Evolution and Dispersal of Protoplanetary Disks

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Outline:

• Disk Mass Evolution – Observational Studies

• Disk Dispersal and Photoevaporation – Theory

• Theory vs. Observations (future with SOFIA)
DISK DISPERSAL OBSERVATIONS
Disk Evolution and Lifetimes

- Disk contains gas (mostly H) and solids (dust, $a \leq \mu$m), gas not well probed.
- Dust readily emits (but is only $\sim$1% of mass).
- Dust disk evolves, grains grow, settle, amorphous to crystalline
Disk Evolution and Lifetimes

- Disk contains gas (mostly H) and solids (dust, $a \leq \mu$m), gas not well probed.
- Dust readily emits (but is only $\sim$1% of mass).
- Dust disk evolves, grains grow, settle, amorphous to crystalline, structure

Fukuğawa et al. 2004

e.g. AB Aur shows disk asymmetries, spiral structure

SED changes indicate gaps/holes, rings

Image: D. Hines
Disk Evolution and Lifetimes

(Hillenbrand 2008)

Dust disk lifetimes ~ 5 Myrs.
Disk Evolution and Lifetimes

\[ \text{Dust disk lifetimes} \sim 5 \text{ Myrs.} \]

\( (\text{Hillenbrand 2008}) \)

\( (\text{Andrews & Williams 2005}) \)
Disk Evolution and Lifetimes

\( (\text{Hillenbrand 2008}) \)

Dust disk lifetimes ~ 5 Myrs.

Gas? Dominates mass, but is hard to observe.
Disk Evolution and Lifetimes

\[\text{(Hillenbrand 2008)}\]

Dust disk lifetimes ~ 5 Myrs.

Gas? Dominates mass, but is hard to observe. Accretes onto star.

\[\text{(Gullbring et all. 1998)}\]
Disk Evolution and Lifetimes

\[(\text{Hillenbrand 2008})\]

Dust disk lifetimes \(\sim 5 \text{ Myrs.}\)

Gas:

Fedele et al 2010
Mass accretion rate fraction in clusters, measures gas.
Disk Evolution and Lifetimes

\[(Pascucci \text{ et al. 2006})\]

Dust disk lifetimes $\sim 5$ Myrs.

Gas in (1-40AU) region has lifetimes less than $\sim 5$-30Myr.
Disk Evolution and Lifetimes

Zuckerman, Forveille & Kastner 1995

Co observations of young disks; inferred lifetimes ~ 10 Myrs

Dust disk lifetimes ~ 5 Myrs.

Gas in (1-40AU) region has lifetimes less than ~5-30Myr.

Condition of the massive gaseous envelope in ~10^7 yr (refs 1–5). But how and when the gas of the solar nebula dissipated, and how this compares with the predicted timescale of gas-giant formation, remains unclear, in part because direct observations of circumstellar gas have been made only for stars either younger or older than the critical range of 10^6–10^7 yr (refs 8–15). Here we report observations of the molecular gas surrounding 20 stars whose ages are likely to be in this range. The gaseous mass rapidly; after a few million years the mass remaining is typically much less than the mass of Jupiter. Thus, if gas-giant planets are common in the Galaxy, they must form even more quickly than present models suggest.
Disk Evolution and Lifetimes

Zuckerman, Forveille & Kastner 1995

Dust disk lifetimes ~ 5 Myrs.

Gas in (1-40AU) region has lifetimes less than ~5-30Myr.

CO observations of young disks; inferred lifetimes ~ 10 Myrs

Dust disks ~ 5Myrs, Gas disks ~ 5-30Myrs

ENTIRE DISK IS DISPERSED
DISK DISPERSAL THEORY
Disk Dispersal

1. Viscous Evolution

![Graph showing disk dispersal over time](image-url)
**Disk Dispersal**

1. **Viscous Evolution** – *Long timescales*

2. **Stellar winds**

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*Not important, need* $dM_w/dt \sim dM_{\text{acc}}/dt$ *(Matsuyama, Johnstone & Hollenbach 2010)*
Disk Dispersal

1. Viscous Evolution – Long timescales

2. Stellar winds

3. Close stellar encounters and tidal stripping

Need very close encounters, only possible in very dense star clusters, hence cannot be a general mechanism.
**Disk Dispersal**

