Thermodynamics of GMCs and the initial conditions for star formation

Paul Clark & Simon Glover
ITA, Zentrum für Astronomie der Universität Heidelberg

ARI ITA LSW

RUPRECHT - KARLS - UNIVERSITÄT HEIDELBERG
EXZELLENZUNIVERSITÄT
Cluster modelling

**Magnetic fields**

- Dale & Bonnell (2008)
- Price & Bate (2007)
- Offner et al (2009)

**Outflows/jets/winds**

- Dale & Bonnell (2008)

**Radiative feedback**

- Offner et al (2009)
- Bate (2008)

+ MHD
What about initial conditions...?

... the sphere is king.

\[ n = 10^{4-5} \text{ cm}^{-3} \]
\[ T \sim 10 \text{K} \]
\[ m_{\text{Jeans}} \sim 1 \, M_\odot \]

Bonnor-Ebert, top-hat or power-law \( n(r) \)

Open questions:
- When SF occurs, how many Jeans masses in protocluster ´clump´?
- What sets the Jeans mass (and what is it)?
- How long does it take to assemble the ´clump´?
- How do these properties vary with the environment?
Molecular clouds aren’t isothermal!

Larson (1985, 2005):

\[ p = K \rho^\gamma \]
\[ T \propto \rho^{\gamma - 1} \]

Characteristic Jeans mass for fragmentation?

(Jappsen et al 2005; Bonnell et al 2006)

\[ m_{\text{Jeans}} \propto T^{3/2} \rho^{-1/2} \]

Important for both “competitive accretion” and pure “fragmentation” IMF theories.
Thermodynamic model

• Heating by photoelectric emission from UV-irradiated dust grains and PAHs (Bakes & Tielens 1994; Wolfire et al 2003).

• Excitation and photodissociation of H2 (Black & Dalgarno 1977; Draine & Bertoldi 1996).

• Heating by H2 formation on dust grains (Duley & Williams 1993; Glover 2009).

• Cosmic ray ionisation (Goldsmith & Langer 1978).

• Energy transfer between the gas and dust (Hollenbach & McKee 1979).

• Heating of the dust by the interstellar radiation field (Mathis et al 1983; Black 1994; Ossenkopf & Henning 1994).

• Fine-structure atomic line cooling from CI, CII, OI, Sil, Sil I (Glover & Mac Low 2007a).

• Molecular line cooling from H2 (Le Bourlot et al 1999), CO and H2O (Neufeld & Kaufmann 1993; Neufeld, Lepp & Melnick 1995; Glover & Clark in prep).

• Accurate treatment of the adiabatic index (Boley et al 2007).

• pdV and shock-heating from gas dynamics.

+ time-dependent H2 (Glover & Mac Low 2007) and CO (Nelson & Langer 1997) formation/destruction
Cloud model

- Chemistry and cooling module incorporated into Gadget-2, publicly available SPH code (Springel 2005)
- Conditions in cloud:
  \[ 10^4 \, M_\odot \quad 8.7 \, \text{pc} \quad n = 100 \, \text{cm}^{-3} \]
  \[ 5,000,000 \, \text{SPH particles} \quad m_{\text{res}} \sim 0.2 \, M_\odot \]
  \[ v_{\text{turb,3D}} \sim 8 \, \text{km s}^{-1} \quad (P(k) = P_0 k^{-4}) \]
  periodic boundary conditions
- Initial chemistry: H, C, O fully atomic.
- Look at 3 different values for the background radiation field:
  \[ 1.7 \, G_0 \, (\text{Habing 1968}) \sim \text{solar neighbourhood} \]
  \[ 17 \, G_0 \]
  \[ 170 \, G_0 \sim \text{Galactic centre} \]

Extinction estimate from ‘6-ray’ approximation
Nelson & Langer (1997)
+ Background \( A_V = 1 \)
Overall $T - \rho$ relation consistent with Larson’s predictions.

As background UV increases, the scatter in the relation get wider.

