PASJ: Publ. Astron. Soc. Japan **58**, 793–796, 2006 October 25

Threshold between Spontaneous and Cloud-Collisional Star Formation

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(Received 2006 April 24; accepted 2006 August 8)

Abstract

Based on simple physical and geometric assumptions, we have calculated the mean surface molecular density of spiral galaxies at the threshold between star formation induced by cloud-cloud collision and spontaneous gravitational collapse. The calculated threshold is approximately $\log\Sigma_{\rm crit} \sim 2.5$, where $\Sigma\,[M_\odot\,{\rm pc}^{-2}]$ is the observed surface mass density of an assumed flat gas disk. Above this limit, the rate of molecular cloud collisions dominates over spontaneous molecular cloud collapse. This model may explain the apparent discontinuity in the Schmidt law found recently at $2 \lesssim \log\Sigma \lesssim 3$.

Key words: galaxies: ISM — ISM: molecules — stars: formation

1. Spontaneous and Collisional Star Formation

The beginning of star formation within an ensemble of molecular clouds is thought to have two modes, spontaneous (stochastic) gravitational collapse (Bonnell et al. 2004; Krumholz, McKee 2005) and collisions between molecular clouds (e.g., Tan 2000). Most studies to date have focused on one of these two possibilities. In actual physical situations, which cover a range of physical parameters, these two processes should both have effect on the overall star formation in galaxy disks. In regions of higher molecular density, collisions should become dominant over spontaneous formation, because collisions will occur on time scales shorter than spontaneous star formation. In regions with scarce cloud number density, collisions should also be rare, and therefore star formation from other stochastic means should dominate. The transition from spontaneous to collisional star formation may have observable effects on the relation between the molecular gas content and the star formation rate (SFR). However, this expected transition has not been clearly observed yet.

There is growing observational evidence to indicate that cloud collision can trigger star formation (Loren 1976; Scoville et al. 1986; Hasegawa et al. 1994; Koda, Sofue 2006). These studies show that cloud collisions are seen mainly in high-density regions, and therefore merging and interacting galaxies are candidates for galaxies forming stars mainly by collision. A comparison of these galaxies with normal galaxies was conducted by Young et al. (1986). They found that merging/interacting galaxies exhibit SFRs that are an order of magnitude higher than normal galaxies of the same molecular gas density. Similarly, central regions and spiral arms of normal galaxies, which generally have high molecular densities, may include star formation induced by collision. However, quantitative calculations that give direct (observable) parameters exactly *where* in parameter space star formation transits from spontaneous to collisional mechanisms have not been proposed.

2. Model

We consider a spiral galaxy that can be modeled as a thin disk. We take a cylinder of height $2d$ and base area S within the same plane as the galaxy disk (see schematic figure 1). We can think of d as the scale height, and S as the area of the deprojected beam of the observation. Within this cylinder are n spherical molecular clouds with diameter D, mass M, and mean molecular density ρ. Assuming that the observer can see through the disk and derive a surface molecular gas density Σ, the obvious equations are:

$$\Sigma = \frac{nM}{S}, \tag{1}$$

$$M = \frac{4\pi}{3}\left(\frac{D}{2}\right)^3 \rho. \tag{2}$$

These molecular clouds are moving about inside the cylinder with an inter-cloud velocity dispersion σ.

For further analysis, we have several simple assumptions:

- star formation occurs on the free-fall time scale, dependent only on the initial density,
- molecular clouds are moving about within the thin cylinder in random motion,

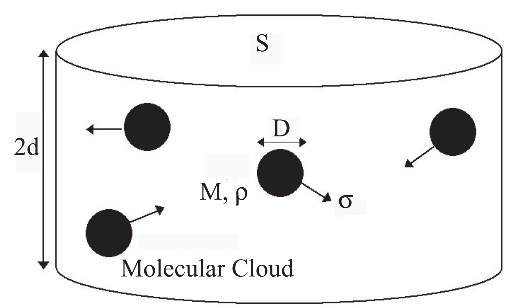

Fig. 1. Schematic picture of the model. The base of the cylinder is parallel to the galactic disk. Each of the molecular clouds has size D, mass M, density ρ, and mean velocity dispersion σ.

- star formation in galactic disks is a two-dimensional process.

The third assumption is motivated by the fact that giant molecular clouds have sizes comparable to the scale height, d (Malhotra 1994; Stark, Lee 2005). We can therefore assume that all processes occur in two dimensions and we can hereafter ignore d.

