Evolution of Circumstellar Disks

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- Motivation: long term goals
- Evolutionary timescales of dust and gas
- Evolution of spatial structure
Evolutionary Stages of Disks

**Accretion phase** | **Post-accretion** | **Debris disks**
---|---|---
Gas giant planets | - - - ? | 
Terrestrial planet formation | - - - ? | 
Ice giant formation | - - - ? |

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Log age (years)
Motivation

Long term goals

• When/where in disks do planets form?
• How common are planetary systems?
• What is the diversity of planetary systems?

Circumstellar Disks and Planet Formation

• What is the initial distribution of disk masses?
• How long do primordial disks survive?
• What is the spatial structure of disks?
Size Scales of Circumstellar Disks

Circumstellar Disk

Solar System

Adapted from Najita & Strom
Near-Infrared Emission as Disk Diagnostics
K-L excesses vs. cluster age

K-L Excesses and Inner Hole Size

![Graph showing the relationship between wavelength (\(\lambda\)) and logarithm of flux density (\(\log \lambda F_\lambda\)). The graph includes curves for different inner hole radii (R_{inner}) and mass of the disk (M_{disk}). The photosphere is marked at 4000 K and 140 pc.]
Spitzer Photometry
Spitzer/Herschel/SOFIA Spectrophotometry
Sensitivity to Disk Mass

\[ \log \lambda F_{\lambda} \text{ [ergs cm}^{-2} \text{s}^{-1}] \]

-9
-10
-11
-12
-13
-14

\[ \lambda \text{ [\mu m]} \]
0.1
1
10
100
1000

Photosphere
(4000 K, 140 pc)

Sensitivity limits (10σ, 5 min)

IRAC
UBVR, JHK 1 2 3 4
MIPS
24 70 160
Millimeter

\[ M_{\text{disk}} = 10^{-2} M_\odot \]

\[ 10^{-4} M_\odot \]

\[ 10^{-6} M_\odot \]
Dust Masses around 0.5-2 Mo Stars
Sensitivity to Dust Mass

![Graph showing sensitivity to dust mass.](image)
Molecular Gas in Disks

- CO overtone
- H$_2$O ro-vibrational
- CO fundamental
- H$_2$ ro-vibrational
- H$_2$ rotational

Wavelength (angstroms)

0.1 AU, 1.0 AU, 10 AU, 100 AU
Diagnostics of Gaseous Disks

• **Current Status**
  – Young (~ 1 Myr) stars rich in molecular gas
  – $\text{H}_2$ results controversial (ISO vs. near-IR vs. UV)
  – Older stars typically lack CO (but see TW Hydra)

• **Future Observations**
  – $\text{H}_2$ (17 and 28 um)
    • Spitzer: $R \sim 600$
    • SOFIA, VLT, Gemini: $R \sim 35,000$
  – HD, $\text{H}_2\text{O}$, CO,…

• **Ideally, want $R \sim 10^5 - 10^6$**
  ⇒ Increased line to continuum ratio
  ⇒ Dynamical studies of the molecular gas
Sensitivity to Molecular Hydrogen ($\lambda 28$ um)

10 sigma, 1 hour
No continuum
Spatially Resolved Observations of Disks

• Critical to remove degeneracies in SED models
  – $M_{\text{disk}}$, inclination, radius, flaring, composition, etc…

• Resolve gaps in disks
  – Potential signatures of orbiting planets

Geoff Bryden
Inferring Gaps in Disks from SED’s
Resolution at $\lambda 70$ um, distance=140 pc
Imaging Disks with SPIRIT/SPECS @ 70um

\[ T(r) = 150 \ r_{\text{AU}}^{-0.5} \text{ K} \]

\[ \Sigma(r) = \Sigma_0 \ r_{\text{AU}}^{-1.0} \]

SNR \geq 10

Distance = 140 pc
Summary

• Dust evolution from SED’s
  – Inner disk evolution will be well established (Spitzer)
  – Herschel/SOFIA to provide higher resolution for clusters and near continuous SED’s from 5-500 um

• Gas evolution
  – Sensitive H$_2$ observations with Spitzer
  – High spectral observations required for sensitivity and kinematic analysis (SOFIA/JWST/SAFIR)

• Spatial resolved observations of gas and dust
  – Resolve disks on scale of primitive solar nebula (SPIRIT)
  – Resolve disks on gas-giant zones (SPECS)