PPV

Millimeter Arrays and Their Future

Plateau de Bure

- mostly 115-230 GHz
- 6 15-m dishes (1060 m^2)
- 0.6” at 1.3 mm

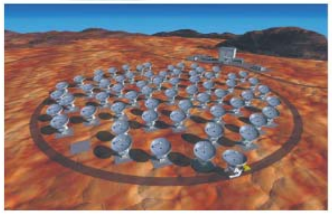
SMA (Mauna Kea)

- 180-900 GHz
- baselines up to 500 m
- sub-arc second synthesized beam
- dual channel measurements

CARMA

- 115-230 GHz very broad backend
- Nine 6-m & six 10.4-m (772 m^2)
- Angular resolution = 0.1" (230 GHz/A-array)

ALMA Site



- About sixty-four 12-meter antennas located at 4990 m in Llano de Chajnantor, Chile
- Imaging instrument in all atmospheric windows between 30–900 GHz
- Array configurations from approximately 150 meters to 10 km
- Spatial resolution of 10 mas, 10 times better than HST

3. Initial Mass Functions

A classic problem in astronomy in the context of the mass distribution of molecular cloud core masses.

Measurements of the absolute magnitude of the stars in the solar neighborhood revealed a preponderance of large magnitudes, I.e., faint low-mass stars. This is due to the long main-sequence lifetimes of low-mass stars and to the seeming preference for forming low-mass stars.

See the excellent discussion in Palla & Stahler, Sec. 4.5 on how these two effects can be separated :

distribution in $M_V \Rightarrow$ distribution in mass $N(M)$

making use of the distribution of main-sequence lifetimes and assumptions about the star- formation rate over time

Salpeter and Other IMFs

Salpeter (ApJ 121 161 1955) argued for *N(M)* ~ *M* $^{-2.35}$, and many people have tried unconvincingly to derive it.

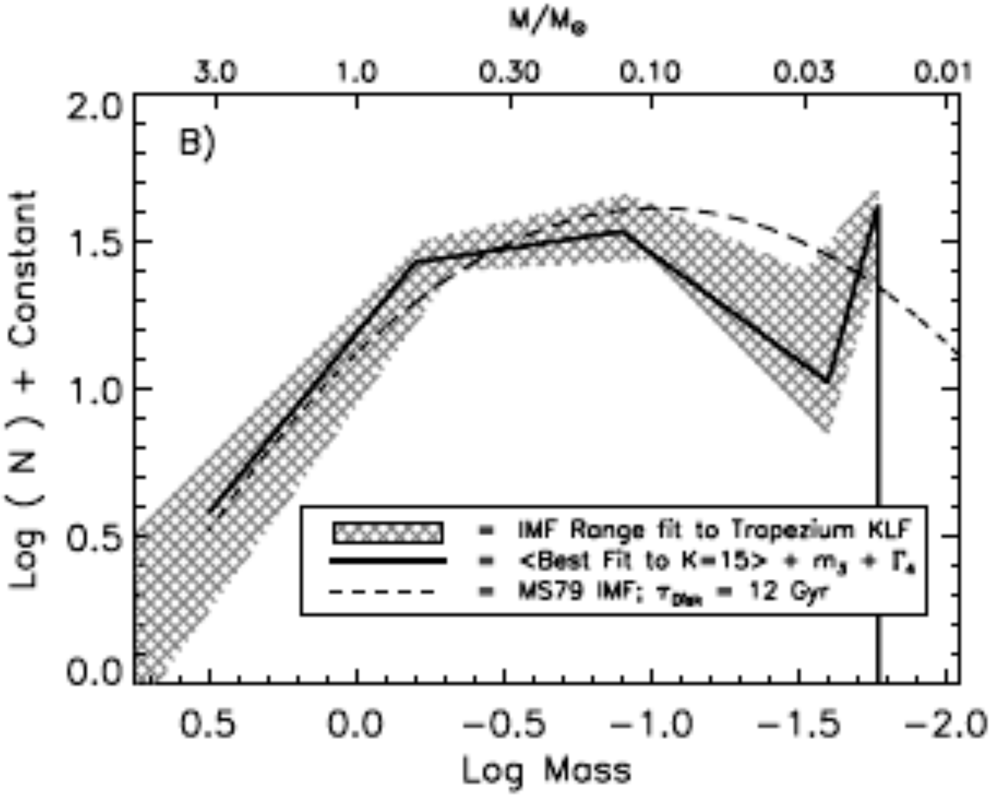
The facts are that *N(M)* is *not* a simple single power law:

$$
\begin{aligned}
N(M) &= C(M/M_{\rm sun})^{-1.2} & 0.1 < M/M_{\rm sun} < 1.0 \\
&= C(M/M_{\rm sun})^{-2.7} & 1.0 < M/M_{\rm sun} < 10 \\
&= 0.4C(M/M_{\rm sun})^{-2.3} & 10 < M/M_{\rm sun}
\end{aligned}
$$

