STAR FORMATION IN DISK GALAXIES. I. FORMATION AND EVOLUTION OF GIANT MOLECULAR CLOUDS VIA GRAVITATIONAL INSTABILITY AND CLOUD COLLISIONS

Tasker & Tan 2009, ApJ 700, 358 (2009)

STAR FORMATION IN DISK GALAXIES.II. THE EFFECT OF STAR FORMATION AND PHOTOELECTRIC HEATING ON THE FORMATION AND EVOLUTION OF GIANT MOLECULAR CLOUDS

Tasker 2011 , ApJ 730, 11 (2011)

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Introduction

- 星形成は銀河の性質を決める上で、もっとも重要な過程のひとつである
- 星形成は分子雲の中で生じる

→　星形成を理解するために、分子雲の形成・進化を理解する必要がある

- 巨大分子雲(Giant Molecular Cloud,GMC)の形成メカニズム

″ top-down” → large-scale gravitational disk instability(e.g.Shetty & Ostriker 2006; Kim et al 2003; Glover & Mac Low 2007a,2007b)

“bottom-up” → colliding flows(e.g.,Heitsch et al. 2008) or via agglomeration from inelastic collisions between clouds(Kwan 1979)

銀河の環境によって、どちらが重要か変わる

- 円盤銀河内での大部分の星形成(parsec scale)は、GMC-GMC collision によって圧力が高くなった領域で生じる(Tan 2000)
- GMC-GMC collisionは銀河内でのglobalなGMCの分布に依存している

→ globalな銀河のダイナミクスとparsec-scaleの星形成の間には関連がある

- 銀河サイズ(~ 10^4 pc)のシミュレーションで巨大分子雲(< 10 pc)の形成を追うのは非常に難しく、今までやられていなかった
- 今回reviewする２つの論文では、high-resolution (<10pc) global (20kpc) simulation with a fully multiphase atomic ISM

- Tasker & Tan 2009: 巨大分子雲の形成・進化をflat rotational curve disk galaxyのglobal dynamicsから考察する

  → model 1 : 重力不安定と分子雲の衝突・相互作用に注目、disk NoSF

- Tasker 2011: 巨大分子雲の性質に星形成とphotoelectric heatingが及ぼす影響を考察する

  → model 2 : model 1 + 星形成、 disk SFOnly

  → model 3 : model 2 + FUV photoelectric heating、disk SF+PEheat

Simulation

- コード:Enzo,三次元適合細分化格子(Adaptive Mesh Refinement)自己重力流体コード (Bryan&Norman 1997;Bryan 1999;O'shea et al.2004)
- 支配方程式：

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \overrightarrow{v}) = -\dot{\rho}_*$$

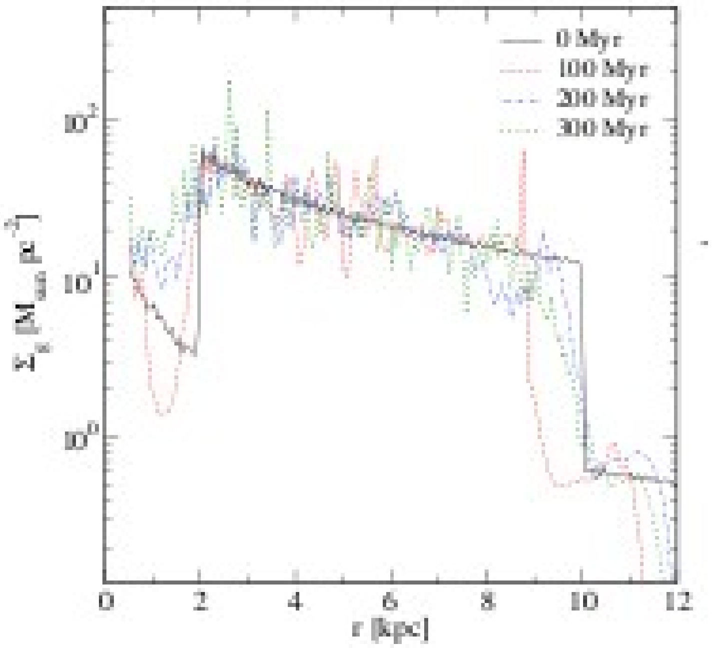
$$\frac{\partial \overrightarrow{v}}{\partial t} + (\overrightarrow{v} \cdot \nabla)\overrightarrow{v} = -\frac{1}{\rho}\frac{dP}{dt} - \nabla \Phi$$

$$\frac{\partial}{\partial t}\{\rho(\frac{1}{2}v^2 + \varepsilon + \phi)\} + \nabla \cdot \{\rho \overrightarrow{v}(\frac{1}{2}v^2 + h + \phi)\} = H - C$$

- シミュレーションスケール: 32[kpc]^3
- グリッド: 256^3 ,4段階の格子の細分化，最小のセルサイズ 7.8[pc]
- Time : 0 ~ 324 [Myr]
- Coolng: 10^4 [k] > T >300[K] → Rosen & Bregman 1995

  T > 10^4 [k] → solar metallicity cooling curve (Sarazin & White 1987)
- GMC definition : $n_H > 100\,\mathrm{cm}^{-3}$ 4cell以上

- 銀河ポテンシャル: flat rotation curve $\Phi = \frac{1}{2} v_{c,0}^2 \ln[\frac{1}{r_c^2}(r_c^2 + r^2 + \frac{z^2}{q_\phi^2})]$
- Circular velocity : $v_{c,0} = 200[km/s]$
- Initial vertical radial profile of the gas : $\rho(r,z) = \frac{\kappa \sigma_g}{2\pi G Q z_h} sech^2(\frac{z}{z_h})$
- Total gas mass : $6 \times 10^9 [\mathrm{M}_\odot]$
- Initial temperature : 7450[K]
- Initial velocity dispersion : $\sigma_g = 9.0[km/s]$
- Initial surface density :