1. Viscous Evolution – *Long timescales*

2. Stellar winds

3. Close stellar encounters and tidal stripping

4. Planet Formation – May deplete solids, *but gas dispersal needed*
Disk Dispersal

1. Viscous Evolution – Long timescales

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4. Planet Formation – May deplete solids, but gas dispersal needed

5. Photoevaporation
   - Disk surface is irradiated by high energy photons (EUV, FUV, X-rays).
   - Gas is heated to thermal speeds that exceed escape speeds.
   - Mass is lost from disk resulting in photoevaporation.
   - Gravitational radius $R_G \sim \frac{GM}{c_s^2} \sim 7$ AU for $10^4 K$ gas for a $1M_\odot$ star
   - Angular momentum support gives $R_{\text{crit}} \sim 0.1-0.2 R_G$
Disk Dispersal

1. Viscous Evolution – Long timescales - Mainly inner disk, ~ 50% of mass?
2. Stellar winds
3. Close stellar encounters and tidal stripping
4. Planet Formation – Gas dispersal needed - Some fraction (?) of solid mass
5. Photoevaporation - Mainly outer disk, ~50% of mass?
   - Disk surface is irradiated by high energy photons (EUV, FUV, X-rays).
   - Gas is heated to thermal speeds that exceed escape speeds.
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Disk Dispersal: Photoevaporation

- First applied to disks in clusters near the high radiation field of massive OB stars. 
  
  \cite{Hollenbach1994}

External irradiation of disks by a nearby massive O star

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{protoplanetary_disks_orion_nebula.png}
\caption{Protoplanetary Disks in the Orion Nebula \\
Hubble Space Telescope \& WFPC2}
\end{figure}

\textsuperscript{NASA, J. Bally (University of Colorado), H. Throop (JWST), and C. R. O'Dell (Vanderbilt University)}

\textsuperscript{STScI-PRC01-13}
Disk Dispersal: Photoevaporation

- First applied to disks in clusters near the high radiation field of massive OB stars.

\[(\text{Hollenbach et al. 1994})\]

External irradiation of disks by a nearby massive O star

\[(\text{Mann & Williams 2011})\]
Disk Dispersal: Photoevaporation

- First applied to disks in clusters near the high radiation field of massive OB stars.  
  \(\text{(Hollenbach et al. 1994)}\)

- Young, low-mass stars are very UV and X-ray luminous, central star can also photoevaporate disk.  \(\text{(Alexander et al. 2006, Gorti \\& Hollenbach 2008, Ercolano et al. 2009)}\)

\[
r_g = \frac{G M_*}{c_s^2} \approx 10AU \left(\frac{10^4}{T}\right) \left(\frac{M_*}{1M_\odot}\right)
\]

Higher Temperatures \(\rightarrow\) Greater Escape Speeds
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\]

• Heating by Extreme Ultraviolet (EUV) (hv > 13.6eV) photons 
• EUV photoevaporation of disk around central star *(e.g., Shu et al 1993, 
  Hollenbach et al. 1994, Johnstone et al. 1998, Richling & Yorke 2000)*
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r_g = \frac{GM_\ast}{c_s^2} \approx 10 \text{AU} \left( \frac{10^4}{T} \right) \left( \frac{M_\ast}{1 M_\odot} \right) \\
\text{Higher Temperatures} \rightarrow \text{Greater Escape Speeds}
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• Heating by Extreme Ultraviolet (EUV) (\( h\nu > 13.6\text{eV} \)) photons
• EUV photoevaporation of disk around central star (e.g., Shu et al 1993, Hollenbach et al. 1994, Johnstone et al. 1998, Richling & Yorke 2000)

• Combined effects of EUV radiation from central star and viscosity “Ultraviolet switch” scenario (Clarke et al. 2001) \( t_{\text{disk}} \approx 20 \text{ Myrs} \)
Disk Dispersal: Photoevaporation

- First applied to disks in clusters near the high radiation field of massive OB stars. (Hollenbach et al. 1994)

- Young, low-mass stars are very UV and X-ray luminous, central star can also photoevaporate disk. (Alexander et al. 2006, Gorti & Hollenbach 2008, Ercolano et al. 2009)

\[ r_g = \frac{GM_*}{c_s^2} \approx 10\text{AU} \left( \frac{10^4}{T} \right) \left( \frac{M_*}{1\text{M}_\odot} \right) \]  Higher Temperatures \rightarrow Greater Escape Speeds

