The Spectral Energy Distribution of Galaxies
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The star-formation histories of early-type galaxies from ATLAS^{3D}

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Abstract. We present an exploration of the integrated stellar populations of early-type galaxies (ETGs) from the ATLAS^{3D} survey. We use two approaches: firstly the application of line-indices interpreted through single stellar population (SSP) models, which provide a single value of age, metallicity and abundance ratio. And secondly, by fitting a linear combination of SSP *spectra* to our data, smoothly weighted in the free parameters of age and metallicity, thereby inferring a star-formation history of these galaxies. Despite the significant differences in these approaches, we obtain generally consistent results, such that galaxies that are more massive appear older with enhanced abundance ratios using line indices, and have shorter star-formation histories weighted to early times. We highlight two limitations of the index-SSP approach. Firstly the SSP-equivalent ages belie the fact that ETGs are overwhelmingly composed of ancient stars. Secondly, the young stellar contributions implied in our star formation histories are *required* to obtain realistic UV-optical colours. We remark that, even fitting solar-abundance models, we can recover a star-formation duration that correlates with the measured alpha-enhancement, in agreement with other recent work.

Keywords. galaxies: elliptical and lenticular, cD; evolution; formation; stellar content

1. Introduction

The measurement of absorption features in the integrated light of galaxies has been a key tool to understanding the chemistry and star-formation history of these complex systems. Early-type galaxies (ETGs: ellipticals and lenticulars) have been particularly well studied with this technique, thanks to their relative lack of dust extinction and nebular emission which obfuscate the stellar continuum. These galaxies contain the so-called 'fossil record' of a Hubble Time of evolution, being among the most massive and ancient systems in the Universe. Untangling 13 Gyr of star formation and evolution is

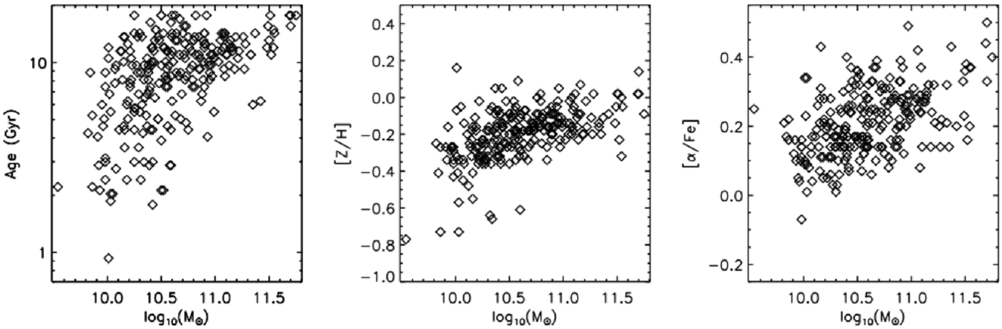

Figure 1. *From left to right:* SSP-equivalent values of stellar age, metallicity and abundance ratio for the ATLAS^{3D} sample as inferred from the measurement of absorption line indices, and finding the best-fitting SSP model. All population parameters are plotted as a function of dynamical mass. Indices were measured for each galaxy using a single spectrum integrated within an aperture of one effective radius.

complicated by the strong degeneracies of the key free parameters, such as age, metallicity and abundance ratios, not to mention that we observe these properties integrated in space and time. The degeneracies can be broken by using specific absorption lines to track the stellar chemistry, and relate these combined properties to predictions from stellar population models. These models mimic the time-varying properties of ensembles of stars consistent with an assumed initial mass function (IMF) and a single shared chemistry. In this way, a set of measured absorption line strengths, or *indices*, can be compared to these single stellar population (SSP) models, and the free parameters of age, metallicity and abundance ratios inferred.

