Star Formation in Disc Galaxies

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Star Formation in Disc Galaxies

Star formation scales linearly with dense gas
- star formation is additive over galaxy?
- not so simple: Schinnerer, Meidt, Longmore

1. Gravitational instabilities


Spacing between clouds ~
Mass of clouds ~

\[
\lambda_{max} = 2c_s^2/G\Sigma, \\
M = \Sigma \left(\frac{\lambda_{max}}{2}\right)^2 = \frac{c_s^4}{G^2\Sigma}
\]

clear in clumpy z~2 galaxies:

Kim & Ostriker 2006

figure from Bournaud, Daddi, & Elmegreen 2008
2. Collisions / Coalescence / Agglomeration


C$^{18}$O emission in Serpens
Duarte Cabral et al. 2011


separation of features $\alpha$
epicylic radius (shock strength) Dobbs 2008

section of galactic disc
Dobbs, Bonnell & Pringle 2006

3. Colliding flows


From Spiral shocks, Supernovae flows

Fig. 2.— Integrated intensity images showing subregions of interest in GSH 287+04–17. Greyscale images are \( \text{H}_\text{i} \) and pink contours are \( ^{12}\text{CO}(J=1–0) \). The velocity integration ranges and contour levels are as follows: (a1) \( 26.5 < v_{\text{lsr}} < 19.9 \text{ km s}^{-1} \), \( 1.5+3.0 \text{ K km s}^{-1} \); (a2) \( 23.2 < v_{\text{lsr}} < 21.5 \text{ km s}^{-1} \), \( 1.3+1.0 \text{ K km s}^{-1} \); (b) \( 33.0 < v_{\text{lsr}} < 25.6 \text{ km s}^{-1} \), \( 1.5+5.0 \text{ K km s}^{-1} \); (c) \( 14.1 < v_{\text{lsr}} < 10.8 \text{ km s}^{-1} \), \( 1.5+3.0 \text{ K km s}^{-1} \). Panels (a1) and (b) show the regions referred to in the text as the ‘approaching limb complex’ and ‘high latitude complex’, respectively. CO clouds labelled 1 and 2 indicate those specifically referred to as ‘embedded’ and ‘o\( \cdot\)set’ in the text.

Ntormousi et al. 2011: 2 adjacent supernovae bubbles also Gaczkowski poster

Dawson et al. 2011

CO emission at edges of supershells

LMC: responsible for only few % of clouds (Dawson, et al. in prep)
4. Thermal instabilities


- very small structures (0.1 pc)

5. Parker instabilities


- Generally gravitational instabilities believed to dominate magnetic

Elmegreen 1982; Kim et al 1998; Kim et al. 2002
Formation of dense clouds

In fact all occur:

• no self gravity - less massive, less coherent clouds

• spiral arms - promote coalescence of gas clouds

• thermal instabilities - lead to dense, small scale structure which coalesces into more massive clouds

• spiral shocks / feedback - lead to ‘colliding flows’
Numerical simulations

- Potential with 4 armed spiral component (also no spiral, model with stars later)
- Heating and cooling (Glover & Maclow 2006)
- Self gravity
- Stellar feedback
  - instantaneous, inserted above a critical density
  - energy added: $\varepsilon \frac{M(H_2) \times 10^5}{160 \, M_\odot}$ ergs as Sedov solution
    (thermal + kinetic)
- 1 million particles (8 million later)
$\varepsilon = 5\%$

$\Sigma = 8 M_\odot pc^{-2}$
What do cloud properties tell us about cloud formation?

**Mass spectrum**

$\frac{dN}{dM} \propto M^{-1.9}$

- $\epsilon = 1\%$
- $\epsilon = 5\%$
- $\epsilon = 20\%$

**Rotation**

$\sim 40\%$ retrograde

Dependent on feedback

Dobbs, Burkert & Pringle 2011

Cloud-cloud interactions important

(see also Tasker & Tan 2009, Tasker 2011, Hopkins 2012, Khoperskov, Fujimoto posters)
What do cloud properties tell us about cloud formation?

With spiral potential

![Graph showing mass versus radius with spiral potential.]

