The Assembly Histories of Quiescent Galaxies Since $z = 0.7$

Jieun Choi
Harvard/CfA
University of California, Santa Cruz

Charlie Conroy
John Moustakas
Genevieve Graves
Brad Holden
Mark Brodwin
Michael Brown
Pieter van Dokkum
massive quiescent galaxies appear to be mostly assembled by $z \sim 1$ then passively evolve to $z \sim 0$

e.g., Bundy+ 2006; Renzini 2006; Cirasuolo+ 2007; Vergani+ 2008; Marchesini+ 2009; Banerji+ 2010; Moustakas+ 2013; Muzzin+ 2013
quiescent galaxies appear to grow inside-out

x4 size growth

e.g., Daddi+ 2005; Trujillo+ 2006; van Dokkum+ 2008; van der Wel+ 2008; Cimatti+ 2008; Bezanson+ 2009; Damjanov+ 2009; Williams+ 2010; Cassata+ 2010; van Dokkum+ 2010; López-Sanjuan+ 2012; McLure+ 2013; Belli+ 2013

x2 mass growth
stellar pop. analysis offers another channel for studying galaxy evolution
goal: to measure the age and abundance ratios of a mass-complete sample of quiescent galaxies as a function of $M_\star$ at $0.1 < z < 0.7$
our model uses simple stellar populations

Conroy & van Dokkum+ 2012; Conroy+ 2014

Conroy 2013
our model uses **simple stellar populations**

Conroy & van Dokkum+ 2012; Conroy+ 2014

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Kroupa (can be arbitrary)

Dartmouth Padova Lyon

MILES IRTF + response functions
MESA Isochrones & Stellar Tracks coming soon!

Paxton+ 2011, 2013

0.08 – 150 $M_\odot$

many evolutionary phases

a variety of [Fe/H], [a/Fe]

in collaboration with:

Charlie Conroy
Aaron Dotter
Matteo Cantiello

Choi, (Conroy, (et al.) in prep

**MIST – MESA Isochrones & Stellar Tracks**

- New grids of stellar tracks
- Isochrones from MESA
- Collaboration with MESA developers
- Aaron Dotter & Matteo Cantiello
- Lead by graduate student Jieun Choi at UCSC
- Primary goal is to constrain uncertain physical ingredients with resolved stellar populations

Choi+ in prep
the galaxy sample

SDSS II, DR7
0.07 < z < 0.09
Abazajian+ 2009

AGES
0.1 < z < 0.7
Jannuzi & Dey 1999; Kochanek+ 2012

R ~ 2000
52,908 galaxies
14.5 < r < 17.6

R ~ 1000
10,839 galaxies
15 < I_{Vega} < 20
quiescence selection using specific SFR

stellar mass and SFR estimates from iSEDfit Moustakas+ 2013
stacked spectra in bins of logM-z

Choi+ 2014
testing the stacking procedure

62 SDSS galaxies with $\log(M/M_\odot) \sim 11.5$
example fits

SDSS

AGES

Choi+ 2014
effective single-burst SF at $z < 1.5$

the addition of newly quenched galaxies at $z > 0.7$

the ages of massive quiescent galaxies are consistent with passive evolution

Choi et al. 2014

Effective single-burst SF at $z < 1.5$
the abundance ratios show no redshift evolution

* we also measure [C/Fe], [N/Fe], [Ca/Fe]
a comparison with toy models indicates that the inner regions (~0.3 – 3 $R_e$) of massive quiescent galaxies appear to be passively evolving since $z \sim 0.7$

scenario I
passive evolution within $\sim 1R_e$
what’s next?

ongoing survey at UCSC using Keck DEIMOS
~500 quiescent galaxies at <z>~0.7 with 8 - 36 hr exposures

low S/N regime (~20 Å\(^{-1}\) with ~0.1 dex precision)
z ~ 1, e.g., MOSFIRE
radial gradient studies, e.g., MaNGA
there is negligible evolution in abundances at fixed M over the last ~7 Gyr, consistent with passive evolution in the inner ~0.3 – 3 R_e.

