Massive, Embedded, Accreting, Protostellar Disks

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Collaborators:
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KITP
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...a theorist’s version of a survey

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Disks in Massive Star Formation?

- **Theoretically**: existence of disks is a robust result independent of specific formation mechanism

- fundamental in circumventing accretion barrier of radiation pressure (e.g. Wolfire & Cassinelli, 1987, Krumholz et al. 2005)

- may play a role in determining binarity and upper mass cutoff (e.g. Kratter & Matzner, 2006, Moeckel & Bally, 2007)

- **Observationally**: just beginning to probe proper size and time scales. more soon from ALMA & EVLA

How can we make useful predictions for these disks as $f(M_*, t)$?
Massive Embedded Disks: what do we want to know?

What dominates angular momentum transport?

Do disks fragment? If so, what do they make?

How will these disks appear to ALMA and the EVLA?
Massive Embedded Disks: what do we want to know?

What dominates angular momentum transport?

Do disks fragment? If so, what do they make?

How will these disks appear to ALMA and the EVLA?

Krumholz, et al. 2007
Physical Scenario

- Turbulent region (core / “entity”) begins to collapse
- Cloud pressure and core temperature determine the magnitude of turbulent support
- Net angular momentum determines circularization radius of the infalling material as $f(t)$
- Magnetic fields?

**Problem I:** high column cores make these phenomena very difficult to observe

**Problem II:** large parameter space to explore numerically with MHD + SG + radiation + ...
Physical Scenario

- Turbulent region (core / “entity”) begins to collapse
- Cloud pressure and core temperature determine the magnitude of turbulent support
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**Problem I:** high column cores make these phenomena very difficult to observe

**Problem II:** large parameter space to explore numerically with MHD + SG + radiation + ...
Physical Scenario

- Turbulent region (core / “entity”) begins to collapse

...and core temperature

Momentum determines radius of the infalling

...the parameter space of disks in HMSF

Solution: A global, single zone model that incorporates these processes can characterize the parameter space of high column cores...phenomena very difficult to observe

Problem II: large parameter space to explore numerically with MHD + SG + radiation + ...
Dimensionless Parameters of Accreting Disks

**external**, imposed quantities vary with environment, while **local** quantities are derived from physical model within the disk

### Environment

\[ \frac{\dot{M}_{\text{in}}}{M_\ast d \Omega (R_{\text{circ}})} \]

### Derived

\[ \mu = \frac{M_d}{M_d + M_\ast} \]

\[ Q = \frac{c_s \kappa}{\pi G \Sigma} \]

\[ \frac{\dot{M}_\ast}{M_d \Omega} \]

1. set by core: increase in system mass / orbital time

2. global disk quantity

3. local disk quantity

4. within the disk: orbital times to drain disk
Dimensionless Parameters of Accreting Disks

**external**, imposed quantities vary with environment, while **local** quantities are derived from physical model within the disk

### Environment

\[
\frac{\dot{M}_{\text{in}}}{M_* \Omega (R_{\text{circ}})}
\]

### Derived

\[
\mu = \frac{M_d}{M_d + M_*}
\]

\[
Q = \frac{c_s \kappa}{\pi G \Sigma}
\]

\[
\frac{\dot{M}_*}{M_d \Omega}
\]

1. set by core: increase in system mass / orbital time

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Model Structure

- survey the conditions of intermediate-mass and massive star formation
- consider fluctuations of the vector angular momentum in the infall due to realistic turbulence in the collapsing core
- account for dependence of gravitational torques on disk-to-total mass ratio Toomre's Q
- consider possibility that disks fragment when sufficiently unstable
- employ a realistic model for irradiation of the disk midplane

Core Model
\[ \dot{M}_{\text{in}}(t), \dot{J}_{\text{in}}(t) \]

infall update
\[ M_d \uparrow, J_d \uparrow \]

Initial Conditions
\[ M_\ast 0, M_d 0, J_d 0 \]

global disk properties
\[ M_d, J_d, M_\ast \]

find thermal & mechanical equilibrium

internal disk properties
\[ Q, \dot{M}_\ast \]

Thermal Physics
- viscous heating
- irradiation
- radiative cooling

Accretion Model
\[ \frac{\dot{M}_\ast}{M_d \Omega} = f \left( Q, \frac{M_d}{M_\ast} \right) \]

