Birthing star forming clouds in the grand design

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Star formation in galaxies

30 years ago…

But, now…

Clear relation (^^^)!!

Large scatter (>_<)!!

Kennicutt 1989

Daddi et al. 2010

Gas density is not the only factor for star formation. We have to consider the local process.
Giant molecular clouds = stellar nurseries

Their properties and evolution are the controlling factor that determines the production of the cloud core and galaxies’ star formation.
It has been hard to investigate the GMC formation and evolution taking the global gas dynamics into account.
High resolution simulations

Milky-Way type disk galaxy simulation

Tasker & Tan 2009, Tasker 2011, Tasker et al. 2015

Spiral galaxy simulation


These works indicate impacts of global gas dynamics on the GMCs formation and evolution.
GMCs in a barred spiral galaxy

We performed M83 type barred galaxy simulation (Fujimoto et al. 2014a).

We investigated the impact of the galactic structures (bar and spiral arms) on GMC formation and evolution.
**Code**

- **Enzo**: a 3D adaptive mesh refinement (AMR) hydrodynamics code
  (e.g. Bryan et al. 2014, ApJS)

**Box size**: $(50 \text{ kpc})^3$  \hspace{1cm} **Root grid**: $128^3$

- **radiative cooling**
- **Self-gravity of the gas**

(No star formation or feedback)
Galaxy model

Initial gas distribution

gas distribution of the barred galaxy M83 (Lundgren et al. 2004)

Stellar potential

potential model based on 2Mass K-band image of the barred galaxy M83 (Hirota et al. 2009)

Static dark matter potential

NFW profile (Navarro, Frenk & White 1997)
Cloud definition and tracking

cloud: coherent structure contained within contours at the threshold density of

\[ \rho \geq 100 \text{cm}^{-3} \]

cloud tracking to analyse a lifetime of cloud and merger rate
RESULTS

Three galactic regions

- **Bar region**: box-like region at the galactic centre
- **Spiral region**: ring region within the radii $2.5 < r < 7.0$ kpc.
- **Disc region**: ring region outside the spiral region
Cloud radius-mass scaling relation

- Hard to see the difference between the three galactic regions.
Three cloud types

- Normal
- Monster
- Transient

The graph shows the relationship between the cloud mass ($M_c$ [M$_\odot$]) and the cloud radius ($R_c$ [pc]) in a barred galaxy. The distribution extends to 0.4 Myr.

- Type A clouds have smaller surface density than 230 M$_\odot$.
- Type B clouds have larger surface density than 230 M$_\odot$.
- Type C clouds are transient, have quite smaller mass, radius, velocity dispersion, and quite higher virial parameter vs. radius relation than those of Type A clouds.

The merger rate is the number of mergers with the virial parameter vs. radius relation at 240 Myr. The distribution extends to 0.4 Myr.

These three clouds have clear differences in their proper-origins of clouds between regions as shown in Table 1.

In the bar region, Type A is 83.3%, Type B is 13.0%, and Type C is 37.7%.

In the spiral region, the percentages of these three clouds are clearly different from those in the other regions: Type B is 10.8% and Type C is 37.7%.

On the other hand, in the disc region, almost all clouds are Type A: the percentage is 83.3%.

The percentages of Type B and Type C are quite low: Type B is 5.9% and Type C is 37.7%.

The pictures of these three types of clouds are in Figure 8.
Three cloud types

Cloud classification based on radius-mass relation

- **Normal**: the most common clouds. $M_c \sim 5 \times 10^5 M_\odot$, $R_c \sim 15$pc, $\sigma_c \sim 6$km/s, $\alpha_c \sim 1$

- **Monster**: massive GMA's which have larger radius than 30 pc.

- **Transient**: unbound clouds which have lower density than $230 M_\odot$/pc$^2$
RESULTS

Cloud lifetime and merger rate

- **Monster**: long lifetime (> 40 Myr), high merger rate (t_merger < 10 Myr)
- **Transient**: short lifetime (< 10 Myr), low merger rate (t_merger > 100 Myr)
- **Normal**: middle properties between Monster and Transient.

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![Graphs showing lifetime and merger rate distributions for different cloud types.](image-url)
### Percentage of each cloud type in each galactic region

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- In all regions, the most numerous cloud type is **normal**.
- In the **bar** region, percentages of **monster** and **transient** are highest.
- In contrast, in the **disc** region, these percentages are lowest.
Do GMCs care about the galactic structure?

