Dynamical cooling of galactic disks by molecular cloud collisions – Origin of giant clumps in gas-rich galaxy disks

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ABSTRACT

Different from Milky-Way-like galaxies, disks of gas-rich galaxies are clumpy. The formation of the clumps is still a mystery. Efficient cooling is the necessary condition for a disk to fragment into clumps, yet the major cooling mechanism is not well understood. We propose that collisions (coagulation) between molecular clouds is the major way through which a gas-rich galactic disk dissipates its kinetic energy. This process is called cloud collision cooling. The evolution of a disk is thus determined by the dissipation parameter $D$, which is the ratio between the free-fall time $t_f \approx 1/\sqrt{G\Sigma_{\text{disk}}}$ (which is roughly the disk dynamical time) and the cooling time determined by the cloud collision process $t_{\text{cool}}$. This ratio is related to the ratio between the mean surface density of the disk $\Sigma_{\text{disk}}$ and the mean surface density of molecular clouds in the disk $\Sigma_{\text{cloud}}$. When $D < 1/3$ (corresponds to $t_{\text{cool}} > 3\Omega_{\text{kep}}^{-1}$, $\Sigma_{\text{disk}} < 1/3\Sigma_{\text{cloud}}$), cloud collision cooling is inefficient, and fragmentation is suppressed. When $D > 1/3$ (corresponds to $\Sigma_{\text{disk}} > 1/3\Sigma_{\text{cloud}}$, $t_{\text{cool}} < 3\Omega_{\text{kep}}^{-1}$), cloud-collision collisions lead to a rapid cooling which enables the formation of giant clumps commonly observed in gas-rich disks. The clumps from through the collective motions of the clouds, and is a consequence of the high rate of cooling caused by the cloud-cloud collisions. This dynamical cooling process can be taken into account in numerical simulations as a subgrid model to simulate the global evolution of galaxies.

Key words: Galaxy: disc – Galaxy: evolution – ISM: clouds – ISM: kinematics and dynamics – instabilities

1 INTRODUCTION

Star formation occurs in the cold phase of the galactic interstellar medium (ISM), which exhibits diverse morphologies in different galaxies. The Milky Way is a well-studied example where molecular gas is distributed in molecular clouds whose sizes are much smaller than the disk scale height. In contrast to this, in high-redshift, gas-rich galaxies, molecular gas seems to concentrate in giant (kpc-size), massive clumps, and a major part of the star formation occurs in the clumps (Abraham et al. 1996; Noguchi 1998; Elmegreen & Elmegreen 2005; Genzel et al. 2008; Guo et al. 2015; Elmegreen et al. 2009; Förster Schreiber et al. 2009). To understand the evolution of galaxies one must understand why these disks fragment into clumps whereas the disk of the Milky Way does not.

It is believed that the clumps form due to disk gravitational instability. In the standard picture (called VDI, Violent Gravitational Instability Dekel et al. 2009a,b; Kereš et al. 2005; Inoue et al. 2016), gas get accreted from the cosmic web. Gas accretion renders the disk gravitationally unstable, and as a result the disk fragments into clumps. The stability of the disk is quantified by the Toomre $Q$ parameter where $Q_{\text{disk}} = \sigma_{v,\text{disk}} \Omega_{\text{disk}} / \pi G \Sigma_{\text{disk}}$, $\sigma_{v,\text{disk}}$ is the velocity dispersion, $\Sigma_{\text{disk}}$ is the disk surface density, and $\Omega_{\text{disk}}$ is disk angular frequency. In Toomre’s formalism, fragmentation is driven by gravity (which is characterised by $\Sigma_{\text{disk}}$), which is balanced by a combination of pressure ($\sigma_{v,\text{disk}}$), which, to be precise, should be the ram-pressure of the ISM and shear ($\Omega_{\text{disk}}$, which is roughly the epicyclic frequency). Fragmenting disk should have $Q_{\text{disk}} < 1$

However, except for some very simplified cases, the Toomre $Q$ parameter can not be used to predict the long-term evolution of the disk. This is because for the Toomre $Q$ to determine the disk fragmentation, one requires the the
velocity dispersion of the disk $\sigma_{\text{disk}}$ to be fixed. This is true for isothermal disks, but is not true for galactic disks. For them, evolution can inject kinetic energy into the disk and increase $\sigma_{\text{disk}}$; at the same time, cooling processes in the disk will be able to reduce $\sigma_{\text{disk}}$. In these disks, accretion and stellar feedback regulate the disk to $Q_{\text{disk}} \approx 1$. This self-regulation has been observed in simulations with various settings (e.g. Gammie 2001; Johnson & Gammie 2003; Hopkins et al. 2012; Lehner et al. 2013; Goldbaum et al. 2016), and has been confirmed by observations of both spiral and clumpy galaxies (Hitschfeld et al. 2009; Puech 2010; Cacciato et al. 2012; Fisher et al. 2014). For these evolved disks, measuring the Toomre $Q$ merely reassures that they are self-regulating systems, but does not provide information concerning if they will fragment into clumps or not.  

