ISM Dynamics and Star Formation

Ralf Klessen

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thanks to ...

many thanks to the members of the star formation group at the Institute for Theoretical Astrophysics at the Center for Astronomy of Heidelberg University

- Robi Banerjee
- Paul Clark
- Christoph Federrath
- Simon Glover
- Thomas Greif
- Susanne Horn
- Stefan Schmeja
- Thomas Peters
- Dominik Schleicher
- and many guests
agenda

- phenomenology
- theoretical approach
- formation of molecular clouds
  - on galactic scales
  - locally, in convergent flows
- fragmentation of molecular clouds
  - interplay between gravity and turbulence
- star formation: now and then
  - initial mass function at present days (models & caveats)
  - speculations about Pop III and transition to Pop II
Stars form in galaxies and protogalaxies

(less than 1Gyr after big bang)

(Hubble Ultra-Deep Field, from HST Web site)
Star formation in interacting galaxies:

Antennae galaxy

- NGC4038/39
- distance: 19.2Mpc
- vis. Magn: 11.2
- optical: white, green
- radio: blue

(from the Chandra Webpage)
Star formation in interacting galaxies:

- Star formation burst in interacting (merging) galaxies
- Strong perturbation SF in tidal “tales”
- Large-scale gravitational motion determines SF
- Stars form in “knobs” (i.e. superclusters)

(HST: Whitmore & Schweizer 1997)
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
Star formation in Orion

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.
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 Θ1C Orionis

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

(images: Doug Johnstone et al.)

Ralf Klessen: Paris 03.04.2009
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 ....
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 wavelengths. 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 ....
Early dynamical theory

**Jeans (1902):** Interplay between self-gravity and thermal pressure

- stability of homogeneous spherical density enhancements against gravitational collapse
- dispersion relation:

\[
\omega^2 = c_s^2 k^2 - 4\pi G \rho_0
\]

- instability when \( \omega^2 < 0 \)

- minimal mass:

\[
M_J = \frac{1}{6} \pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{-3/2}
\]

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)
First approach to turbulence

von Weizsäcker (1943, 1951) and Chandrasekhar (1951): concept of MICROTURBULENCE

- BASIC ASSUMPTION: separation of scales between dynamics and turbulence
  \[ \ell_{\text{turb}} \ll \ell_{\text{dyn}} \]
- then turbulent velocity dispersion contributes to effective sound speed:
  \[ C_c^2 \rightarrow C_c^2 + \sigma_{\text{rms}}^2 \]

- Larger effective Jeans masses \( \rightarrow \) more stability
- BUT: (1) turbulence depends on \( k \):
  \[ \sigma_{\text{rms}}^2(k) \]
  (2) supersonic turbulence \( \rightarrow \) usually \( \sigma_{\text{rms}}^2(k) \gg C_s^2 \)

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)
Problems of early dynamical theory

- Molecular clouds are *highly Jeans-unstable*
  Yet, they do *NOT* form stars at high rate and with high efficiency.
  (the observed global SFE in molecular clouds is \(\sim 5\%\))
  \(\rightarrow\) *something prevents large-scale collapse.*

- All throughout the early 1990’s, molecular clouds had been thought to be long-lived quasi-equilibrium entities.

- Molecular clouds are *magnetized.*

*(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)*
Magnetic star formation

**Mestel & Spitzer (1956):** Magnetic fields can prevent collapse!!!

- Critical mass for gravitational collapse in presence of B-field
  \[ M_{cr} = \frac{5^{3/2} B^3}{48\pi^2 G^{3/2} \rho^2} \]

- Critical mass-to-flux ratio
  (Mouschovias & Spitzer 1976)
  \[ \left[ \frac{M}{\Phi} \right]_{cr} = \frac{\zeta}{3\pi} \left[ \frac{5}{G} \right]^{1/2} \]

- Ambipolar diffusion can initiate collapse

*(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)*
The "standard theory" of star formation:

- **BASIC ASSUMPTION**: Stars form from magnetically highly subcritical cores

- Ambipolar diffusion slowly increases \((M/\Phi)\): \(\tau_{AD} \approx 10 \tau_{ff}\)

