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The Star Formation History of Late Type Galaxies

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Abstract. The combination of huge databases of galaxy spectra and advances in evolutionary synthesis models in the past few years has renewed interest in an old question: How to estimate the star formation history of a galaxy out of its integrated spectrum? Fresh approaches to this classical problem are making it possible to extract the best of both worlds, producing exquisite pixel-by-pixel fits to galaxy spectra with state-of-the-art stellar population models while at the same time exploring the fabulous statistics of mega-surveys to derive the star-formation and chemical enrichment histories of different types of galaxies with an unprecedented level of detail. This review covers some of these recent advances, focusing on results for late-type, star-forming galaxies, and outlines some of the issues which will keep us busy in the coming years.

Keywords. galaxies: stellar content, galaxies: evolution, galaxies: spiral, galaxies: starburst

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1. Introduction

Understanding the cosmological and internal processes which drive galaxy evolution is a major goal of contemporary astrophysics. Empirical information on the star formation history (SFH) of galaxies is a key piece in this quest. Impressive progress has been made both with high z studies, which measure evolution directly by comparing galaxy properties at different cosmic times, and with SFH recovery techniques based on color-magnitude diagrams of our closest neighbors, which recover time information from stellar evolution clocks. Most of the data comes from between here and there, where galaxies are neither far enough to use cosmological clocks nor close enough to resolve individual stars, and hence SFHs must be retrieved from integrated light measurements.

Generations of astronomers have worked in this field, and even limiting the scope of this review to techniques based on optical spectra and biasing it towards applications to large surveys in the past few years, so much has been done that it would be impossible to make justice to all. This contribution thus presents an inevitably incomplete review of recent progress in the field. The focus is not so much on results but mainly on the diversity of methods to go from integrated optical spectra to SFHs. Browsing through this volume you will see that so much more is being done as we “speak” that I will close this with a few lines about issues to be explored in the very near future.

2. Stellar population mixtures: Ingredients & observables

Late type galaxies are evidently composite systems, where multiple generations of stars contribute to the integrated light. Unlike with elliptical galaxies, which are often modeled as single age systems, for spirals and irregulars one cannot evade the challenge of unscrambling the mixture of photons reflecting different cosmic times, from the ~ 10 Gyr populations of the bulge to the new-born stars in the disk and starbursting nuclei. This mixture can be represented by a sum of $N_\star$ populations of different ages and metallicities,

$$L_\lambda^{gal}(\vec{x}, A_V) = L_{\lambda_0}^{gal} \sum_{j=1}^{N_\star} x_j l_\lambda(t_j, Z_j) \otimes \mathrm{LOSVD} \times 10^{-0.4 A_V r_\lambda} \tag{2.1}$$

where l_λ represents the spectrum of population j normalized at λ_0, x_j is its light fraction and $r_\lambda = (A_\lambda - A_{\lambda_0})/A_V$ denotes the reddening law. The fossile record of the SFH is encoded in the *population vector* $\vec{x}$. Conversion of this discrete representation to a continuous one, or from light to mass fractions is straightforward. It is equally simple to generalize this formalism to allow for population dependent extinctions, reddening-laws and Line Of Sight Velocity Distributions. Though this would surely produce a more realistic model, the task of deriving SFHs from a comparison of L_λ^{gal} with actual galaxy spectra would become so much harder that this would be an academic refinement at this stage (more on this in §4), so lets stick to this simple, yet useful approach.

Behind its formal simplicity, eq. (2.1) hides a multitude of astrophysical, mathematical and computational issues which propagate to a substantial diversity in SFH recovery methods. For starters, what should one use as the spectral building blocks $l_\lambda(t_j, Z_j)$?

Bica & Alloin (1986) and Bica (1988) proposed to work with a base of observed star cluster spectra, founding a fruitful and inspiring empirical approach to population synthesis. Since then, the modeling of Simple Stellar Populations (SSP) has evolved so much that one can now ∼ safely replace observed clusters by theoretical ones with (arguably) more pros than cons. This major advance came about with the incorporation of medium–high spectral resolution libraries into evolutionary synthesis models (Bruzual & Charlot 2003; Le Borgne *et al.*2004; González Delgado *et al.*2005), which quickly became a standard ingredient in SFH studies. With the release of new spectral libraries and evolutionary tracks announced in this conference, fossil methods now have a long menu of $l_\lambda(t_j, Z_j)$'s to choose from. Diversity is certainly healthy! Yet, it inevitably brings some entropy to the field, so it is important to understand how and why these models differ and how this affects the derived SFHs in practice. Important steps in this direction have been presented by Moleva, Panter and Prugniel in this meeting.

