



A critical view on stellar population synthesis

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Abstract. There has been considerable progress in recent years in determining abundance ratios of individual elements in unresolved galaxies using a method called differential stellar population synthesis. Here I discuss in a critical way those developments and some of their implications for the future. The paper consists of 2 parts: first I look at methods measuring calibrated abundance ratios, and secondly I investigate the evidence from current observations for variations in abundance ratios as a function of galaxy environment.

Keywords : Galaxies: abundances – Galaxies: stellar content – Galaxies: elliptical and lenticular

1. Introduction

The chemical composition of a star provides important clues about its formation. Apart from the metallicity (mass fraction of all elements except H and He), one can derive the composition of many chemical elements in stars in our Galaxy and in the local group (e.g. Edvardsson et al. 1993). The fact that in our Galaxy the relative abundances correlate so well with their kinematics and spatial distribution shows that the abundance distribution contains important information about the formation of the stellar populations that are concerned. More recent results show that abundance ratios in local group galaxies show values that are characteristic for each galaxy: the total metallicity depends mainly on the galaxy mass (the mass-metallicity relation, e.g. Terlevich et al. 1981), while the abundance ratios depend on the formation of the galaxy (see Tolstoy et al. 2009 (T09) for a review). Mapping abundance ratios of stars, one can retrace the merging history of galaxies. This technique is used nowadays to trace the merging history of our Milky Way (e.g. Freeman & Bland-Hawthorn 2002).

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In T09 details are given of how abundance ratios can tell us something about the formation of stars and stellar populations. The main idea here is that element enrichment in galaxies comes from 2 types of supernovae, type II, from massive stars, and from type Ia, originating from binary stars containing a white dwarf. Type II supernovae produce large amounts of α -elements as compared to Fe, much larger than SN type Ia. Type II supernovae, being from massive stars, are generally very young ($\sim$ a few million years), while SN Type Ia are much older ($\sim$ hundreds of years, since a white dwarf has to be made). If stars are formed on very short timescales, i.e. if enrichment is mainly due to SN Type II, the α /Fe element ratios will be larger than if the enrichment is mainly due to SN Type Ia. Another process that affects abundance ratios in stars is the relative importance of the r and s -process. Since the s or slow process is mainly occurring in TP-AGB stars and the r -process mainly in massive stars, this ratio depends on the relative importance of the TP-AGB phase during the formation of the galaxy. There are other processes affecting abundance ratios. Here I just want to mention that the relative abundances of the elements C, N and O can also be altered by of various dredge-ups in AGB stars.

Determining abundance ratios in unresolved galaxies is much more difficult than in the local group. First of all, the internal velocity dispersion of galaxies is such that element abundances need to be obtained from data with a much lower spectral resolution than in individual stars, which means that measured absorption lines are almost always blends of lines, and as such harder to interpret. It has been known for more than 2 decades that [Mg/Fe] in massive galaxies is larger than in the solar neighbourhood (Peletier 1989, Worthey et al. 1992). This results was obtained by fitting galaxy spectra with stellar population models which had an input library consisting of stars from our Solar neighbourhood, with the result that the Mg b line at 5170Å is much stronger in the observations than in the models. It was found that less massive galaxies had smaller [Mg/Fe] overabundances. Later on, it was found that other elements (N, Na, C) were also found to be enhanced in massive ellipticals, while the α -element Ca was found to be decreasing slightly with galaxy mass (see Henry & Worthey 1999, Worthey et al. 2013 (W13)). The problem for many years has been that measuring these element ratios quantitatively has been very difficult or impossible, due to the fact that stellar population models with non-solar abundance ratios cannot be made, because of the lack of observed stars with these ratios. The only way, through theoretical libraries, was unfeasible, since such spectra were not reliable enough. In the last decade, however, attempts have been made to create such libraries using a semi-theoretical approach. Coelho et al. (2007) started with an approach where observed spectra were modified using theoretical spectra, which were the ratio of a stellar spectrum with the required abundance distribution and the solar composition. This approach was subsequently improved by Walcher et al. (2009), and Conroy & van Dokkum (2012). Very recently, Conroy et al. (2014) (C14) determined abundance ratios of 14 elements in stacked SDSS spectra of elliptical galaxies in various bins of increasing galaxy velocity dispersion. Here I will discuss this method and comment on the reliability of the results.

