Formation and Evolution of Galaxy Outskirts
Proceedings IAU Symposium No. 321, 2016
A. Gil de Paz, J.H. Knapen & J.C. Lee, eds.

doi:10.1017/S1743921316011248

What shapes stellar metallicity gradients of massive galaxies at large radii?

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Abstract. We investigate the differential impact of physical mechanisms, mergers and internal energetic phenomena, on the evolution of stellar metallicity gradients in massive, present-day galaxies employing sets of high-resolution, cosmological zoom simulations. We demonstrate that negative metallicity gradients at large radii (>2Reff) originate from the accretion of metal-poor stellar systems. At larger radii, galaxies become typically more dominated by stars accreted from satellite galaxies in major and minor mergers. However, only strong galactic, stellar-driven winds can sufficiently reduce the metallicity content of the accreted stars to realistically steepen the outer metallicity gradients in agreement with observations. In contrast, the gradients of the models without winds are inconsistent with observations. Moreover, we discuss the impact of additional AGN feedback. This analysis greatly highlights the importance of both energetic processes and merger events for stellar population properties of massive galaxies at large radii. Our results are expected to significantly contribute to the interpretation of current and up-coming IFU surveys (e.g. MaNGA, CALIFA).

Keywords. methods: numerical, galaxies: evolution, galaxies: formation, galaxies: elliptical and lenticular, galaxies: stellar content

1. Introduction

It is a natural prediction of modern hierarchical cosmological models that the assembly of massive galaxies involves major and minor mergers although most stars in most galaxies have been made in-situ from accreted or recycled gas. Nonetheless, these mergers are expected to play a significant role for the structural and morphological evolution of the massive early-type galaxy population. One important structural galaxy property, which is thought to be strongly influenced by mergers, are the (in general negative) metallicity gradients observed early-on in massive, present-day early-type (e.g. McClure & Racine 1969), but also in late-type galaxies (e.g. Wyse & Silk 1989), typically within $1R_{\rm eff}$. Thanks to improved and more elaborated observational techniques, present-day metallicity gradients can nowadays be measured out to much larger radii, partly out to $8R_{\rm eff}$, (e.g. La Barbera *et al.* 2012) and even beyond reaching e.g. $\sim 25R_{\rm eff}$ in a few nearby galaxies like NGC 5128 or M31 (e.g. Rejkuba 2014).

Previous studies (e.g. Kobayashi 2004) only investigate the emergence of *inner* gradients (up to 3 $R_{\rm eff}$) at comparably poor spatial resolution. Here, we focus on the stellar accretion origin of metallicity gradients in high-resolution re-simulated massive galaxies *at large radii* ($2R_{\rm eff} < r < 6R_{\rm eff}$) in a full cosmological context. Specifically, we intend to explore the combined effect of energetic phenomena, such as strong stellar-driven winds and AGN feedback, and of merger histories on stellar metallicity gradients at these large radii (Hirschmann *et al.* 2015, Hirschmann *et al.*, in prep.).

2. High-resolution simulations of individual galaxy halos

We consider the 10 most massive halos (covering a mass range of $6 \times 10^{12} < M_{\rm halo} < 2 \times 10^{13} M_\odot$) of our high-resolution, cosmological zoom simulation sets presented in Hirschmann *et al.* (2013) and Hirschmann *et al.* (2015). The simulations include a treatment for metal enrichment (SNII, SNIa and AGB stars) and a phenomenological feedback scheme for galactic stellar-driven winds (Oppenheimer & Dave 2006, 2008). The dark matter/gas particles have a mass resolution of $m_{\rm dm} = 2.5 \cdot 10^7 M_{\odot} h^{-1}$ and $m_{\rm gas} = m_{\rm star} = 4.2 \cdot 10^6 M_{\odot} h^{-1}$, respectively with a co-moving gravitational softening length for the gas and star particles of 400 h^{-1}pc and for the dark matter particles of 890 h^{-1}pc (Oser *et al.* 2010). These cosmological zoom simulations were shown to be successful in suppressing early star formation at $z > 1$, and in significantly reducing the baryon conversion efficiencies for halos ($M_{\rm halo} < 10^{12} M_{\odot}$) at all redshifts in overall good agreement with observational constraints. In addition, based on the same initial conditions, we performed a set of zoom-in simulations of massive galaxies including different mechanisms for AGN feedback (mechanical-momentum, radiative X-ray as described in Choi *et al.* 2015 and Choi *et al.* in prep.). This additional process is strongly reducing late in-situ star formation in our massive galaxies, effectively making them read and dead in agreement with observations.

3. Metallicity gradients of present-day massive galaxies

In Fig. 1 (left column), we show the total (mass-weighted) stellar metallicity gradients out to 8 $R_{\rm eff}$ for the main galaxies at $z = 0$ with and without stellar-driven winds. For the NoWind galaxies, the (most) central metallicity has values of $Z/Z_{\odot} \sim 0.4$ and drops to $Z/Z_{\odot} \sim 0.1$ at large radii, the slopes reach a minimum value of -0.25 dex/dex†. This gradient is mainly driven by the accreted stars (the in-situ distributions are almost all nearly flat), which have on average roughly solar metallicity (top middle panel of Fig. 1) and dominate most systems outside $1 R_{\rm eff}$. The galaxies including strong stellar feedback (bottom panels of Fig. 1) have lower central metallicities ($Z/Z_{\odot} \sim 0.2$) with much steeper outer gradients down to -0.76 dex/dex with a mean of -0.35 dex/dex. These steeper gradients are mostly caused by the accretion of metal-poorer stellar populations (in minor mergers) as a consequence of suppression of star formation due to stellar-driven outflows.

