The Formation and Evolution of Giant Molecular Clouds

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The Formation and Evolution of Giant Molecular Clouds

1. How do GMCs form and what from?

2. What processes are important for GMC evolution, and star formation within GMCs?

3. How long do GMCs survive and what causes them to disperse?
Some cautionary notes!

i) No standard definition of a cloud

ii) Clouds do not have an edge

iii) $^{12}\text{CO} \neq ^{13}\text{CO} \neq \text{density (numerical)}$

iv) Cloud evolution likely different in different galaxies and environments

v) Simulations in this talk do not resolve internal properties of GMCs
v) Simulations that do resolve internal clouds, and star formation

Bonnell et al. 2013

See also van Loo et al, 2013, Jonathan’s talk
iv) Cloud evolution likely different in different galaxies and environments

Hughes et al. 2013
Evolution of GMCs in a Grand Design Spiral with a fixed spiral pattern
SPH (sphNG code)

8 million particles
2 armed spiral
$\Sigma=8 \ M_\odot \ pc^{-2}$

$M_{\text{particle}} \sim 300 \ M_\odot$

thermodynamics + chemistry (Glover & MacLow 2007)

self gravity

stellar feedback

Dobbs & Pringle 2013
Evolution of individual cloud: Cloud380

6400 particles
GMC Formation

- GMCs form from both diffuse and dense gas

Red = cloud selected
Green = 10 Myr earlier
Blue = 30 Myr earlier
Purple = 50 Myr earlier
Black = galactic average

Dobbs, Pringle & Burkert 2012
GMC Formation

- GMCs are formed by:
  - mergers of smaller clouds in the arms
  - self gravity

Frequency of cloud-cloud collisions much higher in spiral arms (cloud collisions every ~1/5th of orbit otherwise (Tasker & Tan 2009))


GMC Formation

No self gravity (of gas)

Agglomeration in the spiral shock is the primary means of GMC formation - no need for self gravity

Self gravity

But with self gravity, more coherent clouds are formed

\[ \Sigma = 8M_\odot pc^{-2} \]

Self gravity, high \( \Sigma \)

Noticeably more massive clouds form

\[ \Sigma = 20M_\odot pc^{-2} \]
Evolution of GMCs in a Grand Design Spiral with a fixed spiral pattern

- Cloud properties and evolution
A Cloud's Life

55% in clouds 240 Myr

72% in clouds 245 Myr

100% in clouds 250 Myr

55% in clouds 255 Myr

Tuesday, 9 July 13
A Cloud’s Life

- Cloud undergoes significant changes in shape and constituent gas
- Even with fewer collisions, the cloud is still subject to large scale dynamics
GMC evolution

Generally GMCs subject to
- collisions / interactions with other clouds
- shocks (see Bonnell et al. 2013)
- external and internal stellar feedback
- galactic shear
as well as gravity, cooling, UV heating
What do we know about observed GMC properties?

- GMCs exhibit unusual rotations (Blitz 1993, Rosolowsky et al. 2005, Imara & Blitz 2011a,b)

- GMCs both bound and unbound (Heyer et al. 2009, Roman-Duval 2010, Colombo 2013), but α close to 1

- GMCs exhibit a mass spectrum of slope -1.5 to -2.5 (above references)
Rotation - induced by collisions

Dobbs, Burkert & Pringle 2011
see also Tasker & Tan 2009

~40% retrograde

no strong dependence on feedback, but need some feedback
No spiral arms - fewer collisions
Unbound clouds require feedback

\[ \alpha \sim 5\sigma^2 \frac{R}{GM} \]

Observations

low (1% efficiency) feedback

moderate (5%) feedback

see also Hopkins et al. 2011

Dobbs, Burkert & Pringle 2011
Mass spectra - requires clumpy medium, and again that gas is not overly bound

I% feedback: bimodal distribution, with many massive clouds very wrong!

higher feedback: dN/dM~M^{-2}, similar to observations

Dobbs, Burkert & Pringle 2011
Evolution of GMCs in a Grand Design Spiral with a fixed spiral pattern

- Cloud dispersal
Cloud dispersal

Shear

Surface density at which cloud is disrupted:

$r_{\text{cloud}} \frac{dF}{dR} = \Sigma_{\text{crit}} G$

Timescale: $\sim A^{-1}$

Suggest shear most relevant at large scales, at small $r_{\text{gal}}$
Feedback also directly disperses clouds
Cloud dispersal