the young ages we observe & the existence of massive quiescent galaxies at z > 1 indicate the inhomogeneous nature of the z<0.7 quiescent population.

the full-spectrum fitting technique opens the possibility to engage in stellar pop. analysis using low S/N data, e.g., z>1, galaxy outskirts.
response functions allow us to measure variable abundances

13 Gyr simple stellar population
response functions allow us to measure variable abundances

\[
F_{\lambda, \text{empirical(\text{non-solar})}} = \frac{F_{\lambda, \text{synthetic(\text{non-solar})}}}{F_{\lambda, \text{synthetic(\text{solar})}}} \times F_{\lambda, \text{empirical(\text{solar})}}
\]

what we fit to a galaxy spectrum with non-solar abundances

empirical spectrum
simulations suggest dry minor-mergers

e.g., Naab+ 2007; Kereš+ 2009; Naab+ 2009; Hopkins+ 2009; Dekel+ 2009; Lackner+ 2012; Hilz+ 2013
*assuming the spectra are probing ~ $1R_e$

**scenario I**
passive evolution
within ~ $1R_e$

**scenario II**
dry major mergers
within ~ $1R_e$

**scenario III**
dry minor mergers
within ~ $1R_e$

**scenario IV**
newly quenched galaxies
at low mass
within ~ $1R_e$

mass growth of any kind
outside ~ $1R_e$

Choi+ 2014
the scenarios considered here lead to subtle differences in age but more apparent differences in abundances
recall that the abundances show no redshift evolution
stars in massive quiescent galaxies are old.

![Graph showing age vs. log of velocity dispersion](image)

- Age (Gyr)
- log σ (km/s)

Conroy+ 2014

- [Ca/Fe]
- [Mg/Fe]
- [Fe/H]
- [N/Fe]
- [O/Fe]
- [Ti/Fe]

The main results from this paper are summarized in Figure 18. The figure presents a comparison between different techniques for estimating age and metallicity using various elements.

- [Age vs. log of velocity dispersion](chart)

The derived [Mg/H] abundances, and therefore any model using abundance ratios, are also presented in the figure.

- [Comparison of derived abundances](chart)

The qualitative agreement between our results and those of other authors is, for the most part, very encouraging. The figure highlights the strong variation in [Mg/Fe], [C/Fe], and [N/Fe]. It shows excellent agreement in the trends, including the derived weighted ages, the weak variation in [Fe/H], and [Ca/Fe].

Additional free parameters in order to marginalize over our uncertainties of various aspects of stellar evolution and stellar population models are used herein. In addition, we have included a large number of additional free parameters in order to marginalize over our uncertainties of various aspects of stellar evolution and stellar population models.

- Tomkins et al. (2010, T10), Johansson et al. (2012, J12), and Thomas et al. (2010, T10), and many others (e.g., Trager et al. 1998; Thomas et al. 2005; Graves et al. 2007; Schiavon 2007; Smith et al. 2009; Zhu et al. 2010; Thomas et al. 2010; Johansson et al. 2012; Worthey et al. 2013; Conroy et al. 2014).
galaxies become older with decreasing $z$

galaxies become older with increasing mass

Choi+ 2014
focus on the massive end where we have good redshift coverage
... and enriched in elements like Mg and C
the abundance patterns provide clues about star formation processes

high \([a/Fe]\) = short SF timescales
quiescent galaxies

= 

non-star-forming, red, and dead galaxies
radial gradients in stellar population properties support this story (maybe)

radial gradients in stellar population properties support this story (maybe)

Elliptical Outskirts II

F
IG
.5 . — R a d i a l g r a d i e n t s i n a g e , [ F e / H ] , [ M g / F e ] , [ C / F e ] , [ N / F e ] , and [Ca/Fe] as calculated by EZ_Ages from the Lick indices measured in the composite spectra. We show both the measurements for the high-dispersion (circles) and the low-dispersion (squares) galaxies as a function of $R$ in kpc (left) or $R/R_e$ (right).