For non-isothermal disks, the cooling time determines their long-time evolution. This has been demonstrated by Gammie (2001) using local, shearing-box simulations, where they found that if cooling is inefficient (cooling time is long compared to the dynamical time), the disk should evolve into a gravito-turbulent state where turbulence maintained by accretion can effectively suppress the overly-rapid fragmentation, and the disk is dominated by fluffy, filamentary structures that are constantly smeared apart by galactic rotation; when cooling is efficient (cooling time is short compared to the dynamical time), gas in the disk rapidly dissipates kinetic energy and fragments into a few giant clumps. It is interesting to note the striking similarity between the dichotomy found in Gammie (2001) where an accretion disk can be either filamentary or clumpy, and what we observe in galaxies where gas either organises into smaller clouds (e.g. Milky Way) or into clumps (e.g. the gas-rich clumpy galaxies). This similarity poses the question: can we explain the morphological difference of galaxies using the theory of Gammie (2001)? What is the major cooling mechanism in the disks? We remind the reader that there is a lack of understanding of dynamical cooling of the multi-phased ISM. The ISM have structures over multiple scales, and the kinetic energy of the disk is distributed in these different structures. To cool down the disk, one must reduce the velocity dispersion of the disk on the large scale (e.g. scales comparable to the disk thickness $H_{\text{disk}}$). Since the gas-rich disks are mostly molecular, cooling must reduce the velocity dispersion of the molecular gas on the disk scale. We argue that this can be best achieved through the collisions of molecular clouds. Previously, one set of models (e.g. Dekel et al. 2009b; Mayer et al. 2016) assume that the disk cooling time is the radiative cooling time of the warm ISM. Since radiative cooling time is always shorter than the dynamical time, the disk would always fragment if the disk is gravitationally unstable. However, forming molecular gas and driving disk instability are distinct processes. Although radiative cooling can cool down the warm ISM and drive cloud formation, for a disk to fragment, one still need to reduce the kinetic energy contained in the random motions of the molecular clouds. Thus radiative cooling do not lead to large-scale disk fragmentation. Another set of models assume that the kinetic energy of the disk is dissipated because of turbulence (e.g. Romeo et al. 2010; Elmegreen & Burkert 2010; Klessen & Hennebelle 2010; Elmegreen 2011; Forbes et al. 2014) 3. However, the some basic assumptions of the galactic disk turbulence are still unjustified: the standard theory of turbulence has only been shown to be valid for non-self-gravitating gas with well-defined equation of states. In a real galactic disk, gas is separated into different phases where the molecular gas has a density that is two orders of magnitudes larger than the density of the ambient ISM. This density contrast makes many of the assumptions of the turbulence model invalid. For example, in the stand picture of galactic disk turbulence, ideally, one requires energy to cascade from the larger scales continuously down to the Kolmogorov microscales where it dissipates into heat. But in a real galactic disk, because of the density contrast between the molecular clouds and ambient gas as well as the fact that molecular gas forms centrally-condensed structures, it is practically very difficult for the kinetic energy in the warm ISM to cascade into molecular clouds (Ibáñez-Mejía et al. 2016; Li 2017). Another consequence of such a density contrast is that if a dense molecular cloud travels in a galactic disk with a diffuse ambient medium, in most cases the cloud would neglect the drag from the ambient medium and travel on its own (as has been estimated by Marochnik et al. 1983). One must take this dynamical detachment induced by phase separation into account in realistic galactic disk models. Lastly, some models simply steeped over the cooling issue by assuming isothermal equations of states (Behrendt et al. 2015, 2016). They simulated gravitationally unstable isothermal disks, and found that the disk first fragments into rings and then into clouds, and in the final step the clouds merge to form clumps. The possibility of merging clouds found in the simulations is an interesting one. However, since they have assumed an isothermal equation of state, how cooling leads to disk fragmentation remains undressed.

We consider a picture where a galactic disk consists of an ensemble of colliding molecular clouds. On the microscopic scale, cooling occurs because of the collisions between the clouds, and on the macroscopic level this cooling leads to the formation of the clumps. The previous models (Kwan & Valdes 1983; Marochnik et al. 1983; Tomisaka 1986; Tan 2000; Vollmer & Beckert 2002; Dobbs 2008) mainly considered the evolution of clouds in fixed galactic potentials and focused on properties of the clouds. In their models, clouds are objects that passively move around in the disk. These models are valid for Milky Way like galaxies where disk surface densities are low, but are not valid for gas-rich disks. In this paper, we extend their analyses into the non-linear regime, where the cloud-cloud collisions that occur on

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2 There are some variations of the Toomre $Q$ parameter in different galaxies, with clumpy galaxies having smaller $Q$ (e.g. Fisher et al. 2014). But it remains a theoretical issue how to define the Toomre $Q$ in a disk that consists of both gas and stars accurately (Wang & Silk 1994; Elmegreen 2011; Romeo & Wiegert 2011; Inoue et al. 2016), therefore, some of the observed variations in Toomre $Q$ might arise from this theoretical uncertainty. Besides, the variation is much smaller than the difference in the $D$ parameter that we discuss in this paper, and we believe that it is the difference in the $D$ parameter that leads to different evolutions.

3 They are based on earlier models, such as Lynden-Bell & Pringle (1974); Lin & Pringle (1987a,b).
smaller scales are able to back-react on the disk dynamics on the large scale. When the cooling rate is high, clumps form as a result of the collective motion of the molecular clouds included by cloud collision cooling.

2 THE MODEL

We describe the properties of a system consists of coagulating clouds, and derive the timescale for cloud-cloud collisions to significantly remove kinetic energy from the system. This cooling channel is called cloud collision cooling. We evaluate the stability of galactic disks that consist of coagulating clouds, and show that when the mean surface density of a disk is comparable or larger than the mean surface density of molecular clouds in the disk, cloud collision cooling is effective. The mean surface density of molecular clouds is determined by the metallicity of a galaxy, which does not evolve by much through the cosmic time. In contrast to this, variations in disk surface densities can be much larger and is the major driver for different galaxies to evolve differently. A list of variables can be found in table 1.

2.1 General picture

Our coagulating cloud picture is described below (Fig. 1): In a galactic disk, dense molecular clouds are surrounded by a hot ambient medium. The clouds are mainly composed of H₂ gas, and the ambient medium includes gas in both the warm neutral phase and the warm ionized phase.

