Understanding the ISM: Theoretical Aspects

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(from AG meeting in Berlin 2002)
(Andromeda galaxy – Bob Gendler)
(the Antennae galaxy – VLA & HST)

Ralf Klessen: Rundgespräch 17.03.2009
Why study ISM physics?

physical processes
- turbulence theory
- ISM: laboratory for plasm physics
- ISM: laboratory for extreme chemistry

planets
- initial conditions for planet formation (chemical composition)
- diversity of planetary systems
- habitability (life)

stars & star clusters
- ISM: environment for star formation
- IMF
- feedback from stars (winds, radiation, SN)
- MC turbulence

galactic structure & evolution
- chemical enrichment
- global star formation history (Milky Way)
- interrelation between SF and galactic structure

cosmology & galaxy formation
- cooling properties of high-z halos
- primordial star formation
- relation between visible and dark matter

extreme environments
- galactic center
- starburst galaxies
- primordial universe
What do we need to study ISM?

- magneto-hydrodynamics (multi-phase, non-ideal MHD, turbulence)
- chemistry (gas + dust, heating + cooling)
- radiation (continuum + lines)
- stellar dynamics (collisional: star clusters, collisionless: galaxies, DM)
- stellar evolution (feedback: radiation, winds, SN)
- laboratory work (reaction rates, cross sections, dust coagulation properties, etc.)
What do we need to study ISM?

- massive parallel codes
  - particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
  - grid-based: AMR (FLASH, ENZO, RAMSES, Nirvana3, etc), subgrid-scale models (FEARLESS)
  - BGK methods

- magnetohydrodynamics
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What do we need to study ISM?

- ever increasing chemical networks
- working reduced networks for time-dependent chemistry in combination with hydrodynamics
- improved data on reaction rates (laboratory + quantum mechanical calculations)

- magneto-hydrodynamics
  (multi-phase, non-ideal MHD, turbulence)

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What do we need to study ISM?

- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro

**magneto-hydrodynamics**
(multi-phase, non-ideal MHD, turbulence)

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- **statistics**: number of stars (collisional: $10^6$, collisionless: $10^{10}$)
- **transition from gas to stars**
- **binary orbits**
- **long-term integration**
What do we need to study ISM?

- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation

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+ **laboratory work**
  (reaction rates, cross sections, dust coagulation properties, etc.)

methods need to be combined!
Three examples

- **modeling star formation in galactic disk + molecular cloud formation**
  (hydrodynamics, stellar dynamics, chemistry, feedback \[\text{radiation, outflows}\])
  (Schmidt law, star-formation history, relation between global dynamics and SF)

- **cloud fragmentation & prestellar cores**
  (MHD, chemistry, radiation)
  (initial conditions of star formation)

- **transition to stars**
  (MHD, stellar feedback, chemistry, radiation)
  (IMF, multiplicity, planet formation, etc.)
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

- $\Sigma = 4 \ M_\odot pc^{-2}$
- $\Sigma = 10 \ M_\odot pc^{-2}$
- $\Sigma = 20 \ M_\odot pc^{-2}$

molecular gas fraction as function of density

(Dobbs et al. 2008)
molecular cloud formation

(Dobbs et al. 2008)
Compare \( \text{H}_2 \) – H\( \text{I} \) in M33:

- \( \text{H}_2 \): BIMA-SONG Survey
- H\( \text{I} \): Westerbork Radio Telescope

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

Fig. 1.— NGC 5194: the 24 \( \mu \text{m} \) band image is plotted in color scale; the H\( \text{I} \) emission map is overlayed with green contours.

(Tamburro et al. 2009)
molecular cloud scales
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</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>
</tr>
<tr>
<td>Aluminium</td>
<td>Al</td>
<td>3</td>
</tr>
<tr>
<td>Silicium</td>
<td>Si</td>
<td>38</td>
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<tr>
<td>Schwefel</td>
<td>S</td>
<td>20</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<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).
\( A_V \) bezeichnet die Extinktion, dh. die Abschwächung der einfallenden Strahlung.