In Section 2 I will discuss attempts to determine abundances of individual elements in early-type galaxies using this method. In Section 3 I discuss a few aspects of abundance ratio variations from galaxy to galaxy.

2. Abundance ratios in Galaxies - the global picture

Using the continuous improvements in stellar evolution models as well as those of synthetic spectrum calculations, Coelho et al. (2007) were able to present synthetic stellar population models of three metallicities ($[\text{Fe}/\text{H}] = -0.5, 0.0$ and 0.2) and two different α -element-to-iron abundance ratios ($[\alpha/\text{Fe}] = 0.0$ and 0.4). The α -elements considered were O, Ne, Mg, Si, S, Ca and Ti. Interested in quantifying the effects of changing the relative composition of their models to low resolution absorption line indices, they found that there are 2 effects which are important in altering the line strength of model galaxies: the *spectral effect*, causing line strengths to be stronger when the abundance of the element(s) that this feature primarily depends on is increased, and the *evolutionary effect*, the fact that for increasing opacities the total structure of the stellar atmosphere changes, which then also affects the line strengths. They find that the latter effect is much more important to broadband colors than to line strengths (Figure 1).

In a following paper, Walcher et al. (2009) presented differential stellar population models: they used empirical stellar spectra (from various libraries), which they assumed had solar abundance ratios, and calculated spectra with other α/Fe ratios by multiplying them by a correction spectrum calculated from Coelho et al.'s models as the ratio of a model with this α/Fe ratio and a corresponding model with solar abundance ratios. For calibration they fitted the globular clusters NGC 6528 and NGC 6553, clusters with literature ages of ~ 11 Gyr, metallicity around solar and α/Fe slightly above solar with their new models. Although the calibration was not great, they could show that models with enhanced α/Fe showed improved fits. Walcher et al. mention that they have fitted a sample of SDSS spectra of massive galaxies, and find better fits for $[\alpha/\text{Fe}] = 0.2$ than for solar abundance ratios, with a reduced χ^2 close to 1. I also have to mention here the paper of Cervantes et al. (2007), where the same method is presented, but which was never followed up.

Very recently, C14 went one step further with their differential stellar population synthesis. They took stellar isochrones from the Dartmouth project (Dotter et al. 2008), and calculated synthetic spectra, and by varying one element at the time they determined the *imprint* of several individual elements on an integrated galaxy model spectrum. They then determined stacked SDSS spectra by summing the normalized spectra of many galaxies on the FP in several velocity dispersion bins. Then a library of models with a range in age and metallicity and individual abundances for 15 elements were fitted to the data, allowing a star formation history consisting of two population ages. Excellent fits were obtained for all 7 stacked early-type galaxy spectra. On the basis of these fits C14 derived the behavior of 14 elements relative to Fe