- Once \((M/\Phi) > (M/\Phi)_{\text{crit}}\):
  - dynamical collapse of SIS

  - **Shu (1977) collapse solution**

  - \(dM/dt = 0.975 c_s^3/G = \text{const.}\)

  - Was (in principle) only intended for isolated, low-mass stars
Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)


Structure of prestellar cores (Bacman et al. 2000, e.g. Barnard 68 from Alves et al. 2001)

Strongly time varying dM/dt (e.g. Hendriksen et al. 1997, André et al. 2000)

More extended infall motions than predicted by the standard model (Williams & Myers 2000, Myers et al. 2000)
B versus $N(H_2)$ from Zeeman measurements.
(from Bourke et al. 2001)

→ cloud cores are magnetically supercritical !!!

$(\Phi/M)_n > 1$ no collapse
$(\Phi/M)_n < 1$ collapse
Problems of magnetic SF

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)


- Structure of prestellar cores (Bacman et al. 2000, e.g. Barnard 68 from Alves et al. 2001)

- Strongly time varying dM/dt (e.g. Hendriksen et al. 1997, André et al. 2000)

- More extended infall motions than predicted by the standard model (Williams & Myers 2000, Myers et al. 2000)
Molecular cloud dynamics

**Timescale problem:** Turbulence decays on timescales comparable to the free-fall time $\tau_{ff}$ ($E \propto t^{-\eta}$ with $\eta \approx 1$).


Magnetic fields (static or wave-like) cannot prevent loss of energy.

(Mac Low, Klessen, Burkert, & Smith, 1998, PRL)
Problems of magnetic SF

- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps seem to be chemically young (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$) (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Most stars form as binaries
Fig. 1.— The Arecibo telescope primary beam (small circle centered at 0,0) and the four GBT telescope primary beams (large circles centered 6' north, south, east, and west of 0,0). The dotted circles show the first sidelobe of the Arecibo telescope beam. All circles are at the half-power points.

Crutcher et al. (2008)
Crutcher et al. (2008)

Fig. 2.— OH 1667 MHz spectra toward the core of L1448CO obtained with the Arecibo telescope (center panel) and toward each of the envelope positions 6’ north, south, east, and west of the core, obtained with the GBT. In the upper left of each panel is the inferred $B_{LOS}$ and its 1σ uncertainty at that position. A negative $B_{LOS}$ means the magnetic field points toward the observer, and vice versa for a positive $B_{LOS}$. 

Ralf Klessen: Paris 03.04.2009
Table 2. Relative Mass/Flux

<table>
<thead>
<tr>
<th>Cloud</th>
<th>$\mathcal{R}$</th>
<th>$\mathcal{R}'$</th>
<th>Probability $\mathcal{R}$ or $\mathcal{R}' &gt; 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1448CO</td>
<td>0.02 ± 0.36</td>
<td>0.07 ± 0.34</td>
<td>0.005</td>
</tr>
<tr>
<td>B217-2</td>
<td>0.15 ± 0.43</td>
<td>0.19 ± 0.41</td>
<td>0.05</td>
</tr>
<tr>
<td>L1544</td>
<td>0.42 ± 0.46</td>
<td>0.46 ± 0.43</td>
<td>0.11</td>
</tr>
<tr>
<td>B1</td>
<td>0.41 ± 0.20</td>
<td>0.44 ± 0.19</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Fig. 2.— OH 1667 MHz spectra toward the telescope (center panel) and toward each of the west of the core, obtained with the GBT. In this and its 1σ uncertainty at that position. A negative toward the observer, and vice versa for a positive.