A first fact that one should notice is the clouds have densities that are much higher (typically by a factor of ~100) than the density of the ambient medium. This has two consequences: First, the clouds are so dense that their movements are barely affected by the ambient medium (as has been estimated by Marochnik et al. (1983)). Second, because of the density contrast, it would be difficult for turbulence in the ambient medium to cascade into the clouds. Turbulence in the molecular clouds is mainly driven by cloud-cloud collisions, whereas turbulence in the ambient medium is driven by a combination of shear and supernova feedback (Goldbaum et al. 2011; Ballesteros-Paredes et al. 2011; Krumholz & Burkhardt 2016; Ibáñez-Mejía et al. 2016; Li 2017). The system is also characterised by a hierarchy of structures of different velocity dispersions. The disk as a whole has a velocity dispersion $\sigma_{\text{disk}}$, which is mainly contributed from the quasi-random motions of the molecular clouds. The molecular clouds in the disk also have turbulent motions, and the turbulent velocity dispersions of the clouds are characterised by $\sigma_{\text{cloud}}$, which is a function of cloud size (c.f. the Larson relation, Larson 1981). Finally, the gas in the cloud has some velocity divergences due to thermal motion $\sigma_{\text{thermal}}$. In typical spiral galaxies such as M51 and the Milky Way, the value of $\sigma_{\text{disk}}$ is around 50 km/s (Hitschfeld et al. 2009), which is much larger than the velocity dispersion of individual molecular clouds in these disks, which can barely exceed 10 km/s (Roman-Duval et al. 2010). Finally, the velocity dispersion that results from thermal motions of gas in the clouds is very small ($\sigma_{\text{thermal}} \approx 0.5$ km/s for the Milky Way). These different velocity dispersions are determined by difference processes. $\sigma_{\text{disk}}$ is determined mainly by self-regulation (e.g., Gammie 2001; Johnson & Gammie 2003; Hopkins et al. 2012; Lehnert et al. 2013; Goldbaum et al. 2016), $\sigma_{\text{cloud}}$ is determined by turbulence driving due to cloud-cloud collisions (which we further discuss in Sec.2.6), and $\sigma_{\text{thermal}}$ is determined by the temperature of the molecular gas that is maintained by the heating and cooling balance (Field et al. 1969). Typically, $\sigma_{\text{cloud}} > \sigma_{\text{disk}} > \sigma_{\text{thermal}}$, which is true for the Milky Way and is true for the gas-rich disks 4.

Our aim is to understand the major cooling mechanism that leads to disk fragmentation. Since the velocity dispersion of the disk is dominated by the relative motions between the molecular clouds, to cool down the disk, one must reduce this relative motion ($\sigma_{\text{cloud}}$). One way to achieve this is through the collisions between the clouds. In the simplest case, when two clouds collide and merge, momentum is conserved, yet a significant fraction of the total kinetic energy is instantaneously converted into turbulence in the merged cloud. Similarly, when a collision shatters a large cloud into smaller clouds, kinetic energy is converted into turbulence in the smaller clouds. For our model, these collisions have two consequences: on the macroscopic scale, the collisions remove kinetic energy from the system, and on the microscopic scale, the collisions sustain turbulence in the clouds. It is the removal of the macroscopic kinetic energy that leads to disk fragmentation.

We do not explicitly consider the effect of stellar feedback. Together with accretion, stellar feedback is a source of heating to the disk, which maintains its velocity dispersion. Here, we simply assume that both accretion and stellar feedback will drive the velocity dispersion of the disk which ensures $Q_{\text{disk}} \approx 1$, and we study the subsequent evolution of such a $Q_{\text{disk}} \approx 1$ disk. For our purpose we do not need to distinguish these heating sources. The cloud collision cooling mechanism that we are discussing is independent on how the clouds are created, and the link we establish between cloud collision cooling and disk fragmentation is relatively independent on the details of feedback and cloud destruction.

2.2 Disk cooling through cloud-cloud collisions

To obtain a quantitative understanding of the underlying physics, we assume that a typical cloud has a mass $m_{\text{cloud}}$ and a size $r_{\text{cloud}}$. We show later that our results do not depend on the assumed the masses and sizes, but only on the mean surface density of the cloud. We further assume that when averaged over a larger volume (whose size is much larger than the size of a molecular cloud, but is comparable to the disk scale height), the molecular galactic disk as a whole has a local mean density of $\rho_{\text{disk}}$ and velocity dispersion $\sigma_{\text{disk}}$. The number density of clouds is thus $n_{\text{cloud}} = \rho_{\text{disk}}/m_{\text{cloud}}$. The mean free path of clouds is

$$\lambda_{\text{cloud}} = \frac{n_{\text{cloud}}^{-1}}{\sigma_{\text{cloud}}^2} = \rho_{\text{disk}}^{-1} m_{\text{cloud}} r_{\text{cloud}}^{-2},$$

where $r_{\text{cloud}} \approx r_{\text{cloud}}^2$ is the surface area of a cloud. Since cloud-cloud collisions are inelastic (such that each collision removes 4 For example, the cloud temperate should not evolve significantly, and $\sigma_{\text{thermal}}$ is always smaller than $\sigma_{\text{cloud}}$. $\sigma_{\text{disk}}$ and $\sigma_{\text{cloud}}$ is linked by Eq. 14, where in most of the cases $\sigma_{\text{cloud}} > \sigma_{\text{disk}}$.}
Typical time for a cloud to collide with another cloud, which for the system to lose kinetic energy can be estimated from the typical surface density of a molecular cloud, we can use Eq. 11 to evaluate the dissipation property of the system on the macroscopic level.