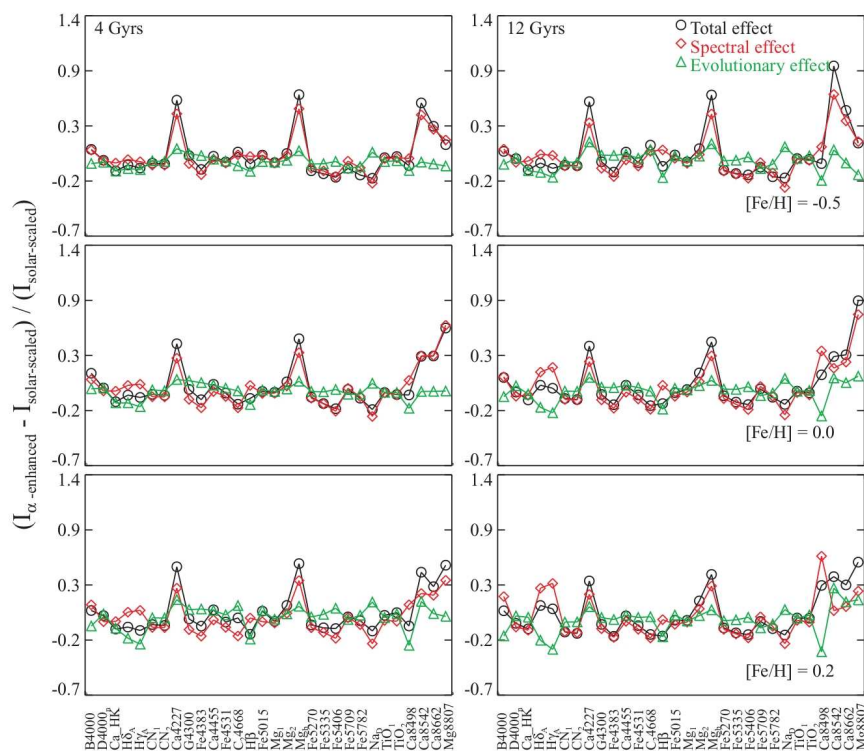


Figure 1. Differences between α -enhanced and solar scaled predictions for a number of often-used line strength indices, in units of the solar-scaled value. Each row corresponds to the prediction of a different [Fe/H]. The left and right-hand columns show the predictions at ages of 4 and 12 Gyr, respectively. The green and red lines correspond to the evolutionary effect and spectral effects, respectively. The black lines are the predictions when both effects are considered together. To avoid division by zero, the scales of the three Balmer indices and Ca 8498 (which can reach negative values) were shifted arbitrarily upwards (from Coelho et al. 2007).

as a function of galaxy velocity dispersion (a good proxy of mass). Fig. 2 shows their main result. In a separate paper they discuss a similar result on Sr and Ba, determined in the same way. Also recently W13, using similar techniques, determined individual element abundances. They also provided fits for individual nearby galaxies, and show that abundance ratios vary considerably from galaxy to galaxy.

Since this paper is supposed to review these developments in a critical way, I will start looking at the basic assumptions. Differential population synthesis only works if the models are at least to first order applicable. I would like to refer here to Fig. 3, which is a figure from Martins & Coelho (2007)(MC07), investigating the quality of synthetic methods to reproduce features in individual stars. In this paper several line

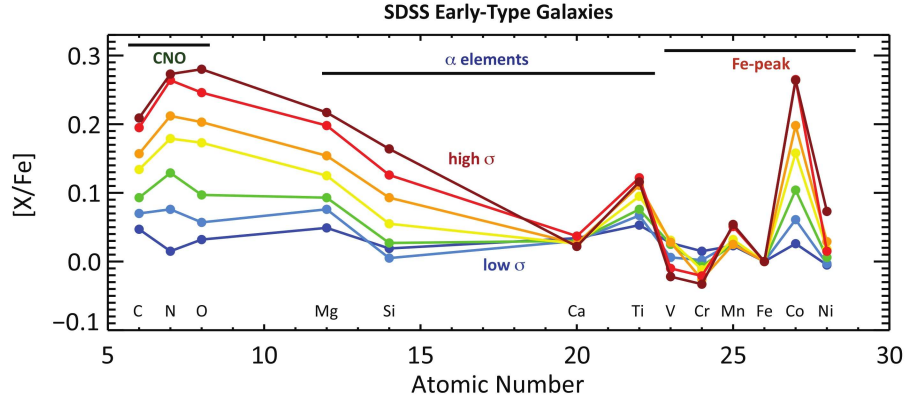


Figure 2. Abundance trends derived from stacked spectra of early-type galaxies from SDSS. The results for Na are omitted from this summary diagram. (From C14)

