Uncovering Early Galaxy Evolution in the
ALMA and JWST Era
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A sub-kiloparsec-scale view of un-lensed submillimeter galaxies

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Abstract. Submillimeter galaxies at $z > 3$ building up their central cores through compact starbursts with an effective radius of 1–2 kpc. Our ALMA high-resolution observations reveal off-center gas clumps in a submillimeter galaxy at $z = 4.3$, COSMOS-AzTEC-1, as well as a rotation-dominated disk. Exploiting the kinematic properties and the spatial distribution of gas mass surface density, we find that the starburst disk is gravitationally unstable. This result is consistent with a scenario where in-situ clumps are formed through disk instability. On the other hand, we find evidence for an ex-situ clump that does not corotate with the starburst disk. The accretion of such a non-corotating clump could stimulate violent disk instability, driving gas inflows into the central regions of the galaxy. Our results suggest that compact cores are formed through an extreme starburst due to a gravitational instability, triggered by non-corotating clumps.

Keywords. galaxies: formation, galaxies: starburst, galaxies: ISM

1. Introduction

When and how did galaxies shape the Hubble sequence? Over the past three decades, high-resolution, high-quality images obtained with Hubble Space Telescope (HST) revealed the rest-optical morphologies for tens of thousands of distant galaxies. The most striking results are
1) a correlation between star-forming activity and morphology of galaxies at $0 < z < 2.5$: star-forming galaxies are typically a disk-dominated system whereas quiescent galaxies are a spheroid-dominated one (e.g., Wuyts *et al.* 2011; Bell *et al.* 2012),
2) a discovery of massive, compact quiescent galaxies at $z \sim 2$: the half-light radius of $R_{1/2} \sim 1$ kpc is a factor of 4–5 smaller than similar mass quiescent galaxies at $z = 0$ (e.g., Trujillo *et al.* 2006; van Dokkum *et al.* 2015), and
3) size evolution from $z = 3$ to $z = 0$: star-forming galaxies are always larger than quiescent galaxies and both galaxies gradually increase size over time (e.g., van der Wel *et al.* 2014).

These findings offered a paradigm for galaxy evolution: high-redshift massive galaxies evolve into giant ellipticals through two channels. In a fast channel, massive compact star-forming galaxies will become compact quiescent galaxies at $z \sim 2$ after quenching star formation (e.g., Barro *et al.* 2013). Repeating minor mergers puffs up compact quiescent galaxies, turning them into giant elliptical galaxies (e.g., Naab *et al.* 2009). In a slow channel, galaxies increase their size by in-situ star formation, and after quenching larger quenched galaxies continuously add to the quiescent population at $z = 0 - 1$ (e.g., Carrolo *et al.* 2013; Belli *et al.* 2015). This two-channel scenario explains the redshift evolution

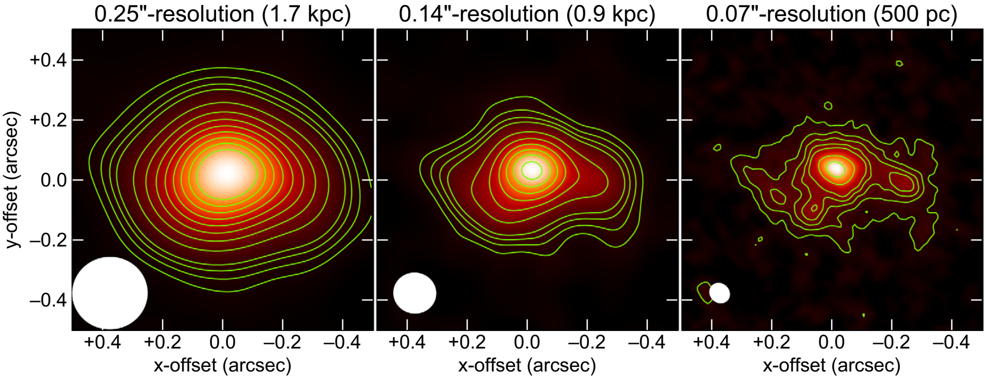

Figure 1. ALMA 870 μm continuum maps at three different spatial resolutions in COSMOS-AzTEC-1 at $z = 4.3$ (Iono *et al.* 2016). The image size is $1'' \times 1.''$Contours are plotted every 3σ from 6σ to 15σ and every 10σ from 15σ.

of both the size and the number density of star-forming/quiescent galaxies (e.g., Barro *et al.* 2013; van Dokkum *et al.* 2015). However, a big problem still remains: how did compact star-forming galaxies form at $z = 3 - 6$?

