Formation and Evolution of Protostellar Disks in Star Clusters

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thanks to ... 

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Ralf Klessen: Tübingen  02.03.2009
How do protostellar disks build-up and evolve in a forming star cluster?

(data: Mark McCaughrean)
agenda

- turbulence in molecular clouds
- formation of star clusters
  - interplay between gravity and turbulence
- protostellar disks
  - formation and evolution
  - effects of environment
- what’s next?
molecular clouds
Taurus molecular cloud

Structure and dynamics of young star clusters is coupled to **structure of molecular cloud**

star-forming filaments in the *Taurus* cloud

(from Alyssa Goodman)
Taurus

\[ V_{\text{LSR}} = 3.4 \text{ km/s} \]

\[ 3.4 \text{ km/s} \]
V_{LSR} = 3.8 \text{ km/s}
\( V_{\text{LSR}} = 4.2 \, \text{km/s} \)
Taurus

$V_{\text{LSR}} = 4.6 \text{ km/s}$
Taurus

$V_{\text{LSR}} = 5.4 \text{ km/s}$
$V_{\text{LSR}} = 5.8 \text{ km/s}$
$V_{\text{LSR}} = 6.2 \text{ km/s}$
Taurus

$V_{\text{LSR}} = 6.6 \text{ km/s}$
Taurus

\[ V_{\text{LSR}} = 7.0 \, \text{km/s} \]
Taurus

$V_{\text{LSR}} = 7.4 \text{ km/s}$
Taurus

\[ V_{\text{LSR}} = 7.8 \text{ km/s} \]
Taurus

$V_{LSR} = 8.2 \text{ km/s}$
Taurus

$V_{LSR} = 8.6$ km/s
Mizuno et al. 1995 $^{13}$CO(1-0) integrated intensity map from Nagoya 4-m
Young star positions courtesy L. Hartmann
turbulence &
star clusters
Turbulent cascade

Kolmogorov (1941) theory incompressible turbulence

inertial range: 

\[
\text{scale-free behavior of turbulence}
\]

„size“ of inertial range:

\[
\frac{L}{\eta_K} \approx \text{Re}^{3/4}
\]

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Turbulent cascade

Shock-dominated turbulence

energy input scale

energy dissipation scale

inertial range: scale-free behavior of turbulence

„size“ of inertial range:

\[
\frac{L}{\eta_K} \approx \text{Re}^{3/4}
\]
Turbulent cascade in ISM

- energy source & scale
  - NOT known
  - (supernovae, winds, spiral density waves?)
- dissipation scale not known
  - (ambipolar diffusion, molecular diffusion?)

\[ \sigma_{\text{rms}} \ll 1 \text{ km/s} \]
\[ M_{\text{rms}} \leq 1 \]
\[ L \approx 0.1 \text{ pc} \]
Density structure of MC’s

Molecular clouds are highly inhomogeneous. Stars form in the densest and coldest parts of the cloud.

ρ-Ophiuchus cloud seen in dust emission.

Let’s focus on a cloud core like this one.

(Motte, André, & Neri 1998)
Evolution of cloud cores

- How does this core evolve? Does it form one single massive star or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO scale separation possible
  --> NO effective sound speed

- Turbulence is supersonic!
  --> produces strong density contrasts:
    \[ \frac{\delta \rho}{\rho} \approx M^2 \]
  --> with typical \( M \approx 10 \) --> \( \frac{\delta \rho}{\rho} \approx 100! \)

- Many of the shock-generated fluctuations are Jeans unstable and go into collapse
  --> expectation: core breaks up and forms a cluster of stars
indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by x, cores with embedded protostars by ★)

(Motte, André, & Neri 1998)
Formation and evolution of cores

- protostellar cloud cores form at stagnation point in convergent turbulent flows

- if $M > M_{\text{crit}} \propto \rho^{-1/2} T^{3/2}$: collapse & star formation

- if $M < M_{\text{crit}} \propto \rho^{-1/2} T^{3/2}$: reexpansion after end of external compression

  (e.g. Vazquez-Semadeni et al 2005)

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr
What happens to distribution of cloud cores?