- The slope of the local IMF becomes less steep going from larger to smaller masses.
- The Salpeter IMF applies to large masses > 10 $M_{\rm sun}$
- Individual cluster IMFs actally turn over in the brown dwarf regime
- Star formation produces characteristic masses of a few tenths of a solar mass

Trapezium Cluster IMF

Muench et al ApJ 577 3662002

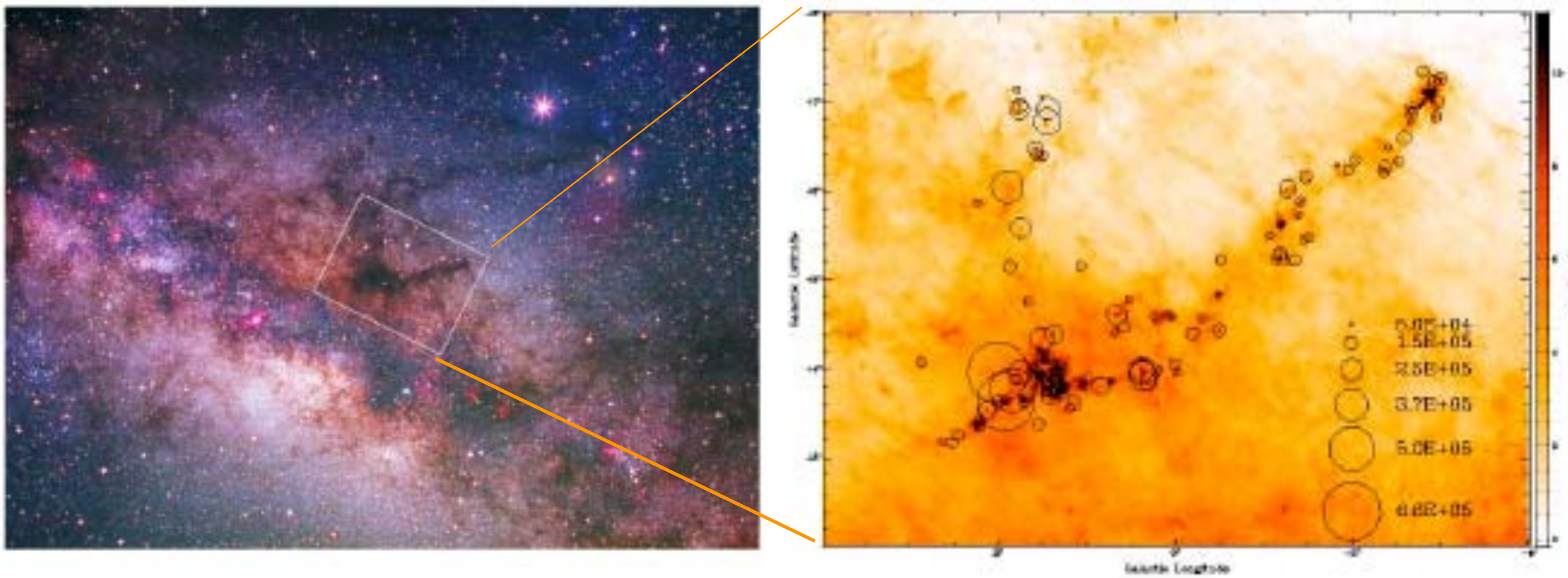


JHK image

Solid curve: best fit IMF from the K magnitude distribution.
Dashed curve; Miller-Scalo IMF (1979).
The sub-stellar fall off is interrupted by a peak at about 13 M_{Jup}

