Tracing the Ancestry of Galaxies (on the land of our ancestors)
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The Chemical Enrichment Histories of SDSS Galaxies

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Abstract. We derive the full chemical enrichment histories for 3800 early-type galaxies, including both star forming and passively evolving systems. For this purpose we have developed a method to simultaneously derive the element abundance ratios [C/Fe], [N/Fe], [Mg/Fe], [Ca/Fe] and [Ti/Fe] for unresolved stellar populations. The method is based on up-to-date stellar population models with varying element abundance ratios. A novelty of the models is that they are flux-calibrated, removing the dependence on the Lick/IDS system. Trends with velocity dispersion are investigated where [Mg/Fe] and [C/Fe] are found to show very similar trends, while [N/Fe] show overall lower abundances ratios. [Ca/Fe] ratios are close to solar values over the velocity dispersion range covered. Tentative, due to large scatter, result for [Ti/Fe] implies that Ti follow the trends of Ca.

Keywords. galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: abundances

1. Introduction

All elements heavier than Li are produced in stellar nucleosynthesis. Stellar populations are therefore the fossil record of chemical evolution in the universe, depending on the star formation history, initial mass function, supernovae rate, efficiency of mixing newly synthesised elements, efficiency of gas outflow and inflow etc. Thus chemical enrichment histories set stringent constraints on galaxy formation.

Element abundance ratios can disentangle the formation of different stellar populations, since different elements are produced in different stellar evolutionary phases. The α-elements are produced in Supernovae type II (SNII), while Fe-like elements are also produced in supernovae type Ia (SNIa). Heavier α-elements might partially be enriched by SNIa, as Ca has been found to be under-abundant to the rest of the α-elements. N and C are produced in both intermediate and massive stars, but the dominant sources are debated. A number of studies have looked at various elements, mostly considering relatively small galaxy samples, including Trager *et al.* (2000) (O and C), Sánchez-Blázquez *et al.* (2003) (C and N), Sánchez-Blázquez *et al.* (2006a) (C, N and Mg), Clemens *et al.* (2006) (C), Kelson *et al.* (2006) (C, N and Ca), Graves *et al.* (2007) (C, N, Mg and Ca) and Smith *et al.* (2009) (C, N, Mg and Ca).

In this work we simultaneously derive all element abundance ratios allowed by the sensitivities of the adopted Lick absorption line indices (e.g. Worthey *et al.* 1994). The maximum amount of information is extracted from the indices to accurately derive the abundance ratios [O/Fe] ([α/Fe] re-named), [C/Fe], [N/Fe], [Mg/Fe], [Ca/Fe] and for the first time for unresolved stellar populations [Ti/Fe]. The method is based on new state of the art flux-calibrated models of stellar populations of absorption indices presented in Thomas *et al.* (2011b). The method is applied to 3800 SDSS (York *et al.* 2000) early-type galaxies. This work is presented in detail in Johansson *et al.* (2011).

2. Data

The selection of early-type galaxies used in this work is the same sample as used in Thomas *et al.* (2010). This is a sub-sample of visually classified early-type galaxies from the MOSES catalogue (MOrphologically Selected Early-types in SDSS) described in detail in Schawinski *et al.* (2007) and Thomas *et al.* (2010). We select galaxies in the narrow redshift range $0.05 < z < 0.06$. The 25 standard Lick absorption line indices were measured on emission line cleaned absorption spectra downgraded to the Lick/IDS resolution. The indices have been corrected for stellar velocity dispersion broadening. A visual classification does not bias against star forming galaxies. The sub-sample of early-type galaxies may therefore include blue galaxies with on-going or recent star formation.

3. Stellar population parameters

3.1. *The TMJ models*

In Thomas *et al.* (2011b) we present new stellar population models of Lick absorption-line indices with variable element abundance ratios (TMJ). The TMJ model is an extension of the Thomas *et al.* (2003a) model, which is based on the evolutionary stellar population synthesis code of Maraston (2005). The key novelty compared to the previous models is that the TMJ model is flux-calibrated, hence not tied anymore to the Lick/IDS system. The new models are based on our calibrations of absorption-line indices with stellar parameters (Johansson *et al.* 2010) derived from the flux-calibrated stellar library MILES (Sánchez-Blázquez *et al.* 2006b).