- Initial Toomre stability parameter Q :

$$Q = \frac{\Sigma_{crit}}{\Sigma_g} = \frac{\kappa \sigma_g}{\pi G \Sigma_g}$$

$$\begin{cases} Q = 1.5 \;\; (2 < r < 10[pc]) \\ Q = 20 \quad (otherwise) \end{cases}$$

Result of disk NoSF

Evolution of Galactic Disk & GMC

- 最初にr=2kpc付近でring状の構造ができる → Toomre ring instability
- t=100[Myr]以降では、全体でcloud formationが起きる
- t=200[Myr] では、the main region of the disk (2.5~8.5[kpc])は完全にfragmentする

t=50[Myr] t=100[Myr] t=200[Myr] t=300[Myr]

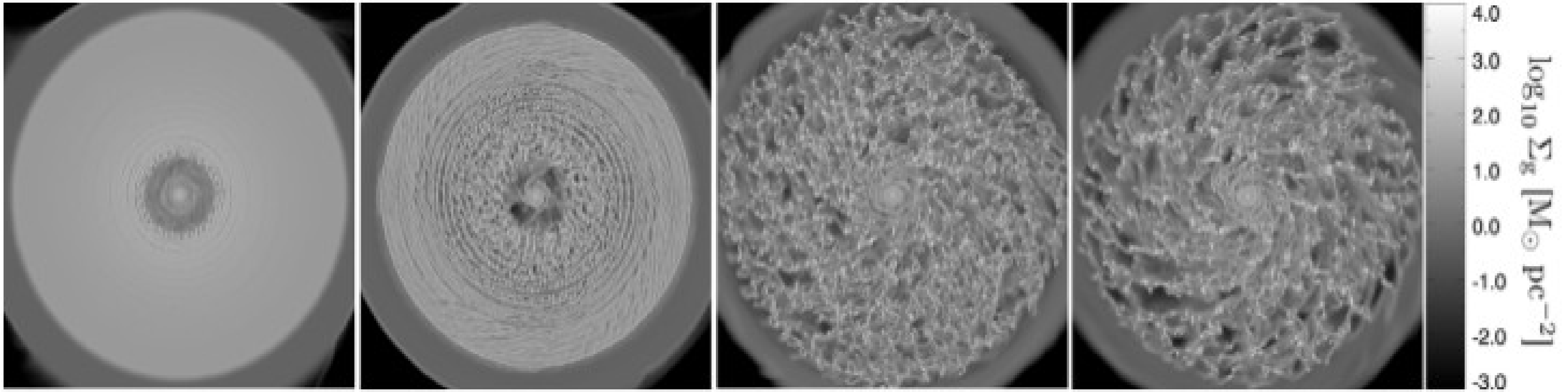


Figure 4. Evolution of the galactic disk. Images are 20 kpc across and show the disk gas mass surface density, Σ_g (integrated vertically over $|z| \leqslant 1$ kpc) at $t = 50$, 100, 200, and 300 Myr. The formation of rings via the Toomre instability is evident at earlier times. These rings fragment into individual clouds, which then suffer interactions via galactic differential rotation. The properties of the clouds in this fully fragmented stage ($t \gtrsim 140$ Myr) are the focus of this paper.

