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Dilution in massive, elliptical galaxies

R. M. Yates and G. Kauffmann

Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741, Garching, Germany
e-mail: robyates@mpa-garching.mpg.de

Abstract. We present a recent study of massive galaxies in the Munich semi-analytic model of galaxy formation and the SDSS-DR7. We find that massive, elliptical galaxies with low-sSFR and low gas-phase metallicity ($Z_{\rm g}$) are undergoing a *gradual dilution* in the model, via accretion of metal-poor cold gas clumps and merging satellites (Yates & Kauffmann 2013). Indirect signatures of this evolution are also found in these systems' analogues in the SDSS-DR7, such as lower gas fractions, older ages (from the $D_{\rm n}4000$ index), and lower $Z_{\rm g} - Z_{*}$. This provides strong evidence that such a gradual dilution could also be occurring in massive, elliptical galaxies in the real Universe. These findings have consequences for the fundamental metallicity relation (FMR) at $z = 0$, as they provide an explanation for the positive correlation between SFR and $Z_{\rm g}$ seen in some observational studies (e.g. Yates et al. 2012). Such a correlation is not considered in the FMR, meaning that its shape at $z = 0$ is not as simple as first thought, and cannot be accurately fit by a simple 2D projection.

Key words. Astronomical databases – ISM: abundances – Galaxies: elliptical and lenticular, cD

1. Introduction

The metal content of galaxies is not only important because of its affect on the key physical processes taking place, but also because it can be directly measured via the absorption and emission lines observed in galaxy spectra. However, current gas-phase metallicity ($Z_{\rm g}$) diagnostics are fraught with both relative and intrinsic biases, which make the true metal content of galaxies of different masses and redshifts very difficult to constrain (Kewley & Ellison 2008). This makes global relations, such as the M_{*} - $Z_{\rm g}$ relation (MZR) and fundamental metallicity relation (FMR), very sensitive to the particular metallicity diagnostic chosen (e.g. Yates et al. 2012).

One way to tackle this problem is to study the chemical evolution of galaxies in sophisticated galaxy formation models. In such models, the mass of various heavy elements is 'known', rather than being inferred given potentially uncertain parameters such as the ionisation state, temperature, redshift, and dust content of the star-forming regions. Instead, the accuracy of the baryonic physics used in these models is the main source of uncertainty. Notwithstanding this, such models allow us to search for physically-motivated *causes* of certain correlations between metallicity and other galaxy properties, and so hopefully distinguish between true relations, and those produced by imprecise metallicity measurements.

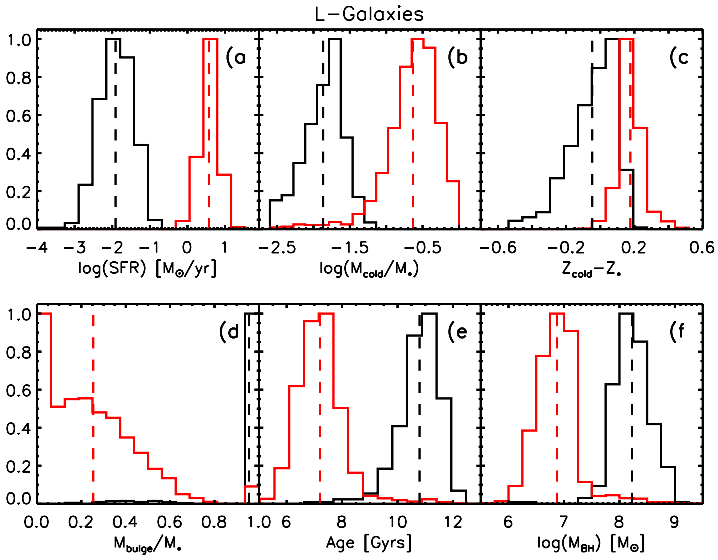

Fig. 1. The distribution of SFR (panel A), gas-to-stellar mass ratio (panel B), metallicity difference (panel C), bulge-to-total stellar mass ratio (panel D), mass-weighted age (panel E), and central black hole mass (panel F) for diluting galaxies (black) and enriching galaxies (red) from the model sample. Mean values are given by the dashed lines.

