What Galaxy Properties Depend on Environment at High Redshift?

Casey Papovich
Texas A&M University
George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy

Ryan Quadri (Texas A&M)
Lalitwadee Kawinwanichakij (Texas A&M)
Robert Bassett (Swinburne)

and collaborators on CANDELS and ZFOURGE teams

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TRACING THE STAR-FORMATION–DENSITY RELATION TO $z \sim 2$

RYAN F. QUADRI$^{1,2,5}$, RIK J. WILLIAMS$^1$, MARJN FRANX$^2$, AND HENDRIK HILDEBRANDT$^{2,3,4}$

$^1$ Carnegie Observatories, Pasadena, CA 91101, USA; quadri@obs.carnegiescience.edu
$^2$ Leiden Observatory, Leiden University, NL-2300 RA Leiden, The Netherlands
$^3$ Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 2C2, Canada
$^4$ Argelander-Institut fuer Astronomie, Auf dem Huegel 71, 53121 Bonn, Germany

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ABSTRACT

Recent work has shown that the star formation (SF) density relation—in which galaxies with low SF rates are preferentially found in dense environments—is still in place at $z \sim 1$, but the situation becomes less clear at higher redshifts. We use mass-selected samples drawn from the UKIDSS Ultra-Deep Survey to show that galaxies with quenched SF tend to reside in dense environments out to at least $z \sim 1.8$. Over most of this redshift range we are able to demonstrate that this SF–density relation holds even at fixed stellar mass. The environmental quenching of SF appears to operate with similar efficiency on all galaxies regardless of stellar mass. Nevertheless, the environment plays a greater role in the buildup of the red sequence at lower masses, whereas other quenching processes dominate at higher masses. In addition to a statistical analysis of environmental densities, we investigate a cluster at $z = 1.6,$
star-formation — density relation out to $z \sim 1.8$

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Environmental Quenching Efficiency vs. galaxy density
Environment affects galaxy star-formation properties out to high redshift.

– What are the physical effect(s) and timescale(s) that cause trends b/w galaxy properties and environment?

Possible insights garnered by studying the evolution:

...in the stellar mass function versus environment
...in galaxy morphological evolution vs. environment (esp. quiescent galaxies).
stellar mass function versus environment:
SDSS $0.02 < z < 0.08$  (Peng et al. 2010, ApJ)
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“... [there is] a faster transition rate in over dense regions, with galaxies in low-density regions [having] a delay of ~2 Gyr between z~1 and z~0.2.”
Bolzonella et al. (2010, arXiv:0907.0013)
stellar mass function versus environment: model to account for evolution for $z < 1$

Collaboration between Leiden Obs, Texas A&M University, Carnegie Obs, Swinburne, and others

Deep (K~25 AB mag) imaging in three CANDELS HST fields (COSMOS, CDFS, UDS) w/Medium-band filters (J1J2J3 HsHl Ks) to provide R~10 “spectroscopy”.

Includes wealth of ancillary data (Spitzer/Herschel, X-ray, radio).

Stellar mass limit, >2 x 10^9 solar masses at z < 2.

Measure precise redshifts (Δz/1+z = 1%) for 0 < z < 4

Exceptional image quality in near-IR (median FWHM < 0.5")
ZFOURGE selected cluster at z=2.1, Spitler et al. (2012)

Ilbert et al. $i < 25$, $z=2.1-2.3$

Whitaker et al. $K<23.5$, $z=2.1-2.3$

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R. Allen and ZFOURGE team (2015)

ZFOURGE selected cluster at z=2.1, Spitler et al. (2012)
stellar mass functions (SMF) from ZFOURGE

SMFs: dependence on environment

- all galaxies
- highest density quartile
- lowest density quartile

Log stellar mass vs. Log M/M_☉ for different redshift bins (0.5 < z < 1.0, 1.0 < z < 1.5, 1.5 < z < 2.0).

- Total SMF
- Quenched galaxies

Graph shows the distribution of galaxies across different redshift bins and density quartiles.
Evolution of Stellar Mass Function (SMF) shows relations with Environment and Galaxy Activity

– SMF of **quiescent massive galaxies** shows dependence on environment and redshift.

