Molecular Cloud Turbulence and Star Formation

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Overview

- concept of gravoturbulent star formation
- three „steps“ of star formation:
  1. formation of molecular clouds in the disk of our galaxy
  - intermezzo: properties of molecular cloud turbulence
  2. formation of protostellar cores
  3. formation of stars: protostellar collapse and the stellar mass spectrum
- summary
the idea
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)
Competing approaches in SF theory:

**quasistatic theories:**
magnetically mediated star formation
Shu, Adams, & Lizano (1987, ARAA)

**dynamical theories:**
turbulent control of star formation
Mac Low & Klessen (2004, RMP, 76, 125)
Elmegreen & Scalo (2004, ARAA)
Scalo & Elmegreen (2004, ARAA)
Gravoturbulent star formation

interstellar gas is highly \textit{inhomogeneous}

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

cold \textit{molecular clouds} can form rapidly in high-density regions at \textit{stagnation points} of convergent \textit{large-scale flows}

- chemical \textit{phase transition}: atomic $\rightarrow$ molecular
- process is \textit{modulated} by large-scale \textit{dynamics} in the galaxy

inside \textit{cold clouds}: turbulence is highly supersonic ($M \approx 1...20$)

$\rightarrow$ turbulence creates large density contrast,

\textit{gravity} selects for collapse

\textbf{GRAVOTUBULENT FRAGMENTATION}

\textit{turbulent cascade}: local compression \textit{within} a cloud provokes collapse

$\rightarrow$ formation of individual \textit{stars} and \textit{star clusters}

\textit{(e.g. Mac Low \\& Klessen, 2004, Rev. Mod. Phys., 76, 125-194)}
cloud formation
Molecular cloud formation

... in convergent large-scale flows

... setting up the turbulent cascade

- Mach 3 colliding flow
- Vishniac instability + thermal instability
- compressed sheet breaks up and builds up cold, high-density „blobs“ of gas

--> molecular cloud formation

- cold cloud motions correspond to supersonic turbulence

(e.g. Koyama & Inutsuka 2002, Heitsch et al., 2005, Vazquez-Semadeni et al. 2004; also posters 8577, 8302)
Correlation with large-scale perturbations

Density/temperature fluctuations in warm atomar ISM are caused by thermal/gravitational instability and/or supersonic turbulence. Some fluctuations are dense enough to form $H_2$ within "reasonable time" → molecular cloud.

External perturbations (i.e. potential changes) increase likelihood.

(e.g. off arm)

(e.g. on arm)

Poster 8170: Dobbs & Bonnell
Poster 8577: Glover & Mac Low
Star formation on global scales

\[ \rho \text{-pdf, each shifted by } \Delta \log N = 1 \]

\[ M_1 > M_2 > M_3 > M_4 > 0 \]

probability distribution function of the density (\( \rho \text{-pdf} \))

varying rms Mach numbers:

(from Klessen, 2001; also Gazol et al. 2005, Mac Low et al. 2005)
Star formation on global scales

$H_2$ formation rate:

$$\tau_{H_2} \approx \frac{1.5 \text{ Gyr}}{n_H / 1 \text{ cm}^{-3}}$$

for $n_H \geq 100 \text{ cm}^{-3}$, $H_2$ forms within 10 Myr, this is about the lifetime of typical MC's.

In turbulent gas, the $H_2$ fraction can become very high on short timescale

(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2005)

Mass weighted $\rho$-pdf, each shifted by $\Delta \log N = 1$

(rate from Hollenback, Werner, & Salpeter 1971, see also poster 8577)
Correlation between $\text{H}_2$ and $\text{HI}$

Compare $\text{H}_2$ - $\text{HI}$ in M33:
- $\text{H}_2$: BIMA-SONG Survey, see Blitz et al.
- $\text{HI}$: Observations with Westerbork Radio T.

$\text{H}_2$ clouds are seen in regions of high $\text{HI}$ density (in spiral arms and filaments)

(Deul & van der Hulst 1987, Blitz et al. 2004)
turbulence
Properties of turbulence

- Laminar flows turn turbulent at high Reynolds numbers

\[
\text{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{V L}{\nu}
\]

- V = typical velocity on scale L, \( \nu = \text{viscosity}, \) \( \text{Re} > 1000 \)

- Vortex stretching \( \rightarrow \) turbulence is intrinsically anisotropic
  
  (only on large scales you may get homogeneity & isotropy in a statistical sense; see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

  (ISM turbulence: shocks & B-field cause additional inhomogeneity)
Vortex Formation

Vortices are stretched and folded in three dimensions

Porter et al. ASCI, 1997
Turbulent cascade

Inertial range:

scale-free behavior of turbulence

\( \frac{L}{\eta_K} \approx \text{Re}^{3/4} \)

Kolmogorov (1941) theory

incompressible turbulence
Turbulent cascade

Shock-dominated turbulence

energy input scale

energy dissipation scale

log $E$

log $k$

$k^{-2}$

transfer

inertial range:

"scale-free behavior of turbulence"

"size" of inertial range:

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

Ralf Klessen: PPV, Oct. 24, 2005
Turbulent cascade in ISM

- Energy source & scale NOT known (supernovae, winds, spiral density waves?)
- Supersonic scale: $\sigma_{\text{rms}} \approx \text{several km/s}$, $M_{\text{rms}} > 10$, $L > 10$ pc
- Subsonic scale: $\sigma_{\text{rms}} \approx \text{few km/s}$, $M_{\text{rms}} \approx 5$, $L \approx 1$ pc
- Dissipation scale not known (ambipolar diffusion, molecular diffusion?)