- Heating by Extreme Ultraviolet (EUV) (hv > 13.6eV) photons
- EUV photoevaporation of disk around central solar-type star (e.g., Shu et al 1993, Hollenbach et al. 1994, Johnstone et al. 1998, Richling & Yorke 2000)

- Combined effects of EUV radiation from central star and viscosity
  “Ultraviolet switch” scenario (Clarke et al. 2001) \[ t_{\text{disk}} \approx 20 \text{ Myrs} \]
- Alexander et al. (2006) considered direct EUV illumination of gap once it forms, and disk disperses rapidly after gap opens. (High EUV fluxes, low disk masses)
Disk Dispersal: Photoevaporation

**FUV and X-rays are important for disk photoevaporation**

- FUV and X-rays have longer penetration depths and are incident on the disk earlier in its evolution.

- FUV and X-rays are measured, can be high. FUV initially comes mainly from accretion, and rates are high at early epochs.

For young solar-type stars,

- \( L_X \sim 10^{28-30} \) erg s\(^{-1}\) ( ~ 100 higher than present-day sun) *(Chromosphere)*

- \( L_{EUV} \sim \) Unknown! Estimates range from \( \varphi_{EUV} \sim 10^{40-44} \) s\(^{-1}\) (Alexander, Clarke & Pringle 2005)
  
  If chromospheric, \( 10^{28-30} \) erg s\(^{-1}\), \( \varphi_{EUV} \sim 10^{40-42} \) s\(^{-1}\)

- \( L_{FUV} \sim 10^{29-32} \) erg s\(^{-1}\) ( ~ 10\(^4\) higher than present-day sun) *(Accretion shocks + Chromosphere)*
Disk Dispersal: Photoevaporation

- Photoevaporative flows begin at the disk surface, depend sensitively on gas density and temperature.

- FUV/X-ray heated gas can be ~ 100 - 5000 K, complex gas chemistry and many different coolants.

- Need to solve accurately for gas structure.

- Detailed gas disk structure models needed.
Disk Evolution Models

Disk surface density evolution is studied.

\[
\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left( \sqrt{\frac{\partial \Sigma}{\partial r}} \right) - \dot{\Sigma}_{pe}(r, t)
\]

- Kinematic viscosity \( \nu \equiv \alpha c_s^2 / \Omega_k \)
- Instantaneous local Photoevaporation rate due to EUV, FUV, X-rays, \( \dot{\Sigma}_{pe} \propto (n \, c_s) \)

Photoevaporation included as a sink term.
Disk Evolution Models

Disk surface density evolution is studied.

\[ \frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left( \sqrt{r} \frac{\partial}{\partial r} \left( \nu \Sigma \sqrt{r} \right) \right) - \dot{\Sigma}_{pe}(r, t) \]

Kinematic viscosity
\[ \nu = \alpha c_s^2 / \Omega_K \]

Instantaneous local Photoevaporation rate due to EUV, FUV, X-rays,
\[ \dot{\Sigma}_{pe} \propto (n c_s) \]

Photoevaporation included as a sink term.

Dust model with grain size distribution, radiative transfer via 1+1D model
Gas heating and cooling, radiative transfer – thermal balance solved with chemistry

At every timestep from \( \Sigma(r,t) \)
Disk Evolution Models

Viscosity, Photoevaporation by EUV, FUV and X-rays

\[ \frac{dM_{\text{acc}}}{dt} < \frac{dM_{\text{PE}}}{dt} \]

GAP by X-rays or high FUV

Erosion of outer disk by FUV
Disk Evolution Models

Viscosity, Photoevaporation by EUV, FUV and X-rays

\[ \frac{dM_{\text{acc}}}{dt} < \frac{dM_{\text{PE}}}{dt} \]

GAP by X-rays or high FUV

Erosion of outer disk by FUV

Disk disperses in 3-5 Myrs

\[ t = 0, 10^5, 3 \times 10^5, 10^6, 2 \times 10^6, 2.4 \times 10^6, 3.6 \times 10^6 \text{ y} \]
Disk Evolution: - Key Questions Remain

• How does the disk surface density distribution evolve?
  – Transition disks with inner dust holes, e.g. TW Hya
  – Planet formation, presence of gas, Jupiters vs. Neptunes
  – Planetary dynamics, migration, orbit circularization