Radial Galactic Profiles

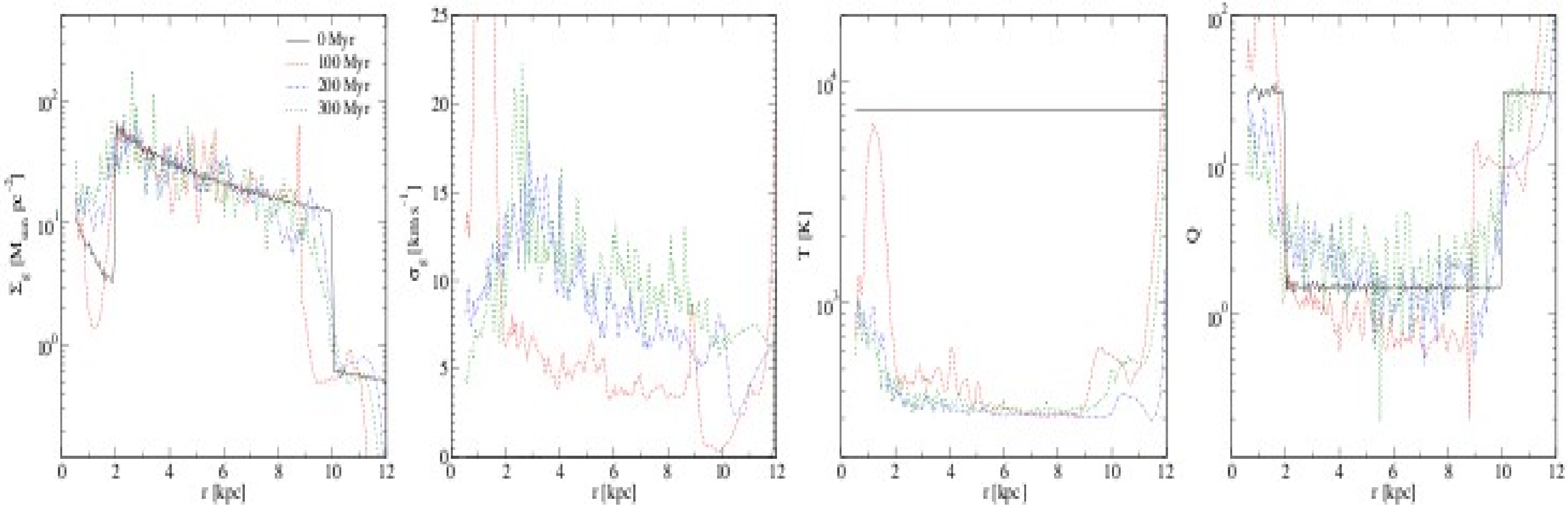


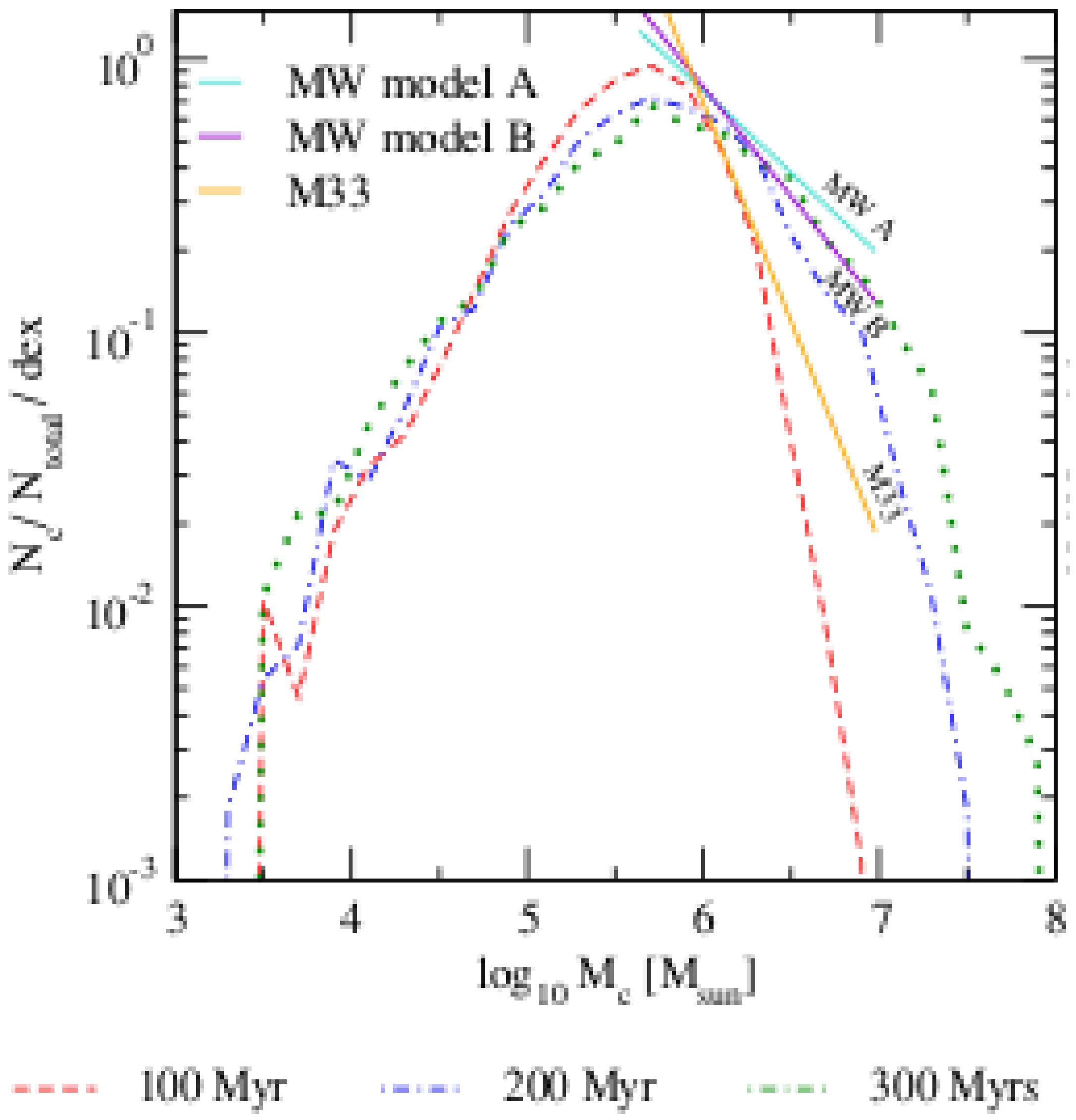
Figure 5. Galactic disk azimuthally averaged (60 pc wide annuli) radial profiles and their evolution; from left to right: (a) gas mass surface density, $\Sigma_g = \int_{-1\,\mathrm{kpc}}^{+1\,\mathrm{kpc}} \rho(z) dz$, (b) one-dimensional gas velocity dispersion, σ_g, (mass-weighted average over -1 kpc $< z <$ 1 kpc utilizing only disk plane velocity components), (c) gas temperature, T, (mass-weighted average over -1 kpc $< z <$ 1 kpc), (d) Toomre Q parameter, evaluated using Σ_g and σ_g.

GMC Properties

	observation	100[Myr]	200[Myr]	300[Myr]
Cloud(>10^6 Msun)の数	100 ~ 200	625	856	694
Cloud(>10^5 Msun)の数	~1000	-	-	-
cloudの半径	3~50[pc]	20~30[pc]		
Surface density	200~400 [Msun/pc^2]	~300[Msun/pc^2]		
Virial parameter	-	$\alpha_{vir} = \frac{< 2T >}{< U >} = \frac{5\sigma_c^2 R_{c,A}}{GM_c}$ ~0.6		
Vertical scale height	< 35[pc]	13[pc]	25[pc]	51[pc]

Other GMC properties agree well with obsevations , including velocity dispersion, angular momentum.

The distribution of cloud mass



William & McKee (1997) derived a cloud mass function of the from

$$\frac{d\mathcal{N}_c}{d\ln M_c} = \mathcal{N}_{cu}\left(\frac{M_c}{M_u}\right)^{-\alpha_c}$$

and estimate there are ~100-200 inner Milky Way GMCs with $M_c > 10^6 M_\odot$ and about 1000 with $M_c > 10^5 M_\odot$.

We find about 400 clouds with $M_c > 2 \times 10^6 M_\odot$

→lack of feedback processes?

threshold density?