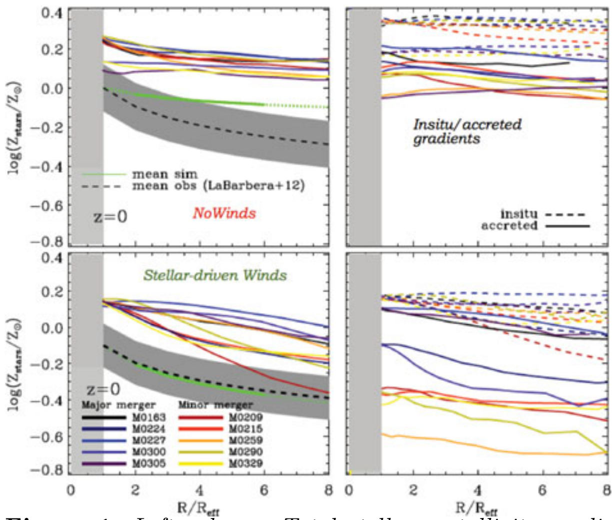

Figure 1. *Left column: Total stellar metallicity gradients (mass weighted) at $z = 0$ for the ten main galaxies (different colors) simulated with the MNoW and WM model. The green solid lines indicate the average gradient at $2 < R/R_{\rm eff} < 6$. Right column: Metallicity gradients at $z = 0$ separated into stars formed in-situ (dashed lines) and accreted stars (solid lines). Figure taken from Hirschmann et al. (2015).*

Fig. 2 illustrates stellar metallicity gradients of massive galaxies out to 10 $R_{\rm eff}$ with and without AGN feedback. AGN-driven outflows clearly reduce the normalization of the metallicity gradient at a given halo mass due to reduced star formation leading to a lower metallicity of both ex-situ and in-situ formed stars. However, interestingly, the slopes beyond 2 Reff are hardly affected by AGN feedback having a mean value of -0.33

† Note that gradients are given in units of $log(Z/Z_{\odot})$ per dex.

https://doi.org/10.1017/S1743921316011248 Published online by Cambridge University Press

to −0.35 dex/dex. Instead, only the innermost gradients ($< 2R_{\rm eff}$) seem to be shaped by that mechanism (Hirschmann et al. in prep.).

A recent study of Pastorello *et al.* (2014), using the SLUGGS survey, investigates metallicity gradients of similar stellar masses at least out to $2.5R_{\rm eff}$ with slopes between −1.15 and +0.18 dex/dex. In addition, in the study by La Barbera *et al.* (2012), they derive metallicity gradients for massive galaxies with $10^{11} < M_{\rm stellar} < 7 \times 10^{11} M_{\odot}$ finding outer metallicity gradients ($1 - 8 \times R_{\rm eff}$) in the range of −0.29 to −0.74 dex/dex depending on the stellar population model (illustrated by the black dashed lines in Fig 1). Overall, irrespective of the AGN feedback scheme, our galaxies including strong stellar feedback are able to cover such a broad range of slopes (e.g. from −0.8 to −0.1 dex/dex) much better than galaxies with only weak/no stellar feedback, whose slopes are on average too flat (e.g. between −0.25 and +0.03 dex/dex). The average metallicity gradient of the galaxies with strong stellar-driven outflows is in excellent agreement with the ones of La Barbera *et al.* (2012).

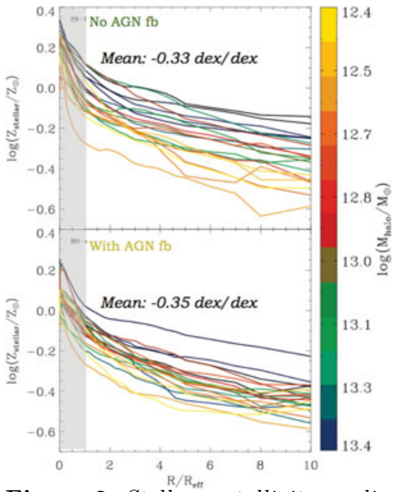

Figure 2. *Stellar metallicity gradients (mass weighted) at $z = 0$ for massive galaxies with and without AGN feedback color-coded by halo mass.*

4. Conclusions

Analysing zoom simulations of massive galaxies, we can conclude that a combination of stellar accretion (in minor mergers) of low mass satellites (as predicted from idealized experiments by Villumsen 1983) and strong stellar feedback results in steep outer metallicity gradients successfully matching the broad range of observed metallicity profiles of local galaxies at large radii (Hirschmann *et al.* 2015). Further simulations including AGN-driven feedback indicate that this additional process does not affect the stellar accretion origin of metallicity gradients at large radii, but seems to mainly shape the inner metallicity gradients (Hirschmann *et al.* in prep.).

Acknowledgements

MH acknowledges financial support from the European Research Council via an Advanced Grant under grant agreement no. 321323NEOGAL.

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https://doi.org/10.1017/S1743921316011248 Published online by Cambridge University Press