2. Overview

Submillimeter bright galaxies (SMGs) at $z > 3$ are the most likely progenitors of compact star-forming galaxies. Recent $0.''2$-resolution dust continuum observations indicate that SMGs are vigorously forming stars in the central 1-2 kpc region, supporting an evolutionary link from SMGs to compact star-forming galaxies with $R_{1/2} \sim 1$ kpc (e.g., Simpson *et al.* 2015; Ikarashi *et al.* 2015; Tadaki *et al.* 2017). What happens if we go to higher resolution? ALMA $0.''07$-resolution observations of 870 μm continuum reveal that a bright SMG at $z = 4.3$, COSMOS-AzTEC-1, is not just compact, but also has clumpy structures in the central 1-2 kpc region (Figure 1; Iono *et al.* 2016). Such off-center clumps are now commonly seen in SMGs (Hodge *et al.* 2019; Rujopakarn *et al.* 2019 although we need a better resolution than $0.''1$ to prove them (Figure 1).

An obvious next step is to investigate the kinematics in the central starburst region to understand the origin of off-center clumps. Unfortunately, dust continuum observations do not provide information of kinematics in galaxies. We therefore obtained $0.''08$-resolution observation of the CO(4-3) line in COSMOS-AzTEC-1 (Tadaki *et al.* 2018). The starburst disk is rotation-dominated with a rotation velocity-to-velocity dispersion ratio of $v/\sigma_0 \sim 3$ (Figure 2). The ordered rotation is also confirmed by [C II] and [N II] line observations (Figure 3; Tadaki *et al.* 2019a). The measured Toomre Q parameter is much below unity over the starburst disk ($Q_{\rm obs} \sim 0.2$), suggesting that off-center clumps are formed through the gravitational instability in the central 1-2 kpc region.

On the other hand, we have discovered a non-corotating clump by $0.''17$-resolution [C II] observations (Tadaki *et al.* 2019b, in prep). The [C II] clump has a large velocity offset of $\sim$200 km s^{-1} from the disk component and is located along the kinematic minor axis of disk rotation. We suggest a scenario where the ex-situ non-corotating clump develops the violent disk instability (VDI), where the disk is turbulent and highly perturbed, driving gas inflow into the central region of the galaxy (Dekel *et al.* 2009; Dekel & Burkert 2014; Danovich *et al.* 2015; Zolotov *et al.* 2015). The extreme starburst is likely to be caused by a combination of minor mergers and efficient star formation due to gravitational instability in the central 1-2 kpc region.