Two extreme cases:

1. Turbulence dominates energy budget:
   \[ \alpha = \frac{E_{\text{kin}}}{|E_{\text{pot}}|} > 1 \]
   --> individual cores do not interact
   --> collapse of individual cores dominates stellar mass growth
   --> loose cluster of low-mass stars

2. Turbulence decays, i.e. gravity dominates: \[ \alpha = \frac{E_{\text{kin}}}{|E_{\text{pot}}|} < 1 \]
   --> global contraction
   --> core do interact while collapsing
   --> competition influences mass growth
   --> dense cluster with high-mass stars
turbulence creates a hierarchy of clumps
as turbulence decays locally, contraction sets in
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while region contracts, individual clumps collapse to form stars
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individual clumps collapse to form stars
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\[ \alpha = \frac{E_{\text{kin}}}{|E_{\text{pot}}|} < 1 \]

in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars
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in *dense clusters*, competitive mass growth becomes important
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in *dense clusters*, *N*-body effects influence mass growth
low-mass objects may become ejected --> accretion stops
feedback terminates star formation
result: *star cluster*, possibly with H\(\text{II}\) region
result: *star cluster* with H\textsc{ii} region
Trapezium Cluster
(detail)

- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

(color composite J,H,K by M. McCaughrean, VLT, Paranal, Chile)
Trapezium Cluster: Central Region

Ionizing radiation from central star \( \Theta 1C \) Orionis

**Proplyds**: Evaporating ``protoplanetary'' disks around young low-mass protostars

(images: Doug Johnstone et al.)
Futher Details: Siluette Disks in Orion

protostellar disks: dark shades in front of the photodissociation region in the background. Each image is 750 AU x 750 AU.

(data: Mark McCaughrean)
Ralf Klessen: Tübingen 02.03.2009
disks in clusters

**MAIN QUESTION:** how do protostellar disks build-up and evolve in a forming star cluster?

(data: Mark McCaughrean)
what is the difference between isolated disks and disks that form in (dense) clusters?

- dense environment $\rightarrow$ perturbations
  - tidal distortions (ang mom. transport $\rightarrow$ binarity?)
  - disk truncation (life times, mass loss)

- feedback from massive stars
  - evaporation (disk lifetimes, morphology, stability)
protostellar disks in clusters

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*comment:* need cluster environment to get IMF

$\rightarrow$ distribution of disk masses is set by environment!
distribution of stellar masses depends on

- turbulent initial conditions
  --> mass spectrum of prestellar cloud cores

- collapse and interaction of prestellar cores
  --> competitive accretion and $N$-body effects

- thermodynamic properties of gas
  --> balance between heating and cooling
  --> EOS (determines which cores go into collapse)

- (proto) stellar feedback terminates star formation
  ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)
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dependency on EOS

- degree of fragmentation depends on \( EOS! \)
  - polytropic EOS: \( p \propto \rho^\gamma \)
  - \( \gamma<1 \): dense cluster of low-mass stars
  - \( \gamma>1 \): isolated high-mass stars

dependency on EOS

for $\gamma < 1$ fragmentation is enhanced $\rightarrow$ cluster of low-mass stars

for $\gamma > 1$ it is suppressed $\rightarrow$ formation of isolated massive stars

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)
how does that work?

