Challenges in Panchromatic Modelling with Next Generation Facilities
Proceedings IAU Symposium No. 341, 2018
M. Boquien, E. Lusso, C. Gruppioni & P. Tissera, eds.

doi:10.1017/S1743921319002734

Evolution histories of massive galaxies at $z \sim 2$ over the past 3 Gyr

T. Morishita[1], L. E. Abramson[2], T. Treu[3], G. B. Brammer[1,4], T. Jones[5], P. Kelly[6], M. Stiavelli[1], M. Trenti[7,8], B. Vulcani[9] and X. Wang[3]

[1]Space Telescope Science Institute, Baltimore, MD, USA
email: tmorishita@stsci.edu

[2]The Observatories of the Carnegie Institution for Science, Pasadena, CA, USA

[3]Department of Physics and Astronomy, UCLA, Los Angeles, CA USA

[4]Cosmic Dawn Centre, University of Copenhagen, Copenhagen, Denmark

[5]University of California Davis, Davis, CA , USA

[6]School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA

[7]School of Physics, University of Melbourne, Parkville VIC, Australia

[8]ARC Centre of Excellence for All-Sky Astrophysics in 3 Dimensions, Parkville VIC, Australia

[9]INAF – Osservatorio Astronomico di Padova, Padova, Italy

Abstract. We study star formation and metallicity enrichment histories of 24 massive galaxies at $1.6 < z < 2.5$. Deep slitless spectroscopy + imaging data set collected from multiple *HST* surveys allows robust determination of their SEDs. Our new SED modeling with no functional assumptions on star formation histories revels that 1. most of the sample galaxies have already formed $> 50\%$ of their extant masses ~ 1.5 Gyr before the time of observed redshifts, with a trend where more massive galaxies form earlier, 2. most of our galaxies already have stellar metallicities compatible with those of local early-type galaxies, and 3. inferred metallicities are on average ~ 0.25 dex higher than observed gas-phase metallicities of star forming galaxies at the time of their formation. Continuation of low-level star formation, rather than abrupt termination of star forming activity, may explain the observed gap of metallicities.

Keywords. galaxies: evolution – galaxies: metallicity

1. Introduction

In the local universe, early-type galaxies dominate the massive end of the galaxy mass function, $\log M_*/\mathrm{M}_\odot \gtrsim 11.5$ (Cole *et al.* 2001; Bell *et al.* 2003). Observations have, in fact, revealed that some galaxies are already massive and passively evolving at $z \gtrsim 2$ (e.g., Daddi *et al.* 2005; van Dokkum *et al.* 2008; Glazebrook *et al.* 2017). Given the short time since the Big Bang and their mass, their earlier star formation must be extremely intense, followed by a rapid cessation of their star formation activity, or quenching.

However, these episodes yet remain observationally indirect. What were their star formation histories like? How and why did they stop forming stars, especially at the peak time of the cosmic star formation? Are they already enriched in metallicity as local counterparts? Do any post-quenching processes play key roles over the following 10 Gyr? These are the central questions that the extra-galactic community has been trying to answer in the past decades.

A number of studies have investigated star formation histories of massive galaxies with different approaches, from archaeological studies of resolved stars in the local galaxies, detailed spectroscopic observations of low-z galaxies, to direct observation of high-z galaxies to reveal their progenitors. While each method has its strength, it is true that none of them is perfect to comprehensively understand the star formation history of galaxies. For example, spectroscopic information from the local galaxies is hampered up to several Gyrs with current observing facilities, which is too short for exploring star formation histories of massive galaxies, which were already dead at $z \sim 2$, or $\gtrsim 10$ Gyr ago.

To explore evolution histories in the earlier epoch, there has been a significant improvement with high-quality data of high-z galaxies. In this study, we target galaxies at high redshift, aiming at earlier evolution histories up to their formation redshift from fossil record obtained with low-spectral resolution yet high sensitivity *HST* spectrophotometric data set. The key of our SED modeling is to determine the best combination of those amplitudes that reproduces the observed data best (akin to Cid Fernandes *et al.* 2005; Panter *et al.* 2008), which gives us flexibility in reconstructed star formation and metallicity histories, leaving them free from any functional forms. Due to the large number of parameters ($N_{age} \times 2 + 1 + 1 = 22$), full exploration of parameter spaces is necessary for unbiased results. We accomplish this by adopting a Bayesian inference MCMC scheme (*emcee*; Foreman-Mackey *et al.* 2014), which is intensively tested with mock data set (for the detail see Morishita *et al.* 2018).

