Star Formation in the Turbulent Interstellar Gas

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Agenda

- phenomenology
  - from large to small scales
- interplay between gravity and turbulence
- examples and predictions
  - star cluster formation: dynamics
  - star cluster formation: thermodynamics
    --> stellar initial mass function
young stars in spiral galaxies

- Star formation *always* is associated with *clouds of gas and dust*.

- Star formation is essentially a *local phenomenon* (on ~pc scale)

- HOW is star formation *influenced* by *global* properties of the galaxy?

(NGC 4622 from the Hubble Heritage Team)
On the night sky, you see **stars** and **dark clouds**: The brightest stars are massive and therefore young. → Star formation is important for understanding the structure of our Galaxy.
We see

- **Stars** (in visible light)
- **Atomic hydrogen**
  (in H\(\alpha\) -- red)
- **Molecular hydrogen** H\(_2\)
  (radio emission -- color coded)
The Orion molecular cloud is the birthplace of several young embedded star clusters. The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.
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.)
Molecular Cloud

Ionization Fronts

Shock-compressed molecular gas

Massive Ionizing Stars

H II Region Interior

alles in einem Bild
*Pillars of God* (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ....
Observations at optical wavelength

Infrared observation
Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ....
Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….
Taurus molecular cloud

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

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star-forming filaments in the *Taurus* cloud

*(from Alyssa Goodman)*
V$_{LSR}$ = 3.4 km/s
V_{LSR} = 3.6 \text{ km/s}
V_{LSR} = 3.8 \text{ km/s}
V_{LSR} = 4.0 \text{ km/s}
\( V_{LSR} = 4.2 \text{ km/s} \)
V_{LSR} = 4.4 \text{ km/s}
Taurus

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

$V_{\text{LSR}} = 4.8 \text{ km/s}$
Taurus

$V_{\text{LSR}} = 5.0 \text{ km/s}$
Taurus

$V_{\text{LSR}} = 5.2 \text{ km/s}$
\[ V_{\text{LSR}} = 5.4 \text{ km/s} \]
$V_{LSR} = 5.8 \text{ km/s}$
\( V_{\text{LSR}} = 6.0 \, \text{km/s} \)
Taurus

\[ V_{\text{LSR}} = 6.2 \text{ km/s} \]
Taurus

$V_{\text{LSR}} = 6.4 \text{ km/s}$
V_{LSR} = 6.6 \text{ km/s}
V_{LSR} = 6.8 \text{ km/s}
Taurus

$V_{\text{LSR}} = 7.0 \text{ km/s}$
Taurus

$V_{\text{LSR}} = 7.2 \text{ km/s}$
V_{LSR} = 7.4 \text{ km/s}
Taurus

$V_{\text{LSR}} = 7.6 \text{ km/s}$
$V_{LSR} = 7.8 \text{ km/s}$
Taurus

$V_{\text{LSR}} = 8.0 \text{ km/s}$

Galactic Longitude

Galactic Latitude
$V_{\text{LSR}} = 8.2 \text{ km/s}$
V_{LSR} = 8.4 \text{ km/s}
$V_{\text{LSR}} = 8.6 \text{ km/s}$

**Taurus**
V_{LSR} = 8.8 \text{ km/s}
Mizuno et al. 1995 $^{13}$CO(1-0) integrated intensity map from Nagoya 4-m
Young star positions courtesy L. Hartmann
Gravoturbulent star formation

Idea:

Star formation is controlled by interplay between gravity and supersonic turbulence!

Dual role of turbulence:

- stability on large scales
- initiating collapse on small scales

(e.g., Larson, 2003, Rep. Prog. Phys, 66, 1651; or Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125)
Gravoturbulent star formation

Idea:

Star formation is controlled by interplay between gravity and supersonic turbulence!

Validity:

This hold on all scales and applies to build-up of stars and star clusters within molecular clouds as well as to the formation of molecular clouds in galactic disk.