2. Model data

2.1. Model samples

We utilise the latest publicly-available version of the Munich semi-analytic model, L-Galaxies (Guo et al. 2011), run on the Millennium-II dark matter, N-body simulation (Boylan-Kolchin et al. 2009). This version is made available by the *German Astrophysical Virtual Observatory* on the Millennium Database (Lemson and the Virgo Consortium 2006). Galaxies at $z = 0$ with masses above $\log(M_*) = 10.5\,M_\odot$ are selected. In order to study the difference between high-Z_g and low-Z_g galaxies, we define two sub-samples: The first contains 2165 galaxies with $\log \mathrm{sSFR} \geq -10.7\mathrm{yr}^{-1}$ and $Z_{\mathrm{cold}} \geq 8.85$ (hereafter, *enriching galaxies*). The second contains 418 galaxies with $\log \mathrm{sSFR} \leq -12.0\ \mathrm{yr}^{-1}$ and $Z_{\mathrm{cold}} \leq 8.9$ (hereafter, *diluting galaxies*). These selection criteria are chosen to cover the high-M_* tip of the main sequence of star formation (Elbaz et al. 2011), and the low-Z_g tail of the galaxy distribution, respectively.

2.2. Model results

In Fig. 1, we show distributions of six key galaxy properties for enriching (red) and diluting (black) galaxies in the model. There are striking differences between these two sub-samples; diluting galaxies have lower gas fractions (panel B), larger bulge fractions (panel D), older mass-weighted ages (panel E), and larger central SMBHs (panel F) than enriching galaxies. In the case of $Z_{\mathrm{cold}} - Z_*$ (panel C), diluting galaxies show a significant tail down to low (even negative) values. The $Z_{\mathrm{cold}} - Z_*$ parameter is a useful diagnostic for dilution of the ISM, as lower values indicate a decrease in the gas-phase metallicity at fixed Z_* (i.e. in the absence of significant star formation).

Yates & Kauffmann (2013) have shown that these galaxies undergo a gas-rich (often major) merger at some time in the past, which quenched the original cold gas reservoir via a starburst and the associated SN feedback. An elliptical system with a large central SMBH was then formed. Thereafter, accretion of metal-poor gas via infalling gas clumps

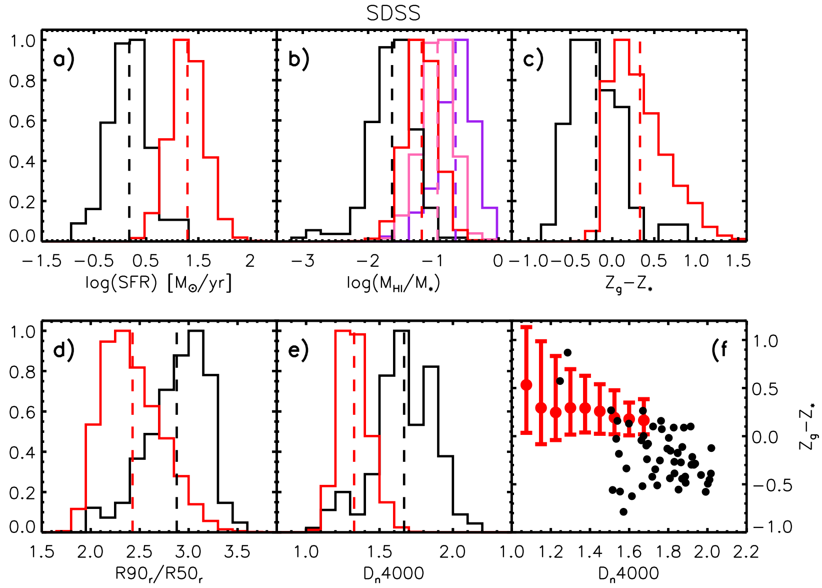

Fig. 2. The distribution of SFR (panel A), $M_{\rm HI}$-to-stellar mass ratio (panel B), metallicity difference (panel C), concentration index (panel D), and 4000 Ångström break strength (panel E) for diluting galaxies (black) and enriching galaxies (red) from the observational sample. In panel B, gas fractions for the enriching galaxies are obtained from direct detections (purple), or HI scaling relations from Catinella et al. (2012b) (pink) and Zhang et al. (2012) (red). For diluting galaxies (black), only the Zhang et al. (2012) scaling relation was used. Panel F shows the D_n4000 - ($Z_{\rm cold} - Z_*$) relation.

and small satellites causes a gradual dilution of their ISM. Quick reignition of star formation is suppressed by AGN feedback, which is present due to the large, accreting central SMBHs.

