star formation
in disk galaxies
agenda

phenomenology
  
  stars
  
  gas

interplay between gravity and turbulence

eamples and predictions
  
  transient cloud structure
  
  stellar initial mass function
stars
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?
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 Hα -- red)
- Molecular hydrogen H₂ (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.
Stars form in clusters and in molecular clouds. (Proto)stellar feedback is important.

(color composite J,H,K by M. McCaughrean, VLT, Paranal, Chile)
center of ONC: the trapezium

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

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

(images: Doug Johnstone et al.)
protostellar disks: dark shades in front of the photodissociation region in the background. Each image is 750 AU x 750 AU.

(data: Mark McCaughrean)
how to observe star forming clouds?

Different wavelength give different information.

→ astronomer use the full electromagnetic spectrum

- **Radio:** interstellar gas
  (line emission -> velocity information)
- **sub-mm range:** dust (thermal emission)
- **infrared & optical:** stars
- **x-rays:** stars (coronae), supernovae remnants (very hot gas)
- **γ-rays:** supernovae remnants (radioactive decay, e.g. $^{26}$Al), compact objects, merging of neutron stars ($γ$-ray burst)
### Abundances, scaled to 1.000.000 H atoms

<table>
<thead>
<tr>
<th>element</th>
<th>atomic number</th>
<th>abundance</th>
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</thead>
<tbody>
<tr>
<td>Wasserstoff</td>
<td>H</td>
<td>1.000.000</td>
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<tr>
<td>Deuterium</td>
<td>( ^1\text{H}^2 )</td>
<td>16</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>68.000</td>
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<td>Kohlenstoff</td>
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<tr>
<td>Eisen</td>
<td>Fe</td>
<td>34</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni</td>
<td>2</td>
</tr>
</tbody>
</table>

Hydrogen is by far the most abundant element (more than 90% in number).
Because hydrogen is the dominating element, the classification scheme is based on its chemical state:

- *ionized atomic hydrogen*: $\text{HII} \ (H^+)$
- *neutral atomic hydrogen*: $\text{HI} \ (H)$
- *molecular hydrogen*: $H_2$

Different regions consist of almost 100% of the appropriate phase, the transition regions between HII, $H$, and $H_2$ are very thin.

Star formation always takes place in dense and cold molecular clouds.
phases of the ISM

A_v bezeichnet die Extinktion, dh. die Abschwächung der einfallenden Strahlung.
correlation between $H_2$ and $HI$

Compare $H_2$ - $HI$ in M33:
- $H_2$: BIMA-SONG Survey, see Blitz et al.
- $HI$: Observations with Westerbork Radio T.

$H_2$ clouds are seen in regions of high $HI$ density (in spiral arms and filaments)

(Deul & van der Hulst 1987, Blitz et al. 2004)
Structure and dynamics of young star clusters is coupled to structure of molecular cloud (from Alyssa Goodman)

star-forming filaments in the Taurus cloud

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

Star-forming filaments in the Taurus cloud (from Hartmann 2002)

- Strukture and dynamics of molekular cloud is determined by supersonic turbulence.

- Thermal line width $\sigma_{\text{therm}}$
- Observed line width $\sigma_{\text{tot}}$
- $\sigma_{\text{tot}} >> \sigma_{\text{therm}}$
LIFE

PLANETARY SYSTEMS

Planet formation

Star formation

STARS

Gas & dust

RED GIANTS

SUPERNOVE

PLANETARY NEBULAE

Gas & dust

LOW MASS STARS

HIGH MASS STARS

WHITE DWARFS

NEUTRON STARS

BLACK HOLES

Inter Stellar Matter

Dust

Molecules

Atoms

Particle physics

Chemistry

Thermodynamics

Hydrodynamics

Cold gas

n: Heidelberg Summer School, 03.09.2007
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)
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 ($M \approx 1...20$)
  - *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)
modeling large scales
molecular cloud formation

Thesis:
Molecular clouds form at *stagnation points* of large-scale convergent flows, mostly triggered by global (or external) perturbations.

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

(density/temperature fluctuations)

external perturbuations (i.e. potential changes) increase likelihood

(e.g. off arm) (e.g. on arm)

space

space

(density)

(density)

(Ralf Klessen: Heidelberg Summer School, 03.09.2007)
star formation on global scales

probability distribution function of the density ($\rho$-pdf) varying rms Mach numbers:

M1 > M2 > M3 > M4 > 0

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

(from Klessen, 2001; also Gazol et al. 2005, Mac Low et al. 2005)
star formation on \textit{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 10Myr, 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 2007a,b)

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

(rate from Hollenback, Werner, & Salpeter 1971)
modeling galactic SF

SPH calculations of self-gravitating disks of stars and (isothermal) gas in dark-matter potential, sink particles measure local collapse --> star formation