(e.g., Larson, 2003, Rep. Prog. Phys, 66, 1651; or Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125)
Gravoturbulent star formation

- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta \rho / \rho \propto M^2$; in atomic gas: $M \approx 1...3$)

- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of convergent large-scale flows
  - chemical *phase transition*: atomic $\rightarrow$ molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy

- inside *cold clouds*: turbulence is highly supersonic ($M \approx 1...20$)
  $\rightarrow$ *turbulence* creates large density contrast,
  *gravity* selects for collapse

  $\text{GRAVOTUBULENT FRAGMENTATION}$

- *turbulent cascade*: local compression *within* a cloud provokes collapse
  $\rightarrow$ formation of individual *stars* and *star clusters*

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)
Turbulent cascade

Kolmogorov (1941) theory incompressible turbulence

scale-free behavior of turbulence

energy input scale

energy dissipation scale

inertial range: \( L^{-1} \eta_K \approx \operatorname{Re}^{3/4} \)

Ralf Klessen: PKU/KIAA, 17.03.2008
Shock-dominated turbulence

Turbulent cascade

\[ \log E \]

\[ \log k \]

energy input scale

energy dissipation scale

inertial range:

scale-free behavior of turbulence

\[ \eta_K^{-1} \approx \frac{L}{\eta_K} \approx \text{Re}^{3/4} \]

„size“ of inertial range:
Turbulent cascade in ISM

- Energy source & scale: Not known (supernovae, winds, spiral density waves?)
- Supersonic scale: \( \sigma_{\text{rms}} \ll 1 \text{ km/s} \)
  \( M_{\text{rms}} \leq 1 \)
  \( L \approx 0.1 \text{ pc} \)
- Subsonic scale: dissipation scale not known (ambipolar diffusion, molecular diffusion?)

\[ \log E \quad \log k \quad \eta_k^{-1} \]

\[ \log E \quad L^{-1} \quad \log k \quad \eta_k^{-1} \]
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.
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 $\rho$-Oph B1/2 contains several cores ("starless" cores are denoted by $\times$, cores with embedded protostars by $\star$)

(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

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr

(e.g. Vazquez-Semadeni et al 2005)
Formation and evolution of cores

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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--> then contain multiple protostars
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\textsc{ii} region
Predictions

**global properties** (statistical properties)
- SF efficiency and timescale
- stellar mass function -- IMF
- dynamics of young star clusters
- description of self-gravitating turbulent systems (pdf’s, Δ-var.)
- chemical mixing properties

**local properties** (properties of individual objects)
- properties of individual clumps (e.g. shape, radial profile, lifetimes)
- accretion history of individual protostars (dM/dt vs. t, j vs. t)
- binary (proto)stars (eccentricity, mass ratio, etc.)
- SED's of individual protostars
- dynamic PMS tracks: $T_{bol}$-$L_{bol}$ evolution
Examples and predictions

example 1: star cluster formation: *dynamics*

example 2: star cluster formation: *thermodynamics*
    --> speculations on the origin of the stellar mass spectrum (IMF)
Example: model of Orion cloud

„model“ of Orion cloud:
15.000.000 SPH particles,
$10^4 \, M_{\odot}$ in 10 pc, mass
resolution $0,02 \, M_{\odot}$, forms
~2.500 „stars“ (sink particles)

isothermal EOS, top bound,
bottom unbound

has clustered as well as
distributed „star“ formation

efficiency varies from 1% to
20%

develops full IMF
(distribution of sink particle masses)

(Bonnell et al. 2007)
Example: model of Orion cloud

15,000,000 SPH particles, $10^4 M_{\odot}$ in 10 pc, mass resolution $0.02 M_{\odot}$, forms $\sim 2,500$ "stars" (sink particles).

MASSIVE STARS
- form early in high-density gas clumps (cluster center)
- high accretion rates, maintained for a long time

LOW-MASS STARS
- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion

(Bonnell et al. 2006) (Spitzer: Megeath et al.)

Bonnell et al. 2007
Models of star cluster formation

- dynamics:
  basic properties are probably okay

- BUT: no feedback
  (outflows, radiation, etc.)

- how much detail are we missing?
  - how does that change properties like IMF, boundedness, efficiency?
Model with ionizing feedback

SPH with radiation feedback: first calculations of star-cluster formation with ionization
Unbound clouds

KE = 2 \times PE (initially), 1000 solar masses, 0.5pc

No global collapse:
local $t_{ff} < \text{global interaction time-scale}$

$\text{barotropic, Larson (2005), style EOS}$

$t_{ff} \sim 2 \times 10^5$ years

Clark, Bonnell & Klessen (2007)
Mass functions

Isothermal EOS

Barotropic, Larson (2005), Style EOS

Clark, Bonnell & Klessen (2007)
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)
Most stars form in clusters $\rightarrow$ star formation = cluster formation

How to get from cloud cores to star clusters?
How do the stars acquire mass?

