

# Is this an Early Stage Merger? A Case Study on Molecular Gas and Star Formation Properties of Arp 240

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## ABSTRACT

We present new high resolution  $^{12}\text{CO } J=1-0$ ,  $J=2-1$ , and  $^{13}\text{CO } J=1-0$  maps of the early stage merger Arp 240 (NGC5257/8) obtained with the Atacama Large Millimeter/submillimeter Array (ALMA). Simulations in the literature suggest that the merger has just completed its first passage; however, we find that this system has a lower global gas fraction but a higher star formation efficiency compared to typical close galaxy pairs, which suggests that this system may already be in an advanced merger stage. We combine the ALMA data with  $^{12}\text{CO } J=3-2$  observations from the Submillimeter Array and carry out RADEX modeling on several different regions. Both the RADEX modeling and a local thermal equilibrium (LTE) analysis show that the regions are most likely to have a CO-to- $\text{H}_2$  conversion factor  $\alpha_{\text{CO}}$  close to or perhaps even smaller than the typical value for (ultra-)luminous infrared galaxies. Using 33 GHz data from the Very Large Array to measure the star formation rate, we find that most star forming regions have molecular gas depletion times of less than 100 Myr. We calculated the star formation efficiency (SFE) per free-fall time for different regions and find some regions appear to have values greater than 100%. We find these regions generally show evidence for young massive clusters (YMCs). After exploring various factors, we argue that this is mainly due to the fact that radio continuum emission in those regions is dominated by that from YMCs, which results in an overestimate of the SFE per free-fall time.

## 概要

- First passageを完了したearly stage mergerだと考えられているArp 240について、ALMA  $^{12}\text{CO } J=1-0$ ,  $J=2-1$ ,  $^{13}\text{CO } J=1-0$ マップを作成した。
- さらにSpitzer 24  $\mu\text{m}$ 、Herschel 70  $\mu\text{m}$ 、VLA 33 GHzなどを組み合わせて星形成率などを調べた。

	NGC 5257	NGC 5258	# References
Coordinates (J2000) <sup>a</sup>	RA= 13 <sup>h</sup> 39 <sup>m</sup> 52.91 <sup>s</sup> Dec=+00°50'24.5"	RA= 13 <sup>h</sup> 39 <sup>m</sup> 57.70 <sup>s</sup> Dec=+00°49'51.1"	...
Morphological Type <sup>b</sup>	SAB(s)b pec	SA(s)b:pec	...
Redshift <sup>b</sup>	0.022676	0.022539	...
Luminosity Distance (Mpc)	98.0	97.4	1
$L_{\text{H}\alpha}$ ( $10^6 L_{\odot}$ )	5	6	2
$L_{\text{TIR}}$ ( $10^{11} M_{\odot}$ ) <sup>c</sup>	1.3	1.5	This work
HI mass ( $10^{10} M_{\odot}$ )	1.2	0.98	3
$\text{H}_2$ mass ( $10^9 M_{\odot}$ ) <sup>d</sup>	4.6	7.2	This work
Stellar Mass ( $10^{10} M_{\odot}$ ) <sup>e</sup>	9.4	10.5	This work
SFR ( $M_{\odot} \text{ yr}^{-1}$ ) <sup>f</sup>	27.8	24.9	3,4

Notes. <sup>(a)</sup>HyperLEDA. <sup>(b)</sup>NED. <sup>(c)</sup>From the combination of 24  $\mu\text{m}$  image from Spitzer and 70  $\mu\text{m}$  image from Herschel. <sup>(d)</sup>From the  $^{12}\text{CO } J=1-0$  ALMA observations assuming a ULIRG conversion factor of  $1.1 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ . <sup>(e)</sup>From the 3.6  $\mu\text{m}$  and 4.5  $\mu\text{m}$  Spitzer data. <sup>(f)</sup>From  $L_{1.4\text{GHz}}$ .