(1) $p \propto \rho^\gamma \rightarrow \rho \propto p^{1/\gamma}$

(2) $M_{\text{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

- $\gamma < 1$: $\rightarrow$ large density excursion for given pressure
  $\rightarrow \langle M_{\text{jeans}} \rangle$ becomes small
  $\rightarrow$ number of fluctuations with $M > M_{\text{jeans}}$ is large

- $\gamma > 1$: $\rightarrow$ small density excursion for given pressure
  $\rightarrow \langle M_{\text{jeans}} \rangle$ is large
  $\rightarrow$ only few and massive clumps exceed $M_{\text{jeans}}$
EOS for solar neighborhood

below $10^{-18}$ gcm$^{-3}$: $\rho$ $\uparrow$ $\rightarrow$ $T$ $\downarrow$

above $10^{-18}$ gcm$^{-3}$: $\rho$ $\uparrow$ $\rightarrow$ $T$ $\uparrow$

$Larson$ 1985, Larson 2005

$P \propto \rho^\gamma$

$P \propto \rho T$

$\rightarrow \gamma = 1 + d\ln T / d\ln \rho$

$\gamma = 0.7$

$\gamma = 1.1$
IMF from simple piece-wise polytropic EOS

\[ \gamma_1 = 0.7 \]
\[ \gamma_2 = 1.1 \]

\[ T \sim \rho^{\gamma-1} \]

(Jappsen et al. 2005)

(Ralf Klessen: Tübingen  02.03.2009)
IMF from simple piece-wise polytropic EOS

(Jappsen et al. 2005)
IMF in nearby molecular clouds

\[ x = -1.3 \]

with \( \rho_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3} \)

at \( \text{SFE} \approx 50\% \)

Isothermal EOS has deficit of very low-mass objects

---> need "better" EOS!

caveats

- mass spectrum depends on scale of turbulence ➔ consistent IMF only for large-scale turbulence
  
  (Klessen 2001)

  ➔ dynamical effects are important
  
  (Bonnell et al., Clark et al.)

- result depends on mechanism of turbulent driving ➔ solenoidal vs. compressive driving
  
  (Federrath et al. 2008)
initial mass function

what is the relation between molecular cloud fragmentation and the distribution of stars?

important quantity: **IMF**

BUT: “everyone” gets the right IMF
→ better look for secondary indicators

- **stellar multiplicity** (see focus group lead by H. Zinnecker)
- protostellar **spin** (including disk)
- **spatial distribution** + **kinematics** in young clusters
- **magnetic field strength** and **orientation**
  (see focus group lead by R. Crutcher)
Plausibility argument for shape

Supersonic turbulence is scale free process

→ POWER LAW BEHAVIOR

But also: turbulence and fragmentation are highly stochastic processes → central limit theorem

→ GAUSSIAN DISTRIBUTION
effects of dynamics
Star cluster formation

Most stars form in clusters → star formation = cluster formation

Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
Mass accretion rates vary with time and are strongly influenced by the cluster environment.

“Empirical” mass accretion law

Simple analytic formula for individual mass accretion rates: \[ \frac{dM}{dt} = At \cdot \exp\left(-\frac{t}{\tau}\right) \]

(Schmeja & Klessen, 2004 -- A&A, 419, 405 - 417)
Angular momentum evolution during protostellar collapse determines disk sizes (and possible binary fraction).

Examples of the time evolution of $j$

Angular momentum evolution lb

Z011/205379/M106/t6.8e4/sm11/sink16

\[ M_{\text{end}} = 1.09 M_\odot \]

\( j \) [cm²/s]

\( M \) [M☉]

- x-comp
- y-comp
- z-comp
details of the time evolution of \( j \)
Angular momentum evolution Ic

detailes of the time evolution of $j$
Angular momentum evolution $I_\theta$

3 of these 5 disks become unstable and may form binary

(Bodenheimer & Klessen, not published)
Angular momentum evolution II

- Statistical dependence of \textit{ang. mom.} on \textit{mass}

\[ j \propto M^{2/3} \]

\[ \beta = \text{constant} \]
\[ R = \text{constant} \]
\[ \rho = \text{constant} \]
\[ \text{(initially)} \]

Angular momentum evolution III

Distribution of $j$ similar to that of observed G-dwarf binaries

Angular momentum loss by gravitational torques in turbulent environment

Angular momentum IV

orientation of disk axes as function of time...

