Review of recent studies for galaxies at z=1-3

Ken-ichi Tadaki (NAOJ)
Extended clumpy disks and nuggets

Introduction

galaxies at $2 < z_{\text{phot}} < 3$ in GOODS–S field

Extended SFGs
Compact SFGs
☆ X-ray AGN
Quiéscent

Extended SFGs

Extended clumpy disks

blue/red nuggets

Extended SFGs
Compact SFGs
☆ X-ray AGN
Quiéscent

σ = 250 km/s

Barro+14, Forster Schreiber+11, van Dokkum+08
Results from IFU studies of high-redshift SFGs

Extended clumpy disk

Genzel+11

Figure 5. Maps of Hα Gaussian fit velocities (top left), Hα Gaussian fit dispersion (bottom left), and the Toomre Q-parameter (right, Equation (2)) for ZC782941. Shown in the center is also the map of Hα-integrated flux from Figure 2. The locations of the main clumps (Figure 2) are denoted by circles/ellipses. The Hα, velocity, and velocity dispersion maps (resolution 0″.18 FWHM) were re-binned to 0″.025 pixels. For construction of the Q-map, the data were smoothed to 0″.25 FWHM. The typical uncertainties in the Q-values are ±0.06 to ±0.4 (1σ) for most of the outer disk of ZC782941. Pixels with ΔQ > 0.5 were masked out.

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

conclude that the Q-maps in Figures 3–6 are consistent with the commonly held view that the clumps form by gravitational instability. However, we cannot exclude the alternative possibility that the instability is driven by a large-scale compression, such as experienced in a galaxy interaction or (minor) merger (e.g., Di Matteo et al. 2007).

3.2. Evidence for Powerful Outflows on Clump Scales

UV spectroscopy of metal absorption lines and of Lyα emission lines provide compelling evidence for ubiquitous mass outflows in “normal” high-z (Pettini et al. 2000; Shapley et al. 2003; Steidel et al. 2004, 2010; Weiner et al. 2009).
Results from CO studies of high-redshift SFGs

\[ f_{\text{mol gas}} = \frac{M_{\text{mol gas}}}{M_{\text{mol gas}} + M_\star} \]

gas fraction $\sim 50$

gas depletion timescale $\sim 700$Myr
Differences between high-z and low-z galaxies

<table>
<thead>
<tr>
<th></th>
<th>high-z</th>
<th>low-z</th>
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<tbody>
<tr>
<td>SFR</td>
<td>~100 M$_{\odot}$/yr</td>
<td>&lt;10 M$_{\odot}$/yr</td>
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<tr>
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\[ Q_{\text{gas}} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{\text{gas}}} \]
Differences between high-z and low-z galaxies

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the main driver of large velocity dispersion is not well understood

1. stellar feedback (outflow)
2. self–regulating disk (inflow within disk)
Self-regulated disks

if $\sigma < \sigma_r$ ($Q < 1$)

![Fragmentation becomes more efficient]

gravitational interaction drive mass inflow to center
(e.g. clump migration)

if $\sigma > \sigma_r$ ($Q > 1$)

![Turbulence decay]

fragmentation process is suppressed

high-redshift galaxies keep a disk unstable ($Q \sim 1$)

**Release of gravitational energy**

$$\dot{M}_{\text{inflow}} \frac{V_{\text{circ}}}{2} \sim \frac{M_{\text{gas}} \sigma_{\text{gas}}^2}{t_{\text{dis}}}$$

$$t_{\text{enc}} \sim 2.1 \alpha^{-1} Q^4 t_d$$

$\sigma_{\text{gas}}$ increases

$$t_{\text{dis}} \sim 1.4 Q^{-1} t_d$$

$\sigma_{\text{gas}}$ decreases

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*Dekel+09*
Blue/red nuggets

Blue/red nuggets

\[
\begin{align*}
\log(r_e) [\text{kpc}] & \quad \log(M_*) [M_\odot] \\
\end{align*}
\]

\[\sigma = 250 \text{ km/s}\]

extended clumpy disks

blue/red nuggets

Barro+14, Forster Schreiber+11, van Dokkum+08
cold stream
(inflow of external gas)

gravitational torque
(inflow of internal gas)

angular momentum of external gas
$\rightarrow$ extended disk

loss of energy/angular momentum
(impossible in stellar systems)
$\rightarrow$ gas contraction (nugget)

a necessary condition is $M_{\text{cold}}/M_{\text{total}} > 0.28$

if $\tau_{\text{infall}} > \tau_{\text{SF}}$

self-regulated!
extended clumpy disks

if $\tau_{\text{infall}} < \tau_{\text{SF}}$

depends on gas fraction!