Accrretion update
\[ M_\ast \uparrow, \Delta M_d, \Delta J_d \]

Disk Braking Model

fragments
\[ \Sigma_d \downarrow, M_{\text{frag}} \uparrow \]

\[ Q < 1? \]

yes

no

\[ M_d > M_\ast? \]

binary
\[ M_d \downarrow, J_d \downarrow, M_{\text{bin}} \uparrow \]

KMK, Matzner, & Krumholz, 2007 (submitted)
Model Structure

- survey the conditions of intermediate-mass and massive star formation
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KMK, Matzner, & Krumholz, 2007 (submitted)
- survey the conditions of intermediate-mass and **massive** star formation
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- employ a realistic model for **irradiation** of the disk midplane

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**Model Structure**

![Diagram](image)

- **Core Model**
  - \( \dot{M}_{\text{in}}(t), \dot{J}_{\text{in}}(t) \)
  - infall update \( M_d \uparrow, J_d \uparrow \)

- **Initial Conditions**
  - \( M_*, M_d, J_d \)

- **Accretion Model**
  - \( \frac{\dot{M}_*}{M_\Omega} = f(Q, M_d, M_*) \)
  - find thermal & mechanical equilibrium

- **Thermal Physics**
  - viscous heating
  - irradiation
  - radiative cooling

- **Disk Braking Model**

- **Toc**

- **KMK, Matzner, & Krumholz, 2007 (submitted)**
survey the conditions of intermediate-mass and massive star formation

consider fluctuations of the vector angular momentum in the infall due to realistic turbulence in the collapsing core

account for dependence of gravitational torques on disk-to-total mass ratio Toomre's Q

consider possibility that disks fragment when sufficiently unstable

employ a realistic model for irradiation of the disk midplane

- \( \dot{M}_{\text{in}}(t), \dot{J}_{\text{in}}(t) \)
- initial conditions \( M_{\ast 0}, M_{d 0}, J_{d 0} \)
- global disk properties \( M_d, J_d, M_{\ast} \)
- internal disk properties \( Q, \dot{M}_{\ast} \)
- accretion update \( M_{\ast} \uparrow, \Delta M_d, \Delta J_d \)
- thermal & mechanical equilibrium
- \( \frac{\dot{M}_{\ast}}{M_d \Omega} = f \left( Q, \frac{M_d}{M_{\ast}} \right) \)
- thermal physics
  - viscous heating
  - irradiation
  - radiative cooling
- disk braking model
- \( M_d \downarrow, J_d \downarrow, M_{\text{bin}} \uparrow \)
- \( M_d > M_{\ast} ? \)
- \( \Sigma_d \downarrow, M_{\text{frag}} \uparrow \)
- \( Q < 1 ? \)
- \( M_d \downarrow, J_d \downarrow, M_{\text{bin}} \uparrow \)

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KMK, Matzner, & Krumholz, 2007 (submitted)
Model Components I: Accretion Model

\[ \log \left( \frac{\dot{M}}{M_d \Omega} \right) \]

MRI Dominated

GI Dominated

\[ Q = \frac{c_s \kappa}{\pi G \Sigma} \]

\[ \mu = \frac{M_d}{M_d + M_*} \]

\[ \alpha_{\text{MRI}} = \text{const} \]

\[ \alpha_{\text{loc}} = \begin{cases} 0, & 1.4 < Q; \\ 0.3 \frac{1.4-Q}{0.4}, & 1 < Q < 1.4; \\ 0.3, & Q < 1 \end{cases} \]

Gammie, 2001

\[ \frac{\dot{M}_{*,\text{glob}}}{M_d \Omega} = \frac{\mu^2}{100} \]

Laughlin and Rozyczka, 1996

\[ \frac{\dot{M}_{*,\text{loc}}}{M_d \Omega} = \frac{3 \alpha_{\text{loc}} Q^2}{8} \left( \frac{M_d}{M_*} \right)^2 \]

\[ \dot{M}_{*,\text{tot}} = \left( \dot{M}_{*,\text{loc}}^2 + \dot{M}_{*,\text{glob}}^2 + \dot{M}_{*,\text{MRI}}^2 \right)^{1/2} \]

dynamical times to drain the disk
- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio and Toomre's $Q$
- consider possibility that disks **fragment** when sufficiently unstable
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**Model Structure**

