Massive Protostellar Disks: Formation, Properties, and Observables

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Transformational Science with ALMA
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Talk Outline

- Introduction and background for the core accretion model
- Properties of massive disks
- Observational predictions for ALMA and the EVLA
- Distinguishing massive star formation models
- Summary
Sites of Massive Star Formation
(Plume et al. 1997; Shirley et al. 2003; Rathbone et al. 2005; Yonekura et al. 2005)

- Massive stars form in gas clumps seen in mm continuum or lines, or in IR absorption (IRDCs)
- Typical properties:
  - $M \sim 10^3 - 10^4 M_\odot$
  - $R \sim 1 \text{ pc}$
  - $\Sigma \sim 1 \text{ g cm}^{-2}$
  - $\sigma \sim \text{ few km s}^{-1}$
- Properties very similar to young rich clusters

Spitzer/IRAC (left) and Spitzer/MIPS (right), Rathbone et al. (2005)
Massive Cores

- Largest cores in clumps: $M \sim 100 \, M_\odot$, $R \sim 0.1 \, \text{pc}$
- Cores have powerlaw density profiles, index $k_\rho \approx 1.5$
- Some are starless

Core density profile in 3 wavelengths, Beuther et al. (2007)

Core in IRDC 18223-3, Spitzer/IRAC (color) and PdBI 93 GHz continuum (contours), Beuther et al. (2005, 2007)
Clue I: The Core Mass Function


- The core MF is similar to the stellar IMF, but shifted to higher mass a factor of a few
- Correspondence suggests a 1 to 1 mapping from core mass to star mass

Core mass function in Pipe Nebula (red) vs. stellar IMF (gray) (Alves, Lombardi, & Lada 2007)
Clue II: Core Spatial Distributions

Fraction of stars vs. radius for stars of low mass (blue) and high mass (red) stars in the ONC (Hillenbrand & Hartmann 1998)

For both stars and cores, the mass function is position-independent at low mass, but high mass objects are only in cluster / clump centers

Core mass function for inner (red) and outer (blue) parts of $\rho$ Oph, Stanke et al. (2006)
The Core Accretion Model

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The Core Accretion Model
Simulations of Massive Cores

- Start with observed massive core properties: \( M \approx 100 \, M_\odot \), \( r \approx 0.1 \, \text{pc} \), virialized turbulence (\( \sigma \approx \) few km/s), centrally condensed with \( k_\rho \approx 1.5 \)


\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) &= -\nabla P - \rho \nabla \phi - \lambda \nabla E \\
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot [\mathbf{v} (\rho e + P)] &= -\rho \mathbf{v} \cdot \nabla \phi - \kappa_p \rho (4\pi B - cE) + \lambda \mathbf{v} \cdot \nabla E \\
\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{v} E + \mathbf{v} \cdot \mathbf{P}) &= \kappa_p \rho (4\pi B - cE) - \lambda \mathbf{v} \cdot \nabla E + \nabla \cdot \left( \frac{c\lambda}{\kappa_R} \nabla E \right) \\
\nabla^2 \phi &= 4\pi G \rho
\end{align*}
\]
Simulation of a Massive Core

- Simulation of $100 \, M_\odot$, $0.1 \, \text{pc}$ turbulent core
- LHS shows $\Sigma$ in whole core, RHS shows 2000 AU region around most massive star
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Massive Disk Properties

- \( \frac{M_{\text{disk}}}{M_*} \approx 0.2 - 0.5, \) 
- \( r_{\text{disk}} \approx 1000 \) AU
- Global GI creates strong \( m = 1 \) spiral pattern
- Spiral waves drive rapid accretion; \( \alpha_{\text{eff}} \approx 1 \)
- Disks reach \( Q \approx 1 \), form stellar fragments
- Small fragments migrate in; some become twins via mass transfer (Krumholz & Thompson 2007)

Surface density (upper) and Toomre \( Q \) (lower)
Aside: Radiative Transfer Matters!