The total number of clouds are 4300, 2770, 1840,respectively

Retrograde Cloud Population

- Phillips(1999) considered the rotational properties of Galactic GMC, finding a significant spread in the directions of the angular momentum vectors, indicating that a substantial fraction of GMCs rotate in a retrograde direction with respect to Galactic rotation.
- At early times, in the same sense as the galactic rotation.
- At later times, 分子雲の相互作用はretrograde cloud population を大きくする(全体の30%)

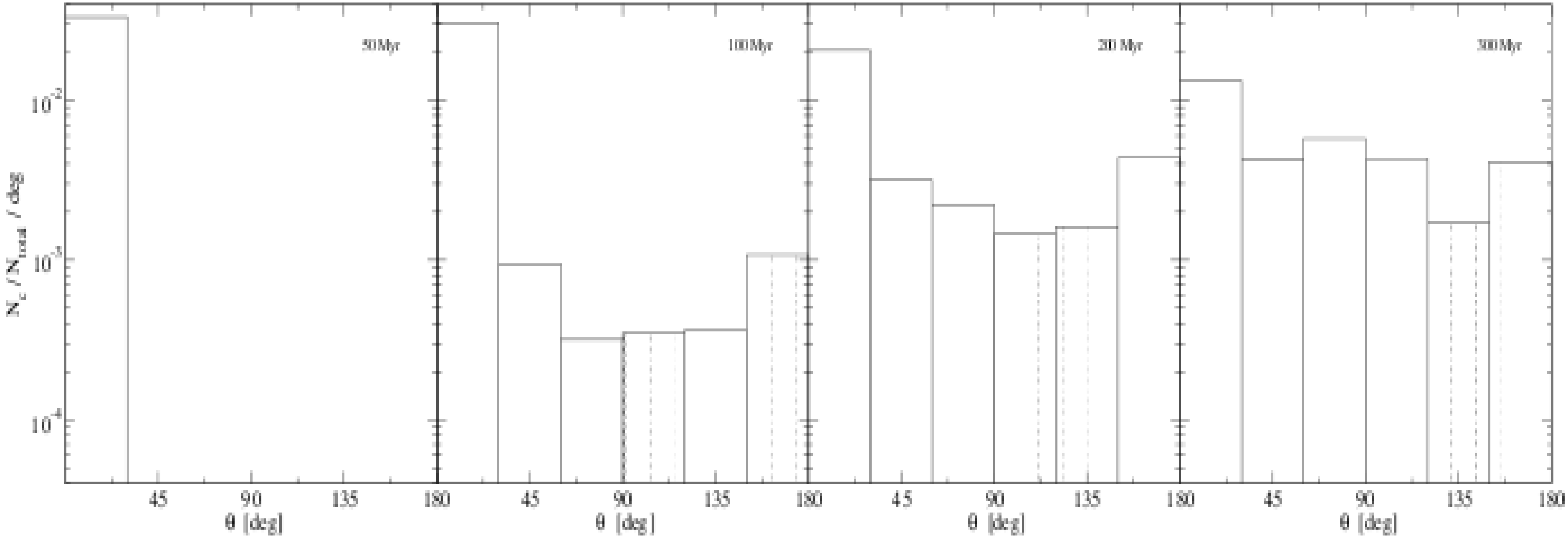


Figure 13. Distribution of the angle, θ, between cloud angular momentum vectors and the galactic rotation axis at different times during the course of the simulation. The shaded bars indicated retrograde rotation, and this population grows with time as more and more clouds experience collisions and close interactions.

Cloud Merger Timescale

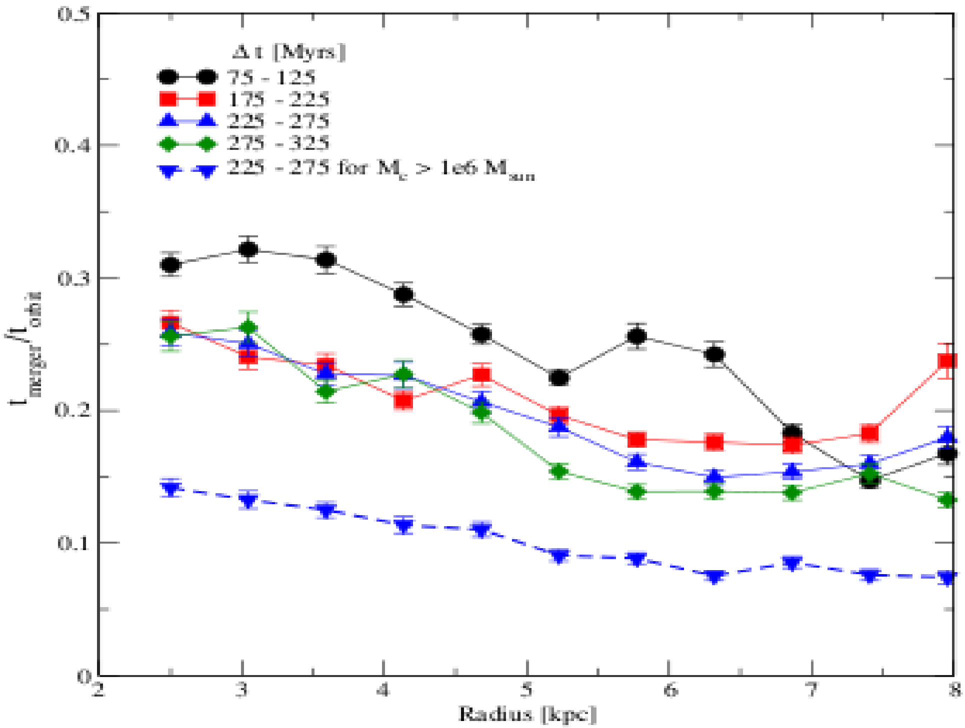


Figure 9. Cloud merger timescales (averaged over 50 Myr intervals of simulation time) compared to orbital timescale as a function of galactocentric radius. The merger rate is driven by differential rotation in the disk, and the cross-section grows as clouds become more gravitationally bound. After the initial fragmentation stage at 100 Myr, the cloud merger timescale settles to small values $\simeq 0.2 t_{\rm orbit}$, with only modest dependence on galactocentric radius. The dashed line shows the merger times of clouds with $M_c > 10^6 M_\odot$ (i.e., the average time for them to undergo a merger with a cloud of any mass, though typically with $M_c > 10^5 M_\odot$ (see Figure 11(a)) evaluated over the interval $t = 225$–275 Myr.

(A color version of this figure is available in the online journal.)