Dichte- / Säulendichte nimmt zu
nearby clouds

- Orion
- Ophiuchus
- Perseus
- Taurus
- Pipe

scales to same scale

(from A. Goodman)
images from Alyssa Goodman
velocity distribution in Perseus

image from Alyssa Goodman: COMPLETE survey
(movie from Christoph Federrath)
H$_2$ column density

$^{12}$CO column density

H$_2$ density

$^{12}$CO density

(Glover, Federrath, et al.)
(Glover, Federrath, et al.)
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)

H2 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\textsc{i} to $H_2$
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. H + H + grain → H₂ + grain</td>
<td>Hollenbach &amp; McKee (1979)</td>
</tr>
<tr>
<td>4. H₂ + γ → 2H</td>
<td>See § 2.2.1</td>
</tr>
<tr>
<td>6. H + e → H⁺ + 2e</td>
<td>Abel et al. (1997)</td>
</tr>
<tr>
<td>7. H⁺ + e → H + γ</td>
<td>Ferland et al. (1992)</td>
</tr>
<tr>
<td>8. H⁺ + e + grain → H + 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>Cooling rates (H₂) – Flower &amp; Launey (1977)</td>
<td></td>
</tr>
<tr>
<td>Cooling rates (H, T &gt; 2000 K) – Keenan et al. (1986)</td>
<td></td>
</tr>
<tr>
<td>Collisional rates (e⁻) – Wilson &amp; Bell (2002)</td>
<td></td>
</tr>
<tr>
<td>Collisional rates (H, H₂) – Flower, priv. comm.</td>
<td></td>
</tr>
<tr>
<td>Collisional rates (e⁻) – Bell, Berrington &amp; Thomas (1958)</td>
<td></td>
</tr>
<tr>
<td>Collisional rates (H⁺) – Poirniet (1990, 1996)</td>
<td></td>
</tr>
<tr>
<td>Collisional rates (H) – Honell (1990)</td>
<td></td>
</tr>
<tr>
<td>Collisional rates (e⁻) – Dufour &amp; Kingson (1991)</td>
<td></td>
</tr>
<tr>
<td>H₂ vibrational lines</td>
<td>Le Bourlot, Pineau des Forêts &amp; Flower (1999)</td>
</tr>
<tr>
<td>Gas-grain energy transfer</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>H collisional ionization</td>
<td>Abel et al. (1997)</td>
</tr>
<tr>
<td>H₂ collisional dissociation</td>
<td>See Table 1</td>
</tr>
</tbody>
</table>

Heating:
- Photodissociative effect | Bakes & Tielens (1994); Wolfire et al. (2003) |
- H₂ photodissociation | Black & Dalgarno (1977) |
- UV pumping of H₂ | Burton, Hollenbach & Tielens (1990) |
- H₂ formation on dust grains | Hollenbach & McKee (1989) |
- Cosmic ray ionization | Goldsmith & Langer (1978) |

here: e⁻, H⁺, H, H₂
in primordial gas we do: e⁻, H⁺, H, H₂, C, C⁺, O, O⁺

(Glover & Mac Low 2007ab)
L = 40 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, $B_0 = 5.85 \mu G$, $v_{\text{rms}} = 10$ km/s

(Glover & Mac Low 2007a)
turbulent cascade

Kolmogorov (1941) theory incompressible turbulence

inertial range: *scale-free behavior of turbulence*

„size“ of inertial range:

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

Kolmogorov (1941) theory incompressible turbulence

energy input scale

energy dissipation scale
Shock-dominated turbulence

\[ \log E \]

\[ L^{-1} \]

\[ \eta_K^{-1} \]

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
molecular clouds: \( \sigma_{\text{rms}} \approx \text{several km/s} \), \( M_{\text{rms}} > 10 \), \( L > 10 \text{ pc} \)

dense protostellar cores: \( \sigma_{\text{rms}} \ll 1 \text{ km/s} \), \( M_{\text{rms}} \leq 1 \), \( L \approx 0.1 \text{ pc} \)

Energy source & scale:
- **NOT known**
- Supernovae, winds, spiral density waves?