3.2. *Iterative method*

This work is a continuation of the analysis of early-type galaxies in SDSS presented in Thomas *et al.* (2010) (T10). We extend this work by deriving the individual element abundance ratios [C/Fe], [N/Fe], [Mg/Fe], [Ca/Fe] and [Ti/Fe] using the stellar population models described in Section 3.1.

Several indices are sensitive to abundance variations of more than one element. To simultaneously derive the abundance ratios we have developed an iterative method. First we determine age, total metallicity, and O/Fe ratio (representing [α/Fe]) from a base set of indices sensitive to these three parameters, using a χ^2 minimization routine (described in T10 and Thomas *et al.* (2011a)). In the subsequent steps we add in turn particular sets of indices that are sensitive to the element the abundance of which we want to determine. In each step we re-run the χ^2 fitting code with a new set of models to derive the abundance of this element, while keeping age, metallicity, and O/Fe fixed. The derivation of individual abundance ratios is iterated until the abundance ratios remain unchanged (convergence after 3-4 iterations). At the end of the sequence we re-determine the overall χ^2 and re-derive the base parameters age, metallicity, and O/Fe for the new set of element ratios. This outer loop is iterated until the final χ^2 stops improving by more than 1 per cent (again convergence after 3-4 iterations).

Both the base models and the iterative method are well calibrated with galactic globular cluster data with independent measurements of stellar population parameters, presented in Thomas *et al.* (2011b) and Thomas *et al.* (2011a), respectively

4. Results

In general our results are well consistent with T10. We reproduce the devision in red sequence and rejuvenated blue cloud galaxy populations as discussed in T10, and all three parameters age, metallicity and α/Fe ratio increase with velocity dispersion (σ). For metallicity we find a slightly shallower slope than T10. Here we focus on the element ratios [Mg/Fe], [C/Fe], [N/Fe], [Ca/Fe] and [Ti/Fe]. The full results including other parameters such as age, [Z/H] and [O/Fe] are presented in Johansson *et al.* (2011).

[Mg/Fe], [C/Fe] and [N/Fe] show strongly increasing abundance ratios with σ (see Fig. 1). These trends are very similar and tight for [Mg/Fe] and [C/Fe], while [N/Fe] show overall weaker abundance ratios and a slightly steeper slope. [N/Fe] also show a larger scatter, but the correlation with σ is still well defined. [Ca/Fe] show weak trends with σ and abundance ratios close to solar over the whole σ range studied (see Fig. 1). Ca is clearly under-abundant compared to Mg for the early-type galaxies studied. [Ti/Fe] (not shown in Fig. 1) show a large scatter due to a weak response to Ti for the Lick indices requiring high S/N data. This makes it difficult to draw any strong conclusions for [Ti/Fe], but Ti seems to be overall less enhanced than Mg. Consistent with Thomas *et al.* (2010). The rejuvenated population show weaker abundance ratios compared to the red sequence population for both [Mg/Fe] and [C/Fe]. This is less pronounced for the other elements.