Fig. 2 plots the cloud collision time and the free-fall time as a function of mean density \( \rho_{\text{disk}} \). One can identify these two regimes: when the density is low, the free-fall time is shorter than the characteristic time for two clouds to collide, \( D < 1 \), and the kinetic energy contained in the system is roughly conserved in a free-fall time. When the density is large enough e.g.

\[
\rho_{\text{disk}} > \rho_{\text{disk, crit}} = \frac{G \Sigma_{\text{cloud}}^2}{\sigma_{v, \text{cloud}}^2},
\]

\( D > 1 \), collisions between the clouds can effectively remove kinetic energy from the system within a dynamical time, and the system is dissipative. If such a system has a kinetic energy density of \( \epsilon_{\text{kin}} \), the cooling rate can be estimated via

\[
\dot{\epsilon}_{\text{kin}} \approx \frac{\epsilon_{\text{kin}}}{t_{\text{cool}}}.
\]

Under appropriate conditions, collisions between molecular clouds that occurs on the microscopic scale can reduce the velocity dispersion of the system, and constitutes as a macroscopic, dynamical cooling channel. This cooling channel is different from radiative cooling, which merely removes the thermal energy but not the kinetic energy. We name this dynamical cooling process “cloud collision cooling”. Previously, the same mechanism has been invoked by Elmegreen (1989) to explain structure formation in a clumpy medium. We demonstrate that this cooling mechanism is efficient in

| Variable Name | Definition |
|---------------|------------|
| \( t_{\text{coll}} \) | typical size of a molecular cloud |
| \( m_{\text{cloud}} \) | typical mass of a molecular cloud |
| \( \Sigma_{\text{cloud}} \) | typical surface density of a molecular cloud. \( \Sigma_{\text{cloud}} = \Sigma_{\text{cloud, crit}} \) |
| \( \Sigma_{\text{cloud, crit}} \) | critical surface density of a molecular cloud (Eq. 11) |
| \( \sigma_{v, \text{cloud}} \) | velocity dispersion of a molecular cloud |

### Microscopic variables

- \( n_{\text{cloud}} \): mean number density of molecular clouds
- \( \sigma_{v, \text{disk}} \): velocity dispersion of the galactic disk
- \( \rho_{\text{disk, crit}} \): critical density for effective cloud collision cooling
- \( \Sigma_{\text{disk}} \): surface density of the galactic disk
- \( t_{\text{collide}} \): cloud collision time = cooling time
- \( \lambda_{\text{cloud}} \): mean free path of molecular clouds
- \( G \): gravitational constant
- \( Z \): metallicity
- \( G_{\text{iso}} \): interstellar radiation field
- \( \Omega_{\text{iso}} \): angular frequency of galactic (which is approximately the epicyclic frequency)
- \( t_{\text{kep}} \): disk dynamical time \( t_{\text{kep}} \approx 3 \Omega_{\text{iso}}^{-1} \)
- \( H_{\text{disk}} \): Disk scale height
- \( Q_{\text{disk}} \): Toomre Q parameter of the disk
- \( f_{\text{fit}} \): Disk scale-height correction due to self-gravity and gravitational force from the stars, \( f_{\text{fit}} = 1 \)
- \( D \): Dissipation parameter (proposed in this paper), dissipative systems have \( D \geq 1 \), clump formation requires \( D > 1/3 \)

### Table 1. List of variable definitions. The microscopic variables are the variables defined on the cloud scale, and the macroscopic variables are the variables defined on the disk scale.

\[
t_{\text{collide}} \approx \frac{\Sigma_{\text{cloud}}^2}{\rho_{\text{disk}} \sigma_{v, \text{disk}}}.
\]

where \( \Sigma_{\text{cloud}} \) is the mean surface density of the clouds. For comparison, the free-fall time of the gas is

\[
t_{\text{ff}} \approx \sqrt{\frac{1}{G \rho_{\text{disk}}}}.
\]

The collision time depends on both the bulk properties of the gas such as the mean density \( \rho_{\text{disk}} \), the mean velocity dispersion \( \sigma_{v, \text{disk}} \), as well as the properties of the individual clouds \( m_{\text{cloud}}, r_{\text{cloud}} \). When the mean surface densities of the molecular clouds \( \Sigma_{\text{cloud}} = m_{\text{cloud}}/r_{\text{cloud}}^2 \) and the velocity dispersion of the systems \( \sigma_{v, \text{disk}} \) are fixed, the cloud collision cooling time is proportional to \( \rho_{\text{disk}}^{-1} \), and the free-fall time is proportional to \( \rho_{\text{disk}}^{1/2} \); it is clear that cloud collision cooling will be important when the mean density of the disk \( \rho_{\text{disk}} \) is sufficiently high. Whether the disk is dissipative or not is quantified by the dissipation parameter

\[
D = \frac{r_{\text{cloud}}^{-1}}{t_{\text{ff}}^{1/2}} = \frac{\rho_{\text{disk}}^{1/2} \sigma_{v, \text{disk}}}{G^{1/2} \Sigma_{\text{cloud}}}.
\]

which is the ratio between the rate of cloud collision cooling \( r_{\text{cloud}}^{-1} \) and the rate of gravitational collapse \( t_{\text{ff}}^{-1} \). Systems large \( D \) are dissipative. Note that the dissipation parameter \( D \) is only dependent on the mean surface density of the cloud. It is independent on if the clouds are massive or not. As long as the clouds share a typical surface density, we can use Eq. 4 to evaluate the dissipation property of the system on the macroscopic level.
environments such as the ISM in gas-rich disks where it leads to the formation of the giant clumps.

2.3 Impact of cooling on disk fragmentation

The ratio between cooling time and dynamical time determines the evolution of accretion disks (Gammie (2001); Johnson & Gammie (2003)) simulated the fragmentation of self-gravitating gas disks, and demonstrated that the evolution of the disk in the nonlinear regime is determined by the ratio between the cooling time $t_{\text{cool}}$ and $3\Omega_{\text{kep}}^{-1} \approx \lambda_{\text{kep}}$, which is roughly the dynamical time $t_{\text{kep}}$. The cooling time plays a determining role in the dynamics of the disk: when $t_{\text{cool}} < 3\Omega_{\text{kep}}^{-1} \approx \lambda_{\text{kep}}$, cooling is not significant, the disk evolves into a gravo-turbulent state where gas forms long, filamentary structures that are constant shear apart by disk rotation; when $t_{\text{cool}} < 3\Omega_{\text{kep}}^{-1} \approx \lambda_{\text{kep}}$, cooling is important, and the disk quickly fragments into clumpy gas condensations.

