Recent Insight and Future Challenges in Theoretical Models of the ISM

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LEBEN
PLANETENSYSTEME

INTERSTELLARE MATERIE

PROTOSTERN

ROTE RIESEN

PLANETARISCHE NEBEL

GAS

STERNENTWÖNSCHUNG

STARDÄTCHUNG

STERNENTWÖNSCHUNG

WEISS ZWERGE

NEUTRONENSUPERNOVEN

SCHWARZE LOCHER

STÄRKE

STÄRKE

RAUMWELT

FRAUEN

MÄNNER

GERECHTigkeit

Ralf Klessen: Rundgespräch, 22.09.2006
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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)

**extreme environments**
- galactic center
- starburst galaxies
- primordial universe

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

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

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

Ralf Klessen: Rundgespräch, 22.09.2006
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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- 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
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)

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- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro
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- **statistics:** number of stars (collisional: $10^6$, collisionless: $10^{10}$)
- transition from gas to stars
- binary orbits
- long-term integration

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- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation
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Methods need to be combined!
Three examples

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

modeling properties of prestellar cores
(MHD, chemistry, radiation)
(initial conditions of star formation, IMF, multiplicity, planet formation, etc.)

modeling extreme environments:
cold, dusty AGN tori
(hydrodynamics, stellar feedback, EOS + cooling)
(AGN properties + evolution, central BH)
Modeling galactic SF

SPH + stars + DM models of isolated disk galaxies with several million particles

→ begin to resolve individual molecular clouds
→ we need to care about „small-scale“ physics (i.e. transition from atomic gas to molecular)

(simple physics: gravity + hydrodynamics (isothermal EOS) + stellar dynamics [stars + DM])

(Li et al 2005, 2006)
Result:
gravitational instability alone leads to the *Schmidt law* (power-law correlation between star formation and surface density)

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

(Li et al 2005, 2006)
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)
(de Avillez & Breitschwerdt)
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. H₂)
- radiation (currently simple assumptions)

H₂ forms rapidly in shocks / transient density fluctuations / H₂ gets destroyed slowly in low density regions / result: turbulence greatly enhances H₂-formation rate

(Glover & Mac Low 2006ab:)

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Reduced chemical network

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. $\text{H}_2 + \text{H}_2 \rightarrow 2\text{H} + \text{H}_2$</td>
<td>Martin, Keogh &amp; Mandy (1968) (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. $\text{H} + \text{e} \rightarrow \text{H}^+ + e$</td>
<td>Liszt (2003)</td>
</tr>
<tr>
<td>6. $\text{H} + e \rightarrow \text{H}^+ + 2e$</td>
<td>Abel et al. (1997)</td>
</tr>
<tr>
<td>7. $\text{H}^+ + e \rightarrow \text{H} + \gamma$</td>
<td>Ferland et al. (1992)</td>
</tr>
<tr>
<td>8. $\text{H}^+ + e + \text{grain} \rightarrow \text{H} + \text{grain}$</td>
<td>Weingartner &amp; Draine (2001)</td>
</tr>
</tbody>
</table>

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

in primordial gas we do:

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

(Glover & Mac Low 2006ab)

Table 2. Processes included in our thermal model.