We have

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}, \tag{3}$$

where $t_{\rm ff}$ is the free-fall time scale and G the gravitational constant. Collisions between molecular clouds should have a mean free path of $\lambda_{\rm mfp}$, for two dimensions, given by

$$\lambda_{\rm mfp} = \frac{1}{\sqrt{2}ND}, \tag{4}$$

where $N = n/S$ is the number density of molecular clouds. A galactic molecular cloud (GMC) harboring spontaneous star formation will move a linear distance of $\sigma t_{\rm ff}$ during its formation of stars. In a regime where spontaneous star formation is dominant over collision, the parameters should satisfy the relation

$$\sigma\, t_{\rm ff} \ll \lambda_{\rm mfp}, \tag{5}$$

so that the GMC does not collide with other GMCs during formation. On the other hand, a regime where collision is dominant should satisfy

$$\sigma\, t_{\rm ff} \gg \lambda_{\rm mfp}. \tag{6}$$

Therefore, if a threshold exists between these two regimes, the parameters should satisfy the equation

$$\sigma\, t_{\rm ff} \approx \lambda_{\rm mfp}. \tag{7}$$

Substituting equations (1) through (4) into (7) and denoting the critical Σ as $\Sigma_{\rm crit}$, we obtain

$$\log\frac{\Sigma_{\rm crit}}{[M_\odot]} = -1.35 + 2\log\frac{D}{[\rm pc]} + 1.5\log\frac{\rho}{[M_\odot\,\rm pc^{-3}]} - \log\frac{\sigma}{[\rm km\,s^{-1}]}. \tag{8}$$

3. $\Sigma_{\rm crit}$ Value

We now apply actual values to equation (8). For typical Galactic molecular clouds with $D \sim 60$ pc and $\rho \sim 30\,\rm cm^{-3} = 1.5\,M_\odot\,pc^{-3}$, and an inter-cloud velocity dispersion of $\sigma \sim 4\,\rm km\,s^{-1}$, we obtain $\log\Sigma_{\rm crit} = 1.91\,M_\odot\,\rm pc^{-2}$. For observed molecular surface densities above this value, collisions dominate.

We can further reduce the number of variables. Dame et al. (1986) found that for Galactic molecular clouds, ρ scales with D such that $\log\rho = 2.80 - 1.32\log D$. Substituting this relation into equation (8) gives

$$\log\frac{\Sigma_{\rm crit}}{[M_\odot]} = 2.85 + 0.02\log\frac{D}{[\rm pc]} - \log\frac{\sigma}{[\rm km\,s^{-1}]}. \tag{9}$$

Table 1. Derived values of $\Sigma_{\rm crit}$.*

D [pc]	σ [$\rm km\,s^{-1}$]	$\log\Sigma_{\rm crit}$ [$M_\odot\,\rm pc^{-2}$]
10	1	2.87
	5	2.17
	10	1.87
100	1	2.89
	5	2.19
	10	1.89

* D, the diameter of molecular clouds, is taken so that it may represent the smallest (10 pc) and largest (100 pc) clouds. σ from the literature ranges from $4\,\rm km\,s^{-1}$ (Liszt, Burton 1981; Clemens 1985) to $7\,\rm km\,s^{-1}$ (Stark, Brand 1989), but we take values from 1 to $10\,\rm km\,s^{-1}$ to demonstrate the range of the values which $\Sigma_{\rm crit}$ may have.

It is apparent from equation (9) that the critical density is practically independent of the GMC diameter. The critical surface density is dependent mainly on the cloud velocity dispersion, σ, which is generally taken to be below $10\,\rm km\,s^{-1}$. Table 1 lists the values of $\Sigma_{\rm crit}$ for a range of parameters to evaluate the lowest and highest cases.

Errors for this value can be evaluated based on the uncertainty of the parameters. Velocity dispersions σ derived from other numerical and observational studies have agreed-upon values of between $1\,\rm km\,s^{-1}$ and $10\,\rm km\,s^{-1}$. The value of D, which must be taken so that D is representative of the size that dominates star formation, is between 10 pc and 100 pc, although the uncertainties in D have little effect on $\Sigma_{\rm crit}$. On the average, we may safely apply errors so that $\Sigma_{\rm crit} = 2.8^{+0.1}_{-1.0}$

4. Comparison with Observation

The empirical relation between the gas density and SFR, often referred to as the Schmidt law, has long been studied, and a relation of the form $\Sigma_{\rm SFR} \propto \Sigma^N$, where $\Sigma_{\rm SFR}$ is the area-averaged SFR, has been extensively studied. Details can be found elsewhere (e.g., Buat et al. 1989; Buat 1992; Kennicutt 1998; Rownd, Young 1999; Wong, Blitz 2002; Boissier et al. 2003; Yao et al. 2003; Gao, Solomon 2004; Heyer et al. 2004). This law, however, owes its dynamic range to the contrast between starburst galaxies and normal spiral galaxies. Since the starbursts have higher molecular density, whereas normal spirals have considerably lower molecular density, the combination of these two types of galaxies contributes dominantly to the linear fit of the Schmidt-type power law.