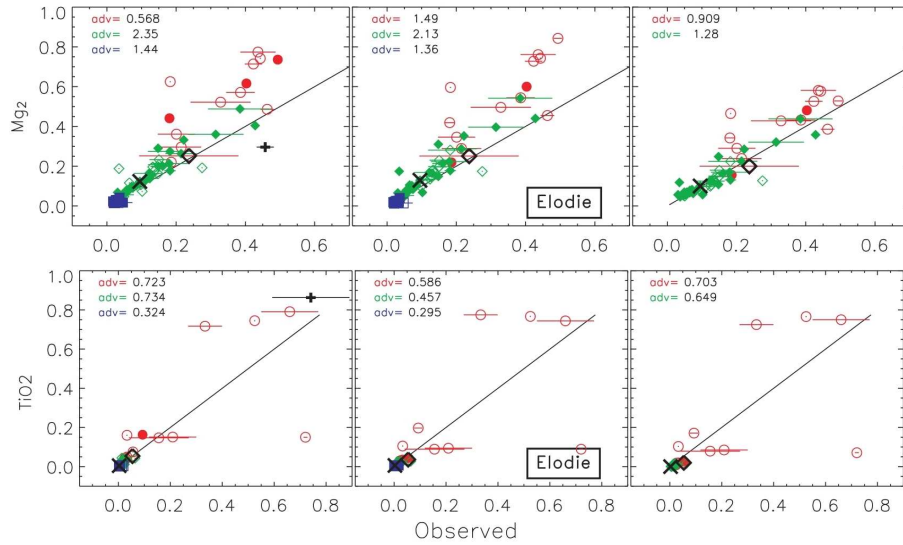


Figure 3. Comparison of the indices Mg_2 and TiO_2 measured on the empirical ELODIE library and on 3 theoretical libraries (Martins, Munari and Coelho; for references see MC07). Different symbols and colours represent three intervals of temperature: blue squares are stars with $T_{\text{eff}} < 7000$ K, green diamonds are stars with $4500 < T_{\text{eff}} < 7000$ K and red circles are stars with $T_{\text{eff}} > 7000$ K. Filled and open symbols represent dwarfs ($\log g > 3.0$) and giant stars ($\log g < 3.0$), respectively. The black crosses are stars with $T_{\text{eff}} < 3500$ K. The solid line is the one to one relation. The thick black symbols represent a Sun-like dwarf (cross) and an Arcturus-like giant (diamond). (from MC07).

indices calculated on synthetic spectra of three different groups are compared with observations. In Fig. 3 I show the comparison for the Lick indices Mg_2 and TiO_2 . The plots are typical for the other indices in this paper as well: atomic indices (mainly in the blue) are much better reproduced than molecular indices, and the agreement for hotter stars is better than for cooler ones. Mg_2 behaves partially as an atomic index, since it has a strong contribution from atomic lines. Where MC07 show that indices like Ca4455 can be reasonably well reproduced, the situation is totally different for TiO_2 , where a huge scatter is seen in the comparison for stars cooler than $4500\text{\AA}$. The picture of Fig. 3 agrees somewhat with W13, who show strong disagreements between observed and synthesized indices in $H\beta$, $Mg\ b$ and $Fe5270$, mainly for the coolest stars. Both MC07 and W13 show that synthetic models might not even to first order be applicable in spectral regions dominated by molecular bands, implying that differential population synthesis also will not give reliable results. C14 do calibrate their models with the open cluster M67 and the globular cluster NGC 6528, but since the spectra they use here are limited to the wavelength region from $3800\text{-}5300\text{\AA}$, a region not dominated by molecular bands, this calibration is not very relevant the molecular regime.

Indices strongly affected by molecular bands are C, N, O, Ti and Na, and to some extent Mg. Indices for which the contribution from molecular bands are certainly dominating are O and Ti. It is not so surprising that the agreement with W13 for O is not very good, and that W13 do not even attempt to derive Ti-abundances. C14 say that they do not understand these differences. To get a better understanding it would be very useful to see measurements of the abundances of all these elements calculated using only atomic lines, if such a thing is possible. For O, the calibration of M67 and NGC 6528 using the spectra of Schiavon et al. (2004) might show some clues. These calibrations, done in the blue, are less affected by molecular bands than the galaxy abundances themselves. For M67, there is a small systematic offset between its O-abundance and high resolution literature measurements. For NGC 6528 it is not clear whether there is an offset, since the literature measurements do not agree as well with each other.

C14 shows that, apart from O, C and N are also mainly originating from molecular bands. Here the agreement between C14 and W13 is not great, contrary to what C14 state. Both papers find that $[C/Fe]$ increases as a function of σ , although the gradient is smaller in W13. $[N/Fe]$ is almost constant in W13, while increasing as one of the steepest elements in C14. I would like to conclude that for the CNO elements the method employed by C14 and W13 has a very weak basis, which in my opinion is the reason for the large differences between the results of C14 and W13.

A further interesting element to consider is Ca. The determination of this element, contrary to CNO, is mostly based on atomic lines (see C14). As a result, there is good agreement between C14 and W13, and reasonable agreement with the earlier finding of Cenarro et al. (2003) that the Ca IR triplet line strengths declines somewhat with increasing galaxy velocity dispersion. Cenarro et al. give a number of explanations.