The cooling time of the disk on the macroscopic scale is comparable to the cloud collision time on the microscopic scale, which is (see Eq. 2)

$$t_{\text{cool}} \approx \frac{\Sigma_{\text{cloud}}}{\rho_{\text{disk}} \sigma_{v,\text{disk}}}.$$  

We can further simply the expression of $t_{\text{cool}}$ using some additional ansatz: When the disk reaches hydrostatic equilibrium along the vertical direction, we can estimate its scale-height

$$H_{\text{disk}} = \frac{f_H \tau_{\text{disk}}}{\Omega_{\text{kep}}},$$  

where $f_H \approx 1$ is a numerical factor taking into account the additional compression contributed from self-gravity and the dark-matter halo alone would provide a good estimate to the disk scale-height in the order of magnitude sense. Details can also be found in Narayan & Jog (2002); Elmegreen (2011). In additional to these, the gravitational force from the stars can further reduce the disk thickness. Since we will be focusing on gas-rich disks, we neglect this term for simplicity.
Characteristic time \( t/t_{\text{crit}} \) analysis, we assume the rate of gravitational collapse \( T_{\text{cool}} \), and the rate of cloud-cloud collisions 

t = \frac{1}{\sqrt{G\rho_{\text{disk}}}} \tag{10} 

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where it is simply decided by the ratio between the mean surface density of the galactic disk \( \Sigma_{\text{disk}} \) and the mean surface density of molecular clouds in the disk \( \Sigma_{\text{cloud}} \). Fragmenting disks should have \( D > 1/3 \) (therefore \( \Sigma_{\text{disk}} > 1/3\Sigma_{\text{cloud}} \)).

**2.4 Surface densities of clouds**

Our next goal is to determine the “typical” surface density of the clouds. In a galaxy, the clouds can have different masses and sizes. The typical surface density is determined from the mass-weighted mean of the surface density of the individual clouds. We argue that is mainly determined by the metallicity of a galaxy.

This is because in a galaxy, a molecular cloud needs enough optical depth to shield against photodissociation, and this optical depth is determined by the metallicity. Krumholz et al. (2008, 2009) considered the atomic-to-molecular transition where they self-consistently modelled the H2 formation, photodissociation and shielding. They found that the limiting surface density of atomic-to-molecular transition is determined mainly by the metallicity, and is only weakly dependent on the interstellar radiation field. Following them, Sternberg et al. (2014) found that the following formula can provide a reasonably good description to the observed H1/H2 transition at Galactic and extragalactic

\[ Q_{\text{cloud}} \approx 1 \] 

The free-fall time is \( t_f = 1/\sqrt{G\rho_{\text{disk}}} \), and the disk dynamical time is \( t_{\text{cool}} = 1/\sqrt{G\rho_{\text{cloud}}} \). Using Eq. 8, \( Q_{\text{disk}} = \Sigma_{\text{disk}}/\rho_{\text{disk}} = \Omega_{\text{disk}}\Sigma_{\text{disk}}/\sigma_{v,\text{disk}}^2 = G^{-1/2}Q_{\text{disk}}^{1/2} \). Since \( Q_{\text{disk}} \approx 1 \), \( t_f = 1/\sqrt{G\rho_{\text{disk}}} = Q_{\text{disk}}^{1/2} \Omega_{\text{disk}}^{-1} = 1/3\Omega_{\text{disk}}^{-1} \).
regimes of disk evolution: When $D < 1/3$, cloud collision cooling is inefficient, and gas is stretched into filamentary structures due to shear. When $D >> 1/3$, cloud collision cooling is efficient, and the disk fragments into clumps. Therefore, efficient cooling ($D >> 1/3$) is the necessary condition for clump formation.

When $D < 1/3$, the clouds do collide, but the rate of the collision is relatively low, and energy dissipation from the cloud-cloud collisions is negligible. Thus the impact of cloud-cloud collisions on the disk dynamics is relatively insignificant.

When $D >> 1/3$, on the microscopic scale, we expect to see the clouds collide with each other at a high frequency, which is much higher than the angular frequency of the disk. Because cooling dissipates the kinetic energy, we expect to see the clouds move collectively, and it is the collective motion of the clouds that leads to the formation of the giant clumps.

Therefore, what distinguishes a clumpy galaxies with normal spiral galaxies is the value of the $D$ parameter. A normal, spiral galaxy does not fragment into clumps since the cloud-cloud collisions in these galaxies are not yet able to cool down the disk within a dynamical time, and in clumpy galaxies, the cooling due to cloud-cloud collisions is efficient which enables the disk to fragment.

Note that the dissipation parameter $D$ is inversely proportional to the metallicity (Eq. 12). In other words, galaxies with higher metallicities will dissipate their kinetic energy faster compared to galaxies with lower metallicities. This can be understood as follows: when one increases the metallicity, the molecular clouds require a lower surface density to shield against the background radiation field, the clouds are thus less condensed. They have lower surface densities, and are more like to collide with each other. This leads to a higher rate of cloud-cloud collisions and a more efficient disk cooling.