- Core Model
  - $\dot{M}_{\text{in}}(t), \dot{\mathbf{j}}_{\text{in}}(t)$
  - infall update $M_d \uparrow, J_d \uparrow$

- Initial Conditions
  - $M_\ast 0, M_d 0, J_d 0$
  - global disk properties $M_d, J_d, M_\ast$

- Accretion Model
  - $\frac{\dot{M}_\ast}{M_d \Omega} = f(Q, M_d, M_\ast)$
  - find thermal & mechanical equilibrium

- Thermal Physics
  - viscous heating
  - irradiation
  - radiative cooling

- Disk Braking Model
  - $M_\ast \uparrow, \Delta M_d, \Delta J_d$

- Stop
  - $t > 5 \text{ Myr}$?

- Fragments
  - $\Sigma_d \downarrow, M_{\text{frag}} \uparrow$

- $Q < 1$?
  - yes
  - binary $M_d \downarrow, J_d \downarrow, M_{\text{bin}} \uparrow$

- no
  - $M_d > M_\ast$?
    - yes $M_d \downarrow, J_d \downarrow, M_{\text{bin}} \uparrow$
    - no

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- employ a realistic model for irradiation of the disk midplane
Model Components II: Heating & Cooling

\[ \sigma T^4 = \left( \frac{8}{3} \tau_R + \frac{1}{4\tau_P} \right) F_v + F_{irr} \]

accretion + irradiation contribute significantly to disk heating even at high \( \dot{M} \)

irradiation model accounts for optically thin & thick regimes for two cases:
Model Components II: Heating & Cooling

\[ \sigma T^4 = \left( \frac{8}{3} \tau_R + \frac{1}{4\tau_P} \right) F_v + F_{\text{irr}}. \]

accretion + irradiation contribute significantly to disk heating even at high \( \dot{M} \).

Irradiation model accounts for optically thin & thick regimes for two cases:

- **during core accretion -- envelope reprocessing**
- **after core accretion -- radiating dust layer**

Matzner & Levin, 2005

Chiang & Goldreich, 1997
survey the conditions of intermediate-mass and massive star formation

consider fluctuations of the vector angular momentum in the infall due to realistic turbulence in the collapsing core

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employ a realistic model for irradiation of the disk midplane

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Core Model

\[ \dot{M}_{\text{in}}(t), \dot{J}_{\text{in}}(t) \]

Infall update

\[ M_d \uparrow, J_d \uparrow \]

Initial Conditions

\[ M_{*0}, M_{d0}, J_{d0} \]

Global disk properties

\[ M_d, J_d, M_* \]

Find thermal & mechanical equilibrium

Internal disk properties

\[ Q, \dot{M}_* \]

Accretion update

\[ M_* \uparrow, \Delta M_d, \Delta J_d \]

Disk Braking Model

Thermal Physics

- viscous heating
- irradiation
- radiative cooling

Initial Conditions

\[ M_{*0}, M_{d0}, J_{d0} \]

Accretion Model

\[ \frac{M_*}{M_d \Omega} = f \left( Q, \frac{M_d}{M_*} \right) \]

Survey the conditions of intermediate-mass and massive star formation and consider fluctuations of the vector angular momentum in the infall due to realistic turbulence in the collapsing core. Account for dependence of gravitational torques on disk-to-total mass ratio and Toomre's $Q$. Consider possibility that disks fragment when sufficiently unstable. Employ a realistic model for irradiation of the disk midplane.
Model Components III: Outer disk braking

Disk radius evolution for $20M_\odot$

$$\dot{J}_d = \dot{j}_{in} \dot{M}_{in} - b_j \left( \frac{\dot{M}_{in}}{M_*} \right) \frac{\dot{M}_{in}}{M_d} \dot{J}_d.$$
survey the conditions of intermediate-mass and **massive** star formation

consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core

account for dependence of gravitational torques on **disk-to-total mass** ratio and Toomre's $Q$

consider possibility that disks **fragment** when sufficiently unstable

employ a realistic model for **irradiation** of the disk midplane

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**Model Structure**

- **Core Model**
  - $\dot{M}_{\text{in}}(t), \dot{J}_{\text{in}}(t)$

- **Initial Conditions**
  - $M_0^*, M_d^0, J_d^0$

- **Accretion Model**
  - $\frac{\dot{M}_\ast}{M_d \Omega} = f(Q, \frac{M_d}{M_\ast})$