Dissipation scale:
- Not known
- Ambipolar diffusion, molecular diffusion?
Large-eddy simulations

- We use **LES** to model the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: \( \text{Re} = L V / \nu \) \( (\text{Re}_{\text{nature}} >> \text{Re}_{\text{model}}) \)
  - 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?
cloud core scales
fragmentation of molecular clouds

- fragmentation of molecular clouds and relation to stellar birth
- some questions
  - how does the turbulence generated by cloud formation influence cloud fragmentation?
  - how important if turbulence from internal feedback? (is that consistent with observations?)
  - interplay between gravity and turbulence? → role of turbulence for star formation
convergent flows: set-up

- convergent flow studies
  - atomic flows collide
  - cooling curve (soon chemistry)
  - gravity
  - magnetic fields
  - numerics: AMR, BGK, SPH

numerical set-up

from Vazquez-Semadeni et al. (2007)

see studies by Banerjee et al., Heitsch et al., Hennebelle et al., Vazquez-Semadeni et al.
convergent flows: set-up

- adopted cooling curve

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MC formation in convergent flows

thermal instability + gravity creates complex molecular cloud structure:

from Banerjee et al. (2008)
(see also studies by Hennebelle et al. and Vazquez-Semadeni et al. and Heitsch et al.)
MC formation in convergent flows

thermal instability + gravity creates complex molecular cloud structure:

from Banerjee et al. (2008)
(see also studies by Hennebelle et al. and Vazquez-Semadeni et al. as well as talk by Fabian Heitsch)
from Banerjee et al. (2008)
from Banerjee et al. (2008)
from Banerjee et al. (2008)
some results: growth of cores

**Figure 2.** Shows the time evolution of a typical clump which initially develops out of the thermally unstable WNM in shock layers of turbulent flows. A small cold condensate grows by outward propagation of its boundary layer. Coalescence and merging with nearby clumps further increases the size and mass of these clumps. The global gravitational potential of the proto-cloud enhances the merging probability with time. The images show 2D slices of the density (logarithmic colour scale) and the gas velocity (indicated as arrows) in the plane perpendicular to the large scale flows.

*two phases of core growth:*

1. by outward propagation of **boundary layer** → Jeans sub-critical phase
2. **core mergers** → super-Jeans → gravitational collapse & star formation

example: **Pipe nebula**

from Banerjee et al. (2008)
some results: growth of cores

Figure 3. Shows the structure of one typical clump which forms in the thermally unstable WNM gas. The images show 2D slices of the temperature (left, log scale), thermal pressure (middle, linear scale), and magnetic field strength (right, linear scale). The arrows in the temperature and pressure plots indicate the velocity field and, in the right panel, the magnetic stream lines. The cold ($T \sim 30 - 50 \, \text{K}$), dense ($n \sim 2 - 5 \times 10^3 \, \text{cm}^{-3}$) molecular clump is embedded in the warm atomic gas ($T \sim 5 \times 10^3 \, \text{K}$) and has a well defined boundary. Due to the thermal properties of the ISM (see Fig. 2 of Vázquez-Semadeni et al. 2007, for the equilibrium pressure), such clumps are almost in pressure equilibrium with their surrounding. The overdense clumps exert a gravitational force on the low density environment where gas continues to stream into the clump predominately anti-parallel to the magnetic flux lines (see also Fig. 2).

some properties of cores:
(1) cores are in approximate pressure equilibrium with surrounding
(2) accretion / mass flow mostly along magnetic field lines
(2) core densities $n \sim 2 - 5 \times 10^3 \, \text{cm}^{-3}$, core temperature $T \sim 30 - 50 \, \text{K}$

from Banerjee et al. (2008)
Lada et al (2007)
Lada et al. (2007)
Barnard 68: a well-studied isolated prestellar core

(Lada et al. 2003)
Barnard 68

- $^{18}\text{C}O (1-0)$
- $\text{N}_2\text{H}^+ (1-0)$
- $\text{CS} (3-2)$
example: model of Orion cloud

„model“ of Orion cloud:
15.000.000 SPH particles,
$10^4 \, M_{\text{sun}}$ in 10 pc, mass
resolution 0.02 $M_{\text{sun}}$, 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 ~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.)
distribution of stellar masses depends on

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

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

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

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

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)
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(e.g. Larson 2003; Mac Low & Klessen, 2004; McKee & Ostriker 2007, Klessen, Krumholz, & Heitsch 2009)
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*

how does that work?