<table>
<thead>
<tr>
<th>Process</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}^+$ fine structure lines</td>
<td>Collisional rates ($\text{H}_2$) – Flower &amp; Loa (1977)</td>
</tr>
<tr>
<td>$\text{H}_2$ fine structure lines</td>
<td>Collisional rates ($\text{H}_2$, $T &lt; 2000 \text{ K}$) – Hollenbach &amp; McKee (1989)</td>
</tr>
<tr>
<td>$\text{H}^+$ fine structure lines</td>
<td>Collisional rates ($\text{H}_2$, $T &gt; 2000 \text{ K}$) – Keenan et al. (1986)</td>
</tr>
<tr>
<td>$\text{e}^-$ fine structure lines</td>
<td>Collisional rates ($\text{e}^-$) – Wilson &amp; Bell (2002)</td>
</tr>
<tr>
<td>Atomic data – Silva &amp; Viegas (2002)</td>
<td>Collisional rates ($\text{H}_2$, $\text{H}_2$) – Flower, priv. comm.</td>
</tr>
<tr>
<td>Collisional rates ($\text{e}^-$) – Bell, Berrington &amp; Thomas (1998)</td>
<td>Collisional rates ($\text{H}^+$) – Peiquig (1990, 1996)</td>
</tr>
<tr>
<td>Atomic data – Silva &amp; Viegas (2002)</td>
<td>$\text{H}_2$ rovibrational lines</td>
</tr>
<tr>
<td>Collisional rates ($\text{H}^+$) – Roueff (1990)</td>
<td>Recombination on grains</td>
</tr>
<tr>
<td>Collisional rates ($\text{H}^+$) – Dufon &amp; Kingston (1991)</td>
<td>$\text{H}^+$ collisional ionization</td>
</tr>
<tr>
<td>Collisional rates ($\text{H}^+$) – Dufon &amp; Kingston (1991)</td>
<td>$\text{H}^+$ collisional dissociation</td>
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<tr>
<td>See Table 1</td>
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Heating:

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<tr>
<td>Photoelectric effect</td>
<td>Bakes &amp; Tielens (1994); Wilf &amp; et al. (2003)</td>
</tr>
<tr>
<td>$\text{H}_2$ photodissociation</td>
<td>Black &amp; Dalgarno (1977)</td>
</tr>
<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>
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</table>
Static collapse

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

(Glover & Mac Low 2006a)
L = 20 pc, \( B_0 = 5.85 \) mG, \( v_{\text{rms}} = 10 \) km/s

(Glover & Mac Low 2006a)
Gravitational collapse within MCs

state of the art 5 years ago: SPH with $N \leq 10^6$ particles

(Klessen et al.)
Gravitational collapse within MCs

today: SPH with N > 10^7 particles

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

still no chemistry, no stellar feedback, no radiation

(Bonnell et al. 2006)
Gravitational collapse within MCs

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

immediate future: SPH with radiation feedback (first validation runs)
IRAM Observations
• $\text{N}_2\text{H}^+$ and $\text{C}^{18}\text{O}$
• 15 arcsecond res.
  • $\sim 3000$ AU
• $\text{N}_2\text{H}^+$ dense gas tracer
  • Most SCUBA
  • Few extinction!

(Perseus: Johnstone et al.)
Barnard 68: a well-studied isolated prestellar core

(Lada et al. 2003)
adaptive mesh refinement:

computational grid gets refined in regions of high interest (e.g. protostellar cores)

formation of 30 $M_{\odot}$ core in turbulent molecular cloud (FLASH with appropriate cooling curve module and turbulent driving)

(Banerjee & Pudritz 2006)
These 2D snapshots show the onset of the **large scale outflow**. After ca. 70.000 years into the collapse a strong toroidal magnetic field builds up whose magnetic pressure reverses the gas flow and drives an outflow (time difference between these snapshots: 1400 years).

(Banerjee & Pudritz 2006)
Initially a magnetic field aligned with the rotation axis of the cloud core threads the entire simulation box. The field strength varies slightly (3.4 – 14 micro Gauss) along the equatorial plane to maintain a constant plasma $b = 8pp/B^2$. In this configuration, prior to the gravitational collapse the sphere loses a considerable amount of angular momentum from ‘magnetic braking’ (Mouschovias & Paleologou, 1980).

(Banerjee & Pudritz 2006)
The 3D structure of the magnetic field line configuration in the jet launching region.

As predicted by analytics the magneto-centrifugally driven disk jet is faster in the inner region (dark red) than further away from the outflow axis (light red).

(Banerjee & Pudritz 2006)
MHD model with proper heating and cooling terms (EOS)

chemical model

line radiative transfer

synthetic images of model cores

(e.g. Semenov & Pavlyuchenkov)
(3D core structure: Steinacker)

compare

observations

theory
cold, dusty AGN tori

(Schartmann, Klahr, Meisenheimer, Camenzind)
cold, dusty AGN tori

(Schartmann, Klahr, Meisenheimer, Camenzind)
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