Crutcher et al. (2008)
Fig. 1.—*Left:* Simulated $^{13}$CO (1–0) map of the model in the z-axis direction. The locations of the cloud cores are shown with squares. The circles indicate the locations of telescope beams used in the synthetic observations of three cores. *Right:* Line-of-sight magnetic field strength as calculated from Zeeman splitting.
Fig. 3.—*Left*: Relative mass-to-flux ratio for the selected cores as a function of column density. Red symbols indicate the cores with $\mathcal{R}_m < 0$. Dots, crosses, triangles pointing down, triangles pointing up, and asterisks denote zero, one, two, three, or four field reversals in the envelopes relative to the core center. *Right*: Relative mass-to-flux ratio as a function of inferred magnetic field strength in the central beam. The symbols have the same meaning as in the left panel.
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*
  - *gravitational instability*
  - *thermal 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

  $\rightarrow$ **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)

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predictions

**star formation on galactic scales**
- global correlations: Schmidt-law
- efficiencies, rates, timescales, and long-term evolution: starburst vs. low surface density gal.
- triggers of star formation on global scales
- formation of dense cold molecular clouds
  properties of these clouds (structure, turbulence, etc.)

**star cluster formation within clouds**
- SF efficiency and timescale
- properties of young star clusters (structure, kinematics)
- stellar mass function – IMF
- multiplicity
- effects of stellar feedback (jets, outflows, radiation, winds, ...)

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agenda

- formation of molecular clouds
  - on galactic scales
  - locally, in convergent flows
  - do molecular clouds loose memory of initial conditions?
- fragmentation of molecular clouds
  - interplay between gravity and turbulence
- star formation
  - initial mass function (models & caveats)
  - some examples
- what’s next?
galactic scales
molecular cloud formation

star formation on galactic scales
→ missing link so far:
  formation of molecular clouds

questions
  where and when do molecular clouds form?
  what are their properties?
  how does that correlation to star formation?
  global correlations? → Schmidt law
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 (Glover & Mac Low 2007a,b)

external perturbuations (i.e. potential changes) increase likelihood (e.g. talk by Clare Dobbs)
star formation on global scales

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

(from Klessen, 2001; also Gazol et al. 2005, Mac Low et al. 2005)
H$_2$ formation rate:

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

for $n_H \geq 100$ 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)
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

We find a correlation between star formation rate and gas surface density:

\[ \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.5} \]

Global Schmidt law

\( \alpha = 1.48 \pm 0.08 \)
observed Schmidt law

\[ \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.5} \]

(from Kennicutt 1998)
molecular cloud formation

(from Dobbs, Glover, Clark, Klessen 2008)
molecular cloud formation

(Dobbs & Bonnell 2007)
molecular cloud formation

molecular gas fraction as function of time

\[ \Sigma = 4 \, M_\odot \, \text{pc}^{-2} \]
\[ \Sigma = 10 \, M_\odot \, \text{pc}^{-2} \]
\[ \Sigma = 20 \, M_\odot \, \text{pc}^{-2} \]

molecular gas fraction as function of density

(Dobbs et al. 2008)
molecular cloud formation

molecular gas fraction of fluid element as function of time

molecular gas fraction as function of density

\( H_2 \) fraction

\( n \) \( (\text{cm}^{-3}) \)

\( R = 7.1 \text{kpc} \)

(Dobbs et al. 2008)
observed timescales

Tamburro et al. (2008)

Fig. 1.— NGC 5194: the 24 μm band image is plotted in color scale; the H I emission map is overlaid with green contours.
observed timescales

Fig. 5.— Histogram of the time scales $t_{\text{HI} \rightarrow 24\mu m}$ derived from the fits in Figure 4 and listed in Table. 2 for the 14 sample galaxies listed in Table. 1. The timescales range between 1 and 4 Myr for almost all galaxies.

Tamburro et al. (2008)
models with B-fields

Figure 9. The column density is shown for the two-phase simulations after 2.50 Myr, for the whole disc (top panel) and a $4 \times 4$ kpc subsection (bottom panel). The left-hand panels show the case where $\beta_{\text{cold}} = 4$ and the right-hand panels where $\beta_{\text{cold}} = 0.4$. Both the cold and warm phases are shown in the plots, but we show them separately for the case where $\beta_{\text{cold}} = 4$ in Fig. 12. There is more structure in the cold gas when the magnetic field is weaker ($\beta_{\text{cold}} = 4$). The vectors show the magnetic field smoothed over a particular grid size. There is more detailed structure on smaller scales, particularly in the spiral arms which are better resolved.
consistent models of ISM dynamics require to go beyond the simple models!