- 円盤銀河内での大部分の星形成は、GMC-GMC collision によって圧力が高くなった領域で生じる(Tan 2000)
- 平均的なmerger time は orbital timeの1/5程度 → very frequently!
- $$t_{orbit} = 123(\frac{r}{4kpc})(\frac{v_c}{200km/s})^{-1} Myr$$
- 巨大分子雲の寿命 → 30~40[Myr] (McKee & Williams 1997;Matzner 2002)
- 巨大分子雲の寿命よりもmerger time が小さい → merger は重要な過程

Results of
disk SFOnly and disk SF+PEheat

星形成とPhotoelectric heating

- 星形成

$$\dot{\rho}_* = \epsilon_{ff} \frac{\rho_{gas}}{t_{ff}}$$

$\varepsilon_{ff} = 0.02$ (Krumholz & McKee 2005)
3000[K]以下
threshold value of $n_H = 100$ cm-3

- Photoelectric heating

electrons are ejected from dust grains via FUV photos.
radially dependent heating term of the form described in Wolfire et al. (2003)

$$\Gamma_{pe} = 10^{-24} \epsilon_h G_0 \begin{cases} e^{-(R-R_0)/H_R} ergs^{-1} & R \geq 4.0kpc \\ e^{-(4-R_0)/H_R} ergs^{-1} & R < 4.0kpc \end{cases}$$

$$\epsilon_h = 0.05, G_0 = 1.7 (Draine 1978), H_0 = 4.2kpc$$

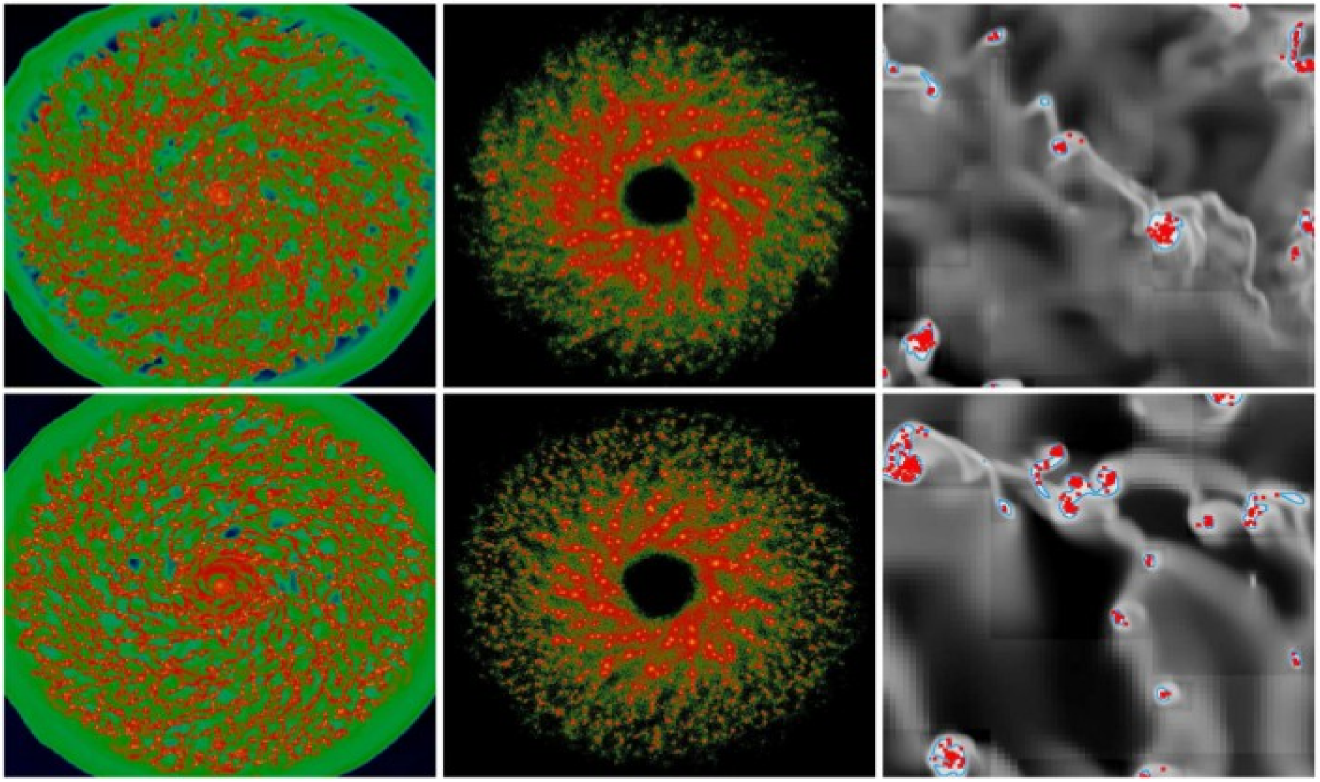
→ Background に入れている!

GMC Properties in three models

At 200[Myr]

	Observation	NoSF	SFOnly	SF+PEheat
Cloud(>10^6 Msun)の数	100~200	856	179	238
cloud(>10^5Msun)の数	~1000	-	1122	1491
cloudの半径	3~50[pc]	20~30[pc]	~15[pc]	~15[pc]
Surface density	200~400[Msun/pc^2]	~300[Msun/pc^2]	~300[Msun/pc^2]	~300[Msun/pc^2]
Virial parameter	-	0.6	~0.56	~0.56
Vertical scale height	< 35 [pc]	~25[pc]	~20[pc]	~25[pc]

Star Formation in Disk



SFOnly

SF+PEheat

Figure 1. Images of the galactic disk at 200 Myr. The top panel is for disk SFOnly, while the bottom panel shows disk SF+PEheat. The left-hand image is 20 kpc across and shows the log-scaled surface density of the disk with range [0.0033, 3715] $M_\odot$ pc^{-2}. The center panel is the projected star particle density and the right-hand image shows a 2 kpc density slice of the mid-plane. Blue contour lines mark the cloud boundaries corresponding to a number density of 100 cm^{-3} and the new star particles (age < 1 Myr) are shown in red.