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)
Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!

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

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

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

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

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

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

\[ P \propto \rho^{\gamma} \]
\[ P \propto \rho T \]
\[ \rightarrow \gamma = 1 + \frac{d\ln T}{d\ln \rho} \]

\( \gamma = 0.7 \)

\( \gamma = 1.1 \)

(Larson 1985, Larson 2005)
IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

$T \sim \rho^{\gamma-1}$

(Jappsen et al. 2005)
IMF from simple piece-wise polytropic EOS

critical density $\uparrow$ $\rightarrow$ median mass $\downarrow$

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

with $\rho_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3}$
at SFE $\approx 50\%$

Isothermal EOS has deficit of very low-mass objects

$\rightarrow$ need “better” EOS!
Plausibility argument for shape

Supersonic turbulence is scale free process

\( \Rightarrow \) \text{POWER LAW BEHAVIOR}

\textbf{But also:} turbulence and fragmentation are highly stochastic processes \( \Rightarrow \) central limit theorem

\( \Rightarrow \) \text{GAUSSIAN DISTRIBUTION}
IMF in starburst galaxies

- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.

- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!

(see Spaans & Silk 2005)
IMF in starburst galaxies

- Starburst EOS --> top-heavy IMF

(Klessen, Spaans, Jappsen, 2007)
Fragmentation depends on EOS

\[ P \propto \rho^\gamma \]
\[ P \propto \rho T \]
\[ \rightarrow \gamma = 1 + \frac{d \log T}{d \log \rho} \]

\( n(H_2)_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3} \)
\( \rho_{\text{crit}} \approx 10^{-18} \text{ g cm}^{-3} \)

\( \gamma = 0.7 \)
\( \gamma = 1.1 \)

\( \log \text{density} \quad \text{[cm}^{-3}\text{]} \)

\( \gamma = 0.7 \)
\( \gamma = 1.1 \)

\( \log_{10} N \quad \text{[M}_\odot\text{]} \)

\( (\text{Larson 2005}) \)

\( (\text{Jappsen et al. 2005}) \)

\( (\text{Spaans & Silk 2005}) \)

\( (\text{Klessen et al. 2007}) \)
transition: Pop III to Pop II.5

(Omukai et al. 2005)
transition: Pop III to Pop II.5

(Omukai et al. 2005, Clark, Glover, Klessen 2007)
dust induced fragmentation at $Z=10^{-5}$

$\begin{align*}
&t = t_{\text{SF}} - 67 \text{ yr} \\
&t = t_{\text{SF}} - 20 \text{ yr} \\
&t = t_{\text{SF}} \\
&t = t_{\text{SF}} + 53 \text{ yr} \\
&t = t_{\text{SF}} + 233 \text{ yr} \\
&t = t_{\text{SF}} + 420 \text{ yr}
\end{align*}$

(Clark et al. 2007)

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dust induced fragmentation at $Z=10^{-5}$

\begin{align*}
\text{t = t}_{SF} - 67 \text{ yr} & \quad \text{t = t}_{SF} - 20 \text{ yr} & \quad \text{t = t}_{SF} \\
\text{t = t}_{SF} + 53 \text{ yr} & \quad \text{t = t}_{SF} + 233 \text{ yr} & \quad \text{t = t}_{SF} + 420 \text{ yr}
\end{align*}

(Clark et al. 2007)
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 $M_{\text{sun}}$
- cluster VERY dense $n_{\text{stars}} = 2.5 \times 10^9 \text{pc}^{-3}$
- fragmentation at density $n_{\text{gas}} = 10^{12} - 10^{13} \text{cm}^{-3}$

(Clarke et al. 2007)
Fig. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5} Z_\odot$ simulation. The graphs show the densities of the particles, plotted as a function of their $x$-position. Note that for each plot, the particle data has been centered on the region of interest. We show here results at three different output times, ranging from the time that the first star forms ($t_{sf}$) to 221 years afterwards. The densities lying between the two horizontal dashed lines denote the range over which dust cooling lowers the gas temperature.