- magnetohydrodynamics
  (account for large-scale dynamics + turbulence)
- time-dependent chemistry
  (reduced network, focus on few dominant species, e.g. H\(_2\))
- radiation (currently simple assumptions)

H\(_2\) forms rapidly in shocks / transient density fluctuations / H\(_2\) gets destroyed slowly in low density regions / result: turbulence greatly enhances H\(_2\)-formation rate

(Glover & Mac Low 2007ab:)

ISM: transition H\(_1\) to H\(_2\)
here: e⁻, H⁺, H, H₂
in primordial gas we do:
e⁻, H⁺, H, H₂⁺, H₂, C, C⁺, O, O⁺

(Glover & Mac Low 2007ab)
Static collapse

\[ \begin{align*}
L &= 40 \text{ pc}, \ n_0 = 100 \text{ cm}^{-3}, \ B_0 = 5.85 \text{ mG}, \ v_{\text{rms}} = 0.0 \\
\end{align*} \]

(Glover & Mac Low 2007a)
$L = 20 \text{ pc, } B_0 = 5.85 \mu\text{G, } v_{\text{rms}} = 10 \text{ km/s}$

(Glover & Mac Low 2007a)
from atomic gas to molecular clouds

hypothesis: **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 galaxy

questions
- are molecular clouds truly “multi-phase” media?
- turbulence? dynamical & morphological properties?
- what is relation to initial & environmental conditions?
- magnetic field structure?
## Interstellar Matter: ISM

Abundances, scaled to 1.000.000 H atoms

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wasserstoff</td>
<td>H</td>
<td>1.000.000</td>
</tr>
<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>
</tr>
<tr>
<td>Kohlenstoff</td>
<td>C</td>
<td>420</td>
</tr>
<tr>
<td>Stickstoff</td>
<td>N</td>
<td>90</td>
</tr>
<tr>
<td>Sauerstoff</td>
<td>O</td>
<td>700</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>100</td>
</tr>
<tr>
<td>Natrium</td>
<td>Na</td>
<td>2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>40</td>
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<tr>
<td>Aluminium</td>
<td>Al</td>
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<tr>
<td>Silicium</td>
<td>Si</td>
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<td>Schwefel</td>
<td>S</td>
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</tr>
<tr>
<td>Calcium</td>
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<td>2</td>
</tr>
<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).
Av bezeichnet die Extinktion, dh. die Abschwächung der einfallenden Strahlung.
nearby clouds

- Orion
- Ophiuchus
- Taurus
- Perseus
- Pipe

scales to same scale

10 pc

(from A. Goodman)

Ralf Klessen: Paris 03.04.2009
images from Alyssa Goodman
image from Alyssa Goodman: COMPLETE survey
velocity distribution in Perseus

velocity cube from Alyssa Goodman: COMPLETE survey
velocity distribution in Perseus

image from Alyssa Goodman: COMPLETE survey
(movie from Christoph Federrath)
consistent models of ISM dynamics require to go beyond the simple models!

- magnetohydrodynamics (account for large-scale dynamics + turbulence)
- time-dependent chemistry (reduced network, focus on few dominant species, e.g. H$_2$)
- radiation (currently simple assumptions)

H$_2$ forms rapidly in shocks / transient density fluctuations / H$_2$ gets destroyed slowly in low density regions / result: turbulence greatly enhances H$_2$-formation rate