<table>
<thead>
<tr>
<th>Cloud</th>
<th>Mass (10^5 M⊙)</th>
<th>No. particles</th>
<th>α</th>
<th>Location at T₀ = 250 Myr</th>
<th>Nature of cloud evolution</th>
<th>Nature of cloud dispersal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud380</td>
<td>20</td>
<td>6386</td>
<td>2.9</td>
<td>Spiral arm (R=3.1 kpc)</td>
<td>forms from and disperses into smaller clouds</td>
<td>shear + feedback</td>
</tr>
<tr>
<td>Cloud788</td>
<td>1.7</td>
<td>559</td>
<td>3.7</td>
<td>Spiral arm (R=4.3 kpc)</td>
<td>remains of, and progenitor of more massive cloud</td>
<td>feedback</td>
</tr>
<tr>
<td>Cloud877</td>
<td>3.1</td>
<td>999</td>
<td>1.8</td>
<td>Spiral arm (R=4.1 kpc)</td>
<td>forms from and disperses into smaller clouds</td>
<td>shear + unbound</td>
</tr>
<tr>
<td>Cloud355</td>
<td>0.96</td>
<td>305</td>
<td>3.6</td>
<td>Inter-arm (R=3.3 kpc)</td>
<td>remains of more massive GMC</td>
<td>shear + unbound</td>
</tr>
<tr>
<td>Cloud159</td>
<td>2.7</td>
<td>863</td>
<td>2.7</td>
<td>Outer disc (R= 8.3 kpc)</td>
<td>forms from and disperses into smaller clouds</td>
<td>unbound</td>
</tr>
<tr>
<td>Cloud1198</td>
<td>13</td>
<td>4291</td>
<td>0.8</td>
<td>Spiral arm (R=3.4 kpc)</td>
<td>remains of more massive GMC</td>
<td>feedback</td>
</tr>
</tbody>
</table>

- Even clouds which have not seen recent star formation events still have relatively high velocity dispersions, due mainly to stellar feedback.
What is the lifetime of GMCs?

- What is ‘lifetime’? No obvious definition

Figure shows most gas in a cloud which is also in chosen 250 Myr cloud

Take time over which at least half the mass is present: Lifetime~20 Myr

Total mass of stars formed~$5 \times 10^4 M_\odot$

Efficiency (stars formed / cloud mass) = 2.5%

Star formation rate regulated by feedback (Dobbs et al. 2011)
What is the lifetime of GMCs?

red = $50 \text{M}_{\odot} \text{pc}^{-2}$ clouds

blue = $100 \text{M}_{\odot} \text{pc}^{-2}$ clouds

Clouds have lifetimes 2-40 Myr

Most frequent ~ 4 to 10 Myr

Dobbs & Pringle 2013
What is the lifetime of GMCs?

Predicting the lifetime of a GMCs

\[ t_{\text{cr}} = \frac{L}{\sigma} \]

crossing time of cloud
don’t know L

Use semi-minor axis:

\[ t_{\text{est}} = \frac{2b}{\sigma} \]

Elmegreen (2000): star formation in a crossing time

see also Hopkins et al. 2012
What happens in the absence of spiral arms

With spiral arms

No spiral arms
Formation of GMCs

GMCs form from diffuse gas, by gravitational instabilities combined with thermal instability.

Dobbs, Pringle & Burkert 2012
Star formation rates
Star formation rates

No strong dependency on spiral structure
Difference in population of clouds though

- Role of spiral arms to gather up gas into more massive clouds
Dispersal of GMCs

- Dispersal of gas quickly back to atomic phase - primarily by feedback
- Clouds likely to have short lifetimes (<10 Myr)

Dobbs, Pringle & Burkert 2012

Red = cloud selected
Green = 10 Myr later
Blue = 30 Myr later
Purple = 50 Myr later
Black = galactic average
Conclusions

- Considered GMC evolution in a grand design spiral
- Clouds form by agglomeration and self gravity
- Clouds undergo a dynamical evolution, subject to collisions, and large scale gas flows, constantly changing their shape and constituent gas
- Feedback (which counters self gravity and also regulates star formation) and cloud collisions determine cloud properties
- Clouds disperse by feedback and shear, most with lifetimes of $\lesssim 10$ Myr