Angular momentum V

correlation of disk axis orientation as function of time...

modeling disks in clusters
numerical difficulties

• Resolving discs such that numerical viscosity doesn’t dominate requires high resolution... e.g. for SPH:

  ⅰ) Lodato & Rice (2004) -> $\alpha_{\text{art}} = (1/8)\alpha_{\text{SPH}} (h/H)$

  ⅱ) Rice, Lodato, Stamatellos, etc typically employ
      > 200,000 particles...

• Today, this is easy for disc/star system, OK for an isolated core, impossible for a whole cluster simulation:

  • 0.1 $M_\odot$ disc requires particle mass $\sim 1 \times 10^{-6} M_\odot$

  • 1000 $M_\odot$ cluster then need > $10^9$ particles

  • (that’s a lot)
**Problem:** still difficult to study global disk properties as cluster evolves.

*possible solution?*

Use large-scale simulations as a input for detailed small-scale simulations

(from Clark et al. in preparation)
how to define a disk in cluster simul.? 

Combine the sinks into systems:
- \( 20 < a < 500 \) au
- material needs to be bound
- must sit in potential well associated with sink/system
- \( v_{\text{rot}} > v_{\text{rad}} \)
- density threshold
- coherent object! (well, at least radially)

Roughly 50% of the systems have ‘resolvable ’ disks.

(from Clark et al. in preparation)
• (very) broad trend with mass of sink system.
• $M_{\text{disc}}/M_\text{•}$ often larger than 0.1
• would expect these discs to be self-gravitating (e.g. Lodato & Rice 2004, 2005).
• is this a feature of accretion in cluster environment (interactions, irregular $dM/dt$ and $dj/dt$?)?
• sinks in systems occupy a different region from isolated sinks.

note that these are lower limits to the mass ...

(from Clark et al. in preparation)
(from Clark et al. in preparation)
• again a broad trend with sink-system mass.
• disks around systems are larger than those around individual sinks (makes sense, given that they must surround larger objects).

(from Clark et al. in preparation)
(from Clark et al. in preparation)
Fig. 7.— This plot is the same as the previous, but this time all the evolution tracks are for discs around sinks which remain isolated.
disk evolution in cluster

Fig. 6.— The time evolution of several discs along with their host sinks, for the case where the sinks enter a multiple system. Points in the evolution in which the disc orbits a single sink are given as open circles, while the filled circles denote times when the disc is orbiting a system of sinks. The accretion rate, denoted by the dashed line, is that of the sink or sink-system.
angular momentum

(from Clark et al. in preparation)
• How does the plane of the disc compare to the preferred plane in the incoming bound material?

\[ \mathbf{j}_{\text{disc}} \cdot \mathbf{j}_{\text{region}} \]

(from Clark et al. in preparation)
accretion through disk ...

\[ \alpha_{\text{eff}} \sim 0.1 \]

\[ \alpha_{\text{eff}} \sim 1 \]
magnetic fields

- ideal MHD $\rightarrow$ effective angular mom. transport
  $\rightarrow$ small disks, no binaries
  $\rightarrow$ is there a fragmentation crisis?

- need non-ideal MHD
  $\rightarrow$ ambipol. diffusion to remove field?
  $\rightarrow$ but on what scales?
caveats

radiative feedback

• rich clusters form O/B stars
  → ionizing radiation can quench subsent star formation
  → how does this influence disks (morphology, life times, stability)
conclusions

• the whole problem of disks in clusters is currently not numerically tractable!
• can use a multi-scale approach to study initial stage of the disks (but still costly!).
• lower-res simulations of a full cluster can provide useful limits and trends.
• disks in the early stages of accretion are (probably) dominated by gravitational angular momentum transport.
• no obvious differences between discs in the competitive accretion picture and the isolated star formation model.
• even low levels of angular momentum can provoke fragmentation in the while the disc is accreting.
thanks