2.6 Driving of molecular cloud turbulence

In previous models of galactic disks (e.g. Romeo et al. 2010; Elmegreen & Burkert 2010; Klessen & Hennebelle 2010; Elmegreen 2011; Forbes et al. 2014), it has been assumed that the kinetic energy in the disk can be efficiently dissipated into heat due to turbulence dissipation. In our model, the kinetic energy of the disk is contained in the random motions of the clouds, and it is converted into molecular cloud turbulence due to cloud-cloud collisions. In the final step, molecular cloud turbulence is dissipated into heat. The cloud-cloud collisions become a first step in the whole energy conversion process, followed by turbulence dissipation. This is illustrated in Fig. 3. As an estimate, the energy dissipation rate (of unit erg g$^{-1}$ s$^{-1}$) of a galactic disk due to cloud-cloud collisions is (Eq. 6)

$$\dot{\varepsilon}_{\text{disk}} = \frac{\sigma_{v, \text{cloud}}^2}{t_{\text{cool}}} \approx \frac{\rho_{\text{disk}} \sigma_{v, \text{disk}}^2}{\Sigma_{\text{cloud}}}.$$  

(13)

Molecular clouds in the Milky Way and presumably other galaxies are characterised by the Larson relation (Larson 1981; Mac Low & Klessen 2004) where, roughly speaking $\sigma_{v, \text{cloud}} \sim l^{1/3}$ where $\sigma_v$ is the velocity dispersion of a molecular cloud and $l$ is the size. Assuming the kinetic energy of
According to our analysis, whether a disk will fragment into clumps is determined by the $D$ parameter. To estimate $D$, we collect data from the literature, and the collected values are listed in Table 2. Through cosmic times, the metallicity of galaxies are determined by the interplay between cosmological gas inflow and metal production due to star formation, and it does not evolve by much. On the other hand, the surface density of the disks $\Sigma_{\text{disk}}$ evolve by a factor of $\sim 100$. Practically speaking, it is the variation of $\Sigma_{\text{disk}}$ that drives the galaxies to evolve differently, where clumps appears preferentially in gas-rich disks.

To look at interplay between cloud collision cooling and disk dynamics in different galaxies. We adopt the following terms:

- Cloud: the term “cloud” refers to typical Milky-Way molecular clouds where for each object there is a dominant emitting structure. The sizes of the clouds should also be smaller than a fraction of the disk scale height.
- Complex: the term “complex” refers to larger, centrally condensed structures where they are allowed to have multiple emitting peaks. However, different from the clumps, they reside in the close vicinity of the spiral arms.
- Clump: the term “clump” is reserved for clumps in gas-rich disks where the sizes of the structure are comparable or larger than disk scale-height.

In our picture, clouds are objects that are ubiquitous in different galaxies. When $D$ is larger ($D \gtrsim 1$), they organise into complexes that stay along the spiral arms, and when $D >> 1/3$, they form clumps. These different regimes are summarized in Fig. 4.

When $D < 1/3$ ($\Sigma_{\text{disk}} < 1/3 \Sigma_{\text{cloud}}$), cloud collision cooling is slow (where, by definition, the time for a cloud to collide with another cloud is longer than the disk dynamical time). The gas clouds coagulates slowly, and at the same time they are sheared apart by the disk differential rotation. This slow coagulation process can produce clouds characterised by power-law mass distributions where small clouds dominate in number Kwan & Valdes (1983). This is the case for gas in interarm region of the Milky Way and M51. In this regime, one expects to observe some instances of cloud-cloud collisions. In fact, such collision candidates has been reported in the literate (Duarte-Cabral et al. 2011; Nakamura et al. 2012; Torii et al. 2015; Fukui et al. 2017; Gong et al. 2017). Such collisions can also produce rotating clouds, as observed in Li et al. (2017); Liu (2017). But we should note that in the majority of the cases one should expect to observe a smaller cloud nudging a larger cloud (Dobbs et al. 2012). Because of shear, one should also see long gas filaments that are parallel to the disk mid-plane. These filaments are also seen (Li et al. 2013; Goodman et al. 2014; Ragan et al. 2014; Wang et al. 2015; Zucker et al. 2015; Wang et al. 2016; Li et al. 2016; Abreu-Vicente et al. 2016), and are predicted by theories (Pringle et al. 2001; Smith et al. 2014; Dobbs 2015).

At some high-density regions such as the spiral arms, $\Sigma_{\text{disk}}$ starts to approach $1/3\Sigma_{\text{cloud}}$ and the velocity dispersion is also locally enhanced due to the spiral density wave. As a result, cloud-cloud collisions become frequent. Molecular clouds start to collide frequently within a relatively short

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8 Here we are interested in the normalisation of the Larson relation, and do not consider the effect of fractal-like underlying density structures on the slope of the Larson relation. Details concerning this can be found in Kritsuk et al. (2007).

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**Figure 3.** A illustration of the proposed energy flow. On the disk scale, the energy dissipation is dominated by cloud collision cooling. The cooling time is $t_{\text{cool}} \approx \lambda_{\text{cloud}}/\sigma v_{\text{cloud}}$, where $\lambda_{\text{cloud}}$ is the mean free path of a molecular cloud in the disk, and $\sigma v_{\text{cloud}}$ is the velocity dispersion of the disk collision cooling converts the kinetic energy of the disk into turbulence in molecular clouds. On the cloud scale, it is the major cooling mechanism is the turbulence energy dissipation, which converts the turbulence energy into heat. The characteristic timescale of turbulence dissipation is $t_{\text{diss}} \approx \lambda_{\text{cloud}}/\sigma v_{\text{cloud}}$, where $t_{\text{diss}}$ is the size of the cloud and $\sigma v_{\text{cloud}}$ is the velocity dispersion of a cloud. Turbulence finally converts kinetic energy of the clouds into heat. On the Kolmogorov microscale where turbulence cascades stops, the kinetic energy is dumped into heat that is dissipated due to radiative cooling.