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

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

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

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

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

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

(Larson 1985, Larson 2005)

$P \propto \rho^\gamma$

$P \propto \rho T$

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

$\gamma = 0.7$

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

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

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

IMF from simple piece-wise polytropic EOS

Critical density \( \uparrow \) \( \rightarrow \) median mass \( \downarrow \)

IMF in nearby molecular clouds

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

EOS as function of metallicity

(Omukai et al. 2005)
EOS as function of metallicity

(Omukai et al. 2005)
EOS as function of metallicity

(Omukai et al. 2005)
present-day star formation

(Omukai et al. 2005)
dependence on Z at low density

(Omukai et al. 2005)
dependence on $Z$ at low density

- at densities below $n \approx 10^2 \, \text{cm}^{-3}$ $H_2$ cooling dominates the behavior. (Jappsen et al. 2007)

- fragmentation depends on initial conditions

  - example: solid-body rotating top-hat initial conditions with dark matter fluctuations (a la Bromm et al. 1999) fragment no matter what metallicity you take (in regime $n \leq 10^6 \, \text{cm}^{-3}$)
    - because unstable disk builds up

  (Jappsen et al. 2008a)
dependence on Z at low density

\[ Z = 0 \] \quad \text{rotating top-hat with dark matter fluctuations fragments, no matter what}

\[ Z = -4 \]

\[ Z = -3 \]

\[ Z = -2 \]

\[ Z = -1 \]

(Jappsen et al. 2008a, see poster by Jappsen et al, see also Clark et al. 2008)
dependence on $Z$ at low density

- fragmentation depends on \textit{initial conditions then}

- example: centrally concentrated halo does not fragment up to densities of $n \approx 10^6 \text{ cm}^{-3}$ up to metallicities $Z \approx -1$

(Jappsen et al. 2008b)
Metal-free star formation

- Slope of EOS in the density range $5 \text{ cm}^{-3} \leq n \leq 16 \text{ cm}^{-3}$ is $\gamma \approx 1.06$.
- With non-zero angular momentum, disk forms.
- This disk will be unstable against fragmentation.
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 2008)
**dust induced fragmentation at $Z=10^{-5}$**

$t = t_{SF} - 67 \text{ yr}$

$t = t_{SF} - 20 \text{ yr}$

$t = t_{SF}$

$t = t_{SF} + 53 \text{ yr}$

$t = t_{SF} + 233 \text{ yr}$

$t = t_{SF} + 420 \text{ yr}$

(Clark, Glover, Klessen. 2008)
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below $1\,M_{\odot}$
- 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. 2008)
cluster build-up

**Figure 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. 2008)
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17.03.2009

γ > 1  
(heating)

γ < 1  
(cooling)

(Clark et al. 2008)
gas properties at time when first star forms

(Clark et al. 2008)
dense cluster of low-mass protostars builds up:

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- fragmentation at density $n_{\text{gas}} = 10^{12} - 10^{13} \, \text{cm}^{-3}$

(Clark et al. 2008)
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. 2008)
studying ISM dynamics

- understanding the *physical* and *chemical processes*
- the shape the behavior of the interstellar medium is important for *many aspects* of modern astrophysics
what do we need to study ISM?

- magneto-hydrodynamics
  (multi-phase, non-ideal MHD, turbulence)
- chemistry (gas + dust, heating + cooling)
- radiation (continuum + lines)
- stellar dynamics
  (collisional: star clusters, collisionless: galaxies, DM)
- stellar evolution
  (feedback: radiation, winds, SN)

+ laboratory work
  (reaction rates, cross sections, dust coagulation properties, etc.)
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  (reaction rates, cross sections, dust coagulation properties, etc.)

methods need to be combined!
current initiatives

DFG:
- SFB in Köln/Bonn
- SFB in Heidelberg

ASTRONET
- CATS
- ARTIST
- STAR FORMAT

in Austria (Univ. Vienna)
- Graduiertenkolleg Cosmic Matter Circuit
discussion

- do we want an SPP on ISM / IGM?
- what shall be included in the SPP?
  - intergalactic medium
  - interstellar medium
    - which processes are important?
  - relation of ISM / IGM to other aspects of astrophysics
    - star formation on different scales
    - chemical enrichment
    - observables at different wavelengths
- laboratory experiments
- instrumentation
- who will do it?