Any systematic differences in the Schmidt law between these two types of galaxies are ignored by fitting both with the same function. Indeed, a possible significant difference in these two types of galaxies was found by Komugi et al. (2005) by a study of high molecular density central regions of normal spirals. The Schmidt law, with normal galaxies and circumnuclear starbursts superposed, is shown in figure 2.

An apparent discontinuity exists in the two sequences, and the critical surface density, $\Sigma_{\rm crit} = 2.8^{+0.1}_{-1.0}$, shown as a vertical line, coincides with the transition. Assuming that this apparent transition is real, it may be explained by a change in the physical nature of star formation, namely the transition from spontaneous to cloud-cloud collisional star formation, induced by an increase in molecular density.

It must be pointed out that the SFR for circumnuclear starbursts is derived from the far-infrared (FIR) luminosities, and those of normal galaxies from the internal extinction corrected Hα luminosities [see Komugi et al. (2005) for details].

These two methods of deriving the SFR are known to differ, in the sense that FIR gives systematically higher SFRs compared to Hα. FIR-derived SFRs overestimate the *true* current SFR because it is contaminated with emission from dust heated by lower mass stars. Hα emission is subject to interstellar dust extinction, therefore underestimating the current SFR. These may lead the reader to believe that the discontinuity is not a *true* one due to physical processes. In figure 2, however, the SFR for normal galaxies is derived from the internal extinction-corrected Hα luminosity, found by Kewley et al. (2002) to agree with FIR based SFR within 10%. The order-of-magnitude offset between the two types of galaxies therefore cannot be attributed to such observational shorthands. The unaccountable offset may be due to differences in the physical process of star formation. Elmegreen (1989) has suggested that a decrease by a factor of 4 in $t_{\rm ff}$ will occur at a shocked surface of a molecular cloud, and this can account for much of the rise in SFR for starbursts, which lies in the "collision" regime in figure 2.

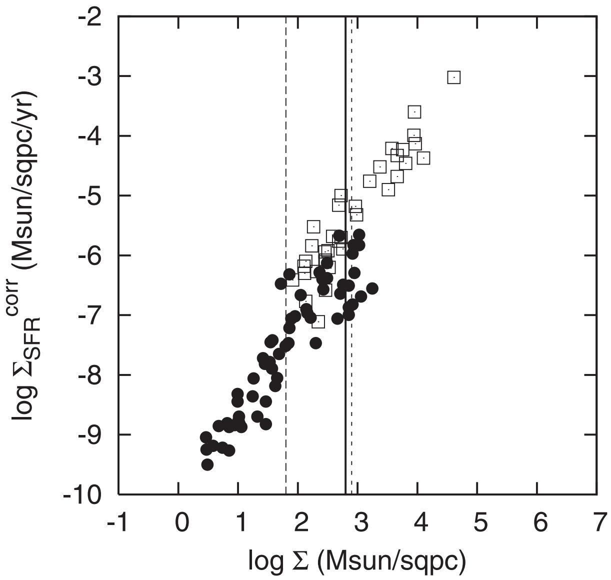

Fig. 2. Schmidt law, from Komugi et al. (2005). Abscissa is $\log\Sigma\ M_{\odot}\,{\rm pc}^{-2}$ and ordinate $\log\Sigma_{\rm SFR}\ M_{\odot}\,{\rm yr}^{-1}\,{\rm pc}^{-2}$. The filled circles represent normal galaxies and the open squares represent circumnuclear starbursts. The center vertical line is the value for $\Sigma_{\rm crit}$ = 2.8, where the dashed lines represent errors, as stated in the text.

5. Discussion

5.1. Other Parameters

The simplicity of equation (7) poses a question of whether this analysis is an oversimplification. Therefore, we go on to consider other parameters that may modify equation (7). The basic assumptions made in section 1 is that star formation occurs on the free-fall time scale $t_{\rm ff}$, but the time scale of star formation is still an unresolved issue, and studies often give longer time scales than $t_{\rm ff}$. Second, we have assumed a random motion of the molecular clouds based on epicyclic motion of the clouds, while in reality the differential rotation in galactic disks is also important concerning the overall motion of clouds.