First of all, $[\text{Ca}/\text{Fe}]$ can remain constant or decline slowly as a function of σ . This possibility is in principle not very attractive. Ca is an α -element, so one expects it to follow Mg, as it does for metallicities below solar (see T09). Another possibility given by Cenarro et al. is that the IMF slope becomes steeper for more massive galaxies. The fact that C14 find that Ca follows Fe closely, using mostly atomic lines, implies that the first possibility is more likely.

There are three more issues related to C14. First the normalization. All the analysis of C14 has been done using normalized data. The normalization was performed using a high order polynomial, but it is not very clear what order has been used, and whether this order was changed for the different model- and data spectra. Fitting polynomials to spectra of old elliptical galaxies, especially in the red, is a very complicated procedure, and there is no best solution. The fact that the residuals between the data and the models (C14, Fig. 11) are so small, with amplitudes of less than 1%, implies that the fit is good, but not necessarily that the fitted solution is correct, and definitely not that the fitted solution is unique. Tests restricting the wavelength range, restricting the order of the normalizing polynomial, etc. would have been welcome to establish more trust in these results. Some tests are performed, with the useful information (Fig. 17 in C14) that the determination of O and N are the least reliable of all indices. The second issue is the correction for telluric absorption. Even though the word *telluric* does not appear in C14, it affects both the SDSS data as well as the empirical stars of MILES (to a lesser extent) and the IRTF library. In the latter, Vacca et al. (2003) claim to have corrected for the telluric absorption down to an accuracy of about 2%, although better in many places. Although the telluric absorption beyond $1\ \mu\text{m}$ is somewhat larger than between 7000 and 10000 Å I do not expect the correction in this latter region to be better than 1%. One might argue what this exactly means, but it is clear that it is a bit of an overkill to fit spectra with a S/N ratio of $1000\ \text{\AA}^{-1}$ with models containing remains of telluric absorption which are considerably larger, and smoothed out in the fitting process. The fact that W13 et al. show the variations in their fitted abundance ratios is a much more honest representation of the fitting process. The third issue is that C14 (and also W13) assume that the empirical stars they use have solar abundance ratios, or at least on average. This is not the case, and will create biases, which will have to be investigated (Milone et al. 2011).

To summarize this section, I like to first of all say that there has been considerable progress in determining individual abundance ratios in galaxies. The differential population synthesis method seems well suited to derive much more information from a galaxy spectrum than is commonly thought at present. However, I have shown that many of the results of C14 are not as reliable as we hope yet - several elements abundance determinations, especially those of O and Ti, need significant improvement, and have errors that are likely larger than quoted in the paper. Also, I feel uncomfortable with the fact that in C14 the spectra have been normalized, something which is traditionally very difficult to do for the considered spectra, and which makes it hard to understand the systematic errors involved.