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**3 COMPARISON TO OBSERVATIONS**

According to our analysis, whether a disk will fragment into clumps is determined by the $D$ parameter. To estimate $D$, we collect data from the literature, and the collected values are listed in Table 2. Through cosmic times, the metallicity of galaxies are determined by the interplay between cosmological gas inflow and metal production due to star formation, and it does not evolve by much. On the other hand, the surface density of the disks $\Sigma_{\text{disk}}$ evolve by a factor of $\sim 100$. Practically speaking, it is the variation of $\Sigma_{\text{disk}}$ that drives the galaxies to evolve differently, where clumps appears preferentially in gas-rich disks.

To look at interplay between cloud collision cooling and disk dynamics in different galaxies. We adopt the following terms:

- Cloud: the term “cloud” refers to typical Milky-Way molecular clouds where for each object there is a dominant emitting structure. The sizes of the clouds should also be smaller than a fraction of the disk scale height.
- Complex: the term “complex” refers to larger, centrally condensed structures where they are allowed to have multiple emitting peaks. However, different from the clumps, they reside in the close vicinity of the spiral arms.
- Clump: the term “clump” is reserved for clumps in gas-rich disks where the sizes of the structure are comparable or larger than disk scale-height.

In our picture, clouds are objects that are ubiquitous in different galaxies. When $D$ is larger ($D \gtrsim 1$), they organise into complexes that stay along the spiral arms, and when $D >> 1/3$, they form clumps. These different regimes are summarized in Fig. 4.

When $D < 1/3$ ($\Sigma_{\text{disk}} < 1/3 \Sigma_{\text{cloud}}$), cloud collision cooling is slow (where, by definition, the time for a cloud to collide with another cloud is longer than the disk dynamical time). The gas clouds coagulates slowly, and at the same time they are sheared apart by the disk differential rotation. This slow coagulation process can produce clouds characterised by power-law mass distributions where small clouds dominate in number Kwan & Valdes (1983). This is the case for gas in interarm region of the Milky Way and M51. In this regime, one expects to observe some instances of cloud-cloud collisions. In fact, such collision candidates has been reported in the literate (Duarte-Cabral et al. 2011; Nakamura et al. 2012; Torii et al. 2015; Fukui et al. 2017; Gong et al. 2017). Such collisions can also produce rotating clouds, as observed in Li et al. (2017); Liu (2017). But we should note that in the majority of the cases one should expect to observe a smaller cloud nudging a larger cloud (Dobbs et al. 2012). Because of shear, one should also see long gas filaments that are parallel to the disk mid-plane. These filaments are also seen (Li et al. 2013; Goodman et al. 2014; Ragan et al. 2014; Wang et al. 2015; Zucker et al. 2015; Wang et al. 2016; Li et al. 2016; Abreu-Vicente et al. 2016), and are predicted by theories (Pringle et al. 2001; Smith et al. 2014; Dobbs 2015).

At some high-density regions such as the spiral arms, $\Sigma_{\text{disk}}$ starts to approach $1/3\Sigma_{\text{cloud}}$ and the velocity dispersion is also locally enhanced due to the spiral density wave. As a result, cloud-cloud collisions become frequent. Molecular clouds start to collide frequently within a relatively short
time to form larger aggregates and produces complexes. The cloud collision cooling can reduce the overall velocity dispersion of molecular gas in the disks which leads to dynamical cooling. Since the disks have just reached the condition for cloud-cloud collisions to be frequent, one needs other processes such as spiral density waves to enhance to density. As a result, these structures are formed along the spiral arms. It is believed that wiggle-like regular-spaced structures seem on the arms of the grand-design spiral galaxy M51 are produced in this way (Dobbs 2008). Molecular complexes in the Milky Way such as W43 and W51 might also belong to this category. In this regime, cloud collision cooling has some influences on the disk dynamics. But these influences are restricted to the close vicinity of the spiral arms where the densities are enhanced.

For a typical massive, gas-rich disk, the cloud collision time is much shorter than the disk dynamical time \((D >> 1/3, \Sigma_{\text{disk}} >> 1/3 \Sigma_{\text{cloud}})\), typically the cloud collision time is shorter than the disk dynamical time by a factor of \(3-10\) at almost everywhere in the disk. Cloud collision cooling rapidly removes kinetic energy from the disk and allows the high-density regions (typically of \(~\) kpc size) to contract from the large scale. The contraction retrospectively enhances the cloud collision rate. This positive feedback enables the masses of the high-density regions to grow rapidly. Thus the clump formation at \(D >> 1/3\) is an non-linear process, where cloud collision cooling starts to back-react on the disk dynamics on the large scale and enables these large perturbations to grow. In this cooling-efficient regime, the clumps are formed by the collective motion of the clouds. One should be able to clumps whose sizes are comparable to the Toomre length \((\text{Toomre} 1964, \ell_{\text{toomre}} \approx 2\pi G \Sigma_{\text{disk}}/\Sigma_{\text{cool}}^2)\), which characterises the sizes of the large-scale perturbations in the disks), as has been reported by a recent observation (Fisher et al. 2017).

4 CONCLUSION

We study the evolution of galactic disks, and aim to understand the formation mechanism of the kpc-sized giant clumps commonly observed in gas-rich disks. We argue that since galactic disks are self-regulating systems where the equation of state is highly non-isothermal, the Toomre \(Q\) parameter does not provide useful information on how the disk would fragment. Rather, it is the cooling time that matters: When cooling is inefficient, gas in the disk organises into filamentary structures that are constantly stretched apart by disk differential rotation; when cooling is efficient, the disk fragment into giant clumps.

