Modeling ISM Dynamics and Star Formation

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... many collaborators abroad!
disclaimer
I try to cover the field as broadly as possible, however, there will clearly be a bias towards my personal interests and many examples will be from my own work.
structure
overview

1. Introduction [~1h]
   -- phenomenology of stellar birth
   -- short historic overview
   -- complexity of star formation, overview of relevant physical processes

2. ISM dynamics and of star formation [~4h]
2.1 Turbulence
   -- turbulence in the interstellar medium (statistical characteristics)
   -- discussion of possible drivers of ISM turbulence
   -- excursion: modeling turbulence
2.2 Gravo-turbulent star formation models
   -- short overview of statistical (turbulence-based) star formation models
   -- competitive accretion vs. monolithic collapse vs. alternative approaches
2.3 Influence of density profile on star-cluster formation
   -- dependence of fragmentation on initial density profile of cluster forming cloud cores
   -- requirement for taking cloud formation into account
2.4 Radiative processes
   -- coupling between gas/dust and the radiation field
   -- long excursion: modeling radiative transfer
2.5 Thermodynamic properties of the ISM
   -- main heating and cooling mechanisms
   -- chemical processes in the ISM
   -- multi-phase ISM
   -- excursion: modeling extinction in dense clouds
2.6 Magnetic fields in the ISM
   -- influence of magnetic fields on molecular cloud dynamics
   -- protostellar collapse and magnetic fields
3. Star formation and feedback [~1.5h]
   -- importance of feedback for locally terminating star formation
   -- excursion: sink particles as subgrid-scale model of protostellar collapse
3.1 Radiative feedback
   -- accretion heating
   -- ionizing radiation, HII regions
   -- excursion: coupling (proto)stellar evolution to sink particles
3.2 Mechanical feedback
   -- controversial role of outflows in star formation
   -- excursion: modeling outflows

4. Some selected applications [~1.5h]
4.1 The stellar initial mass function
   -- theoretical models of the IMF
   -- universality
4.2 Star formation in the primordial universe
   -- formation of the first stars
   -- transition from Population III to Population II (dust vs. atomic cooling lines)
   -- observational constraints
   -- dark stars
4.3 Magnetic field amplification in the early universe
   -- dynamo processes in primordial halos
   -- some notes on numerical resolution
literature
Literature
**Books**

- Draine, B. 2011, “Physics of the Interstellar and Intergalactic Medium” (Princeton Series in Astrophysics)
- Bodenheimer, P. 2012, “Principles of Star Formation” (Springer Verlag)
Literature

Review Articles

Mac Low, M.-M., Klessen, R.S., 2004, "The control of star formation by supersonic turbulence", Rev. Mod. Phys., 76, 125


Internet resources

Cornelis Dullemond: *Radiative Transfer in Astrophysics*
http://www.ita.uni-heidelberg.de/~dullemond/lectures/radtrans_2012/index.shtml

Cornelis Dullemond: *RADMC-3D: A new multi-purpose radiative transfer tool*
http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/index.shtml

List of molecules in the ISM (wikipedia): 

Leiden database of molecular lines (LAMBDA)
http://home.strw.leidenuniv.nl/~moldata/
Part 1: Introduction

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phenomenology
• star formation sets in very early after the big bang
• stars always form in galaxies and protogalaxies
• we cannot see the first generation of stars, but maybe the second one
- correlation between stellar birth and large-scale dynamics
- spiral arms
- tidal perturbation from neighboring galaxy
HI gas more extended
• H2 and SF well correlated
• roughly linear relation between H$_2$ and SFR
• roughly constant depletion time: few x 10$^9$ yr
• super linear relation between total gas and SFR
data from T. Dame (CfA Harvard)

Orion Nebula Cluster (ESO, VLT, M. McCaughrean)
- stars form in molecular clouds
- stars form in clusters
- stars form on $\sim$ dynamical time
- (protostellar) feedback is very important

Orion Nebula Cluster (ESO, VLT, M. McCaughrean)
Ionizing radiation from central star Θ¹ Orionis Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)
• strong feedback: UV radiation from Θ1C Orionis affects star formation on all cluster scales

Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)
Multiplicity in the Orion Trapezium

(Preibisch et al. 1999; Schertl et al. 2003; Weigelt et al. 1999; Kraus et al. 2009)