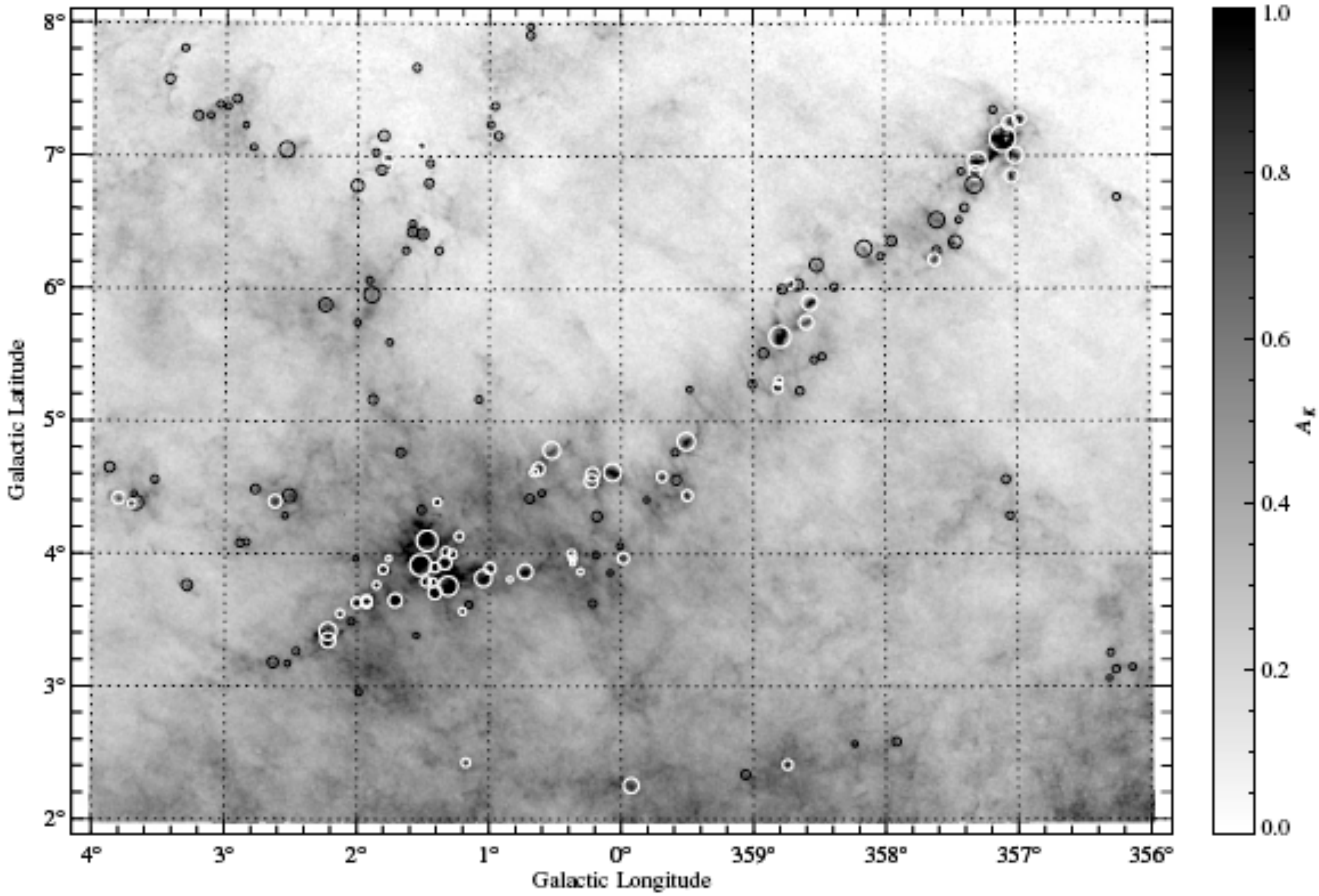
Pipe Nebula Core Mass function

Alves et al. A&A 462 L17 2007
Lada et al. astro-ph 0709.1164



Near field wide field *JHK* extinction map of the Pipe Nebula
Located just above the galactic plane in the direction of the bulge
Based on 4,5 million stars; 160 cores
Circles indicate estimated pressures.