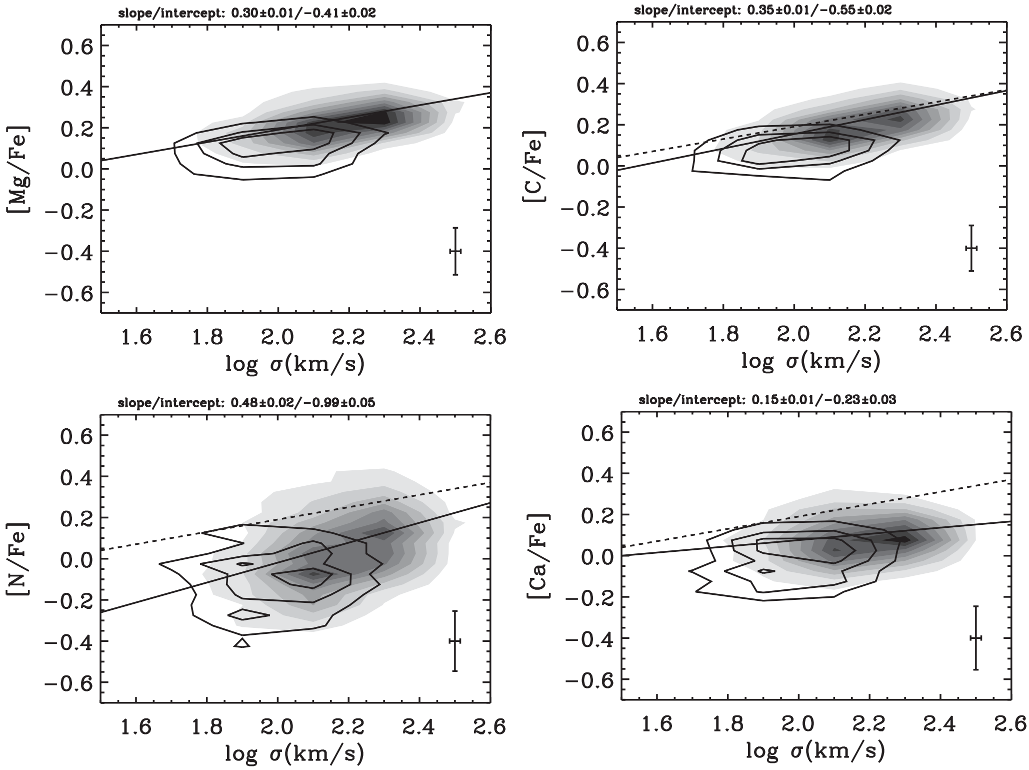

Figure 1. Contour plots for the relationship between stellar velocity dispersion and the different element abundance ratios. Filled contours show the red sequence galaxy population and open contours show the rejuvenated galaxy population. Solid lines are linear least-square fits to the red sequence population for the abundance ratio in each panel and the dashed line show the fit to the [Mg/Fe]-σ relationship for comparison.

5. Discussion

We find trends of increasing [C/Fe], [N/Fe] and [Mg/Fe] with σ, in agreement with Sánchez-Blázquez *et al.* (2006a), Graves *et al.* (2007) and Smith *et al.* (2009). We also find lower [N/Fe] ratios compared to [Mg/Fe] and [C/Fe], in line with Graves *et al.* (2007). Ca is found to be less enhanced than Mg, which is in good agreement with the literature (Thomas *et al.* 2003b; Graves *et al.* 2007; Smith *et al.* 2009).

A flat trend with σ for [Ca/Fe] was first found by Thomas *et al.* (2003b) for a small sample of early-type galaxies. This trend is confirmed by the results presented here. The overall lower [Ti/Fe] ratios compared to [Mg/Fe] indicate that Ti may follow a similar trend to Ca. This implies that the production of α-elements in SNIa is dependent on atomic number, i.e. heavier α-elements have a higher production rate in SNIa. The delayed enrichment of SNIa produce the low [Ca/Fe] and [Ti/Fe] compared to [Mg/Fe] due to short formation time-scales of the systems studied. The findings of lower Ca and Ti abundances compared to other α-elements in the stellar populations of the Milky Way imply that these elements are produced in SNIa at all metallicities, see Thomas *et al.* (2011a) and references therein.

Lower [N/Fe] ratios compared to [C/Fe] are also present in the models of chemical evolution of Pipino *et al.* (2010) (P10). Implementing different recipes of stellar yields with different treatment of stellar rotation and mass-loss, P10 can reproduce the observed trends with σ for [C/Fe], but fail for [N/Fe]. In fact, the models predict even too low [N/Fe] abundance ratios to match the corresponding abundance ratios derived here. The varying models also show a much larger scatter for [N/Fe] than for [C/Fe]. P10 compare the models to the observed abundance ratios of Graves *et al.* (2007), which agree with our results. Thus uncertainties in the adopted theoretical stellar yields seem to produce discrepancies between the modelled and observed [N/Fe] ratios.

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