In the past decade, significant effort has gone into producing predictions for stellar population *spectra*, instead of single line indices. These model spectra can be directly fitted to the observational data, avoiding many of the limitations of measuring indices. This is a powerful approach, but is more directly limited to the properties of the models, who's deficiencies may be hidden by the wish to numerically fit all features of the data set - even those containing no interesting information. In particular, the current generation of population model spectra are largely confined to solar element abundance ratios. These limitations notwithstanding, SSP spectra allow a key development, which is to solve the inverse problem of a galaxy's star-formation history (SFH), being naturally amenable to computing combinations of populations to reproduce the observed galaxy properties.

In this contribution, we explore the application of both techniques to spectroscopy from the ATLAS^{3D} complete survey of 260 nearby ETGs obtained using the SAURON integral-field spectrograph. To measure the SFH, we use the penalized pixel-fitting code pPXF (Cappellari & Emsellem 2004) with the addition of linear regularization constraints (Press *et al.* 1992) to fit linear combinations of SSP spectra from Vazdekis *et al.* (2010), such that variations in the contributions from neighbouring time and metallicity intervals are minimized. The degree of regularization is increased, giving a smoother SFH, until the fit to the spectra is no longer acceptable, as measured via chi-squared. In this way we obtain a 'maximally-smooth' SFH that is consistent with the data.

2. Results

Figure 1 shows the distribution of SSP-equivalent ages, metallicities and abundance ratios of the ATLAS^{3D} galaxies as derived from the line indices measured from an integrated aperture spectrum for each galaxy, as a function of mass. The known trends of increasing age, metallicity and abundance ratios with mass are clearly recovered Thomas

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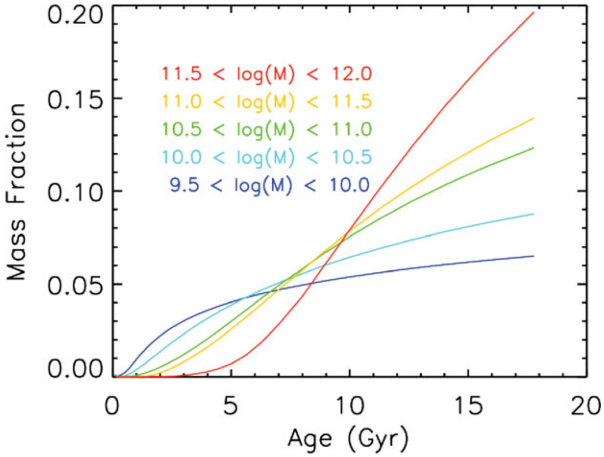

Figure 2. Average star formation histories of ATLAS^{3D} galaxies for five bins of galaxy mass.

et al. (2005). We note the large scatter in age values, spanning 1 to 13 Gyr at some masses. These are SSP-equivalent values of age which do not necessarily reflect the mass-contributions from different populations, making it hard to interpret the distributions in terms of the history of star formation. There is, however, a clear trend that less massive galaxies are younger and have lower abundance ratios, implying a more protracted SFH.

Figure 2 shows the average measured SFH derived from our spectral fitting technique in five bins of mass. The SFHs are normalized within each mass bin to have an integral of unity. This shows what we expect from our SSP analysis: as we decrease in mass, the star formation histories become broader, extending to younger ages. Note, however, that contrary to the classic picture of Thomas *et al.* (2005), the largest stellar age contributions by mass are in the oldest bins, on average. This seems consistent with recent simulations finding galaxy formation is characterized by two-phases: a rapid early phase of gas infall at z$>$ 2, followed by extended accretion at later times (Oser *et al.* 2010).

It is remarkable that, despite fitting solar-abundance models, we recover essentially the same star-formation timescale behavior as implied by the degree of alpha-enhancement measured from the indices and non-solar abundance models. The spectral fits are quite accurate around the Mg *b* feature, though clearly they cannot fit accurately both Fe and Mg *b* in the most over-abundant cases. We note that recently this has even been proposed as a *calibration* of the [α/Fe] parameter (de la Rosa *et al.* 2011). The success in recovering a sensible star-formation timescale with solar models is likely due to the coupling of the age and alpha-enhancement parameters, as evident in Figure 1.