- \( \theta^1 B \)
- \( \theta^1 C \)
- \( \theta^1 E \)
- \( \theta^1 A \)
- \( \theta^1 D \)

- B2 – B3: \( \rho = 0.117'' \)
- A1 – A2: \( \rho = 0.215'' \)
- C1 – C2: \( \rho = 0.024'' \)

- IOTA
- \( 0.02'' \)
- \( 0.025'' \)
- \( 0.1'' \)
- \( 1'' \)
- \( 0.5'' \)

- HST image
- Bally et al. (1998)

- SB (0.13 AU)
- SB (0.2 AU)
- SB (1 AU)

- Herbig & Griffin 2006

- Orbital motion of \( \theta^1 C \) 1–2
- VLTI/AMBER
- 2 mas
- 4 AU
eventually, clusters like the ONC (1 Myr) will evolve into clusters like the Pleiades (100 Myr)
theoretical approach
• **density**
  - density of ISM: few particles per cm\(^3\)
  - density of molecular cloud: few 100 particles per cm\(^3\)
  - density of Sun: 1.4 g/cm\(^3\)

• **spatial scale**
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4 \times 10^{10} cm
- **contracting force**
  - only force that can do this compression is **GRAVITY**

- **opposing forces**
  - there are several processes that can oppose gravity
    - **GAS PRESSURE**
    - **TURBULENCE**
    - **MAGNETIC FIELDS**
    - **RADIATION PRESSURE**
- **contracting force**
  - only force that can do this compression is **GRAVITY**

- **opposing forces**
  - there are several processes that can oppose gravity
    - **GAS PRESSURE**
    - **TURBULENCE**
    - **MAGNETIC FIELDS**
    - **RADIATION PRESSURE**

Modern star formation theory is based on the complex interplay between all these processes.
Historic Overview
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:

\[ M_J = \frac{1}{6\pi^{5/2}G^{3/2}} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{3/2} \]
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 soundspeed:
  \[ C_{\text{eff}}^2 \longrightarrow C_c^2 + \sigma_{\text{rms}}^2 \]
- \( \rightarrow \) Larger effective Jeans masses \( \rightarrow \) more stability
- BUT: (1) turbulence depends on \( k \): \[ \sigma_{\text{rms}}^2(k) \]
  (2) supersonic turbulence \( \rightarrow \sigma_{\text{rms}}^2(k) \gg C_s^2 \) usually
Properties of IMS turbulence

ISM turbulence is:

- Supersonic (rms velocity dispersion $>>$ sound speed)
- Anisotropic (shocks & magnetic field)
- Driven on large scales (power in mol. clouds always dominated by largest-scale modes)

Microturbulent approach is NOT valid in ISM

No closed analytical/statistical formulation known
--> necessity for numerical modeling
Problems of early dynamical theory

- Molecular clouds are *highly Jeans-unstable*, yet, they do *NOT* form stars at high rate and with high efficiency (Zuckerman & Evans 1974 conundrum) (the observed global SFE in molecular clouds is ~5%)
  \[ \rightarrow \text{something prevents large-scale collapse.} \]

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

- Molecular clouds are *magnetized*
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)
    
    \[
    \left( \frac{M}{\Phi} \right)_{cr} = \frac{\xi}{3\pi} \left( \frac{5}{G} \right)^{1/2}
    \]

  - Ambipolar diffusion can initiate collapse

Lyman Spitzer, Jr., 1914 - 1997
**“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
    - $\frac{dM}{dt} = 0.975 c_s^3/G = \text{const.}$

- Was (in principle) only intended for isolated, low-mass stars
problems of “standard theory”

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Structure of prestellar cores (e.g. Bacman et al. 2000, 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)
- Most stars form as binaries (e.g. Lada 2006)
- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps are chemically young (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} \ll \tau_{AD}$) (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)
- Standard AD-dominated theory is incompatible with observations (Crutcher et al. 2009, 2010ab, Bertram et al. 2011)

(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)
**observed B-fields are weak**

*B* versus *N(H₂)* from *Zeeman measurements*. (from Bourke et al. 2001)

→ cloud cores are magnetically supercritical!!!

(Φ/M)ₙ > 1 no collapse
(Φ/M)ₙ < 1 collapse
molecular cloud dynamics

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


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

  (Mac Low, Klessen, Burkert, & Smith, 1998, PRL)
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. (2009)
Field reversal in the outer parts. This is incompatible with “standard” ambipolar diffusion theory!