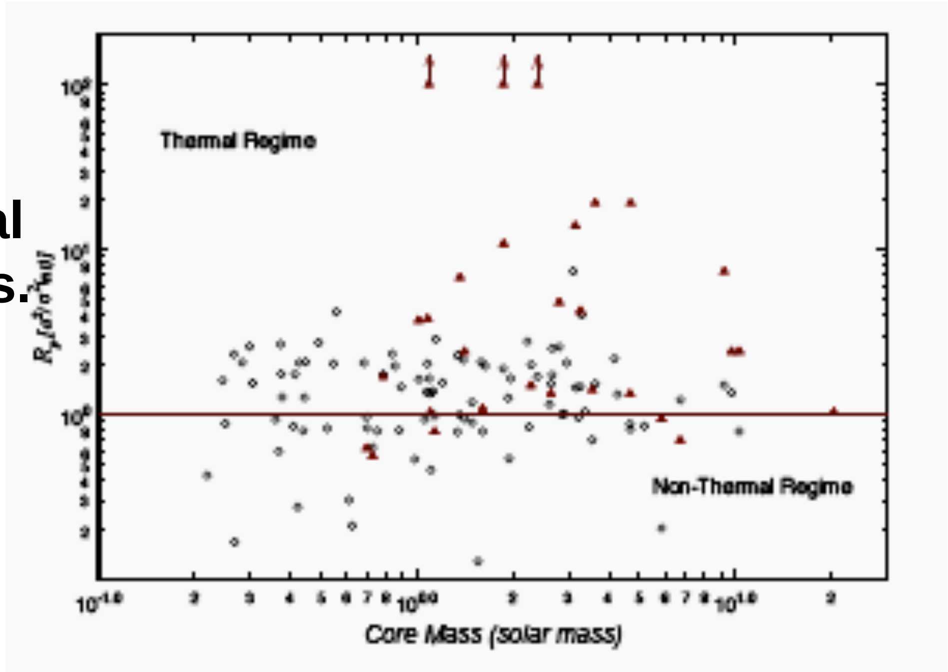
Black and White is Better



Pipe Nebula *JHK* Extinction Map

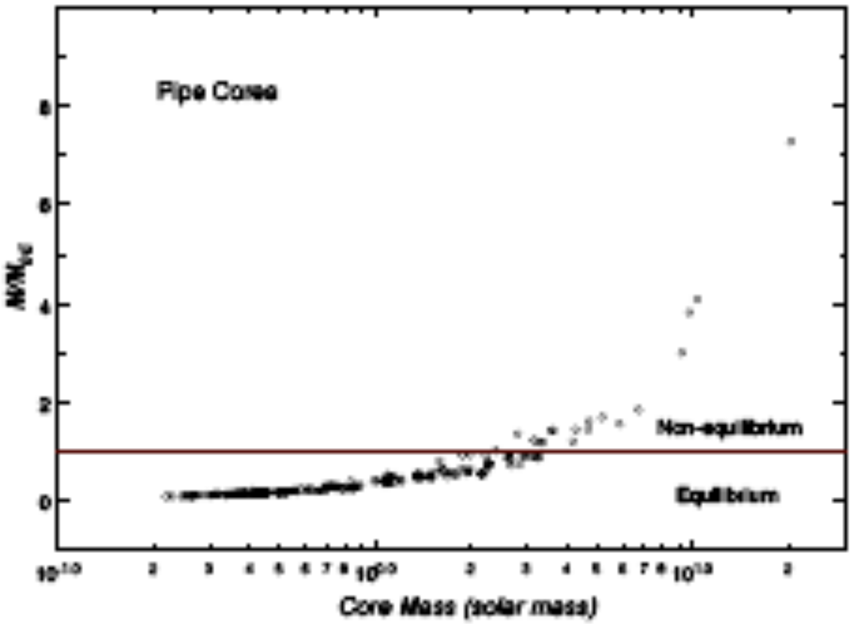
Pipe Nebula Cores

Lada et al. astro-ph 0709.1164



Ratio of thermal to non-thermal pressure plotted vs. core mass.

- mainly thermal
- cores do not satisfy the line-width-size relation



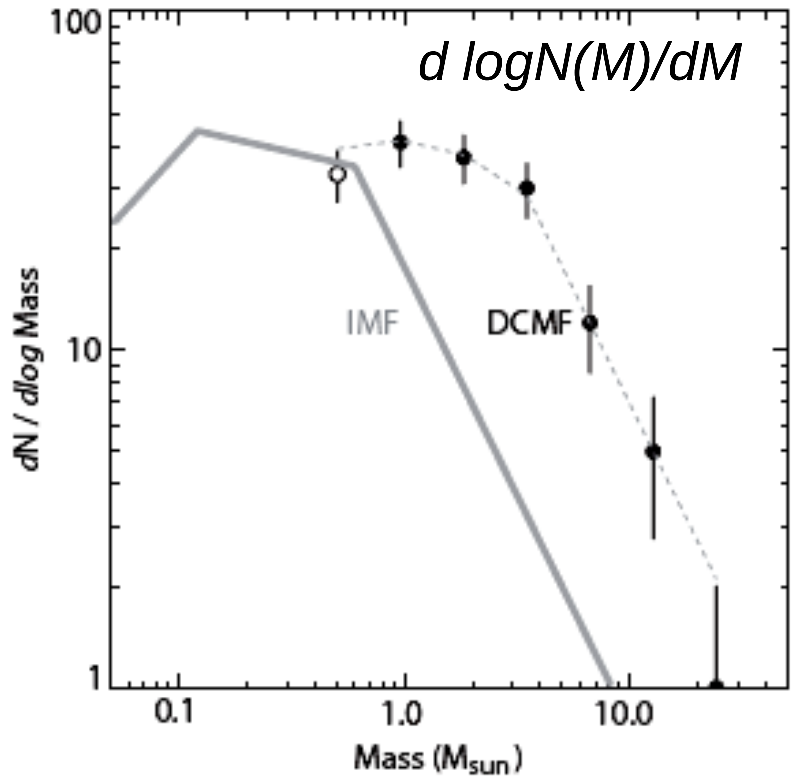
Ratio of core mass to BEM (Jeans) mass plotted vs. core mass.