Moving away from ingredients towards how to use them, the comparison of (2.1) to an observed spectrum can be done either in its full λ-by-λ power (§3) or in terms of selected *spectral indices* such as absorption line equivalent widths and colors. The latter approach, more common until very recently, was applied to star-forming galaxies of several kinds by Raimann *et al.*(2000); Cid Fernandes *et al.*(2003); Kong *et al.*(2003); Westera *et al.*(2004). An important result of these studies is that even the smallest, youngest looking systems contain a mass dominant ∼ 10 Gyr population, and thus, contrary to first impressions, are *not* primeval galaxies. (Work based on full spectral fits confirm this finding and extends it to even more extreme classes of star-forming galaxies; Corbin *et al.*2006; Lisker *et al.*2006). Active galaxies of different brands have also been targeted with such techniques (see Cid Fernandes 2004 for a review). It is fit to recall that studies based on a few spectral features often do what some would call absurd: Fit more populations than observables available! Those who still have their qualms about algebraic degeneracy should read Pelat (1998), who, besides clarifying this issue, proposed an elegant (yet largely overlooked in the literature) inversion method. Index based work has also entered the new era of huge databases. Kauffmann *et al.*(2003) and Gallazzi *et al.*(2005) developed a Bayesian technique based on a handful of indices which does not recover the full time dependent SFH, but provides valuable estimates on some of its associated "moments", like the mean age, metallicity and fraction of mass formed in recent bursts. Its application to SDSS data brought important insights on relations between stellar populations and other galaxy properties, particularly its mass.