Modeling galactic SF

Evolution of 42 isolated disk galaxies

- DM halo, stellar disk & gas disk
- SPH code GADGET with accretion particles
  \( \text{(resolution: } 5 \times 10^5 \text{ to } 3 \times 10^6 \text{ gas particles)} \)
- \( 50 \text{ km/s} \leq v_{\text{circ}} \leq 250 \text{ km/s} \)
- fraction of disk mass: \( m_d = 5\% - 10\% \)
- gas fraction in disk: \( f_d = 20\%, 50\%, \text{ & } 90\% \)
- total mass: \( 4.15 \times 10^{10} M_\odot \leq M_{200} \leq 357.14 \times 10^{10} M_\odot \)
  \( \text{(corresponds to mass resolution of } 138 M_\odot \leq M_{\text{SPH}} \leq 10^5 M_\odot \text{ in models with } 3 \times 10^6 \text{ gas particles)} \)

\( \text{(Li, Mac Low, & Klessen, 2005, 2006a,b, ApJ)} \)
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)
We find correlation between star formation rate and gas surface density:

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$$

**Schmidt law**
Observed Schmidt law

\[ \Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left( \frac{\Sigma_{gas}}{1 \, M_\odot \, pc^{-2}} \right)^{1.4 \pm 0.15} \, M_\odot \, year^{-1} \, kpc^{-2}, \]

(from Kennicutt 1998)
observed Schmidt law

in both cases: \[ \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.5} \]

(from Kennicutt 1998)
modeling small scales
Properties of turbulence

laminar flows turn *turbulent* at *high* Reynolds numbers

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

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

vortex stretching --> 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
Inertial range: scale-free behavior of turbulence

"Size" of inertial range:

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

Shock-dominated turbulence

energy input scale

energy dissipation scale

\[ \log E \quad \log k \]

\[ L^{-1} \quad \eta^{-1}_K \]

\[ k^{-2} \]

inertial range: scale-free behavior of turbulence

„size“ of inertial range:

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

- Energy source & scale: NOT known
  - (supernovae, winds, spiral density waves?)
- Dissipation scale not known
  - (ambipolar diffusion, molecular diffusion?)

- Molecular clouds
  - $\sigma_{\text{rms}} \approx \text{several km/s}$
  - $M_{\text{rms}} > 10$
  - $L > 10 \text{ pc}$

- Massive cloud cores
  - $\sigma_{\text{rms}} \approx \text{few km/s}$
  - $M_{\text{rms}} \approx 5$
  - $L \approx 1 \text{ pc}$

- Dense protostellar cores
  - $\sigma_{\text{rms}} << 1 \text{ km/s}$
  - $M_{\text{rms}} \leq 1$
  - $L \approx 0.1 \text{ pc}$
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

density structure of MCs

(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*
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 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

- 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. Vazquez-Semadeni et al 2005)

(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
individual clumps collapse to form stars
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars

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--> then contain multiple protostars
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--> then contain multiple protostars
in *dense clusters*, competitive mass growth becomes important
in *dense clusters*, competitive mass growth becomes important
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 HII region
predictions
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: transient structure of turbulent clouds

example 2: speculations on the origin of the stellar mass spectrum (IMF)
example 1
Gravoturbulent fragmentation of turbulent self-gravitating clouds

- SPH model with $1.6 \times 10^6$ particles
- Large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- Periodic boundaries
- Physical scaling: “Taurus”
Gravitoturbulent fragmentation

Gravitoturbulent fragmentation in molecular clouds:

- SPH model with 1.6x10^6 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* cloud

(from Alyssa Goodman)
example 2
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
Star cluster formation

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?
Star cluster formation

in dense clusters protostellar interaction may be come important!

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.

fragmentation depends on EOS

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

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

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

\[\gamma > 1: \rightarrow \text{small density excursion for given pressure}\]
\[\rightarrow \langle M_{\text{jeans}} \rangle \text{ is large}\]
\[\rightarrow \text{only few and massive clumps exceed } M_{\text{jeans}}\]
fragmentation depends on EOS

\( \gamma = 0.2 \) \hspace{1cm} \( \gamma = 1.0 \) \hspace{1cm} \( \gamma = 1.2 \)

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)
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)
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

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

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

at SFE \( \approx 50\% \)

 Isothermal EOS has deficite of very low-mass objects

\( \rightarrow \text{need "better" EOS!} \)

Supersonic turbulence is a scale-free process

$\Rightarrow$ POWER LAW BEHAVIOR

But also: turbulence and fragmentation are highly stochastic processes $\Rightarrow$ central limit theorem

$\Rightarrow$ GAUSSIAN DISTRIBUTION
summary

interstellar gas is highly inhomogeneous

- thermal instability
- gravitational instability
- turbulent compression (in shocks $\delta \rho/\rho \approx M^2$; 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

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)

(Larson 2003, PRP; Mac Low & Klessen 2004, RMP, 76, 125-194, Ballesteros-Paredes et al. PPV)
Thanks!
Gravitational collapse within MCs

today: SPH with $N > 10^7$ particles

model for the Orion cloud: $M = 10^4 \, M_{\odot}$, isothermal EOS

still no chemistry, no stellar feedback, no radiation

(Bonnell et al. 2006)
Gravitational collapse within MCs

Ralf Klessen: Heidelberg Summer School, 03.09.2007

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Gravitational collapse within MCs

immediate future: SPH with radiation feedback (first validation runs)