We propose that the major mechanism that leads to cooling of a gas-rich, molecular galactic disk is the coagulation (collision) between molecular clouds. This is because the collisions are inelastic, such that a collision would convert the kinetic energy contained in the relative motions into turbulent motions in the molecular clouds. On the disk scale, this constitutes an efficient way to remove kinetic energy. Following Elmegreen (1989), we name this process cloud collision cooling. Cloud collision cooling is the major mechanism that leads to clump formation. Compared to cloud collision cooling, radiative cooling is not important for the global stability of the disks, as it merely removes the thermal energy and drives phase transitions, but can not directly remove the kinetic energy of the disk.

The effectiveness of cloud collision cooling is characterised by the \(D\) (dissipation) parameter:

\[
D = \frac{\Sigma_{\text{cool}} \Omega_{\text{disk}}}{\Sigma_{\text{disk}} Z M_{\odot} \text{pc}^{-2}},
\]

where \(\Sigma_{\text{disk}}\) is the mean surface density of the galactic disk, and \(\Sigma_{\text{cool}}\) is the typical surface density of a molecular cloud in the disk, and \(Z\) is the metallicity. The \(D\) parameter is a fundamental parameter that determines the disk evolution: When \(D < 1/3\) \((\Sigma_{\text{disk}} < 1/3 \Sigma_{\text{cool}}, \Sigma_{\text{cool}} < 3 \Sigma_{\text{disk}}^{-1})\), the disk should enter a state where shear stretches gas into long, filamentary structures. When \(D > 1/3\) \((\Sigma_{\text{disk}} > 1/3 \Sigma_{\text{cool}}, \Sigma_{\text{cool}} < 3 \Sigma_{\text{disk}}^{-1})\), molecular clouds in a disk form a system that is highly dissipative where energy is dissipated due to cloud collision cooling (cloud-cloud collisions). In this regime, efficient cooling enables the disk to contract on the large scale (which is comparable to the Toomre length), and the clumps are formed because of the local contraction of the disk. Therefore, what distinguishes between a clumpy galaxy and a spiral galaxy is the rate of cloud collision cooling, and clumpy galaxies are clumpy because of cloud-cloud collisions can remove kinetic energy from the disk within a dynamical time. In practise, \(\Sigma_{\text{cool}}\) is determined by the metallicity of a galaxy, and does not evolve significantly. As a result, variations in surface densities of galactic disks \(\Sigma_{\text{disk}}\) is the major cause for different disks to fragment differently.

We have made an effort to understand how the multi-phase ISM dissipates its kinetic energy. The current analysis is carried out in a simplified model, and the dissipation rate estimates are accurate only in the order of magnitude sense. Nevertheless, when the gas is separated into different phases, we expect system to be (almost-)dissipationless when \(D < 1/3\) and dissipative when \(D > 1/3\), and we expect the transition to occur when the surface density of the galactic disk starts to exceed the mean surface density of the molecular clouds by much. Understanding this transition is of crucial importance for understanding the interplay between the ISM and the disk dynamics, and this issue deserves further studies.

Theoretically, one can derive the cloud collision cooling rate using local, shearingbox-like simulations. This would be a crucial test to our model. Once this is verified to a better accuracy, the cooling time estimates can be incorporated into simulations of lower resolutions as subgrid models, and into analytical models to study the fragmentation in different regimes. Such approaches have been previously made Booth et al. (2007), and one should make parameter studies and extend it to simulate formation of the clumps.

Observationally, one can test our scenario by constraining the properties of the molecular clouds and study their interactions in different galactic environments. The prop-

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9 We note that there are alternative explanation to these wiggle, where they come from the wiggle (Kelvin-Helmholtz) instability (Wada & Koda 2004; Dobbs & Bonnell 2006; Shetty & Ostriker 2006; Kim & Ostriker 2006). It seems unclear how Kelvin-Helmholtz instability can develop in such a multi-phased ISM where the equation of states are poorly defined. Therefore, we prefer the explanation provided Dobbs (2008) where these spurs are produced by cloud collisions.
properties of the clouds can be constrained by high-resolution CO observations. The actual cloud collision process can be traced using transitions of shock-tracing molecules such as SiO and methanal. Systematic studies of cloud evolution using these tracers will help to constrain the cooling process.

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Giant molecular clump and molecular cloud collisions

Inefficient cooling
Low rate of cloud collision
Clouds are separated

Efficient cooling
Moderate rate of cloud collision
Clouds are concrete in complexes

Efficient cooling
High rate of cloud collisions
Clouds concentrate in clumps

Figure 4. Different regimes of cloud collision cooling. In regions like the M51 interarm region (see the highlighted box of the image on the left), cloud collision cooling is relatively inefficient ($D < 1/3, t_{\text{cool}} > 3t_{\text{kep}}^{-1}$, which correspond to $\Sigma_{\text{disk}} < 1/3\Sigma_{\text{cloud}}$), and larger clouds are build by slowly accreting smaller clouds. At higher collision rates, cloud collision cooling is responsible for the formation of kpc-size molecular complexes seen on the spiral arms of the M51 galaxy (see the highlighted box in the middle) and for the formation of kpc-size giant clumps seen in gas-rich galaxies (e.g. the clumps seen in the galaxy on the right). In the cooling-efficient regimes (middle and right panels), $D > 1/3, t_{\text{cool}} > 3t_{\text{kep}}^{-1}$ (which also correspond to $\Sigma_{\text{disk}} < 1/3\Sigma_{\text{cloud}}$), and cloud collision cooling can effectively remove kinetic energy from the disk within a dynamical time, which enables the disk to contract locally and form giant clumps. Image credit: The images of M51 galaxy are reproduced from the velocity-integrated $^{12}\text{CO}(1-0)$ data presented in Schinnerer et al. (2013). The image of the clumpy galaxy is reproduced from the Galaxy Zoo project (Fortson et al. 2012), where the data is produced by the Sloan Digital Sky Survey [http://www.sdss.org]. The reuse of the figure is granted by the Creative Commons Attribution-Noncommercial-No Derivative Works 2.0 UK. See Sec. 3 for details.