Our SAURON spectra cover a very short wavelength range (≈4800-5400Å). It is therefore interesting to know how well our derived SFHs predict the galaxy SED at other wavelengths. Figure 2 compares the central spectrum of NGC3379 from the SDSS with the SSP spectrum implied from our SSP analysis (green) and the SFH derived from fitting the independent SAURON spectrum (magenta), using the models of Bruzual & Charlot (2003). The fit region is indicated by vertical dashed lines. The SFH is shown in the insert, where the green vertical line shows the SSP-equivalent age. This shows some typical features seen in other cases, namely that the SED inferred from fitting the short SAURON spectrum does a remarkably good job at predicting the SED at other wavelengths. More importantly, the SFH and SSP-based predictions differ most significantly in the UV, due to the small (by mass) contribution of young populations afforded by the SFH approach.

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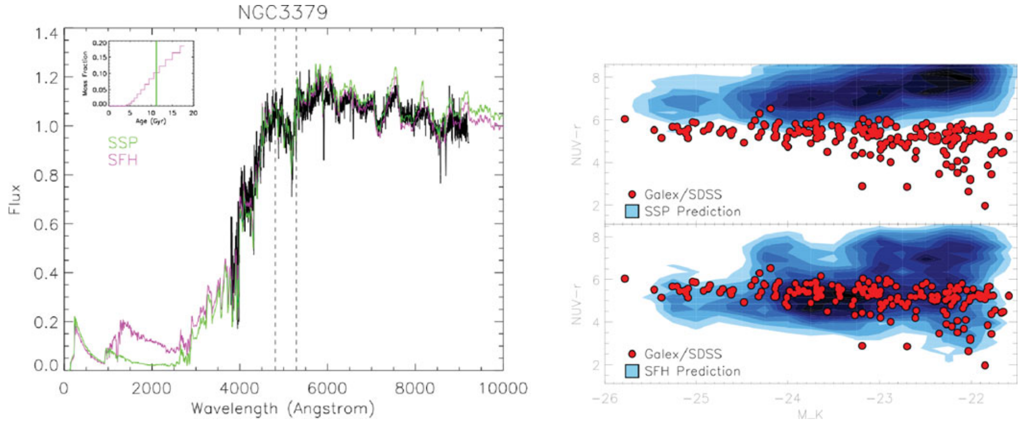

Figure 3. *Left*: Comparison of SDSS spectrum of NGC3379 with stellar population models derived from our `SAURON` spectra, assuming a single SSP and composite SFH. *Right*: Comparison of observed total UV-optical colours from GALEX and SDSS versus K-band absolute magnitude from 2MASS for the ATLAS^{3D} sample (circles) and predictions (regions) from the SSP-equivalent spectrum (top) and the fitted SFH (bottom).

The right-hand panel of Figure 2 shows two (total) UV-r colour-magnitude diagrams using archival GALEX, SDSS and 2MASS data for our sample. Shaded regions indicate the predicted colour distributions based on the SSP-equivalent spectra (*top*) and the SFH spectra inferred from our `SAURON` data (bottom). The SFH does a significantly better job in predicting the UV-r colours. For some galaxies, this could be a feature of the stellar population models used, as the UV range has uncertain contributions from old metal-poor stars and is still a matter for debate. However, the improvement occurs for all objects, suggesting that the need for some small fraction of recently-formed stars is real. The photometry apertures are not matched to the spectroscopy in this analysis, but most ETGs are centrally blue in the UV, thus we underestimate the discrepancy here.

3. Conclusions

In this short contribution, we compare the SSP and SFH properties of the ATLAS^{3D} sample of ETGs, and conclude that the measured SFHs are consistent with the picture inferred from SSPs, namely that galaxies of increasing mass have a shorter star-formation duration, completed at early times. In addition, we directly show that, on average, the majority of stellar mass in all masses of ETGs in our sample are dominated by old stars. We also show that the spread in stellar ages afforded by considering the SFH generally gives a much better prediction of the UV-optical colours of ETGs as compared to SSPs.

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