- **Thermal Physics**
  - viscous heating
  - irradiation
  - radiative cooling

- **Disk Braking Model**

- **Internal Disk Properties**
  - $Q, \dot{M}_\ast$

- **Accretion Update**
  - $M_\ast \uparrow, \Delta M_d, \Delta J_d$

- **Infall Update**
  - $M_d \uparrow, J_d \uparrow$

- **Stop**
  - $t > 5 \text{ Myr}$?

- **Find Thermal & Mechanical Equilibrium**

- **Fragments**
  - $\Sigma_d \downarrow, M_{\text{frag}} \uparrow$

- **Binary**
  - $M_d \downarrow, J_d \downarrow, M_{\text{bin}} \uparrow$

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KMK, Matzner, & Krumholz, 2007 (submitted)
Evolution of $Q$ and $\mu$

- Final Mass
- Fragmentation
- $R_d \sim 150$ AU
- Type I
- Type II
- Type III
- $\log Q$
  - $10^3$
  - $10^4$
  - $10^5$
  - $10^6$
- Years
  - $10^3$
  - $10^4$
  - $10^5$
  - $10^6$
Evolution of $Q$ and $\mu$

Final Mass

Fragmentation

$R_d > 150$ AU

Type I  Type II  Type III

$\log Q$

$10^3$

$10^4$

$10^5$

$10^6$

$10^0$

$10^1$

$10^2$

Binary Formation

$\mu$

$0.05$

$0.1$

$0.15$

$0.2$

$0.25$

$0.3$

$0.35$

$0.4$

$0.45$

$0.5$

years

Type I

Type II

Type III

years
Evolution of $Q$ and $\mu$
Disks with $\mu > 0.2$ around stars with masses $> 8M_\odot$ should be detectable with ALMA ($d \sim$ few Kpc) and EVLA ($d \sim 0.5$ Kpc) Type II disks should have strong spiral arms ($m=1,2$) which are easy to find in surveys by observing the disk morphology in the continuum

**Observational Classification**

- **Type I**
  - $< 10^4$ yrs
  - stable (local & global)
  - small disk mass

- **Type II**
  - $10^4$-$10^{5.5}$ yrs
  - core mass dependence
  - stability:
    - spiral vs fragmentation
  - significant disk mass

- **Type III**
  - $>10^{5.5}$ yrs
  - higher Q
  - small disk mass
Disks with $\mu > 0.2$ around stars with masses $> 8 M_\odot$ should be detectable with ALMA (d ~ few Kpc) and EVLA (d ~0.5 Kpc)

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    - spiral vs fragmentation
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- **Type III**
  - $>10^{5.5}$ yrs
  - higher Q
  - small disk mass
Characteristics of a $15 M_\odot$ star

- **Disk properties:**
  
  $T_d \approx 100$K
  
  $R_d \approx 200$AU
  
  $\Sigma_d \approx 50$ g/cm$^2$
  
  $\mu \approx 0.35$

- **Detectable?**
  
  ALMA: yes ($< 2$-3 Kpc)
  
  EVLA: yes ($< 0.5$ Kpc) (Krumholz et al, 2007)


measure similar characteristics

Evidence for star - disk velocity offset

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Torrelles et al, 2007
Conclusions and Future Directions

• Local instability and fragmentation persists for $\sim 10^5$ years

• Strong spiral arm structure should produce observable, non-Keplerian motion

• Outer disk temperatures exceed 100K for stars $> 10 M_\odot$

• Outer disk peak column densities $\sim 50$ g/cm$^2$

• Environmental variables ($\Sigma_c, T_c$) do not qualitatively change these conclusions

• Accretion model is uncertain: need simulations

• coming: GI physics numerical experiments

• Beyond a core model for infall:
  
  • coming: plug in semi-analytic model as “sub-grid physics” for SPH simulations