- only a few cores satisfy the instability condition
- cores supported by external cloud pressure.
- mainly star-less cores

Dense Core Initial Mass Function

Alves et al. A&A 462 L17 2007

- Core MF based on dust extinction and dense gas tracers (e.g., C18O, HCO+) has same slope as IMF above 3.5 M_{sun} (Salpeter) plus a turnover between 0.5-3.0 M_{sun}
- Earlier core mass functions based on CO gave shallower slopes
- Pipe Nebula cores form a more homogeneous sample
- Analysis assumes ISM optical properties and a dust-to-gas ratio of 1/100



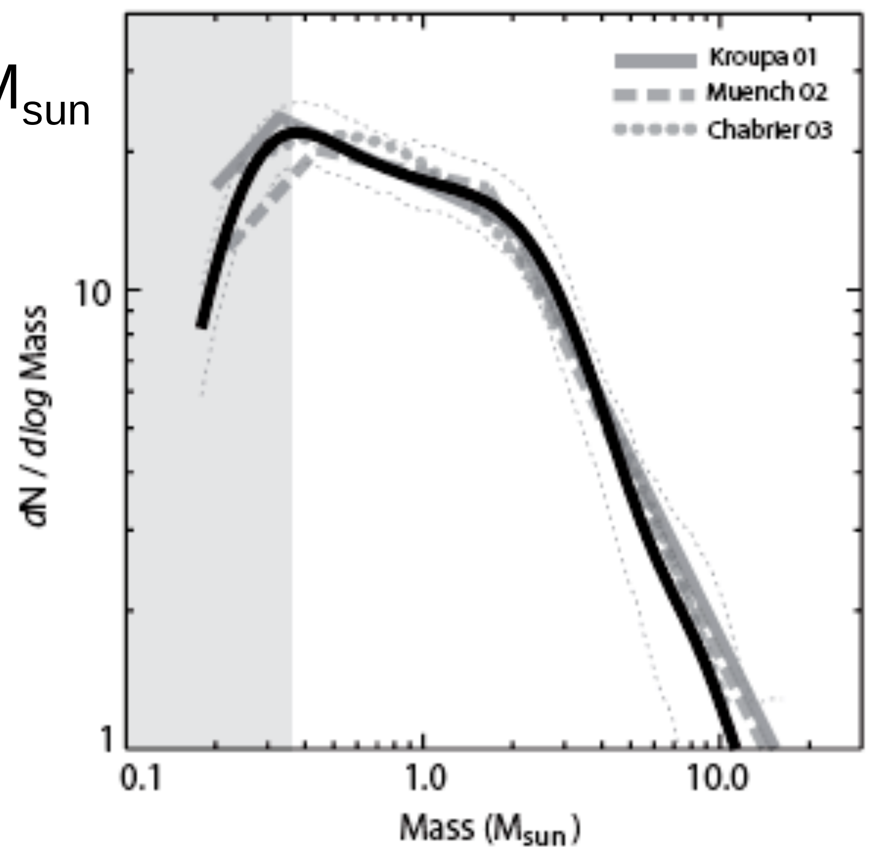
solid circles - binned core data
grey line - trapezium IMF
dashed line - latter smoothed and shifted by 4 in mass

Refined Dense Core Mass function

Alves et al. A&A 462 L17 2007

- DCMF (3M) = IMF (M)
- Two slopes with break at ~ 2 M_{sun}
- IMF seems to be determined by the cloud CMF
- Simple-minded explanation: *efficiency of converting core mass to stellar mass is 1/3*
- Remaining questions: what determines the CMF, e.g. where does the break come from? It determines a characteristic stellar mass in the range 0.2 - 0.7 M_{sun}.

For some answers, see Shu, Li, Allen ApJ 601 930 2004



DCMF after background sub-traction compared to 3 IMFs shifted by 3 in mass