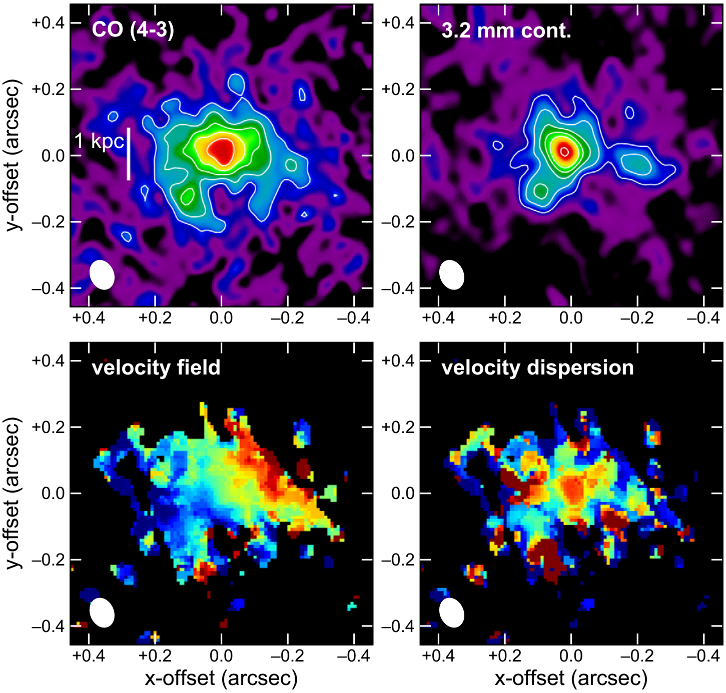

Figure 2. ALMA maps of the CO (4-3) line, 3.2 mm continuum, velocity field, velocity dispersion (Tadaki *et al.* 2018).

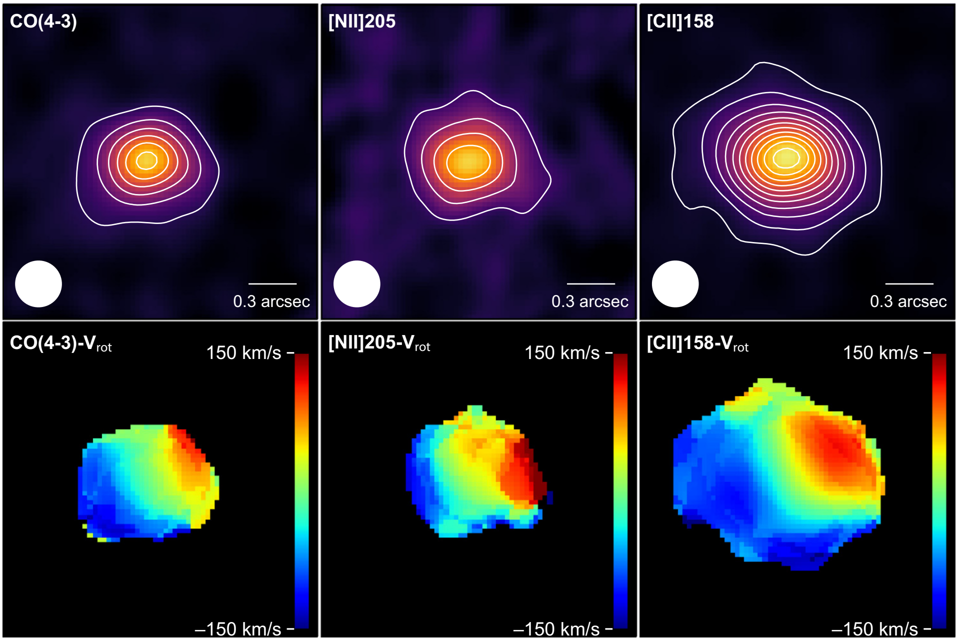

Figure 3. ALMA CO(4-3), [N II] and [C II] maps of flux and velocity field in COSMOS-AzTEC-1 (Tadaki *et al.* 2019a). The spatial resolutions are all $\sim 0.''3$. The image size is $2'' \times 2.''$Contours are plotted every 5σ from 3σ.

ALMA observations of molecular/ionized/PDR gas alone are not enough to reject the possibility of major mergers in COSMOS-AzTEC-1, because gas and new stars formed after mergers become rotation-dominated in both cases of major and minor mergers (Robertson *et al.* 2006). While COSMOS-AzTEC-1 is very faint at < 2 μm, it is sufficiently bright at $3 - 4\mu$m with an AB magnitude of 22. Integral field spectroscopy with Near Infrared Spectrograph on James Webb Space Telescope (Dorner *et al.* 2016) will allow us to investigate the stellar kinematics through observations of stellar absorption lines in the rest-frame optical wavelengths. The ALMA-JWST synergetic observations will enable us to determine whether SMGs experienced major mergers in the past and understand the physical mechanism responsible for the extreme starburst in the early Universe.

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