- At 200[Myr]　SFOnly　→ over 3 million star particles
  SF+PEheat　→ 2.6 million star particles

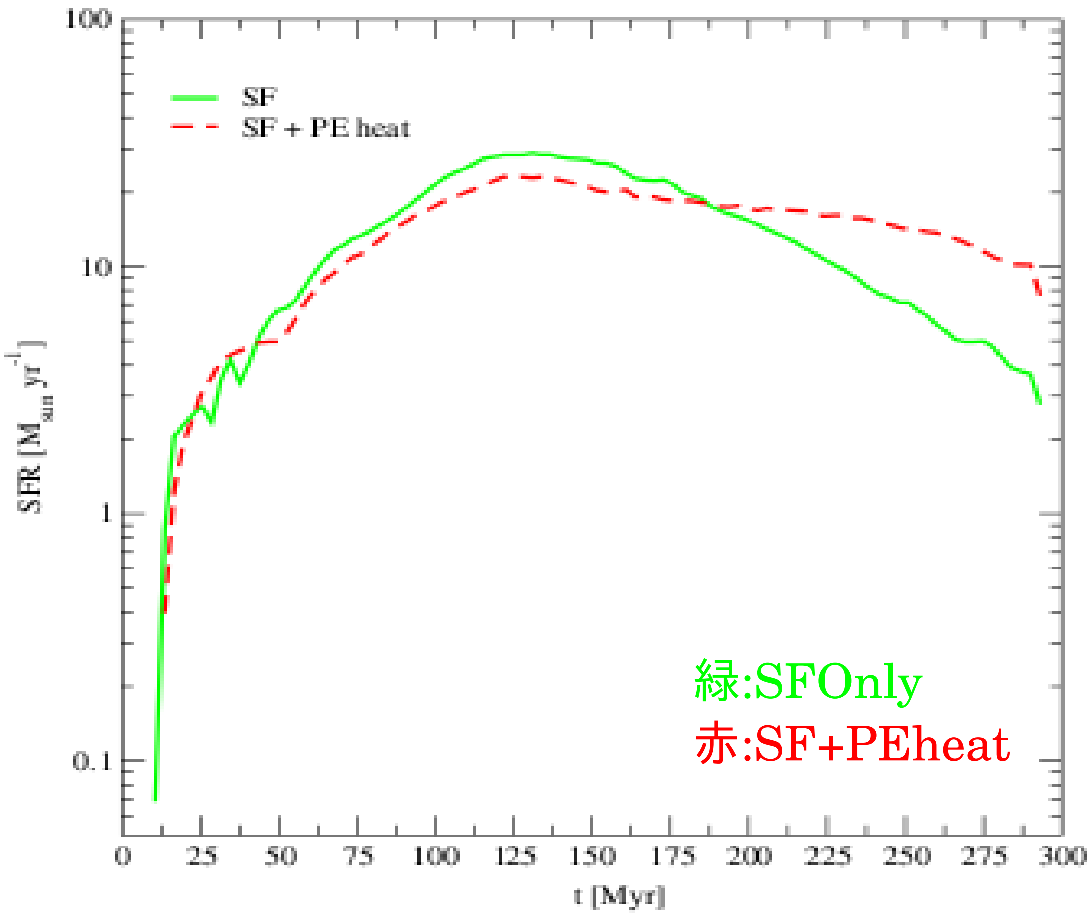
→ Photoelectric heatingがstar formationを抑制している

Star Formation Rate

- 天の川銀河のSFRは1-3$M_\odot$/yr程度である(Murry & Rahman 2010; Williams & McKee 1997)
- 観測より大きい結果がでた

  → no localized feedback
- 175[Myr]以降、SFOnlyのSFRがSF+PEheatのSFRを下回る

  (feedbackを入れたのになぜ？)