(Glover & Mac Low 2007ab:)
Table 1. The set of chemical reactions that make up our model of non-equilibrium hydrogen chemistry.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $\text{H} + \text{H} + \text{grain} \rightarrow \text{H}_2 + \text{grain}$</td>
<td>Hollenbach &amp; McKee (1979)</td>
</tr>
<tr>
<td>2. $\text{H}_2 + \text{H} \rightarrow 3\text{H}$</td>
<td>Mac Low &amp; Shull (1986) (low density), Lepp &amp; Shull (1983) (high density)</td>
</tr>
<tr>
<td>3. $\text{H}_2 + \text{H}_1 \rightarrow 2\text{H} + \text{H}_2$</td>
<td>Martin, Krogh &amp; Mandy (1998) (low density), Shapiro &amp; Kang (1987) (high density)</td>
</tr>
<tr>
<td>4. $\text{H}_2 + \gamma \rightarrow 2\text{H}$</td>
<td>See § 2.2.1</td>
</tr>
<tr>
<td>5. $\text{H} + \text{e.r.} \rightarrow \text{H}^+ + \text{e}$</td>
<td>Liszt (2003)</td>
</tr>
<tr>
<td>6. $\text{H} + \text{e} \rightarrow \text{H}^+ + 2\text{e}$</td>
<td>Abel et al. (1997)</td>
</tr>
<tr>
<td>7. $\text{H}^+ + \text{e} \rightarrow \text{H} + \gamma$</td>
<td>Ferland et al. (1992)</td>
</tr>
<tr>
<td>8. $\text{H}^+ + \text{e} + \text{grain} \rightarrow \text{H} + \text{grain}$</td>
<td>Weingartner &amp; Draine (2001)</td>
</tr>
</tbody>
</table>

Table 2. Processes included in our thermal model.

<table>
<thead>
<tr>
<th>Process</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling:</strong></td>
<td></td>
</tr>
<tr>
<td>CI fine structure lines</td>
<td>Atomic data – Silva &amp; Viswas (2002)</td>
</tr>
<tr>
<td></td>
<td>Collisional rates ($\text{H}_2$ – Flower &amp; Launey (1977)</td>
</tr>
<tr>
<td></td>
<td>Collisional rates ($\text{H}, T &lt; 2000 \text{K}$ – Hollenbach &amp; McKee (1989)</td>
</tr>
<tr>
<td></td>
<td>Collisional rates ($\text{H}, T &gt; 2000 \text{K}$ – Keenan et al. (1986)</td>
</tr>
<tr>
<td>O fine structure lines</td>
<td>Collisional rates ($\text{e}^-$ – Wilson &amp; Bell (2002)</td>
</tr>
<tr>
<td></td>
<td>Collisional rates ($\text{H}, \text{H}_2$ – Flower, priv. comm.</td>
</tr>
<tr>
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<td>Collisional rates ($\text{e}^-$ – Bell, Berrington &amp; Thomas (1958)</td>
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<td></td>
<td>Collisional rates ($\text{H}^+$ – Pequignot (1990, 1996)</td>
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<tr>
<td>SiII fine structure lines</td>
<td>Atomic data – Silva &amp; Visgas (2002)</td>
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<td>Collisional rates ($\text{H}$ – Roueff (1993)</td>
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<tr>
<td></td>
<td>Collisional rates ($\text{e}^-$ – Dufour &amp; Kingson (1991)</td>
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<tr>
<td>$\text{H}_2$ rovibrational lines</td>
<td>Le Bourlot, Pineau des Forêts &amp; Flower (1999)</td>
</tr>
<tr>
<td>Gas–grain energy transfer$^1$</td>
<td>Hollenbach &amp; McKee (1989)</td>
</tr>
<tr>
<td>Recombination on grains</td>
<td>Wolfire et al. (2003)</td>
</tr>
<tr>
<td>Atomic resonance lines</td>
<td>Sutherland &amp; Dopita (1983)</td>
</tr>
<tr>
<td>$\text{H}$ collisional ionization</td>
<td>Abel et al. (1987)</td>
</tr>
<tr>
<td>$\text{H}_2$ collisional dissociation</td>
<td>See Table 1</td>
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<tr>
<td><strong>Heating:</strong></td>
<td></td>
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<tr>
<td>Photoelectric effect</td>
<td>Balbus &amp; Tielens (1994); Wolfire et al. (2003)</td>
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<tr>
<td>$\text{H}_2$ photodissociation</td>
<td>Black &amp; Dalgarno (1977)</td>
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<tr>
<td>UV pumping of $\text{H}_2$</td>
<td>Burton, Hollenbach &amp; Tielens (1990)</td>
</tr>
<tr>
<td>$\text{H}_2$ formation on dust grains</td>
<td>Hollenbach &amp; McKee (1989)</td>
</tr>
<tr>
<td>Cosmic ray ionization</td>
<td>Goldsmith &amp; Langer (1978)</td>
</tr>
</tbody>
</table>