• Disk dispersal – Photoevaporation mass loss rates?
  – Accretion and photoevaporation, their fractions
  – FUV, EUV or X-rays?
  – Nature of dispersal, inside-out or outside-in
  – Wind diagnostics needed

• Disk lifetimes – How long and what do they depend on?
  – Stellar mass, radiation, T Tauri stars and Herbig AeBe stars
  – Disk properties, initial angular momentum, viscosity, dust
  – Planet formation, any feedback?
DISK DISPERSAL: Future Observations
DISK DISPERSAL: Future Observations

- Disk Mass Evolution
- Photoevaporation Diagnostics
Disk Mass/Surface Density Evolution

\[ M_{\text{disk}} = 0.03M_\odot, \quad M_* = 1M_\odot \quad (@150 \text{ pc}) \]

(Gorti & Hollenbach 2008)

\[ (\text{Cl}) \]

Herschel PACS, detected in many disks, unresolved, background emission.

\[ [\text{Cl}] \]

ALMA – CO
Cold gas tracer
Chemistry?
Freezes

\[ [\text{Ar}^+] \]
\[ [\text{Ne}^+] \]

H$_2$ – Ideal, but weak, warm gas (100K)

\[ \text{EXES} \]

\[ \text{SOFIA } 5\sigma - 1\text{hr} \]

\[ \text{GREAT} \]
Disk Mass/Surface Density Evolution

\[ \frac{\text{[O]} 63 \mu m \ (W/m^2) \times (d/140)^2}{10^{-14}} \]

\( T \text{ Tauris} \)

\( \sim 10^{-18} \text{ W/m}^2 \)
Disk Mass/Surface Density Evolution

Why is this interesting from the disk dispersal point of view?

- OI traces bulk of the gas mass in the disk
- Gas evolution in the planet forming regions (1-100AU)
- SOFIA will resolve line (background contamination)
- HAeBes have similar disk lifetimes as T Tauris
Disk Dispersal Diagnostics

Photoevaporative mass loss rates? Depends on the dispersal agent, qualitatively different evolutionary scenarios.

- EUV – Disk evolves mainly by viscosity for a long period. Disk primarily accreted. However, EUV flux unknown. \( \frac{dM}{dt} \approx \) ?? (\( \sim 10^{-10} \text{ M}_\odot \text{ yr}^{-1} \))

- X-rays – High mass loss rates predicted, disk again evolves viscously until gap opening. Disk disperses inside-out. (Different models differ.) X-ray flux is well measured. \( \frac{dM}{dt} \sim 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \)

- FUV – Qualitatively different evolution – Neutral flows dominated by mass loss in the outer disk. Expected \( \frac{dM}{dt} \sim 10^{-9} \text{ M}_\odot \text{ yr}^{-1} \). Predict disk truncation. Gap formation (or not) depends on level of chromospheric FUV and X-rays. FUV dominates disk dispersal for intermediate mass stars.

Different implications for planet formation in disk
Disk Dispersal Diagnostics

\[ \text{[NeII] blueshift seen} \]

\( \text{(Pascucci et al. 2011)} \)

- Models predict equally strong ArII emission.
- Velocity information with EXES – location of emitting gas.
- NeII/ArII ratios may distinguish between EUV X-rays photoevaporation.
- Blue-shifts will provide evidence of wind.
- Possible blue-shifts in OI63um?

\( \text{(Pascucci & Sterzik 2009)} \)
Summary

- Disk gas mass evolution is not well understood: Disk lifetimes ~ $10^7$ yrs and comparable to dust disk lifetimes of a few Myrs. Planets must form on these timescales.

- Photoevaporation and viscous evolution may explain disk evolution qualitatively, with lifetimes ~ few Myrs for low mass stars and shorter for intermediate to high mass stars. Mass loss rates depend on whether flows are EUV, FUV or X-ray driven.

- Gas emission lines will provide valuable information on how disks evolve and get dispersed.

- SOFIA can detect [OI]63um, H$_2$ rot. lines, [NeII]12.8um, [ArII]7um and other lines, and high resolution observations will determine gas kinematics.

- Dust continuum – (not discussed) SOFIA fills important niche FIR region which can discriminate between degenerate dust configurations (SED-matching.)