THE EVOLUTION OF THE AGES AND METALLICITIES OF MASSIVE GALAXIES SINCE Z = 0.7

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The global SFR density has declined by almost a factor 10 since $z \sim 1$ (e.g., Hopkins & Beacom 06, Bell+05, Zheng+07, Karim+11, Cucciati+12) and of massive red-sequence galaxies and of massive star-forming galaxies (e.g., Cimatti+06, Faber+07, Bell+07, Ilbert+10,13, Moustakas+13).

More detailed and complementary insight from stellar populations

Mass, age and chemical composition of stellar populations are the result of the past history of star formation and chemical evolution, the recycling of heavy elements into the ISM/IGM, galaxy-environment interactions.

"Fossil record" approach: infer past history from present-day stellar populations

"Direct" approach: trace the stellar population properties of galaxies at higher redshift and how they connect to the local ones.

Massive end: bulge-dominated, old and metal-rich -> contain more than half of the mass and metal budget in stars at $z=0$ (e.g. Gallazzi et al 2008, Baldry et al 2004, Bell et al 2003).

EARLY-TYPE/QUIESCENT GALAXIES: increase in age, metallicity and $\alpha$/Fe with mass (Thomas+05,Gallazzi+06,Nelan+06,Graves+09,10,de la Rosa+11)

- Scatter in metallicity at all masses
- Scatter in age increases at low stellar masses (anti-correlated at fixed mass - Graves+10)

Episodic rejuvenation through small burst of SF?
Continuous build-up of the red-sequence through quenching of SF in blue-cloud galaxies?
Stellar populations studies at intermediate redshift

- Analysis of stellar continuum and absorption features more challenging at high redshift
- Most studies on co-added galaxies spectra (e.g. Kelson+06, Schiavon+06, Sanchez-Blazquez+09, but see Jørgensen 2005 and Jørgensen & Chiboucas 2013)
- Most works target cluster galaxies and focus on quiescent/red-sequence galaxies

Most massive CLUSTER galaxies agree with passive evolution and high formation redshift (e.g. Sanchez-Blazquez+09, Jørgensen & Chiboucas 2013). But non-passive evolution for lower-mass galaxies; and chemical differences among clusters (Jørgensen & Chiboucas 2013)

Evidence for non passive evolution in the mean FIELD population even in the most massive galaxies (e.g Schiavon+06) but no evidence of abundance evolution in massive quiescent galaxies (Choi et al 2014)

Can we distinguish between EVOLUTION OF INDIVIDUAL RS GALAXIES and EVOLUTION OF THE POPULATION through addition of newly “formed” RS galaxies?

Can STAR-FORMING GALAXIES provide the necessary population for the observed evolution?

Is there an ENVIRONMENTAL dependence?

Thursday, July 24, 2014
IMACS spectroscopy of z=0.7 massive galaxies

* Deep multi-object spectroscopy with IMACS on Magellan on a sample of ≳70 galaxies selected at 0.65<z<0.75 and apparent magnitude R<22.7: mapping the Red Sequence down to its completeness limits of $3\times10^{10} \, M_\odot$ and the massive end of the Blue Cloud

* CDFS field: COMBO-17 photometry, HAWK-I J and K, HST/GEMS for 75% of the sample, Spitzer 24μm
10h exposure on source reaching an average S/N of 20

3700-5500Å rest-frame; resolution of 3.4Å FWHM (~100km/s), comparable to SDSS and SPS models
FROM SPECTRA TO PHYSICAL PARAMETERS:
A BAYESIAN APPROACH

Library of model spectra

BC03 models convolved with MONTE CARLO LIBRARY OF COMPLEX SFHS and metallicities

Optimal set of absorption features: D4000, Hβ, Hγ+Hδ, [Mg2Fe], [MgFe]′

combined with J-K color (rest-frame I-J) to estimate dust attenuation and mass

build full probability density function of LUMINOSITY-WEIGHTED AGE, STELLAR METALLICITY; STELLAR MASS

uncertainties from width of the PDF, account also for parameter degeneracies

comparative analysis with low-redshift study based on SDSS (Gallazzi et al 2005)

Thursday, July 24, 2014
PHYSICAL PARAMETER ESTIMATES

* Similar accuracy in light-weighted age as for SDSS, but slightly larger errors for mass and metallicity

* Stellar mass distribution peaks around $10^{11} \, M_\odot$, similar to SDSS

* Distribution in stellar age peaks at 4.6 Gyr, as opposed to 7 Gyr in SDSS

* lower fraction of old galaxies if we shift SDSS to $z=0.7$

* Similar metallicity distribution
THE EVOLUTION IN THE AGE-MASS RELATION

At z=0.7 similar trend of increasing mean light-weighted age with stellar mass as observed at z=0.1 (~2.5 Gyr over an order of magnitude in mass)

\[ P \sim P^\gamma \log(1 + (M^\gamma / M^\ast)^\gamma) \]

Age at \(10^{11.5} M_\odot\): 4 Gyr

Similar shape as the local relation

Characteristic mass: mild indication of an increase by 2x
At both z similar to transition mass of Q and SF mass functions

Too shallow and too old:

mass-dependent rate of evolution in age

PURE PASSIVE EVOLUTION OF Z=0.7 POPULATION, EVEN AT MASSES >10^{11}, DOES NOT CORRECTLY PREDICT THE LOCAL RELATION
large dispersion in metallicity, but median value increases by 0.2 dex over an order of magnitude in mass.