a theoretical study predicts that about 50% of high-$z$ SFGs are expected to contract to blue nuggets

Dekel+14
Two evolutionary paths for QGs

1. fast/early-track: extended clumpy disks → blue/red nuggets → massive QGs
2. slow/late-track: extended clumpy disks → massive disks → massive QGs
Next agenda

2003–2013

Observations with SINFONI, IRAM–PdBI, HST/WFC3 revealed the detailed properties of high–z galaxies and predicted the formation scenarios of massive galaxies

Sample number

50–100

2013–2020

Observations with KMOS and ALMA will provide a comprehensive view of the predicted scenarios

Sample number

500–1000

What are we to do by using ULTIMATE–Subaru?

Wide-field imager
→ statistical study of nuggets
Ifu
→ statistical study of population before nugget phase
Population before nugget phase

why is dispersion dominated?

gas inflow is efficient?

candidates of nuggets?
rotating-dominated

IFU

dispersion-dominated

high-resolution imager

blue nugget

red nugget

Population before nugget phase

low-z spheroids
dry mergers
red nuggets

low-z discs
gas contraction
blue nuggets

slow mode
low z

fast mode
high z

wet VDI+mergers → compact → high SFR, AGN, bulge

compactness
Beam smearing effect

Figure 3. Top row, left to right: HST WFC3 image, seeing-limited velocity field, and AO velocity field. Bottom row, left to right: Hα AO image, seeing-limited velocity dispersion field, and AO velocity dispersion field of Q1623-BX455 (Förster Schreiber et al. 2009). Much of the rotation apparent from the AO velocity field is beam-smeared out with the seeing-limited data. (A color version of this figure is available in the online journal.)

Figure 4. Top row, left to right: HST ACS I-band image, seeing-limited velocity field, and AO velocity field. Bottom row, left to right: Hα AO image, seeing-limited velocity dispersion field, and AO velocity dispersion field of GMASS-2363 (Förster Schreiber et al. 2009). (A color version of this figure is available in the online journal.)

size (smaller galaxies are more likely dispersion dominated), although they are not perfectly matched. But as we see from the first two panels, this classification also depends on the ratio of resolution to source size, such that poorly resolved galaxies are very likely classified as dispersion dominated. Given the criteria above, formally 41% of the 34 SINS/zC-SINF galaxies are classified as dispersion dominated based on seeing-limited data. That fraction drops to 6%–9% for the same galaxies using AO data. If we include 1σ error bars, up to 59% of the galaxies could be classified as dispersion dominated with seeing-limited data and less than 35% with AO data.

In turn, the strong majority of the SINS/zC-SINF SFGs observed with AO can then be characterized by a velocity gradient along a single axis that is identical with or close to the morphological major axis. This suggests that rotation dominates the larger scale velocity field, although the observed pattern could also be matched by orbital motion in a binary minor merger in a few cases. However, we do not detect symmetric double light distributions or velocity reversals in any of the SFGs in our sample, which would be indicative of a major merger.

The empirical assessment drawn from Figure 5 is supported by creating simple toy models of turbulent but rotationally supported disks with intrinsic $v_{\text{rot}}/\sigma_0 \sim 1–5$. We “observe” model disks with varying sizes, masses, and inclinations with seeing and AO scale resolutions and analyze them in the same way as our SINS/zC-SINF data. Their location in the empirical $\Delta v_{\text{grad}}/2\sigma_{\text{tot}}–R_{1/2}$ and $v_{\text{rot}}/\sigma_0–R_{1/2}$ planes overlaps with the majority of the data. A fraction of the model disks indeed...
KMOS GTO programs (only high-z)

to my knowledge...
- KMOS$^3$D (PI: Förster Schreiber)
- KMOS Kinematic Survey (PI: Sharples)
- KMOS Deep Survey (PI: Cirasuolo)
- KMOS clusters program (PI: Bender/Davies)
- VIRIAL (PI: Mendel)

and so on.