Figure 10. 2k pc surface density image for region with bar (left) and disc, 8k pc from the galactic center. The position of these two sections is shown on Fig. 5. Markers show the location of the three different cloud types. Green diamonds label type A clouds, blue circles mark type B and red triangles are type C.

The top panel in Fig. 11 shows the Kennicutt–Schmidt relation (equation 1) using this model. Each point on the graph marks the value for a cylindrical region with radius 500 pc in the galactic plane. This region size was chosen to be comparable to the observational data in nearby galaxies, which finds a near linear relationship between the gas surface density, $\Sigma_{gas}$, and the surface star formation density, $\Sigma_{SFR}$, for densities higher than $10 M_\odot pc^{-2}$ (Bigiel et al. 2008). Since multiple GMCs exist within these regions, the star formation rate is calculated as the sum for each cloud within the cylinder.

In agreement with observations, the gas and star formation rate surface densities follow a nearly linear trend in all three galactic environments. There is a small deviation towards a steeper gradient at densities below $\sim 10 M_\odot pc^{-2}$ and also an increased scatter due to the smaller number of clouds found within our measured region. Note that this change has a different origin to the observational results, where the break at the same threshold is due to the transition between atomic and molecular hydrogen. In our simulations, only atomic gas is followed, so we do not expect to observe such a split.

It is more likely that clouds in low-density regions are less centrally concentrated, due to fewer interactions resulting in tidal stripping. The overall star formation rate is approximately a factor of 10 higher than that observed. Such elevation in simulations is usually put down to the absence of localized feedback, which would be expected to dissipate the densest parts of the cloud and thereby reducing the star formation rate regardless of whether the cloud itself was also destroyed (Tasker 2011). In our case, we also lack an actual star formation recipe, meaning that our densest gas is allowed to accumulate inside the cloud without being removed to create a star particle. This adds to the cloud mass and raises the expected star formation rate.

While there is an overall agreement in the gradient, the difference in the star formation rate in the bar, spiral and disc is also apparent. The bar region contains the highest density of clouds, as well as a larger fraction of the massive type B clouds. This produces the upper end of the gas and star formation rate surface densities. The sparser, smaller clouds of the disc region result in correspondingly lower values and the spiral region sits in between.

3.4.2 GMC turbulence star formation model

We can compare the results of the straightforward free-fall collapse with a star formation model that also considers the importance of turbulent motions within the GMCs. Proposed by Krumholz & McKee (2005), this power-law model assumes that the clouds are supersonically turbulent, producing a log-normal density distribution. By demanding that gas collapses when the gravitational energy

RESULTS

• In the bar region, massive monster clouds are the most obvious, forming GMAs that drag in surrounding gas. In the dense tidal filamentary structures, transient clouds are formed.

• In the disc region, the clouds are more widely spaced and lack filament structures around them. The vast majority of the clouds are normal clouds.
Summary

- The typical value of the cloud properties is **independent** of galactic environment.

\[ M_c \sim 5 \times 10^5 \, M_\odot \quad R_c \sim 15 \text{pc} \]

- The percentages of the three cloud types are different between the three regions.

○ Bar region

  - **Highest fraction of monster and transient clouds**
    due to the high cloud density from the elliptical motion boosting the interaction rate between clouds.

○ Spiral region

  - **The next high fraction of monster and transient clouds**
    due to the spiral potential encouraging interactions.

○ Disc region

  - **A large population of normal clouds**
    due to the lack of the grand design potential to gather gas.

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see also Fujimoto et al. (2014a)
Important message

Cloud-cloud interactions is quite different between galactic environment. That gives different cloud populations in each galactic regions.
Stellar feedback to the ISM
**Method of SF and FB**

**Star formation**

Star particle is formed in the denser cell than $10^4$ atoms/cc.

**Supernova feedback**

$10^{51}$ ergs energy input per 1 SN.
The images show the gas surface density of the face-on disc at $t = 200 \text{ Myr}$. Each image is $20 \text{kpc}$ across. The galactic disc rotates anticlockwise.

High inter-cloud density due to gas dispersion by SN.

Fujimoto+ 2015 (in prep)
Inflow of clouds by the high density ISM

Angular momentum loss

\[ f_{\text{drag}} = -\frac{1}{2} C \rho A v^2 \]

Fujimoto+ 2015 (in prep)
Thank you!