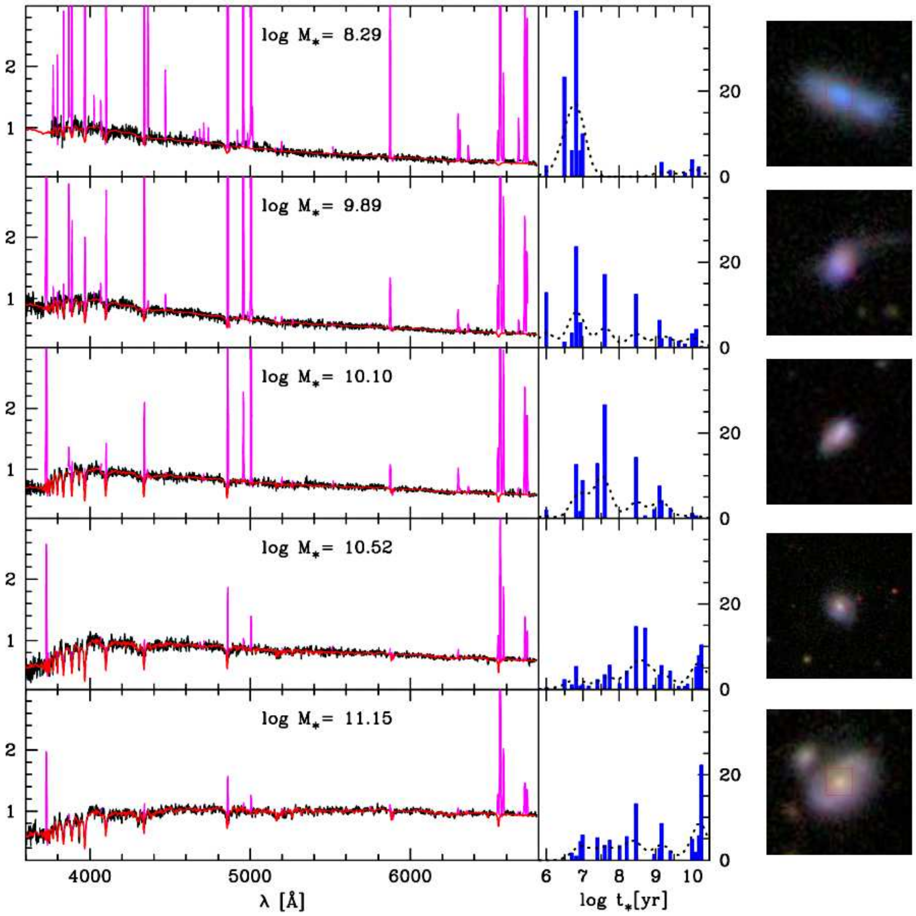

Figure 1. *Left:* Observed (black) and fitted (red) spectra of 5 SDSS star-forming galaxies at similar distances (except for the 1^{st}, which is closer). Emission line masks are plotted in magenta. Galaxies are sorted according to their stellar mass, increasing from $10^{8.29}$ to $10^{11.15}$ $M_\odot$ from top to bottom. *Middle:* SFH, given in terms of the light fraction at 4020 Å associated with each of the 25 ages included in the fits and marginalizing over Z. Dotted curves show a 0.5 dex gaussian-smoothed version of the population vector $\vec{x}$. Notice how the balance between recent and past star-formation changes in pace with the $M_\star$ sequence. *Right:* SDSS image.

3. Spectral fits: Methods & results

The new vintage of high spectral resolution evolutionary synthesis models offered the long awaited possibility of performing detailed "Å-by-Å" fits of galaxy spectra. Fig.1 illustrates that this is no longer just a possibility, but a reality.

Emission line studies have welcome this advance. Before it, the traditional approach to clean up starlight for emission line measurements was to subtract a suitable template galaxy, but as soon as your target contains a young population (as is the case of late types) it becomes impossible to find a suitable template which does not have emission lines of its own. Let me open a parenthesis to illustrate that this is not as minor a problem as it may seem to this audience. For ~ 2 decades studies of Seyfert 2 nuclei used elliptical galaxy templates to represent the stellar spectrum, which often produced a seemingly featureless residual continuum (see Sarzi's contribution for an update on this). This was first attributed to accretion disk light, then to scattered photons from a hidden nucleus, but these interpretations clashed head-on with other pieces of AGN phenomenology. It took many papers and telescope time to realize that these nuclei are often surrounded by stars much younger than those found in ellipticals, and that the mysterious residual continuum was essentially a side effect of a template-mismatch. All this work (including mine!) would have been superfluous if the ingredients for spectral fits like those used in Fig. 1 existed back then. The main message here is that progresses in stellar population modelling have an impact well outside the stellar population field.

Our interest here, of course, is not to get rid of stellar photons, but to retrieve the SFH information they carry in a peculiarly scrambled way. The fits in Fig. 1 were constructed combining SSPs of 25 different t_j's and 6 Z_j's from the BC03 models, all extincted by the same screen of Galactic-like dust, and adjusting the velocity dispersion $\sigma_\star$ as well as possible velocity off-sets with respect to the rest-frame. Emission lines and bad pixels are masked from the fits, which minimize a standard χ^2 figure of merit.

Fitting all pixels saves you the trouble of picking and measuring indices. On the other hand, the factor of ~ 1000 increase in the number of observables slows computations, though this can be handled efficiently with mathematical and programming tricks. Apart from such minor technical differences, the fundamental issues faced by index-based and full spectral synthesis methods to recover SFHs are the same, like: which $l_\lambda(t_j, Z_j)$ building blocks to use, how to go from the observables to the parameters, how to handle astrophysical and mathematical degeneracies and uncertainties, and to which degree can one trust the resulting SFHs. Let us browse through some of these inter-related points.

It is intuitively obvious that the $N_\star = 150$ populations used in Fig. 1 cannot be trusted individually. This over-dimensioned parameter space, philosophically rooted in a "principle of maximal ignorance", must somehow be *compressed* to produce SFHs with only as much resolution as afforded by the data. This issue has a long history in index methods. In the context of spectral fits, it was first seriously tackled by the MOPED group, who developed a data compression method which preserves information on the SFH (Heavens *et al.*2000; Panter *et al.*2003; Reichhardt *et al.*2001; Mathis *et al.*2006). The STECMAP group (Oczvirk *et al.*2006) analyzed this issue from a different perspective, and proposed a regularization technique which controls the smoothness of the resulting SFHs in a data driven fashion, while STARLIGHT (the code used to produce Fig. 1; Cid Fernandes *et al.*2005) works with an oversampled population vector $\vec{x}$ all the way through the fit, and only then rebins or smooths spectrally similar components onto a coarser but more robust $\vec{x}$. At the risk of oversimplifying the issue, these 3 examples could be described as *a priori*, "on the fly" and *a posteriori* compression approaches, respectively. Experiments indicate that the age resolution achievable with optical spectra of realistic S/N is somewhere between $\Delta \log t = 0.5$ and 1 dex, which even in the worst case represents a great improvement over a SFH description based only on mean ages.