In this study, we collect 24 massive ($\log M_*/\mathrm{M}_\odot \gtrsim 11$) galaxies at $z \sim 2$ that have deep WFC3/G102 and G141 grism spectra coverage in their rest-frame 4000 Å, from multiple surveys (van Dokkum *et al.* 2013; Skelton *et al.* 2014; Schmidt *et al.* 2014; Treu *et al.* 2015; Kelly *et al.* 2016; Momcheva *et al.* 2016). The combination of grism spectra and wide broadband photometry (0.2 μm to 8.0 μm by *HST* and *Spitzer*) provides a unique opportunity to constrain not only the age but also the metallicity from the entire SED shape.

2. Results

While the result of individual fits and their detailed properties are shown in Morishita *et al.* (2018), we here focus on the global properties of our 24 galaxies. The left panel of Figure 1 shows their cumulative mass accumulation histories as a function of lookback time. The average trend is shown in the middle panel. We see that our galaxies on average form half of their observed mass by ~ 1.5 Gyr prior to the observation (which corresponds to $z \sim 2.5$-5). In the right panel, we see a positive correlation between the two parameters ($\log t_{\mathrm{half}}/\,\mathrm{Gyr} \propto 0.5 \log M_*/\mathrm{M}_\odot$). This means that the trend (downsizing) is observed in the early time of the universe, providing a further insight into their evolution at even earlier epoch, especially when those galaxies are in the star-forming phase. While it is possible our galaxies were once typical (but bright) Lyman break galaxies given the half mass (e.g., Verma *et al.* 2007), it should be reminded that there is also a population that are dusty and missed in most of current optical/NIR observations (e.g., those in Tao Wang's contribution).

In the left panel of Figure 2, we plot our galaxies in the stellar mass-stellar metallicity plane, for a comparison with massive galaxies at $z \sim 0$ (Gallazzi *et al.* 2005). Surprisingly, most of our galaxies are already above the local relation — median value of $\log Z_*/Z_\odot \sim 0.25$ with scatter of ~ 0.15 dex. While uncertainty of individual metallicity is still nonnegligible (~ 0.2 dex), the similar scatter to the local relation may indicate that metallicity evolution of the most massive galaxies completed by the time of $z \sim 2$. The consistent result was reported in Gallazzi *et al.* (2014) but for galaxies at $z \sim 0.7$.

https://doi.org/10.1017/S1743921319002734 Published online by Cambridge University Press

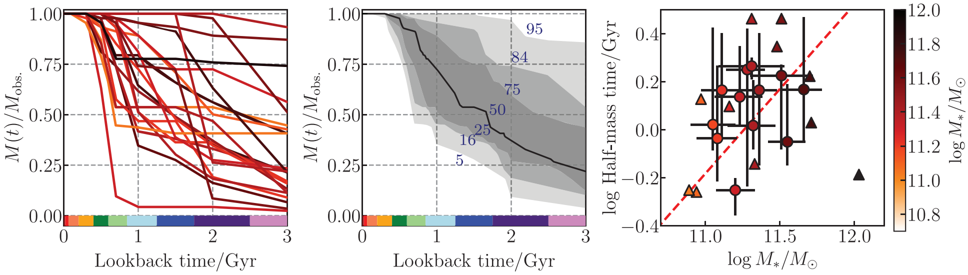

Figure 1. Left: Cumulative stellar mass evolution of individual galaxies. Color corresponds to the final stellar mass. **Middle:** Summary of individual cumulative stellar mass evolution, where contour boundaries and line correspond to 5/16/25/75/84/95th percentiles and median. **Right:** Half-mass time (lookback time from t_{obs} to the time when 50% of their current mass formed) as a function of observed stellar mass. Those with lower limits are shown with triangles.