The star-formation time scale, $t_{\rm sf}$, is equal to $t_{\rm ff} \sim 10^6$ yr when star formation is dominated by gravitational perturbations, and this type of formulation, $t_{\rm sf} \sim t_{\rm ff}$, has been adopted in many studies. Other studies argue that $t_{\rm sf}$ is longer than $t_{\rm ff}$ because magnetic fields provide support against gravitational contraction, and star formation is impossible without ambipolar diffusion (Tan 2000), in which case the star-formation time scale is longer by an order of magnitude (McKee, Holliman 1999). Still, some observational studies suggest that star formation occurs on scales of $\sim 10^6$ yr, based on the observed offset between CO and Hα arms in spirals (Egusa et al. 2004). This issue is not resolved, and we adopt $t_{\rm sf} \sim t_{\rm ff}$ for the sake of simplicity. However, if $t_{\rm sf} > t_{\rm ff}$ by an order or more, collisional star formation will dominate at a much lower observed density of about $\Sigma_{\rm crit} = 1.8 - \log\sigma$. The differential rotation of galactic disks causes molecular clouds to collide, as in the case of random motion. Gammie, Ostriker, and Jog (1991) find $\sigma = 5.1\,{\rm km\,s^{-1}}$ for cloud encounters owing to differential rotation, whereas random velocity dispersion of GMCs is $\sim 7\,{\rm km\,s^{-1}}$ (see Stark, Brand 1989), or $\sim 4\,{\rm km\,s^{-1}}$ (Liszt, Burton 1981; Clemens 1985). Therefore, we can say that the value of the cloud collision velocity, σ, is comparable even with the assumption of differential rotation.

5.2. Mergers and Interacting Galaxies

The argument of threshold surface density proposed in this paper cannot specify what kind of change will appear in the $\Sigma_{\rm SFR}$–Σ relation, such as that seen in figure 2. The discontinuity may well be the result of a transition from spontaneous to collisional star formation, but our results do not predict or necessitate a discontinuity. A sudden rise in SFR as collision dominates, however, is physically intriguing and easy to understand. In a collision between two GMCs, the shocked region between the clouds is compressed so that the density abruptly becomes higher in this layer compared to other parts of the GMC. This will shorten $t_{\rm ff}$, and consequently the SFR is higher. Elmegreen (1989) finds that $t_{\rm ff}$ is shortened by four times; this should appear as a discontinuity in the Schmidt law.

In this respect, it is reasonable to expect that merging and interacting galaxies form stars mainly by cloud-cloud collision, and therefore exhibit higher SFR than galaxies with the same molecular gas density. In these systems, the critical density, $\Sigma_{\rm crit}$, is far lower than that of normal spirals, because GMCs in colliding galaxies will have a far higher collision velocity, σ. In a collision between two spirals, the typical rotation velocity of the galaxies will become representative of σ, with about $\sim 200\,{\rm km\,s^{-1}}$, depending on the sense of rotation of the colliding spirals. In this case, $\log\Sigma_{\rm crit}$ can be 0 to 1, the typical global surface molecular mass density of spirals, so that most of the star formation can be attributed to cloud-cloud collision.

6. Conclusion

We have constructed a simple model to consider the threshold between star formation dominated by spontaneous gravitational collapse and cloud-cloud collision. Although both cloud-cloud collision and gravitational collapse processes have for decades been thought to cause star formation, the threshold of these two processes has not attracted much attention. Most studies of collisional star formation have focused on qualitative aspects. Numerical studies, such as that by Mazzei (1987), have pointed out a threshold, but with the contradictory result that collisions between clouds result in lower star-formation rates.

Our model, by assuming that star formation is a bimodal process dominated either by spontaneous gravitational collapse or cloud-cloud collision, does not take into account the possibility of star formation induced by expanding SNR shells (self-propagating star formation), or complicated structures in temperatures or chemistry. Simple as our model is, it succeeds in explaining the apparent discontinuity in the Schmidt law. Moreover, our formulation coupled with the empirical implication that most clouds are virialized, and thus the GMC size and mean density are anticorrelated, leads to the conclusion that the threshold surface mass density, $\log \Sigma_{\rm crit}$, is practically independent of the cloud parameters (size, density, and mass), but that it depends on the mean velocity dispersion, σ, of clouds.

Further tests of our formulation can be expected from observations of mergers. In merging spiral pairs, whose rotations are oriented in the reverse direction, the relative velocity of the clouds are increased so that, according to equation (9), collisional star formation starts at a very low surface mass density. However, if the rotation is oriented in the same direction, σ will not increase as much as in the reverse orientation. Thus, the threshold, $\log \Sigma_{\rm crit}$, starts at a higher density. Assuming that collisional star formation results in a discontinuity in the SFR relation with the surface gas density, we can compare mergers with these two orientations with average normal galaxies, which we can assume to be dominated by a spontaneous process. Then, we should see that mergers with reverse rotation orientation will start their discontinuity in the Schmidt law at a lower surface mass density than mergers with ordered rotation.

The authors thank H. Nakanishi, S. Onodera, and K. Kohno for fruitful discussions. S. K. and F. E. were financially supported by a Research Fellowship for Young Scientists from Japan Society for the Promotion of Science.

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