At low dispersion, our observations do not reach beyond 9 kpc. The lines show models assuming $[O/Fe] = 0.1$ rather than the default $[O/Fe] = 0.5$, keeping $[O/Fe]$ constant with radius in both cases (high-dispersion composite in dash and low-dispersion in dot-dash).

Note the decline with radius in $[Fe/H]$ and $[C/Fe]$ in contrast with the radially constant age, $[Mg/Fe]$, $[N/Fe]$, and $[Ca/Fe]$. 

Greene+ 2013
[C/Fe], [N/Fe], and [Ca/Fe] also show no redshift evolution.

SDSS, 0.07 < z < 0.09
0.1 < z < 0.2
0.2 < z < 0.3
0.3 < z < 0.4
0.4 < z < 0.55
0.55 < z < 0.7
Choi+ 2014
advantages of full-spectrum fitting:

1. low S/N

\[ \Delta \log \text{Age} \]
\[ \Delta \text{[Fe/H]} \]
\[ \Delta \text{[Mg/Fe]} \]

\( \times 10 \) difference in S/N = \( \times 100 \) difference in integration time!

full-spectrum fitting: see also, e.g., Walcher+ 2009, Ocvirk+ 2006a,b
advantages of full-spectrum fitting:
2. age-metallicity degeneracy
a popular way to measure abundances is the **Lick/IDS index system**

Burstein+ 1984; Worthey+ 1994

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Table 2. Spectral observing parameters.

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Figure 1. The spectrum of NGC 1407 and NGC 1400, obtained from co-adding the individual 1D spectra. The flux scale is arbitrary. The shadowed regions indicate the central band of the Lick/IDS indices used in the stellar populations analysis.

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Figure 2. The average deviation in units of error (i.e. $\chi^2$) for the 16 observed Lick/IDS indices. Indices are listed in increasing wavelength order. Error bars represent the rms scatter in the deviations. Deviations after the removal of the poorly fitted Mg and NaD indices (open circles) and of the indices omitted by the iterated 3σ-clipping routine (see text for details).

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NGC 1407 Slit P.A. 44°

NGC 1400 Slit P.A. 42°

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4.1 Stellar population model fitting procedure

The observed Lick/IDS indices have been used to derive luminosity-weighted log(Age), total metallicity $[Z/H]$ and $\alpha$-abundance ratio $[\alpha/Fe]$. The $\alpha$-abundance ratio is parametrised by $[E/Fe]$; the latter quantifies the enhancement from the $\alpha$-elements (N, O, Mg, Na, Si, Ti) with respect to the Fe-peak elements (Cr, Mn, Fe, Co, Ni, Cu, Zn; see Thomas et al. 2003 for details).

Briefly, the technique (Proctor & Sansom 2002) involves the simultaneous comparison of as many observed indices as possible to single stellar population (SSP) models. The best fit is achieved throughout a statistical $\chi^2$-minimisation technique, which reduces the deviations between the observed and the modelled values as a fraction of the index errors, i.e. $\chi^2$. The strength of the method is that it works with as many indices as possible in order to break the age-metallicity degeneracy that affects each index differently.

In this work, we use Thomas et al. (2003) SSP models. Models are provided with: $[\alpha/Fe] = -0.3, 0.0, 0.3, 0.5$; ages from 0.1 to 15 Gyr ($-1 \leq \log(\text{age}) \leq 1.175$, in steps of 0.025 dex); $[Z/H]$ from $-2.25$ to 0.8 in steps of 0.025 dex.

We began the model fitting process obtaining the best fit to all 16 observed indices. The residuals are expressed in terms of index errors $\chi$. We found that Mg and NaD indices are poorly fit by the Thomas et al. (2003) SSP models.