Dust is hotter than gas at $n < 10^{4-5}$ cm$^{-3}$, so gas heats up as it thermally couples.

Jeans mass at plateau in $T - \rho$ relation is different, ranging from ~0.2 to 0.05.

However, only a factor of 4 change in Jeans mass for factor of 100 in UV (e.g. Elmegreen et al 2008).

Set by when dust is fully shielded, rather than when dust-gas coupling set in.
Temperature-density evolution

- Overall T - ρ relation consistent with Larson's predictions.
- As background UV increases, the scatter in the relation get wider.
- Dust is hotter than gas at n < 10^{4-5} cm^{-3}, so gas heats up as it thermally couples.
- Jeans mass at plateau in T - ρ relation is different, ranging from ~0.2 to 0.05.
- However, only a factor of 4 change in Jeans mass for factor of 100 in UV (e.g. Elmegreen et al 2008).
- Set by when dust is fully shielded, rather than when dust-gas coupling set in.

\[ T(n) \propto n^{-0.25} \]
**Temperature-density evolution**

- Overall $T - \rho$ relation consistent with Larson’s predictions.
- As background UV increases, the scatter in the relation get wider.
- Dust is hotter than gas at $n < 10^{4-5} \text{ cm}^{-3}$, so gas heats up as it thermally couples.
- Jeans mass at plateau in $T - \rho$ relation is different, ranging from $\sim 0.2$ to $0.05$.
- However, only a factor of 4 change in Jeans mass for factor of 100 in UV (e.g. Elmegreen et al 2008).
- Set by when dust is fully shielded, rather than when dust-gas coupling set in.

$T(n) \propto n^{-0.25}$
• Even for 1.7 $G_0$, considerable fraction (~ 1/2) of the cloud’s volume is hotter (30 - 40K) than normally assumed (10 - 20 K).
• More extreme for the higher background UV fields.
• For 170 $G_0$, almost all the cloud (by volume) sits above 30K.
Large-scale density structure almost unaffected by the environmental conditions in the cloud.

Gas cools efficiently as it is compressed -> $t_{\text{cool}} < t_{\text{dyn}}$.

Behaves like a soft EOS (e.g. Larson 2005), and compresses easily, provided $v_{\text{turb}} > c_s$.

Turbulence can sweep together large regions of gas relatively unhindered.
Cluster assembly timescales

- After ~ 1Myr, can assemble ~ 500 -1000 \( M_\odot \)
- Roughly independent of UV since controlled by turbulence (cloud is easily compressed).
- Fast / slow star formation?

Potentially a large age spread, just from the assembly time.
- Dense (well-shielded) regions/cores have high CO fractions, regardless of background field.
- Dense regions move slowly within the parent cloud --> **Observed velocity dispersion?**

(Glover, Clark, Shetty & Dullemond, in prep)
Future projects?

Can study a wide range of cloud formation scenarios....

Stutz et al 2009
Summary

• Density structure of molecular clouds is not sensitive to the ambient UV.
• Approximately recover the temperature density relation suggested by Larson, but relation is not as tight:
  1) Photoelectric emission from dust introduces scatter
  2) Dust is hotter than gas before coupling, so $T_{\text{gas}}$ increases as the thermal coupling get stronger.
• At onset of star formation, protocluster clumps have roughly the same degree of thermal support in high and low field clouds.
• Time to accumulate large amounts of mass is ‘long’, $\sim$ Myr
• Large (volume) fraction of GMCs is hotter than normally assumed
• As UV field increases, CO formation is increasing confined to denser (better shielded) regions.
Clump assembly and number of Jeans masses

- Similar number of Jeans masses.
- Higher UV case is actually more bound overall --> higher ambient cloud pressure.
- Both cases show that the turbulence is still the dominant energy source.
- After ~ 1Myr, can assemble ~ 500 -1000 M\(_\odot\)
- Roughly independent of UV since controlled by turbulence (cloud is easily compressed).
- Fast / slow star formation?