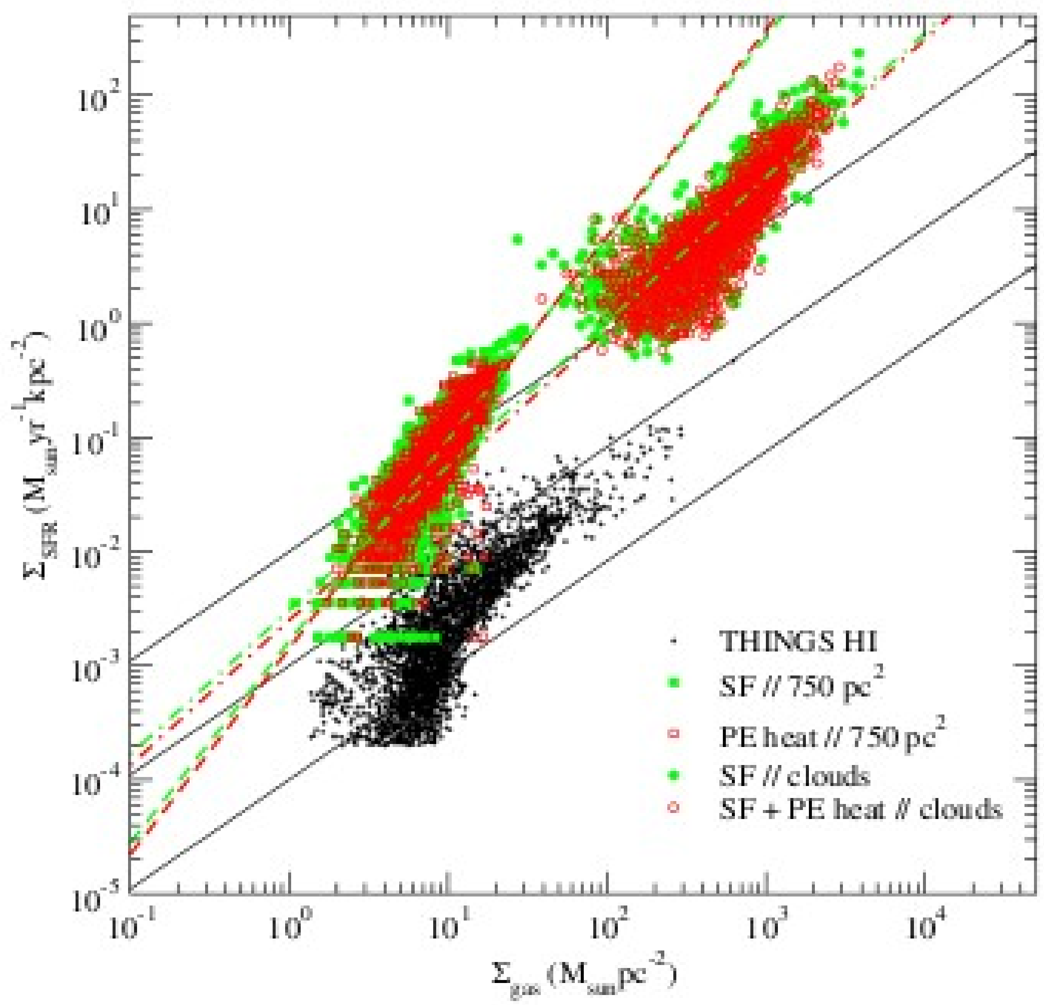


緑:SFOnly
赤:SF+PEheat

→　SFRが高いため、星の元となるガスが減るから

•Photoelectric heatingがstar formationを抑制している

Kennicutt-Schmidt law



- Kennuicutt(1998) found relatively simple relations between the globally averaged SFR per unit area and total(HI and H_2)gas mass surface density

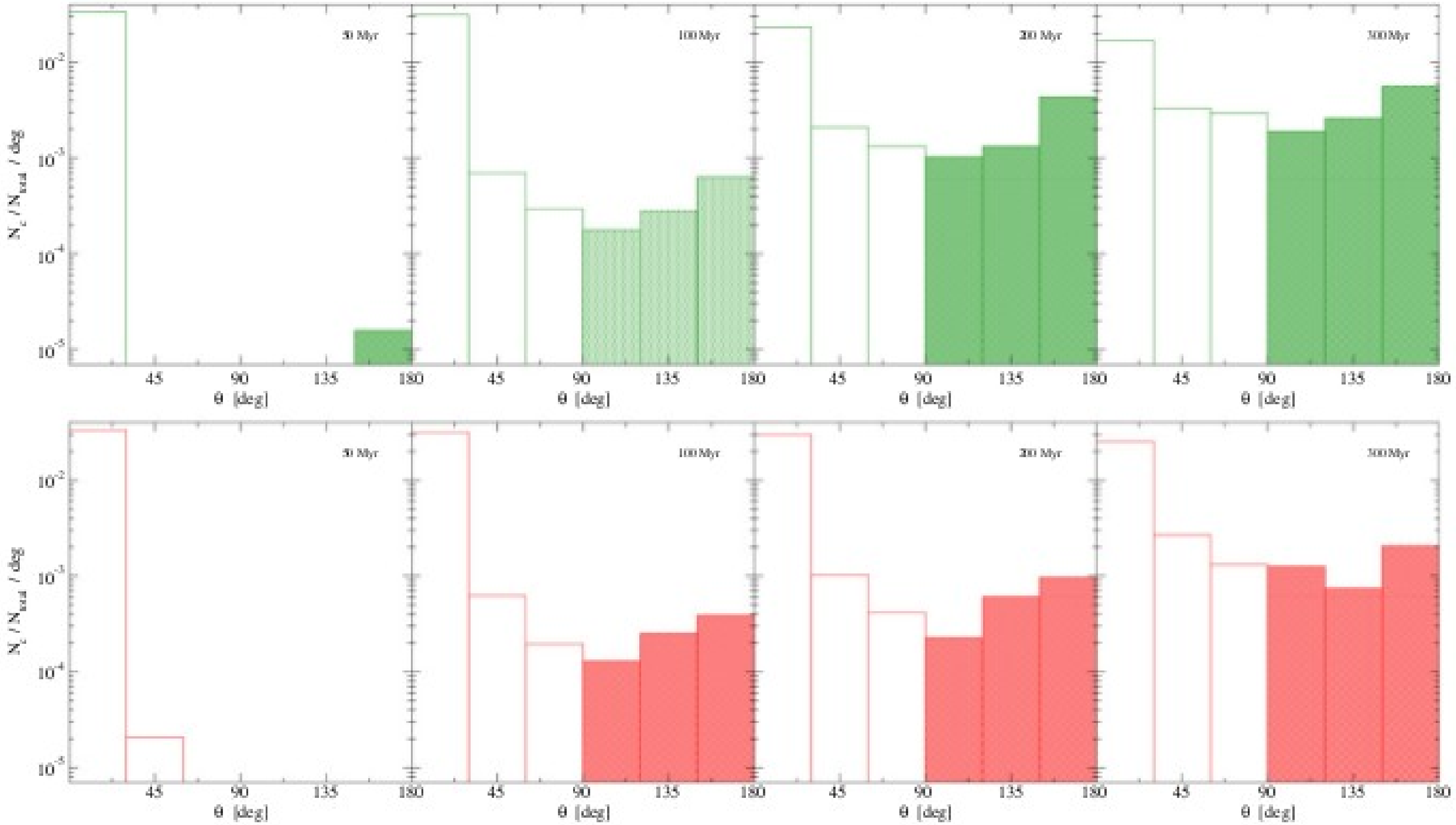
$$\bar{\Sigma}_{sfr} = A_{sfr}\bar{\Sigma}_g^{\alpha_{sfr}}$$

- The HI Nearby Galaxy Survey (Bigiel et al. 2008) : $\alpha_{sfr}=1.0\pm0.2$
- SFOnly : $\alpha_{sfr}=1.77$
- SF+PEheat : $\alpha_{sfr}=1.81$

→ no localized feedback

Retrograde Cloud Population

- By 300Myr, PE heatingがない場合、retrograde cloudの数は30%に及ぶが、PE heating を入れると12%に下がる
- The denser warm ISM, whose filamentary structure acts to encourage the clouds to remain prograde