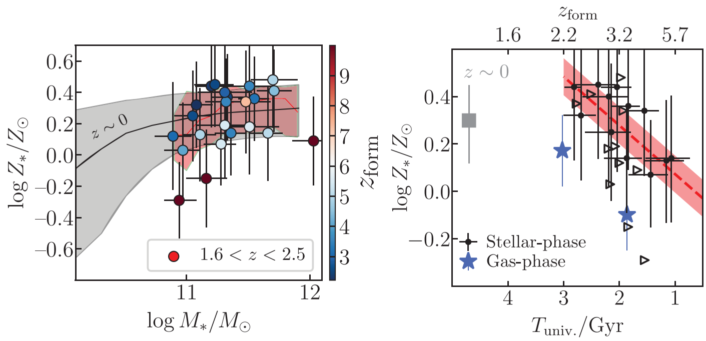

Figure 2. Left: Stellar mass-metallicity relation of 24 galaxies in this study (circles). The symbols are color-coded by formation redshift, z_{form}. Running median (~0.25) is shown with 16-84th percentile range (red line with hatched region; $\sigma_{\log Z}\sim0.15$). **Right:** Observed stellar metallicity as a function of the formation time, or z_{form} (black circles/triangles for those with an upper limit in age estimate). The linear fit with a slope (0.20 ± 0.08 dex/Gyr) and standard deviation ($\sigma\sim0.16$ dex) is shown (red dashed line and hatched region).

Despite its tight relation in the plane, we see a trend for metallicity in Figure 2, where the color of metallicity as a function of formation redshift. In the right panel of Figure 2 we show the stellar metallicity but as a function of formation redshift, derived from the star formation history of individual galaxies. While some sample galaxies have a lower limit for their formation time (due to the low resolution power), the linear fit still shows an evolution of metallicity as a function of cosmic time, with a slope of $\log Z_*/dt\sim0.20\pm0.08$ dex/Gyr. This reveals the rapid evolution of metallicity in the most massive galaxies, which is in fact consistent with other measurements but in e.g., star forming galaxies (e.g., Erb *et al.* 2006; Maiolino *et al.* 2008).

Interestingly, there is a nonnegligible gap (~0.25 dex) between the two different metallicities (stellar for ours and gas phase from Maiolino *et al.* (2008)) when compared at the time of formation. While the comparison is very challenging and may be hampered by systematics, this may hint at physical mechanisms for galaxy quenching. For example, Peng *et al.* (2015) demonstrated a chemical modeling by using the SDSS data for $z\sim0$ galaxies and showed that strangulation is the main mechanism for quenching. While AGN feedback is one of popularly discussed quenching mechanisms, the gap should not be observed, as the feedback would blow the gas and leave no time for chemical enrichment from gas to stellar phase metallicities. Our result also supports the strangulation. In fact, there are several observations that reveal low-level star formation activity in quenched

https://doi.org/10.1017/S1743921319002734 Published online by Cambridge University Press

galaxies (Belli *et al.* 2017; Gobat *et al.* 2018). Direct comparison of both metallicities inside individual galaxies would provide more promising insight into this.

3. Conclusion

a. Our massive galaxies have already formed $> 50\%$ of their current mass by ~ 1.5 Gyr prior to the epoch of observation with a downsizing trend.

b. Stellar-phase metallicities of most of our galaxies are compatible with local values, indicating a rapid metallicity enrichment being associated with the early stellar mass formation.

c. By using the reconstructed SFHs and inferred metallicity, we revealed a rapid metallicity enrichment of this class of massive galaxies, at a rate of ~ 0.2 dex/Gyr in $\log Z_*/Z_\odot$ from $z \sim 5.5$ to $z \sim 2.2$.

d. The observed gap between the stellar phase metallicity and gas phase metallicity can be explained by continuation of low-level of star formation in quiescent systems. The scenario provides a picture where galaxy quenching happening more continuously, rather than abrupt/rapid termination, consistently but independently confirming our findings of individual star formation activity.

References

Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, *ApJS*, 149, 289

Belli, S., Newman, A. B., & Ellis, R. S. 2017, *ApJ*, 834, 18

Cid Fernandes, R., Mateus, A., Sodré, L., Stasińska, G., & Gomes, J. M. 2005, *MNRAS*, 358, 363

Cole, S., Norberg, P., Baugh, C. M., Frenk, C. S., Bland-Hawthorn, J., Bridges, T., Cannon, R., Colless, M., *et al.* 2001, *MNRAS*, 326, 255

Daddi, E., Renzini, A., Pirzkal, N., Cimatti, A., Malhotra, S., Stiavelli, M., Xu, C., Pasquali, A., *et al.* 2005, *ApJ*, 626, 680