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requires S/N~100 per Angstrom
quiescent galaxies appear to grow inside-out

e.g., Daddi+ 2005; Trujillo+ 2006; vanDokkum+ 2008; vanderWel+ 2008; Cimatti+ 2008; Bezanson+ 2009; Damjanov+ 2009; Williams+ 2010; Cassata+ 2010; vanDokkum+ 2010; LópezSanjuan+ 2012; McLure+ 2013; Belli+ 2013
and simulations support this notion as well.

![Graph showing size vs. redshift and lookback time](image)

- At low redshift, the system is more extended.
- This is in agreement with the system being flattened and disk-like.
- The density at larger radii subsequently increases toward smaller values, whereas the central region of the galaxy remains constant.
- The in situ system is very compact (see also Joung et al.).
- Spherical half-mass radii of the in situ stellar component, show more than an order of magnitude toward lower redshifts. The central part of the galaxy is always dominated by in situ stars whereas at redshifts around 2–3, the galaxies are dominated by accreted stars.
- At high redshift, stars made in situ (open diamonds) in the galaxy and stars formed outside the galaxy and then accreted later on (bottom plot).
- In general, the half-mass radii trace the half-light radii even at redshifts of 3–4.

- The half-mass radius of this component is significantly larger than for the in situ stars.
- The density at larger radii subsequently increases toward smaller values.
- The density is not dominated by stellar evolution.
- The central physical 30 kpc as a function of time. At large redshifts, the system is extended at all redshifts and has a shallower density profile. Its density resembles the density at large redshifts reasonably well.
- The density at larger radii subsequently increases toward smaller values.

The errors given in the figure are bootstrap errors for the diameter at a redshift of around 3.

check that the sample is mass-complete then stack spectra in bins of $\log(M-z)$
Age of the Universe (Gyr)

- $z_f = 1.4$, $\tau = 0.1$ Gyr
- $z_f = 1.1$, $\tau = 0.1$ Gyr
- $z_f = 0.9$, $\tau = 0.1$ Gyr

$10.6 < \log(M/M_\odot) < 10.9$
$10.9 < \log(M/M_\odot) < 11.2$
$11.2 < \log(M/M_\odot) < 11.5$

The ages of massive quiescent galaxies are consistent with passive evolution.

Choi+ 2014
uncertainties as a function of S/N
there is no significant bias introduced due to artificial smoothing

\[ \delta_{\text{log Age}} (\text{Gyr}) \]

\[ \delta_{\text{[Fe/H]}} \]

\[ \delta_{\text{[Mg/Fe]}} \]

Choi+ 2014
examining the residuals

![Graph showing residuals for different mass-to-light ratios and signal-to-noise ratios.](Choi+ 2014)
we create stacked spectra in bins of $\log M-z$

continuum-normalize

coadd with

$$w_\lambda = \frac{1}{\sigma_\lambda^2}$$

smooth with a Gaussian
even in the presence of radial gradients (worst-case scenario),
we expect negligible aperture bias

\[ \nabla_{[\text{Fe/H}]} = -0.23 \]

\[ \langle [\text{Fe/H}] \rangle_{z=0.1} - \langle [\text{Fe/H}] \rangle_{z_{\text{max}}} \]

\[ \log(M/M_{\odot}) \]

Choi+ 2014
where is the light coming from?

Choi+ 2014
where is the light coming from?

\[ \frac{R_{\text{fiber}}}{R_e} \]

\[ \log(M/M_\odot) \]

<table>
<thead>
<tr>
<th>SDSS</th>
<th>AGES</th>
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<tbody>
<tr>
<td>10.6 - 10.9</td>
<td>10.9 - 11.2</td>
</tr>
<tr>
<td>11.2 - 11.5</td>
<td></td>
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SDSS: 3”
ACES: 1”.5

Choi+ 2014
Keck DEIMOS spectra of two quiescent galaxies in a cluster at $z = 0.83$

Choi+ 2014
tantalizing clues of the role of environment on stellar population properties

Choi+ 2014
age-dependent response functions

Choi+ 2014