- With RT: 3 fragments, $M_{\text{disk}} / M_* \sim 0.5$, inner disk column density $\sim 1000 \text{ g cm}^{-2}$
- Without RT: more than 7 fragments, $M_{\text{disk}} / M_* \sim 0.15$, inner disk column density $\sim 100 \text{ g cm}^{-2}$
- **Conclusion:** simulations without RT get incorrect bulk properties of massive disks

Column density with and without RT, for identical times and initial conditions
Understanding Massive Disks

- Accretion rate onto star + disk is $\sim \sigma^3 / G$ 
  $\sim 10^{-3} \, M_\odot / \text{yr}$ in a massive core, but max transfer rate through a stable disk ($\alpha \ll 1$) is $\sim c_s^3 / G \sim 5 \times 10^{-5} \, M_\odot / \text{yr}$ at $T = 100 \, \text{K}$

- Core accretes faster than stable disk can process $\Rightarrow$ massive, unstable disks

- Study disk evolution using semi-analytic core model, including accretion, radiative heating, parameterized treatment of angular momentum transport
Model Disk Evolution

The plot shows the evolution of disks in 1 $M_\odot$ and 15 $M_\odot$ cores.

Prediction:
- $M_{\text{disk}} / M_*$ increases with $M_*$ or $M_{\text{core}}$
- Toomre Q decreases with $M_*$ or $M_{\text{core}}$
Variation in Disk Properties

The plot shows $Q$ as a function of core mass and the evolutionary time of the system.

**Prediction:** incidence of spiral structure and disk fragmentation both increase with $M_{\text{core}}$ or $M_*$.
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A proper theorist attitude toward observations
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General Considerations on Massive Disk Observations


- Density $> 10^{10}$ cm$^{-3}$ $\Rightarrow$ all species in LTE
- $T > 50 – 100$ K $\Rightarrow$ can use high temp. lines to avoid envelope contamination
- Inner disk column density $\sim 10^3$ g cm$^{-2}$ $\Rightarrow$ dust optical depth $\sim 1$ at 100 GHz
  - Bad: kinematics in central few hundred AU impossible with ALMA (need EVLA)
  - Good: spiral arms have optical depth $\sim 1$ in dust / strong lines, very easy to do with ALMA
Predictions from Simulations

- Solve transfer equation on rays through adaptive grid
- Include molecular line and dust continuum processes at radio and sub-mm
- Model ALMA, EVLA performance
- Simulations must include radiative transfer to make realistic predictions
- Caveats: chemistry, outflows
ALMA: Rotating $m = 1$ Spiral

Simulated 1000 s / pointing ALMA observation of disk at 0.5 kpc in CH$_3$CN 220.7472 GHz, $T_{up} = 69$ K (KKM 2007c, ApJ, in press)
Simulated 24 hr / pointing EVLA observation of disk at 0.5 kpc in NH$_3$(8,8) hyperfine line, 26.5910 GHz, $T_{\text{up}} = 687$ K (KKM, 2007c, ApJ, in press)
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Competitive Accretion / Collision Model

- There is no direct core to star mapping
- Gas always fragments to Jeans mass at $T \sim 10$ K; all stars born small, $\sim 0.1 - 0.5 \, M_\odot$
- Close encounters between protostars common, especially for massive stars
- Requires that gas clumps undergo global collapse, turn into stars in a time of order $t_{\text{ff}}$ (Krumholz, McKee, & Klein, 2005, Nature, 438, 332)
Disks in the Competitive Accretion / Collision Model

- In CA model, almost all massive stars have close encounters that truncate their disks.
- Disks can grow back, but this takes a while.
- **CA prediction:** a non-trivial fraction of massive stars should be close to diskless.

Distribution of encounter distances in a competitive accretion simulation (Bonnell et al. 2003)
Looking for Global Collapse
Using the Star Formation Rate

- Compute ratio of SFR to free-fall time in observed objects of varying densities (e.g. Gao & Solomon 2004, Wu et al. 2005, Rathborne et al. 2006)

- Compute ratio from simulations with and without competitive accretion

Can do this test much better with ALMA!

Ratio of free-fall time to depletion time in gas clouds of varying density
Summary

- The core accretion model predicts
  - Massive protostellar disks have $r \sim 1000$ AU, $m \sim M_*/2$, $m = 1$ spirals, $v$ offset $\sim$ few km s$^{-1}$
  - $M_{\text{disk}} / M_*$, $r_{\text{disk}}$, spiral mode strength, fragmentation all increase with $M_*$

- CA models predict a diskless population, and $t_{\text{ff}} \sim t_{\text{dep}}$ in protocluster gas

- ALMA and EVLA can test these predictions in reasonable integration times
  - ALMA is good for fast mapping of outer disks
  - EVLA is slower, but can see inner disks
Finally and most importantly, thanks to the organizers for putting together this meeting...

...and thanks to the audience for showing up at 9 AM on a Saturday morning!