(Clark et al. 2007)
cluster build-up

\( \gamma > 1 \) (heating)

\( \gamma < 1 \) (cooling)

(Clark et al. 2007)
dust induced fragmentation at $Z=10^{-5}$

- mass spectrum peaks below $1 \, M_{\text{sun}}$
- cluster VERY dense $n_{\text{stars}} = 2.5 \times 10^9 \, \text{pc}^{-3}$
- fragmentation at density $n_{\text{gas}} = 10^{12} - 10^{13} \, \text{cm}^{-3}$

(Clark et al. 2007)
Fig. 4.— Mass functions resulting from simulations with metallicities $Z = 10^{-5} Z_\odot$ (left-hand panel), $Z = 10^{-6} Z_\odot$ (center panel), and $Z = 0$ (right-hand panel). The plots refer to the point in each simulation at which 19 $M_\odot$ of material has been accreted (which occurs at a slightly different time in each simulation). The mass resolutions are 0.002 $M_\odot$ and 0.025 $M_\odot$ for the high and low resolution simulations, respectively. Note the similarity between the results of the low-resolution and high-resolution simulations. The onset of dust-cooling in the $Z = 10^{-5} Z_\odot$ cloud results in a stellar cluster which has a mass function similar to that for present day stars, in that the majority of the mass resides in the lower-mass objects. This contrasts with the $Z = 10^{-6} Z_\odot$ and primordial clouds, in which the bulk of the cluster mass is in high-mass stars.

even zero-metallicity case fragments
(although much more weakly)

(Clark et al. 2007)
how good is EOS approach?

- time to reach chemical and thermal equilibrium shorter than dynamical time?
- how does EOS depend on dynamics? (e.g. 1D collapse with large-gradient approx. versus complex 3D turbulent flows)

how important is heating from stars?

- accretion luminosity may heat gas and reduce degree of cloud fragmentation (cluster formation vs. high-mass SF)

how can we model that best?

- full radiation transfer vs. approximate schemes
Summary
Summary I

- interstellar gas is highly inhomogeneous
  - thermal instability
  - gravitational instability
  - turbulent compression (in shocks $\delta_\rho/\rho \propto M^2$; in atomic gas: $M \approx 1...3$)

- cold molecular clouds can form rapidly in high-density regions at stagnation points of convergent large-scale flows
  - chemical phase transition: atomic $\rightarrow$ molecular
  - process is modulated by large-scale dynamics in the galaxy

- inside cold clouds: turbulence is highly supersonic ($M \approx 1...20$)
  $\rightarrow$ turbulence creates density contrast, gravity selects for collapse
  $\rightarrow$ GRAVOTUBULENT FRAGMENTATION

- turbulent cascade: local compression within a cloud provokes collapse $\rightarrow$ formation of individual stars and star clusters

- star cluster: gravity dominates in large region ($\rightarrow$ competitive accretion)

(e.g. Mac Low & Klessen, 2004, Ballesteros-Paredes et al. 2006, McKee & Ostriker 2007)
thermodynamic response (EOS) determines fragmentation behavior

- characteristic stellar mass from fundamental atomic and molecular parameters
  -> explanation for quasi-universal IMF?

stellar feedback is important

- accretion heating may reduce degree of fragmentation
- ionizing radiation will set efficiency of star formation

CAVEATS:

- star formation is multi-scale, multi-physics problem --> VERY difficult to model
- in simulations: very small turbulent inertial range (Re < 1000)
- can we use EOS to describe thermodynamics of gas, or do we need time-dependent chemical network and radiative transport?
- stellar feedback requires (at least approximative) radiative transport, most numerical calculations so far have neglected that aspect

(e.g. Mac Low & Klessen, 2004, Ballesteros-Paredes et al. 2006, McKee & Ostriker 2007)
Thanks!
Stadien der Sternbildung 1

Prästellare Kerne in Dunkelwolken

Gravitativer Kollaps: Klasse 0 Objekt
Stadien der Sternbildung 2

eingebetteter Protostern: Klasse 1

Klassischer T Tauri Stern: Klasse 2

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Stadien der Sternbildung 3

Klassischer T Tauri Stern: Klasse 2

Stern auf Hauptreihe (Kernfusion im Zentrum) mit Planetensystem

100 AU  \( t = 10^5 - 10^6 \) Jahre

50 AU  \( t > 10^7 \) Jahre

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