Crutcher et al. (2009)

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 $B_{\text{LOS}}$ and its 1σ uncertainty at that position. A negative $B_{\text{LOS}}$ means the magnetic field points toward the observer, and vice versa for a positive $B_{\text{LOS}}$. 
Fig. 2.— OH 1667 MHz spectra toward the telescope (center panel) and toward each of the other six positions west of the core, obtained with the GBT. In the latter, we show $T_a(K)$ and its $1\sigma$ uncertainty at that position. A negative number toward the observer, and vice versa for a positive number.

<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>$0.02 \pm 0.36$</td>
<td>$0.07 \pm 0.34$</td>
<td>0.005</td>
</tr>
<tr>
<td>B217-2</td>
<td>$0.15 \pm 0.43$</td>
<td>$0.19 \pm 0.41$</td>
<td>0.05</td>
</tr>
<tr>
<td>L1544</td>
<td>$0.42 \pm 0.46$</td>
<td>$0.46 \pm 0.43$</td>
<td>0.11</td>
</tr>
<tr>
<td>B1</td>
<td>$0.41 \pm 0.20$</td>
<td>$0.44 \pm 0.19$</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Crutcher et al. (2009)
Figure 3. We also varied the number of clumps in our distribution. We do not find any significant differences between the PPP and PP measurements. We also noticed that the magnetic field component and the number of clumps in our distribution are well correlated. We therefore conclude that the number of clumps in our distribution is a function of time, as is the Alfvén number $R_{\alpha}$.

In Section 2.3, we have described two different methods of computing the magnetic field strength. We might expect that the average values of the mean magnetic field strength as we go to higher plasma beta $\beta$ would scale like $B \propto \sqrt{\beta}$.

We might expect that the average values of the mean magnetic field strength as we go to higher plasma beta $\beta$ would scale like $B \propto \sqrt{\beta}$. This is caused by the fact that a weaker field cannot resist as well against turbulence as strong magnetic fields.

Table 3 gives an overview of the average values of the magnetic field, their standard deviations, and the standard deviation of the medians. If we consider the small-scale dynamo effects as well against turbulence as strong magnetic fields, we therefore notice that the average values of the mean magnetic field strength as we go to higher plasma beta $\beta$ would scale like $B \propto \sqrt{\beta}$.

The simulations with $\beta = 0.01$ to $\beta = 0$ correspond to simulations with $\beta = 0.1$ to $\beta = 1$. If we consider the small-scale dynamo effects as well, we therefore notice that the average values of the mean magnetic field strength as we go to higher plasma beta $\beta$ would scale like $B \propto \sqrt{\beta}$.

Let us now analyse the consequences of field reversals in our clumps. Fig. 5 shows the corresponding amount of field reversals for each clump plotted in Fig. 4. Besides the fact that the distribution of clumps in Fig. 5 qualitatively moves to lower magnetic field strengths as we go to higher values of plasma beta $\beta$, we notice that the distribution of clumps in Fig. 5 qualitatively moves to lower magnetic field strengths as we go to higher values of plasma beta $\beta$.

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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.
Figure 4. Distribution of clumps in different LoS directions for (i) PPP and (ii) PP measurements and observed cores by Crutcher et al. (2009). From the top to bottom: different values of $\beta_0$ ($\beta_0 = 0.01, 0.1, 1, 10$ and $100$). From the left-hand to right-hand side: different time-steps ($t = 2.0, 2.4$ and $2.8$ $T$). The initial magnetic field strength for $\beta_0$ is marked with a vertical line. Plotted is the absolute value of $R$ against the absolute value of the average of the magnetic field components for a given LoS. In general, we observe a small value of $|R|$ for small magnetic field strengths that might be caused by field reversals. The stronger the magnetic field lines, the higher the value of $|R|$. For PPP and PP configurations, as well as for the three different times, we get statistically the same distribution.

Also numerical models of prestellar cores forming in turbulent MHD simulations of ISM dynamics show a large number of field reversals.
gravoturbulent star formation

- BASIC ASSUMPTION:
  star formation is controlled by interplay between supersonic turbulence and self-gravity

- turbulence plays a dual role:
  - on large scales it provides support
  - on small scales it can trigger collapse

- some predictions:
  - dynamical star formation timescale $\tau_{ff}$
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .

Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
McKee & Ostriker, 2007, ARAA, 45, 565
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 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)
turbulent cascade in the ISM

- scale-free behavior of turbulence in the range
  \[ \frac{L}{\eta_K} \approx \text{Re}^{3/4} \]
- slope between -5/3 ... -2
- energy “flows” from large to small scales, where it turns into heat

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

dissipation scale not known
(ambipolar diffusion, molecular diffusion?)
molecular clouds

\[ \sigma_{\text{rms}} \approx \text{several km/s} \]

\[ M_{\text{rms}} > 10 \quad L > 10 \text{ pc} \]

log \( E \)

energy source & scale

NOT known
(supernovae, winds, spiral density waves?)

\[ \sigma_{\text{rms}} << 1 \text{ km/s} \]

\[ M_{\text{rms}} \leq 1 \quad L \approx 0.1 \text{ pc} \]

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

dense protostellar cores

supersonic

subsonic

massive cloud cores

supersonic cascade in the ISM
dynamical SF in a nutshell

- 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
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(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)
Density structure of MC’s

Molecular clouds are highly inhomogeneous.

Stars form in the densest and coldest parts of the cloud.

ρ-Ophiuchus cloud seen in dust emission.

Let's focus on a cloud core like this one.

(Motte, André, & Neri 1998)
Evolution of cloud cores

- How does this core evolve?
  Does it form one 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
- --> expectation: core breaks up and forms a cluster of stars
Evolution of cloud cores

indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ⧫, cores with embedded protostars by ⚫)

(Motte, André, & Neri 1998)
Formation and evolution of cores

- protostellar cloud cores form at stagnation point in convergent turbulent flows

- if $M > M_{\text{crit}} \propto \rho^{-1/2} T^{3/2}$: collapse & star formation
- if $M < M_{\text{crit}} \propto \rho^{-1/2} T^{3/2}$: reexpansion after end of external compression

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

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr
Formation and evolution of cores

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
as turbulence decays locally, contraction sets in
while region contracts, individual clumps collapse to form stars
while region contracts, individual clumps collapse to form stars
individual clumps collapse to form stars
individual clumps collapse to form stars
in dense clusters, clumps may merge while collapsing
--> then contain multiple protostars

\[ \alpha = \frac{E_{\text{kin}}}{|E_{\text{pot}}|} < 1 \]
in *dense clusters*, clumps may merge while collapsing

--> then contain multiple protostars
in *dense clusters*, clumps may merge while collapsing
--> 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 H\textsubscript{II} region
some concerns of simple model

- **energy balance**
  - in molecular clouds:
    - kinetic energy $\sim$ potential energy $\sim$ magnetic energy $>\,$ thermal energy
  - models based on HD turbulence misses important physics
  - in certain environments (Galactic Center, star bursts), energy density in *cosmic rays* and *radiation* is important as well

- **time scales**
  - star clusters form fast, but more slowly than predicted by HD only (feedback and magnetic fields do help)
  - initial conditions do matter (turbulence does not erase memory of past dynamics)

- **star formation efficiency (SFE)**
  - SFE in gravoturbulent models is too high (again more physics needed)
current status

- stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)
- the relative importance of these processes depends on the environment
  - prestellar cores --> thermal pressure is important
  - molecular clouds --> turbulence dominates
  \[ \text{(Larson's relation: } \sigma \propto L^{1/2} \)\]
  - massive star forming regions (NGC602): radiative feedback is important
  - small clusters (Taurus): evolution maybe dominated by external turbulence
- star formation is regulated by various feedback processes
- star formation is closely linked to global galactic dynamics (KS relation)

Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive theoretical approach.
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theoretical approach

ISM dynamics and SF

- 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.)
theoretical approach

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

- 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)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics (collisional: star clusters, collisionless: galaxies, DM)

stellar evolution (feedback: radiation, winds, SN)
theoretical approach

- magneto-hydrodynamics (multi-phase, non-ideal MHD, turbulence)
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- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro
The theoretical approach involves:

- **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)

- **statistics**: number of stars (collisional: $10^6$, collisionless: $10^{10}$)
- **transition from gas to stars**
- **binary orbits**
- **long-term integration**
theoretical approach

- 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)

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

methods need to be combined!

**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.)
end