Reduced chemical network

here: $\text{e}^-$, $\text{H}^+$, $\text{H}$, $\text{H}_2$

in primordial gas we do:

$\text{e}^-$, $\text{H}^+$, $\text{H}$, $\text{H}_2^+$, $\text{H}_2$, $\text{C}$, $\text{C}^+$, $\text{O}$, $\text{O}^+$

(Glover & Mac Low 2007ab)
Static collapse

$L = 40 \text{ pc}, n_0 = 100 \text{ cm}^{-3}, B_0 = 5.85 \text{ mG}, v_{\text{rms}} = 0.0$

(Glover & Mac Low 2007a)
L = 20 pc, \( B_0 = 5.85 \, \mu \text{G} \), \( v_{\text{rms}} = 10 \, \text{km/s} \)

(Glover & Mac Low 2007a)
effects of chemistry

(Federrath, Glover et al.)
(Glover, Federrath, et al.)
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)
what drives turbulence?

- turbulence characteristics
  - molecular cloud turbulence seems to be dominated by large-scale models
  - consistent with external driving
  - convergent flows?
    - the same process that creates the cloud supplies internal turbulence ...
  - alternative mechanisms:
    - gravity (spiral shocks), supernovae, HII regions?
    - internal sources: jets, outflows?

Polaris flare (from Ossenkopf & Mac Low 2002)
what drives turbulence?

- turbulence characteristics
  - molecular cloud turbulence seems to be dominated by large-scale models
  - consistent with external driving
  - *convergent flows?*
    - the same process that creates the cloud supplies internal turbulence..
    - caused by
      - *gravity (spiral shocks)*, supernovae, HII regions?
  - alternative mechanisms:
    - internal sources: jets, outflows?

Polaris flare (from Ossenkopf & Mac Low 2002)
what drives turbulence?

- some words on internal sources
  - molecular cloud turbulence seems to be dominated by large-scale models
  - jets / outflow can only work after onset of star formation
    - what about turbulence in non-star forming parts of clouds, or during initial phases?

- there is debate on effectiveness of internal sources for driving supersonic turbulence
  (Li & Nakamura vs. Banerjee, Klessen, Fendt)

(Nakamura & Li 2007)  (Banerjee, Klessen, Fendt 2008)
local feedback

- individual jets cannot drive supersonic turbulence in a space-filling way → need additional physics

Banerjee, Klessen, & Fendt (2008)
jets from cluster with self-gravity
with AMR code
FLASH

Banerjee et al. (very preliminary study)
Kolmogorov (1941) theory of incompressible turbulence

Inertial range: scale-free behavior of turbulence

"Size" of inertial range:

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

Turbulent cascade

Energy input scale

Energy dissipation scale

\[ k^{-5/3} \]
Turbulent cascade

Shock-dominated turbulence

energy input scale

log $E$

energy dissipation scale

log $k$

inertial range: 

scale-free behavior of turbulence

„size“ of inertial range:

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

Ralf Klessen: Paris 03.04.2009
Turbulent cascade in ISM

energy source & scale
NOT known
(supernovae, winds, spiral density waves?)

\[ \sigma_{\text{rms}} \ll 1 \text{ km/s} \]
\[ M_{\text{rms}} \leq 1 \]
\[ L \approx 0.1 \text{ pc} \]

dissipation scale not known
(ambipolar diffusion, molecular diffusion?)
gravoturbulent fragmentation

- turbulence sets power-law distribution of clumps, gravity then selects for collapse

\[ L_0 = 10 \text{ pc} \]
\[ n_0 = 500 \text{ cm}^{-3} \]

\[ N(m) \propto m^{-3/(4-\beta)} \]

-Padoan & Nordlund (2002)

Hennebelle & Chabrier (2008)
Large-eddy simulations

- We use LES to model the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: \( \text{Re} = \frac{LV}{\nu} \) \( (\text{Re}_{\text{nature}} \gg \text{Re}_{\text{model}}) \)
  - dynamic range much smaller than true physical one
  - need subgrid model (in our case simple: only dissipation)
- but what to do for more complex when processes on subgrid scale determine large-scale dynamics
  (chemical reactions, nuclear burning, etc)
- Turbulence is “space filling” --> difficulty for AMR (don’t know what criterion to use for refinement)
- How large a Reynolds number do we need to catch basic dynamics right?