Ralf Klessen: PPV, Oct. 24, 2005
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

- Does core form 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
  --> core breaks up and forms a cluster of stars
Evolution of cloud cores

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 the stagnation points of convergent turbulent flows

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

- if $M < M_{\text{Jeans}} \propto \rho^{-1/2} T^{3/2}$: reexpansion after external compression fades away

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

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

- because turbulent ambipolar diffusion time is short, this time estimate still holds for the presence of magnetic fields, in magnetically critical cores

  (e.g. Fatuzzo & Adams 2002, Heitsch et al. 2004)
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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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\textsubscript{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, $\Delta$-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: transient structure of turbulent clouds

example 2: quiescent and coherent appearance of molecular cloud cores

example 3: speculations on the origin of the stellar mass spectrum (IMF)
example 1
Transient cloud structure

Gravoturbulent fragmentation of turbulent self-gravitating clouds

- SPH model with \(1.6 \times 10^6\) particles
- large-scale driven turbulence

- Mach number \(M = 6\)
- periodic boundaries
- physical scaling: “Taurus”
Gravoturbulent fragmentation

Gravoturbulent fragmentation in molecular clouds:
- SPH model with $1.6 \times 10^6$ particles
- large-scale driven turbulence
- Mach number $M = 6$
- periodic boundaries
- physical scaling:

“Taurus”:
- density $n(H_2) \approx 10^2 \text{ cm}^{-3}$
- $L = 6 \text{ pc}$, $M = 5000 \, M_\odot$
Star-forming filaments in the Taurus molecular cloud

Quiescent & coherent cores

correlation between linewidth and column density
(e.g. Goodman et al. 1998; Barranco & Goodman 1998; Caselli et al. 2002; Tafalla et al. 2004)

map of linewidth (contours column density)

column density map (contours column density)
Quiescent & coherent cores

correlation between linewidth and column density
(e.g. Goodman et al. 1998; Barranco & Goodman 1998; Caselli et al. 2002; Tafalla et al. 2004)

map of linewidth (contours column density)

column density map (contours column density)
cores form at stagnation points of convergent large-scale flows
--> often are bounded by ram pressure
--> velocity dispersion highest at boundary

correlation between linewidth and column density

(e.g. Goodman et al. 1998; Barranco & Goodman 1998
Caselli et al. 2002; Tafalla et al. 2004)

map of linewidth
(contours column density)

column density map
(contours column density)
Quiescent & coherent cores

Statistics:

23% of our cores are **quiescent** (i.e. with $\sigma_{\text{rms}} \leq c_s$)

48% of our cores are **transonic** (i.e. with $c_s \leq \sigma_{\text{rms}} \leq 2c_s$)

half of our cores are **coherent** (i.e. with $\sigma_{\text{rms}}$ independent of $N$)

Quiescent & coherent cores

Statistics:

- Most cores have masses smaller than $M_{\text{vir}}$ (should reexpand once external compression fades).
- Some cores have more mass than $M_{\text{vir}}$ (should collapse).
- Indeed, all cores with protostars have $M > M_{\text{vir}}$. 

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)
Star cluster formation

Most stars form in clusters \(\rightarrow\) \textit{star formation} = \textit{cluster formation}

How to get from \textit{cloud cores} to \textit{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)
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.

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
- \( \langle M_{\text{jeans}} \rangle \) becomes small
- number of fluctuations with \( M > M_{\text{jeans}} \) is large

\( \gamma > 1: \Rightarrow \text{small} \) density excursion for given pressure
- \( \langle M_{\text{jeans}} \rangle \) is large
- only few and massive clumps exceed \( M_{\text{jeans}} \)
Implications

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

implications for extreme environmental conditions
- expect Pop III stars to be massive and form in isolation
- expect IMF variations in warm & dusty starburst regions
  (Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2005)

Observational findings: isolated O stars in LMC (and M51)?
  (Lamers et al. 2002, Massey 2002; see however, de Witt et al. 2005 for Galaxy)
More realistic EOS

But EOS depends on chemical state, on balance between heating and cooling.

\[ P \propto \rho^\gamma \]
\[ \rho_{\text{crit}} \approx 10^{-18} \text{ g cm}^{-3} \]
\[ n(\text{H}_2)_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3} \]
\[ \gamma = 0.7 \]
\[ \gamma = 1.1 \]

\[ \rightarrow \gamma = 1 + d\log T / d\log \rho \]

IMF in nearby molecular clouds

\[
\rho_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3}
\]

at SFE \( \approx 50\% \)

"Standard" IMF of single stars (e.g. Scalo 1998, Kroupa 2002)

Summary

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

- cold *molecular clouds* form rapidly in high-density regions
  - 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 structure, *gravity* selects for collapse

\[ \text{GRAVOTUBULENT FRAGMENTATION} \]

- *turbulent cascade*: local compression within a cloud provokes collapse

- individual *stars* and *star clusters* form through *sequence* of highly *stochastic* events:
  - *collapse* of cloud cores in turbulent cloud (cores change during collapse)
  - plus mutual *interaction* during collapse (importance depends on ratio of potential energy to turbulent energy) (buzz word: *competitive accretion*)
Thanks!
SF Flow Chart

High SFR → Starburst → Warm gas Toomre unstable? → Is warm gas compressed and cooled? → Can cold gas overwhelm turbulent support?

- Y → Local Burst (Orion)
- N → Is LSB galaxies, outer disks

Low SFR → Isolated SF (Taurus)

V_{rms} from SFR → Σ from dynamics

(from Mc Low & Klessen, 2004, Rev. Mod. Phys., 76, 125 - 194)