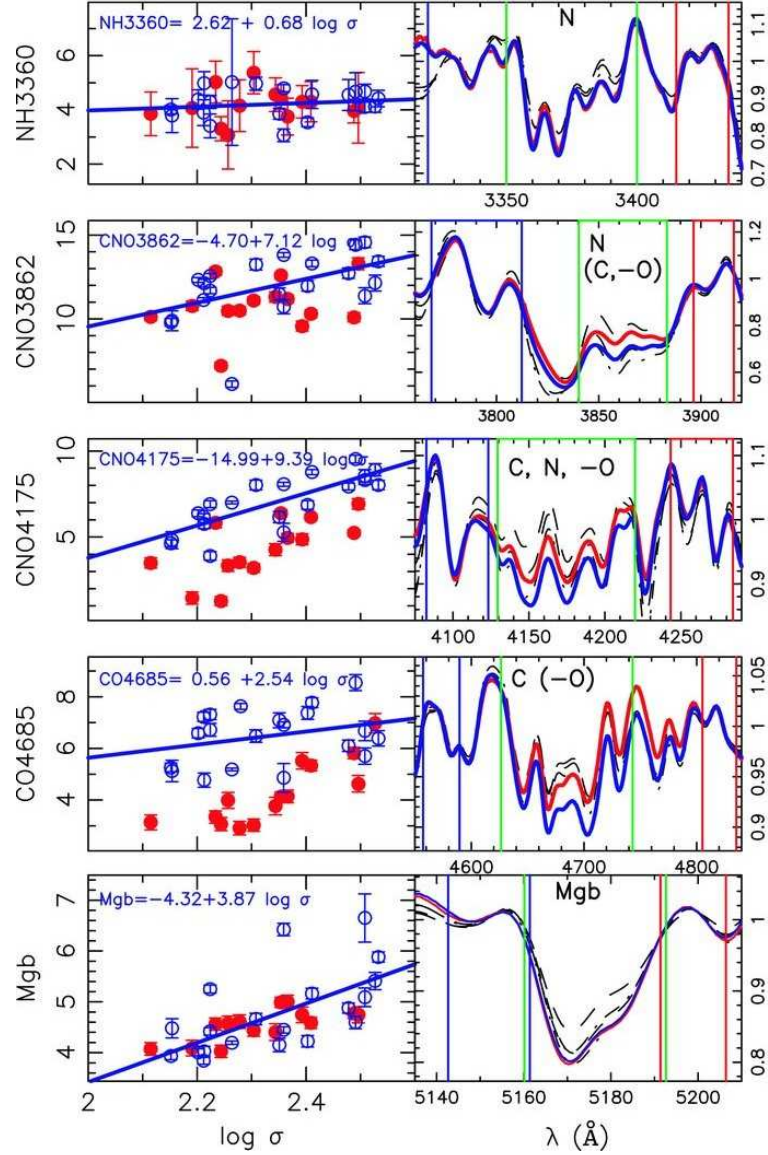


Figure 4. Left column: line-strength indices vs. σ . Red solid circles correspond to cluster galaxies, while blue open circles are LDEG. Right column: observed spectra compared with models. Black lines represent stellar population models. Models with solar (dashed lines) and supersolar (dotted lines) metallicity are plotted, with 2 ages per metallicity. The stacked spectra for LDEG are plotted in blue, while the cluster galaxies are represented in red. Dominant species and other important species (within brackets) contributing to the indices are shown within the panels. A - symbol indicates that an increase in the abundance of that element makes the index weaker.(from Toloba et al. 2009).

3. Abundance ratios as a function of environment

In the previous section I discussed global relations of abundance ratios as a function of galaxy mass (or velocity dispersion). Here I will here talk about abundance ratio variations at the same dispersion.

While in the local group such abundance ratio variations are very frequent (see e.g. Fig. 15 of T09) and visible for many elements, the situation for unresolved galaxies is much less clear. W13 shows a considerable scatter in many of their abundance ratios at a given σ , but it is unclear what the real error in the points is, and how large the real scatter in the abundance ratios is. The SAURON survey (Kuntschner et al. 2010) shows that for a given σ galaxies don't have a large scatter in $[\text{Mg}/\text{Fe}]$, assuming that the Mg b and the Fe5015 line are reliable indicators of resp. Mg and Fe. For other elements, there are very few papers that discuss the scatter in its relative abundances. An exception is Toloba et al. (2009), which also refers to the earlier work of Sánchez-Blázquez et al. (2006). In Fig. 4 (their Fig. 1) they show the index - σ relations for Mg b and 4 less well known indices defined by Serven et al. (2005). While the Mg b - σ relation is the same for a sample of Coma cluster galaxies and another sample of low density environment galaxies (LDEG), the same 2 sample show considerably different relations when Mg b is replaced by 3 CNO indices. One can explain the differences if the elements responsible for the CNO4175 and CO4682 indices are overabundant in the field galaxies, but not for the cluster galaxies. For another nitrogen-based index no difference is seen. Similar results are shown by another study in the infrared. In Mármol-Queraltó et al. (2009) indices in a Fornax cluster sample are compared to indices in early-type galaxies in the field. Here again the Mg b - σ relation is the same for both samples. However, the D_{CO} index at $2.3 \mu\text{m}$ and the C_24668 - σ relations show much more scatter in the field-sample than in the Fornax cluster sample, which is clearly not caused by observational uncertainties.

Although an accurate interpretation of these indices is not possible at this moment, it is very likely that there are environmental CNO/Fe abundance variations in galaxies. They do impose an important constraint on chemical evolution and galaxy formation models. It is likely that, as in the local group, the CNO variations are caused by varying fractions of intermediate mass stars enriching the gas in these galaxies. So, there is hope that it will be possible to derive in the future the enrichment histories of galaxies to a much higher level of detail than is possible at the moment, in the way that people are currently studying galaxies in the Local Group.

Acknowledgements

The author thanks Philippe Prugniel, the organizer, for a nice and stimulating conference.

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