Ralf Klessen: Paris 03.04.2009
compressive vs. rotational driving

- statistical characteristics of turbulence depend strongly on ”type“ of driving
- example: dilatational vs. solenoidal driving
- question: what drives ISM turbulence on different scales?
compressive

larger structures, higher $\rho$-contrast

rotational

smaller structures, small $\rho$-pdf

Federrath, Klessen, Schmidt (2008a,b)
Fig. 1. Maps showing density, vorticity and divergence in projection along the x-axis at time $t = 2T$ as an example for the regime of statistically fully developed compressible turbulence for solenoidal forcing (left) and compressive forcing (right). Top panels: Column density fields in units of the mean column density. Both maps show three orders of magnitude in column density with the same scaling and magnitudes for direct comparison. Middle panels: Projections of the modulus of the vorticity $|\vec\Omega|$ in units of $\Omega_0$. Regions of intense vorticity appear to be elongated filamentary structures often coinciding with positions of interacting shocks. Bottom panels: Projections of the divergence of the velocity field $\nabla \cdot \vec{v}$ showing the positions of shocks. Negative divergence corresponds to compression, while positive divergence corresponds to rarefaction.
density pdf depends on “dimensionality” of driving

- relation between width of pdf and Mach number

\[ \sigma_\rho / \rho_0 = b \mathcal{M} \]

- with \( b \) depending on \( \zeta \) via

\[ b = 1 + \left[ \frac{1}{D} - 1 \right] \zeta = \begin{cases} 
1 - \frac{2}{3} \zeta, & \text{for } D = 3 \\
1 - \frac{1}{2} \zeta, & \text{for } D = 2 \\
1, & \text{for } D = 1
\end{cases} \]

- with \( \zeta \) being the ratio of dilatational vs. solenoidal modes:

\[ \mathcal{P}_{ij}^\zeta = \zeta \mathcal{P}_{ij}^{\perp} + (1 - \zeta) \mathcal{P}_{ij}^{\parallel} = \zeta \delta_{ij} + (1 - 2\zeta) \frac{k_i k_j}{|k|^2} \]

Federrath, Klessen, Schmidt (2008a)
density pdf depends on “dimensionality” of driving

- relation between width of pdf and Mach number

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- with \( \zeta \) being the ratio of dilatational vs. solenoidal modes:

\[ \mathcal{P}^\zeta_{ij} = \zeta \mathcal{P}_{ij}^\perp + (1 - \zeta) \mathcal{P}_{ij}^\parallel = \zeta \delta_{ij} + (1 - 2 \zeta) \frac{k_i k_j}{|k|^2} \]
dilatational vs. solenoidal

- density pdf depends on “dimensionality” of driving
  → is that a problem for the Krumholz & McKee model of the SF efficiency?

- density pdf of compressive driving is NOT log-normal
  → is that a problem for the Padoan & Nordlund IMF model?

- most “physical” sources should be compressive (convergent flows from spiral shocks or SN)

good fit needs 3rd and 4th moment of distribution!

Federrath, Klessen, Schmidt (2008b)
density power spectrum differs between dilatational and solenoidal driving!

→ dilatational driving leads to break at sonic scale!

can we use that to determine driving sources from observations?

compensated density spectrum $kS(k)$ shows clear break at sonic scale. below that shock compression no longer is important in shaping the power spectrum ...