3. Observational data

3.1. Observational samples

To compare with the massive galaxies studied in the semi-analytic model, galaxies with $\log(M_*) \geq 10.5\,{\rm M}_\odot$ were also selected from the SDSS-DR7 MPA-JHU spectroscopic catalogue, following the criteria outlined in (Yates et al. 2012, §2 and Appendix C). This sample was cross-matched with data from the *ALFALFA* and *GASS* surveys, to obtain gas fractions. Where direct HI detections were not available, the scaling relations of Zhang et al. (2012) and Catinella et al. (2012b) were used. Z_* (as derived by Gallazzi et al. 2005) was also obtained for some galaxies, by cross-matching with the SDSS-DR4. As with the model sample, two sub-samples were selected in order to study high- and low-$Z_{\rm g}$ galaxies: The first contains contains 28838 galaxies with log sSFR ≥ -10.8 yr^{-1} and $Z_{\rm cold} \geq 8.85$. The second contains 196 galaxies with log sSFR ≤ -10.7 yr^{-1} and $Z_{\rm cold} \leq 8.9$. For convenience, we also label these as enriching and diluting galaxies, respectively.

We note that these criteria are slightly different to those used for our model subsamples. This is because the low-$Z_{\rm g}$ tail of the galaxy distribution is much more poorly sampled observationally, due to low signal-to-noise emission lines, and the removal of AGN hosts containing contaminated spectra. Therefore, a higher threshold on the maximum sSFR for diluting galaxies is used in the observational sample, to obtain a statistically significant number of galaxies. Here, we have also removed all galaxies which are clear edge-on discs (from their SDSS images) from the diluting sub-sample. These systems are likely assigned unrealistically low-SFR and low-Z_g due to heavy obscuration of the light from their central star-formating regions.

3.2. Observational results

In Fig. 2, we show distributions of five key galaxy properties for observed enriching (red) and diluting (black) galaxies, and the observed D_n4000 - ($Z_{cold} - Z_*$) relation. *All* the properties distinguishing low- and high- Z_g, massive galaxies in the model are also seen in the observations: diluting galaxies have lower gas fractions (panel B), lower $Z_{cold} - Z_*$ (panel C), higher concentrations (panel D), and older ages (from D_n4000, panel D) than enriching galaxies. They also have larger SMBHs ($\langle \log M_{BH} \rangle = 6.77\,M_\odot$ for enriching galaxies, and $7.45\,M_\odot$ for diluting galaxies). The maximum $Z_{cold} - Z_*$ measured in diluting galaxies also decreases with age (panel F), suggesting a gradual dilution process. These results hold even when switching metallicity diagnostic from the Bayesian method of Tremonti et al. (2004), to the combination of strong-line ratios used by Mannucci et al. (2010).

4. Conclusions

We have described how *gradual dilution* via metal-poor accretion is lowering Z_g in massive, elliptical galaxies after a gas-rich merger event, in the L-Galaxies semi-analytic model. This evolution leaves a set of specific signatures at $z = 0$, namely, low SFRs, low gas fractions, old ages, large central SMBHs, and importantly, low $Z_{cold} - Z_*$. All these properties are also qualitatively seen in low-Z_g, early-type galaxies in the local Universe, providing a strong indication that the same process of post-merger dilution is occurring in real elliptical galaxies.

Gradual dilution provides a natural explanation for the positive correlation seen between SFR and Z_g in massive galaxies at $z = 0$ (e.g. Yates et al. 2012). In the absence of a clear understanding as to which metallicity diagnostic is best suited to studying the metal content of nearby, massive galaxies, this provides independent support for those diagnostics that reveal such a positive correlation at high M_*. The FMR, as described by Mannucci et al. (2010), does not take account of such a positive correlation, instead assuming a weak *anti*-correlation between SFR and Z_g at high M_*. We therefore caution against using such projections when studying massive galaxies in the local Universe.

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