– SMF of **quiescent low-mass galaxies** shows build-up with time, with strong dependence on environment.

– Evidence for **Environment Quenching**, at least since $z=1.5$ (but see also Nancy Kawinwanichakij’s talk Thursday).

– SMF of **star-forming galaxies** shows little evolution with redshift or environment.

– Consistent with extrapolations of trends seen by Peng et al. (2010), Mortlock et al. (2015), Vulcani et al. (2015), Darvish et al. (2015), and others.
Environmental Effects on the Morphologies
environmental drivers of galaxy morphology at $z=1.6$ in the CANDELS UDS field

Contours are galaxy density in UDS at $z=1.6$

$z=1.62$ proto-cluster (Papovich+10)
environmental drivers of galaxy morphology at $z=1.6$ in the CANDELS UDS field

Contours are galaxy density in UDS at $z=1.6$

$z=1.62$ proto-cluster (Papovich+10)
Accelerated evolution:
see also: Lotz, Papovich, and CANDELS team (2013, ApJ);
see also similar results from Lani et al. (2013, MNRAS)
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Cluster galaxies have higher $R_e$.


Evolution of the size-environment relation.
cluster galaxies have higher $R_e$

... present samples are too small to rule out a modest size increase [in cluster quiescent galaxies compared to field samples].” (Newman et al. 2013)
morphology-environment relation at z~1.6


Quiescent (UVJ-selected) galaxies with $M/M_\odot > 2 \times 10^{10}$
morphology-environment relation at $z \sim 1.6$


Quiescent (UVJ-selected) galaxies with $M/M_\odot > 2 \times 10^{10}$
morphology-environment relation at $z \sim 1.6$


Quiescent (UVJ-selected) galaxies with $> 2 \times 10^{10} M_{\odot}$

Quiescent, $n < 1$
Quiescent, $1 < n < 2.5$
Quiescent, $n > 2.5$
non-Quiescent galaxy

$R = 1$ Mpc
$R = 1.5$ Mpc
$R = 3$ Mpc

CANDELS UDS field

$z = 1.62$
(proto-)cluster

$M/M_{\odot} > 2 \times 10^{10}$
morphology-environment relation at $z \sim 1.6$


quenched galaxies only

Cumulative distribution

$10^{10.3} M_\odot < M < 10^{11} M_\odot$

field
$R > 3 \text{ Mpc}$

cluster

cluster core
$R < 1 \text{ Mpc}$

cluster annulus
$R = 1-1.5 \text{ Mpc}$

medians

effective radius (kpc)

Sersic Index
Sersic Index excellent predictor of star-formation activity

Sersic Index excellent predictor of star-formation activity

morphology-color-density relation at $z \sim 1.6$

morphology-color-density relation at z~1.6

...low-mass, red objects with \( n > 2.5 \) are rarer...

Mortlock and the CANDELS team (2015, MNRAS)

\[
\text{Fraction of red objects which have } n > 2.5
\]

\[
\text{Fraction of } n > 2.5 \text{ objects which are red}
\]
SUMMARY

Evolution of Stellar Mass Function (SMF) shows correlations with Environment and Galaxy Activity

– High-mass end of quiescent galaxy SMF consistent with mass quenching independent of redshift, with environmental dependence.
– Low-mass end of quiescent galaxy SMF seems to requires environment quenching out to at least z=1.5.

Morphology-Density Relation shows dependence on Environment at high-redshifts.

– (Weak?) evidence for increased sizes of quiescent galaxies in dense regions at high-redshift: accelerated evolution (dry merging)?
– Evidence for environmental quenching at z~1.6: population of disk-like quiescent galaxies (only?) in high-density regions.
  – constrains timescales for processes (slow-acting versus fast-acting?) ** See Nancy Kawinwanichakij’s talk thursday.
– Samples too small at present: HST-like image quality of large samples of homogeneously selected field and cluster galaxies needed.