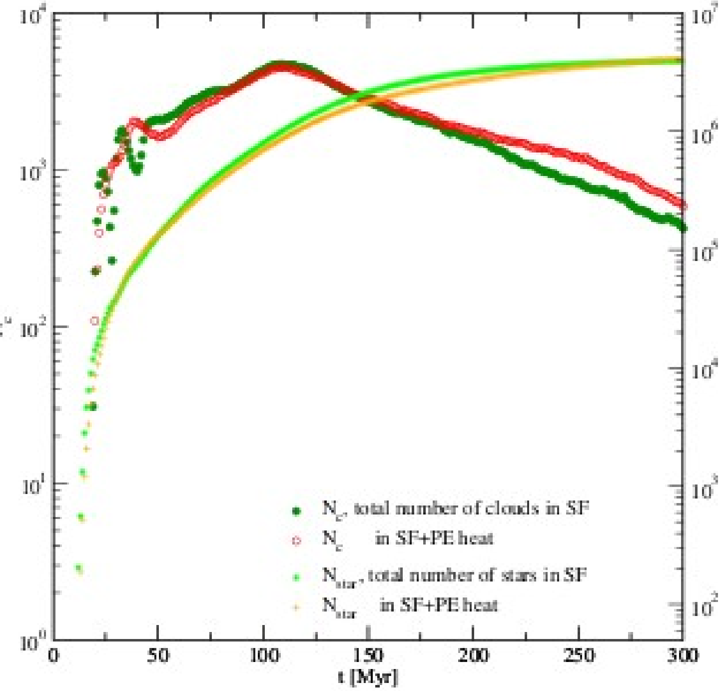


Distribution of the angle between the cloud angular momentum vector and galactic rotation axis

Cloud Merger Timescale

- 銀河中心からの距離にあまり依存していない
- Within the first three time frames, merger timeはどちらのシミュレーションでもほぼ一定でorbital timeの0.25倍である

→ 星形成により、cloudが減った



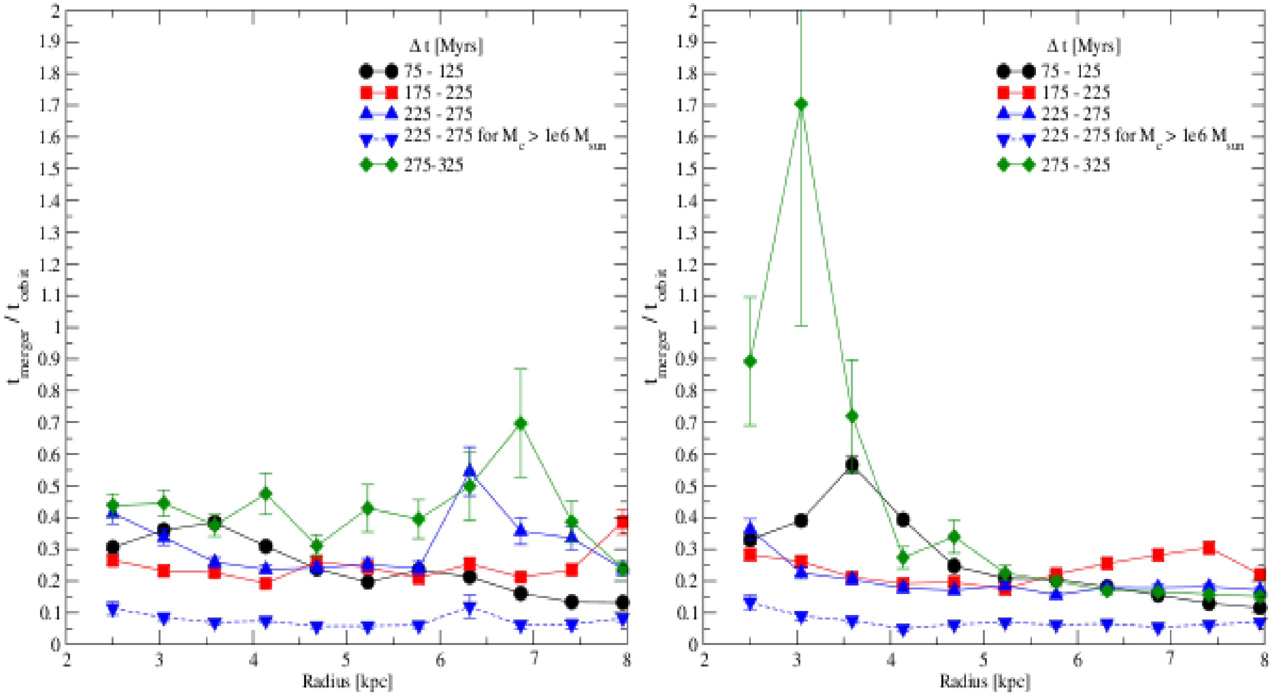


Figure 6. Cloud merger timescales, averaging over 50 Myr intervals of simulation time, for disks SFOnly (left) and SF+PEheat (right). Only clouds born after 140 Myr, the initial fragmentation of the disk, are included in the analysis. The average time for a merger is low at ~0.25 of an orbital period and largely independent of galactocentric radius. The dashed line shows the merger times of clouds with $M_c > 10^6\, M_\odot$ (i.e., the average time for a cloud of that size to undergo a merger with a cloud of any mass), evaluated over the interval $t = 225$–275 Myr, which is lower by a factor of two.

Summary

- 円盤銀河内の巨大分子雲の形成と進化を解明するため、３つのMilky Way-type galaxiesのモデル(disk NoSF, SFOnly and SF+PEheat)についてhigh-resolusion (<10pc)シミュレーションを行った
- In disk NoSF, many observed GMC properties (e.g. mass surface density, cloud size.etc) are reproduced and cloud collisions and mergers occur very frequently.
- From disk SFOnly and SF+PEheat, the effect of photoelectric heating is to suppress the fragmentation of ISM or the formation of stars
- Star formation reduces the number of clouds

- But SFR is a factor of 10 higher than observations in local galaxies.

  → due to absent of localized feedback in our models.