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<th>KMOS</th>
<th>ULTIMATE with GLAO</th>
<th>SINFONI with AO</th>
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<tbody>
<tr>
<td>spatial resolution</td>
<td>~0.6″</td>
<td>?</td>
<td>0.1-0.2″</td>
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<tr>
<td>multiplicity</td>
<td>24</td>
<td>?</td>
<td>1</td>
</tr>
<tr>
<td>sample size of large survey</td>
<td>500-1000</td>
<td>?</td>
<td>30-40</td>
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3D-HST sample in CANDELS field

<table>
<thead>
<tr>
<th>Selection</th>
<th>N (Total) in five CANDELS field</th>
<th>N/13.6′FoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 &lt; z &lt; 1.5, logM* &gt; 10</td>
<td>3115 galaxies</td>
<td>~300</td>
</tr>
<tr>
<td>F_{Hα} &gt; 8e-17</td>
<td>636 galaxies</td>
<td>60-80</td>
</tr>
</tbody>
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If we target mass-complete sample, 52 are reasonable.

If we target only SFGs with strong Hα emission, 26 or 52 bundles are reasonable.

Note that these are targets of KMOS^{3D} project.

KMOS: F_{Hα} > 8e-17

ULTIMATE-Subaru: F_{Hα} > 4e-17?

It depends on the capability of ULTIMATE-Subaru.

Wuyts et al. 2013
Progenitors of Milky way-like galaxies

**3. Milky Way Progenitors from \(z = 0\) to \(z = 2.5\)**

**3.1. Rest-frame Images**

Having determined the stellar mass evolution with redshift, we can now select galaxies in mass bins centered on this evolving mass and study how their properties changed. We selected galaxies in GOODS-North and GOODS-South as progenitors of Milky Way-like galaxies.

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**Figure 1.** (a) Stellar mass density of the universe as a function of galaxy mass, as determined from the SDSS-GALEX \(z = 0\) mass function of Moustakas et al. (2013). (b) Evolution of the cumulative galaxy mass function from \(z = 0\) to \(z = 3.5\) (SDSS-GALEX and Marchesini et al. 2009). The horizontal line indicates a constant cumulative comoving number density of \(1.1 \times 10^{-3} \, \text{Mpc}^{-3}\). (c) Mass evolution at a constant number density of \(1.1 \times 10^{-3} \, \text{Mpc}^{-3}\).

(More graphs and subfigures for mass evolution and other properties are shown, including redshifts, mass functions, and SFRs.)

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Based on the variation between mass functions of different authors, and the results of Leja et al. (2013), we estimate that the uncertainty in the evolution out to \(z = 2.5\) is approximately 0.2 dex.

More than half of the present-day mass was assembled in the 3 Gyr period between \(z = 2.5\) and \(z = 1\), and as we show later the mass growth is likely dominated by star formation at all redshifts. The mass evolution is significantly faster than that of more massive galaxies (van Dokkum et al. 2010; Patel et al. 2013), consistent with recent results of Muzzin et al. (2013).
Summary

straightforward strategy with ULTIMATE–Subaru

1. update the bottom panel for targeting the mass–complete sample
2. investigate the properties (σ, V_{rot}, Q) in multi–parameter spaces (stellar/dynamical mass, SFR, redshift, environment...)
3. provide a comprehensive view of the formation scenario of massive galaxies
My answers about specifications

- **sampling, sensitivity and resolution**
  we want to obtain kinematic information from galaxies with $F_{\text{line}}=(4-8)\times10^{-17}$ and source size of 0.5"-1.5"
- **multiplicity**
  26 or 52
- **uniqueness**
  I’m not sure...

← SFGs at $z\sim1.5$
(Sobral et al. 2013)