Identification and Morphologies of Galaxies with Old Stellar Populations at High Redshift

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How did the first massive galaxies form?

Theoretical modeling cannot yet answer this question, partly because global feedback from star formation and AGN winds is extremely complicated and difficult to model, both in semi-analytic and hydrodynamic approaches to galaxy formation.

“Ab initio calculations, beginning with inflationary fluctuations that evolve into mature galaxies, are currently a theorist’s dream and are likely to remain so.”
Need observational evidence....

Two projects:

- Investigation of group of red galaxies found in the IfA Deep Survey with SuprimeCam.
- Morphologies of galaxies with old stellar populations found in radio-source fields at high redshift.

In both cases, morphologies of the galaxies can give constraints on formation scenarios.
I. A group of galaxies with old stellar populations at $z = 1.34$


SuprimeCam $R$ and $I$, CISCO $K'$
Subaru AO + IRCS $K'$
ER +101736

de Vaucouleurs
Exponential
Sersic $n = 2.84$

$r_e^{(deV)} = 0''.25$
$r_e^{(exp)} = 0''.15$
Sersic $n = 2.84$ $r_e = 0''.21$
de Vaucouleurs
Exponential
Sersic $n = 6.19$

$\mu_k (\text{mag arcsec}^{-2})$

$r_0(\text{dev}) = 0''.13$
$r_0(\text{exp}) = 0''.09$
Sersic $n = 6.19$ $r_0 = 0''.18$

$\Delta\mu_k$

$r ($arcsec$)$

1''
$r_e(\text{dev}) = 0''.70$
$r_e(\text{exp}) = 0''.33$
Sersic $n = 1.14$ $r_e = 0''.34$

SUBARU IRC+S+AO
ER +101738

de Vaucouleurs
Exponential
Sersic $n = 1.14$
Results:

- Galaxies in this group at $z = 1.34$ appear to be fully formed, with a high degree of symmetry.
- Three of the four galaxies for which we have AO imaging look very similar to types of galaxies with old stellar populations at the present epoch.
  - The two ellipticals lie fairly close to the Kormendy relation, taking into account passive evolution.
- The fourth galaxy appears to be a pure exponential disk of old stars, a type of galaxy that is rare or absent at the present epoch.
II. Galaxies with old stellar populations in fields of high-redshift radio sources.

Why radio sources?

- Radio sources track highly overdense regions.
- Radio sources with known redshifts allow redshift selection to optimize discrimination between galaxies with old stellar populations and other red galaxies.

Morphologies of these old galaxies can give constraints on formation scenarios.
Observations

First we must find suitable targets. Our criteria are quite stringent, so the objects are fairly rare.

1. Subaru CISCO for NIR imaging
2. Keck ESI or LRIS for optical imaging
3. Spitzer IRAC for highest-z objects

High-resolution imaging:

1. Subaru AO + IRCS
2. HST NICMOS
3. Keck AO (natural or laser guide star)
Object selection issues

We need to have a clean separation between truly “old” stellar populations and highly reddened objects.

Choose objects in fields of radio sources with redshifts that allow standard filter bands to achieve the best discrimination.

Obtaining all of the necessary bands to sufficient depth requires large amounts of telescope time.

Use a photometric sieve approach.
4C 15.55 Field

- $z_Q = 1.406$
- ER1 is a starburst
- ER2 has an old stellar population
4C 15.55 ER2

![Graph](image-url)
4C 15.55 EROs

Subaru AO + IRCS
Defining a reference galaxy

In order to evaluate photometric detection schemes, we define a strawman reference galaxy:

- All stars form 500 Myr after the Big Bang (corresponds to $z = 9.5$).
- Luminosity set to give $K' = 2L^*$ at $z = 0$ (passive evolution).
- We use Bruzual-Charlot (2003) models to give the SED at any given redshift.
$z = 2.5$

$\tau = 2.1 \text{ Gyr}$
4C 15.55 ER2

4C 15.55 ER2 (Keck II ESI)
BC03 3.0 Gyr model

$F_\lambda$ (10^{-17} erg cm^{-2} s^{-1} Å^{-1})

$\lambda_0$
4C 15.55 ER2

Exponential Profile:

$r_e = 0''.36$

Stellar nucleus 8% of total
4C 23.56 ER1

$Z_{RG} = 2.483$

4C 23.56 ER1

$z_{RG} = 2.483$
4C 23.56 ER1
4C 23.56 ER1

SUBARU IRCS + AO

\( r_e(\text{exp}) = 0.12 \)
4C 23.56 ER1

Sersic $n = 1.49$

$r_e = 0''.22$
4C 05.84 ER1

$z_q = 2.323$
4C 05.84 ER1

NICMOS Image | Model (with PSF) | Residual

Model | Bulge Component | Disk Component
TXS 2332+154 ER1

$z_{RG} = 2.48$
TXS 2332+154 ER1

$z_{RG} = 2.48$
TXS 2332+154 ER1
TXS 2332+154 ER1

\[ \mu_{\text{eff}} \text{ vs. Semi-Major Axis (arcsec)} \]
4C 29.28 ER2

$z_0 = 2.617$
4C 29.28 ER2

$z_q = 2.617$

$F_{\lambda}$ (10$^{-18}$ watt m$^{-2}$ $\mu$m$^{-1}$)

$\lambda (\mu$m$)$
4C 29.28 ER2
$z = 3.8$

$\tau = 1.1$ Gyr
B3 0032+154

$z_{RG} = 3.67$
## Summary

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>z</th>
<th>$r_e$ (kpc)</th>
<th>Sersic n</th>
<th>Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C 15.55 ER2</td>
<td>1.41</td>
<td>3.0</td>
<td>1.92</td>
<td>Exp + point source (8%)</td>
</tr>
<tr>
<td>4C 05.84 ER1</td>
<td>2.32</td>
<td>9.4</td>
<td>2.56</td>
<td>Exp (63%) + bulge (37%)</td>
</tr>
<tr>
<td>4C 23.56 ER1</td>
<td>2.48</td>
<td>1.8</td>
<td>1.49</td>
<td>Exponential</td>
</tr>
<tr>
<td>TXS 2332 ER1</td>
<td>2.48</td>
<td>0.6</td>
<td>2.30</td>
<td>(Exponential)</td>
</tr>
<tr>
<td>4C 29.28 ER1</td>
<td>2.62</td>
<td>2.4</td>
<td>0.05</td>
<td>Uncertain</td>
</tr>
<tr>
<td>B3 0032+154</td>
<td>3.67</td>
<td>0.7</td>
<td>2.38</td>
<td>(Exponential)</td>
</tr>
</tbody>
</table>
Formation of massive galaxies

- The apparent prevalence of disks (or at least of exponential light distributions) means that it is unlikely that most of these galaxies have suffered major mergers in their lifetimes.

- This means that at least some massive ($\sim 2 \times 10^{11} \, M_\odot$) galaxies almost certainly formed monolithically early on.

- The masses and conservative limits on the ages imply average star formation rates of at least a few hundred $M_\odot$ per year, sustained for a few $10^8$ years.

- This raises the question: How can one arrange such a sustained starburst to end up with what appears (in at least some cases) to be a well relaxed disk?