Erb, D. K., Shapley, A. E., Pettini, M., Steidel, C. C., Reddy, N. A., & Adelberger, K. L. 2006, *ApJ*, 644, 813

Foreman-Mackey, D., Sick, J., & Johnson, B. 2014, doi:10.5281/zenodo.12157

Gallazzi, A., Bell, E. F., Zibetti, S., Brinchmann, J., & Kelson, D. D. 2014, *ApJ*, 788, 72

Gallazzi, A., Charlot, S., Brinchmann, J., White, S. D. M., & Tremonti, C. A. 2005, *MNRAS*, 362, 41

Glazebrook, K., Schreiber, C., Labbé, I., Nanayakkara, T., Kacprzak, G. G., Oesch, P. A., Papovich, C., Spitler, L. R., *et al.* 2017, *Natur*, 544, 71

Gobat, R., Daddi, E., Magdis, G., Bournaud, F., Sargent, M., Martig, M., Jin, S., Finoguenov, A., *et al.* 2018, Nature Astronomy, 2, 239

Kelly, P. L., Brammer, G., Selsing, J., Foley, R. J., Hjorth, J., Rodney, S. A., Christensen, L., Strolger, L.-G., *et al.* 2016, *ApJ*, 831, 205

Maiolino, R., Nagao, T., Grazian, A., Cocchia, F., Marconi, A., Mannucci, F., Cimatti, A., Pipino, A., *et al.* 2008, *A&A*, 488, 463

Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., Skelton, R. E., Whitaker, K. E., Nelson, E. J., Fumagalli, M., Maseda, M. V., *et al.* 2016, *ApJS*, 225, 27

Morishita, T., Abramson, L. E., Treu, T., Brammer, G. B., Jones, T., Kelly, P., Stiavelli, M., Trenti, M., *et al.* 2018, arXiv e-prints, arXiv:1812.06980

Panter, B., Jimenez, R., Heavens, A. F., & Charlot, S. 2008, *MNRAS*, 391, 1117

Peng, Y., Maiolino, R., & Cochrane, R. 2015, *Natur*, 521, 192

Schmidt, K. B., Treu, T., Brammer, G. B., Bradač, M., Wang, X., Dijkstra, M., Dressler, A., Fontana, A., *et al.* 2014, *ApJL*, 782, L36

Skelton, R. E., Whitaker, K. E., Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., Labbé, I., Franx, M., van der Wel, A., *et al.* 2014, *ApJS*, 214, 24

Treu, T., Schmidt, K. B., Brammer, G. B., Vulcani, B., Wang, X., Bradač, M., Dijkstra, M., Dressler, A., *et al.* 2015, *ApJ*, 812, 114 van Dokkum, P., Brammer, G., Momcheva, I., Skelton, R. E., Whitaker, K. E., & for the 3D-HST team, 2013, ArXiv e-prints, arXiv:1305.2140

van Dokkum, P. G., Franx, M., Kriek, M., Holden, B., Illingworth, G. D., Magee, D., Bouwens, R., Marchesini, D., *et al.* 2008, *ApJL*, 677, L5

Verma, A., Lehnert, M. D., Förster Schreiber, N. M., Bremer, M. N., & Douglas, L. 2007, *MNRAS*, 377, 1024

Discussion

David Rosario: Are the SFHs of the passive galaxies themselves consistent with the slow quenching scenario suggested by comparison to co-eval SFHs?

Takahiro Morishita: Many degeneracies and a lack of gas mass estimates make the check fairly unconstrained, but this is a valuable exercise.

Tomotsugu Goto: Sub-mm flux or 24-micron flux?

Takahiro Morishita: Will check.

Chiara D'Eugenio: How was the gas-phase metallicity of quiescent galaxies measured?

Takahiro Morishita: The gas-phase metallicity was derived from another sample. It would be interesting to have direct estimates for our galaxies.

Joel Leja: Have you tested using different priors for your non-parametric SFHs? The posteriors have a spiky shape which is likely related to the linear weighting system.

Takahiro Morishita: No.

Adam Carnall: How do you go about fitting 22 free parameters with MCMC? Have you looked at sensitivity to starting parameters?

Takahiro Morishita: We average our uncertainties over many randomized starting positions.

https://doi.org/10.1017/S1743921319002734 Published online by Cambridge University Press