References. (1) Mould et al. (2000); (2) Sofue et al. (1993); (3) Iono et al. (2005); (4) Yun et al. (2001)

## 背景

- Mergerはtidal interactionがcentral starburstを引き起こす (Mihos & Hernquist 1996)
- 一方でOff-nuclearなstarburstを示すものも
- より詳細なガスのマップを調べる

Table 4. Depletion time of different regions in NGC 5257 and NGC 5258

Galaxy	Region	$\Sigma_{\text{SFR}}^a$ ( $M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ )	$\Sigma_{\text{mol}}^b$ ( $M_{\odot} \text{ pc}^{-2}$ )	$t_{\text{dep}}$ ( $10^8 \text{ yr}$ )
NGC5257	center	2.5	550	2.16
	arm	1.1	86	0.77
	west	1.1	45	0.42
	south	3.0	79	0.27
NGC5258	south arm	2.4	338	1.5

Note: The different regions are identified in Fig. 6.

a.  $\Sigma_{\text{SFR}}$  is calculated using the 33 GHz image  
b.  $\Sigma_{\text{mol}}$  is calculated using  $^{12}\text{CO } J=2-1$  assuming  $^{12}\text{CO } J=2-1/1-0$  ratio of 0.8 and typical ULIRG conversion factor

Table 1

Table 4



Fig. 1

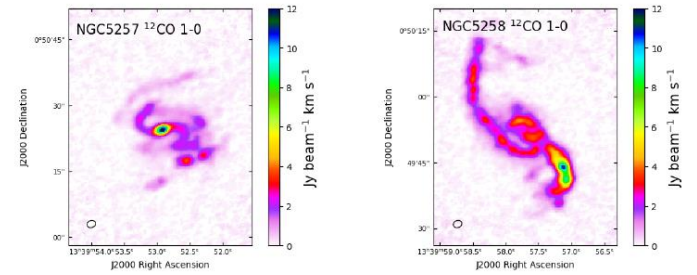
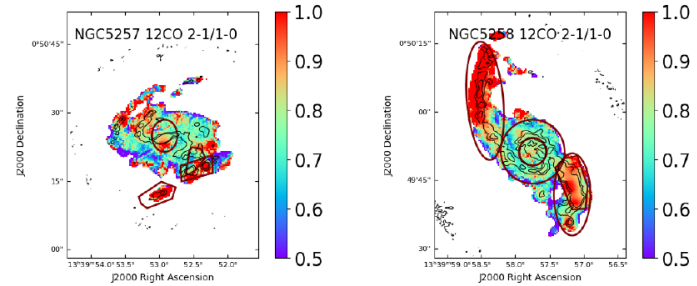
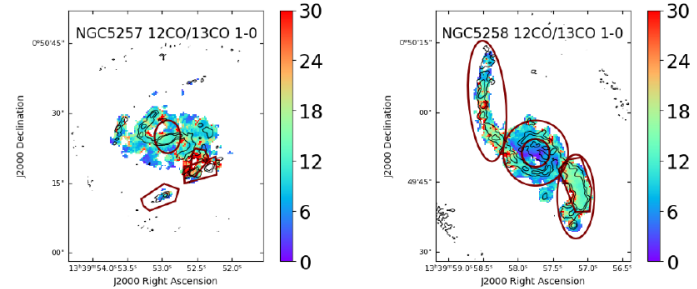


Fig. 5



Bright X-ray source, not in LTE

$$t_{\text{dep}} = M_{\text{mol}} / \text{SFR} = \Sigma_{\text{mol}} / \Sigma_{\text{SFR}}$$

## 結論

- Gas fractionは典型的な渦巻銀河程度( $\sim 0.05$ )だが、gas depletion timeは渦巻銀河よりも低い値( $10^8 \text{ yr}$ )
  - Early type mergerは渦巻銀河に比べて高いgas fraction、同程度のSFEを持つ (Violino et al. 2018; Pan et al. 2018)
  - Arp 240はlate stage mergerであることを示唆している
- NGC 5257はガスが中心集中しgas inflowとconsistentだが、NGC 5258は渦巻腕にガスが集中している
  - Tidal効果によるもの
- NGC 5257では高い $^{12}\text{CO}/^{13}\text{CO}$ 比が見られる
  - Outer diskからのfreshなガス流入
- NGC 5258では中心部で低い $^{12}\text{CO}/^{13}\text{CO}$ 比が見られる
  - $^{13}\text{CO}$ のoverproduction、 $^{12}\text{CO}$ のoverconsumptionが考えられる
- NGC 5257におけるoff-nuclear starburst領域では典型的なULIRGに比べて短いdepletion timeを持つ
  - Young massive clusterを伴う
- pcスケールのデータが必要