No spiral potential

![Graph showing mass versus radius with no spiral potential.]

more massive clouds formed by coalescence in spiral arms
**What do cloud properties tell us about cloud formation?**

**Virial parameter**

**Scale height in disc**

**Bound and unbound clouds** (Dobbs et al. 2011): gravity not dominant in many clouds

Feedback required to reproduce scale height (Acreman et al. 2012)
What do velocity flows in galaxies tell us about cloud formation?

Dobbs, Pringle & Burkert 2012
Gas flows in galaxies - 4 examples

5, 20% indicates level of feedback in the simulation

‘Flocculent’ spiral contains star particles rather than potential

1 million gas particles
Gas flows in galaxies - 4 examples

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1 million gas particles
What are the signatures of cloud formation?

Take Cauchy strain tensor: 

\[ e_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

Evaluate eigenvalues, \( \lambda_1, \lambda_2 \)

Then use \( \alpha = \lambda_1 + \lambda_2 \) (divergence), \( \beta = |\lambda_1 - \lambda_2| \) (‘measure of asymmetry’)

\( \alpha \) shows convergence, \( \alpha \beta \) plane indicates nature of flows

(2D gas flows, neglect vertical dimension)
What are the signatures of cloud formation?

Maps of divergence ($\alpha$)  
Contours from grid of 100 pc resolution

Red - converging on 4 Myr  
Orange - converging on 10 Myr  
Purple - diverging on 4 Myr  
Blue - diverging on 10 Myr
What are the signatures of cloud formation?

Red = dense
Blue = low density

ID Converging flows (dense gas)

Spiral 5% (Spiral shock)
Spiral 20% (Feedback)
What are the signatures of cloud formation?

Red=dense
Blue=low density

1D Converging flows (dense gas)

Gas converges / diverges on short timescales (< 1 Myr)
Gas gathered together independently of density
What are the signatures of cloud formation?

For other cases see paper!
What gas do GMCs form from? and
How long do they take to disperse?

Use SPH to trace gas in GMCs to earlier and later times

Dobbs, Pringle & Burkert 2012
Gas flows in galaxies - 4 examples

5, 20% indicates level of feedback in the simulation

‘Flocculent’ spiral contains star particles rather than potential

1 million gas particles
Gas which forms GMCs is atypical 30 Myr beforehand (overdense)
What gas goes in to GMCs?

Gas which forms GMCs is atypical 30 Myr beforehand (overdense)

No spiral - sudden phase change

Spiral 5% - gradually more gas becomes dense (molecular)
When is gas in GMCs?

Very dense gas occurs 5-10 Myr around star formation

Moderately dense gas exists for much longer
What happens to gas which was in GMCs?

Gas also takes a long time (50 Myr to return to typical ISM)

For spiral 5% and flocculent models, gas is not completely recycled!
Evolution of a $2 \times 10^6 \, M_\odot$ GMC

- 8 million particles
- Cooling / heating
- Self gravity
- $n=2$ spiral potential
- Supernovae feedback
Evolution of individual cloud

6400 particles
Evolution of $2 \times 10^6 \, M_\odot$ cloud
10% in clouds  270 Myr
Lifetime of $2 \times 10^6 \, M_\odot$ GMC

- What is ‘lifetime’?
- No obvious definition

Most gas in a cloud which is also in chosen 250 Myr cloud

Lifetime $\sim 20$ Myr?

Total mass of stars formed $\sim 5 \times 10^4 M_\odot$
Efficiency (stars formed / cloud mass) = 2.5%
What about star formation?

Star formation from galactic scales:
What about star formation?

Star formation from galactic scales:
- reproduce ~ linear relation
- but star formation too efficient

Bonnell et al., in prep.
What reduces star formation efficiency?

Feedback

Dobbs, Pringle & Burkert 2011

see also Hopkins talk, Agertz poster

Vazquez-Semadeni et al. 2010
Conclusions

Formation of dense clouds complex:
• observational and theoretical evidence for a variety of processes - cloud coalescence, self gravity, thermal instabilities, supernovae flows
• cloud properties in good agreement with observations
• cloud formation mechanisms can be distinguished by velocity flows
• evolution of individual GMC very complex, involving clouds merging, splitting apart, accreting gas
  - cloud lifetimes difficult to determine
• star formation too efficient - but both feedback and magnetic fields shown to reduce amount of star formation