Federrath, Klessen, Schmidt (2008b)

there is a weak $\log$ density – $\log$ Mach number relation ...
Fig. 14. z-slices through the local density (top panels) and Mach number fields (bottom panels) at $z = 0$ and $t = 2T$ for solenoidal forcing (left), and compressive forcing (right). Regions with subsonic velocity dispersions (Mach < 1) are distinguished from regions with supersonic velocity dispersions (Mach > 1) in the colour scheme used. The correlation between density and Mach number is quite weak. However, as shown in Fig. 4, high-density regions exhibit smaller Mach numbers on average.
Fig. 7. PDFs of centroid velocity increments computed using equations (18) and (19) are shown as a function of the lag $\ell$ in units of grid cells $\Delta = L/1024$ for solenoidal forcing (left) and compressive forcing (right). The PDFs are very close to Gaussian distributions for large lags $\ell$, whereas for small lags, they develop exponential tails, which is a manifestation of intermittency (e.g., Hily-Blant et al. 2008).
Fig. 8. Kurtosis $\mathcal{K}$ of the PDFs of centroid velocity increments shown in Fig. 7 as a function of the lag $\ell$ in units of grid cells $\Delta = L/1024$ for solenoidal and compressive forcing. Note that a kurtosis value of 3 (horizontal dot-dashed line) corresponds to the value for a Gaussian distribution. Non-Gaussian values of the kurtosis are obtained for $\ell \lesssim 100\Delta$. The error bars contain both snapshot-to-snapshot variations as well as the variations between centroid velocity increments computed by integration along the $x$, $y$ and $z$ axes. This figure can be compared to observations of the Polaris Flare and Taurus MC (see Fig. 7 of Hily-Blant et al. 2008).
Fig. 11. Principal component analysis (PCA) for solenoidal (left) and compressive forcing (right). The PCA slopes obtained for solenoidal and compressive forcings are summarised and compared with observations by Heyer et al. (2006) in Table 4. The error bars contain the contribution from temporal variations and from three different projections along the x, y and z-axes. The data were resampled from $1024^3$ to $256^3$ grid points prior to PCA. The resampling speeds up the PCA and has virtually no effect on the inertial range scaling (see e.g., Padoan et al. 2006; Federrath et al. 2009).
Fig. 12. **Top panels:** Total, transverse (rotational) and longitudinal (compressible) velocity Fourier spectra $E(k)$ defined in equation (25) and compensated by $k^2$ for solenoidal (left) and compressive forcing (right). Error bars indicate temporal variations, which account for an uncertainty of roughly $\pm 0.05$ of all scaling slopes reported for the inertial range $5 \leq k \leq 15$. The inferred inertial range scaling exponents for both solenoidal and compressive forcing are consistent with independent numerical simulations and with observations of the size-linewidth relation (see text).

**Bottom panels:** Ratio of the energy in longitudinal velocity modes $E_{\text{long}}$ to the total energy in velocity modes $E_{\text{tot}} = E_{\text{trans}} + E_{\text{long}}$. For solenoidal forcing, we obtain $E_{\text{long}}/E_{\text{tot}} \approx 1/3$ in the inertial range (horizontal dash-dotted line), because compression can only occur in one of the three spatial dimensions on average (Elmegreen & Scalo 2004; Federrath et al. 2008b). For compressive forcing, this ratio is roughly 1/2, which corresponds to an equipartition of longitudinal and transverse velocity modes. Note however that compressive forcing can compress the gas in all three spatial dimensions directly, whereas solenoidal forcing can only induce compression indirectly through the velocity field (Federrath et al. 2008b). The excess of longitudinal modes at high wavenumbers $k \gtrsim 40$ stems from numerical dissipation, which is more effectively dissipating transverse than longitudinal modes on small scales due to the discretisation onto a grid. This suggests that roughly 30 grid cells are needed to accurately resolve a vortex, while a shock is typically resolved with roughly 3 grid cells using the piecewise parabolic method (Colella & Woodward 1984). However, for a numerical resolution of $1024^3$ grid cells, we find that wavenumbers $k \lesssim 40$ are almost unaffected by the discretisation and by the parameters of the numerical scheme (see Appendix C).
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

---

**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
Summary II

- **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)