Metallicity at $10^{11.5} M_\odot$:
solar metallicity, i.e. 0.13 dex lower than at $z=0.1$

Shape of the relation consistent with the local one
Uncertain whether the relation steepens at low masses

Similar evolution in the characteristic gas-phase oxygen abundance over the redshift range 0.7–0.1 (e.g. Moustakas et al. 2011)
The galaxy specific SFR plays a role in the scatter of both age and metallicity at fixed mass.

**QUIESCENT GALAXIES:** $>10^{11} M_\odot$; 
$<\text{Age}>=5$ Gyr; solar metallicity

**SF GALAXIES:** larger mass range; younger ages and larger spread to lower metallicities

**Analogy with Mass-SFR-$Z_{\text{gas}}$ relation?**
- no clear detection of a joint dependence of stellar metallicity on Mass and (s)SFR in star-forming galaxies only
- star-forming galaxies with higher sSFR deviate to younger ages
similar increase in log (Age) with mass as at z=0, but offset by \(-0.2\) dex (\(-3\) Gyr)

stellar metallicity-mass relation fully consistent with local quiescent galaxies

\(\sim3\)Gyr (5Gyr) younger than local SF (Q) galaxies

median metallicity lower by 0.12 (0.2) dex wrt to local SF (Q) galaxies

chemical enrichment to z=0 in at least a fraction of massive SF galaxies

A fraction of \(~40\%\) of z=0.7 massive SF galaxies with high metallicity

- similar evolution in gas-phase metallicity (e.g. Moustakas et al 2011)
- slightly higher than what predicted by average SFHs of SF galaxies (Peeples & Somerville 2013; 0.07 dex)
Passively evolved Q galaxies consistent with local population, but smaller age scatter

Low fraction of post-SB (~3%) argues against significant SF episodes prior to quenching - Only small amount of ‘frosting’ is allowed

Require quenching and passive evolution of (high-metallicity) SF galaxies to populate the younger portion of local Q galaxies
Simple Evolutionary Scenarios: average SFHs

Overall consistency with observed local relation, but slightly steeper relation other variables to differentiate SFHs, e.g. morphology? incompleteness at low masses in high-z observations?

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differential analysis OK but not trivial to match observed and predicted ages in an absolute sense.

predicted age evolution based on average SFHs of Behroozi et al 2013 as function of mass from SMF, cosmic SFH, sSFR-M relation for log(M•) 10.5,11,11.3,11.5

Behroozi et al 2013

Continued SF

sdss all

z=0.7

evolved:
quiescent

SF high metallicity

SF
Can we distinguish between EVOLUTION OF INDIVIDUAL RS GALAXIES and EVOLUTION OF THE POPULATION through addition of newly “formed” RS galaxies?

Quiescent z=0.7 galaxies have metallicities and ages consistent with local quiescent galaxies: CAN evolve passively. However scatter in age is too low. Low fractions of post-SF galaxies allows only small amount of ‘frosting’. Need additional population of SF galaxies that get quenched since z=0.7.

Can STAR-FORMING GALAXIES provide the necessary population for the observed evolution?

yes, a fraction (40%) of SF galaxies >10^{11}M_\odot have the right properties to end up on the present-day red-sequence: populate the younger portion and leave the metallicity distribution unchanged. BUT, passive evolution of the whole SF galaxy population is not consistent with local relations and with metallicity distribution of local SF galaxies. 40% of massive SF galaxies need evolution in stellar metallicity similar to gas-phase met.

Is there an ENVIRONMENTAL dependence?

maybe, from comparison with literature. In the FIELD addition of newly-quenched galaxies onto the red-sequence need to occur even at masses >10^{11}M_\odot , contrary to CLUSTER (Kelson+01, Sanchez-Blazquez+06, Jorgensen&Chiboucas+13) -> the mass threshold above which entire galaxy population evolve passively is lower in clusters: massive galaxies that reside today in clusters were quenched at an earlier epoch
CONCLUDING REMARKS

Large spectroscopic surveys and advances in SPS modeling have allowed to build a comprehensive picture of today’s galaxy populations

intermediate-redshift range has started to be explored only recently

**Importance of parallel study of star-forming galaxies**: still need to better sample this population - down to which SF can we observe and model their stellar continuum?

**Extend to lower stellar masses** with complete coverage down to $10^{10} \, M_\odot$ where evolution may be faster (do relations steepen below $10^{10.5} \, M_\odot$? do lower mass galaxies contribute to the evolution at masses > $10^{11} \, M_\odot$?)

are the observed stellar populations at different redshifts consistent with the population-average SFHs and chemical evolution inferred from gas-phase O abundance?

**recently-started and upcoming large spectroscopic programs** (VIMOS Public Survey PI: van der Wel) to gather large samples at z<1

**Extend to higher redshift** where most of the evolution is expected to happen: NIR multi-object facilities