MOPED, STARLIGHT and STECMAP are just examples of the booming business of spectral synthesis codes. A staggering variety of techniques are being explored, including active instance-based machine learning (Solorio *et al.*2005), convex algebra (Moultaka 2005), PCA (Li *et al.*05), Bayesian latent variable modelling (Nolan *et al.*2006), direct fitting (Tadhunter *et al.*2005; Moustakas & Kennicutt 2006; Walcher *et al.*2006), and others (see also MacArthur, van der Marel and Sarzi contributions.) This diversity may look scary, so let me remind the reader that all these methods share a same goal, namely, to map the space of observables to the SFH parameters, and so should produce similar results despite differences in formalism, elegance, complexity and speed. Though more tests are desirable, the amazing agreement between MOPED, STARLIGHT and STECMAP results for the challenge proposed by the organizers of this meeting suggests that algorithm should *not* be considered another free parameter in fossil methods.

This convergence of independent codes is even more reassuring when we consider that, besides algorithm, they also differ in dozens of more subtle, yet relevant details, some more technical, others more astrophysical. "Technical" differences include data pre-processing steps, handling of kinematical parameters, choice of extinction-law and whether $A_V < 0$ is allowed or not (see Gallazzi *et al.*2005 and Mateus *et al.*2006 for more on this curious point), whether pure SSPs or constant star-formation episodes within time bins are used for $l_\lambda(t_j, Z_j)$, which time-bins are used and whether cosmological consistency ($t < 14$ Gyr) is enforced *a priori*, whether the continuum is fitted or rectified, emission line masks, non-stellar components such as nebular emission and AGN, etc.

A more astrophysically relevant difference is the handling of metallicities. Some algorithms work at fixed Z, some impose simple Z-t relations, some allow one Z per t-bin in a non-parametric way, and others treat Z and t independently. The information on *chemical evolution* retrievable by the synthesis clearly depends on this choice. As a matter of fact, unlike the stellar mass assembly histories retrieved by fossil methods, which are getting a lot of (well deserved) attention, not much has been done on the way of chemical evolution, probably because of fears that degeneracies plus noise would kill the $Z(t)$ signal. On the other hand, Cid Fernandes *et al.*(2005) and Gallazzi *et al.*(2005) showed that fossil methods applied to SDSS data do recover mean stellar metallicities which behave in an astrophysically expected manner when correlated with stellar mass and gas-phase metallicity, showing that, in agreement with test-simulations, at least the first moment of the Z distribution is well recovered. This lead us to venture into the next step, i.e., checking whether fossil methods recover reasonable chemical evolution patterns.

Fig. 2 illustrates results for a sample of star-forming galaxies. The bottom-left panel shows the *time dependent* mean stellar metallicity averaged over galaxies in 5 mass ranges. Besides the fact that lower $M_\star$ galaxies have lower Z nowadays, the curves show that chemical evolution proceeds at a slower pace the smaller $M_\star$ is, with the lower $M_\star$ bin reaching its present day stellar metallicity as recently as $\sim 10^8$ yr ago, whereas in massive galaxies all evolution occurs early and within ~ 1 age-resolution element. The mass assembly histories retrieved from the spectral fits show this same speed-mass downsizing pattern. The panels on the right show the less detailed (but still useful) first moments of the t and Z distributions, deliberately mixing light and mass-weighted quantities to remind the reader of the various ways in which the synthesis results can be manipulated in the interpretation stage. An important "detail" is that the growth curves in Fig. 2 were smoothed by $\Delta \log t = 1$ dex, which yields robust results while still providing a reasonably detailed picture of evolution. No such compression was applied in Cid Fernandes *et al.*(2006), where these same curves were smoothed by just enough to disguise the discreteness of our base while not hiding features like humps close to ages of 1 Gyr. Such fine details reflect deficiencies in the base (e.g., mismatch between spectroscopic and stellar evolution Z's) or artifacts of the method, and, while not changing the general picture, serve to remind us of our limitations and fight temptations of over-interpreting the fits. Notwithstanding these caveats, this exercise demonstrates that fossil methods are mature enough to contribute to chemical evolution studies.

4. Summary and outlook

This highly incomplete overview tried to outline recent progresses in studies which recover the SFH of galaxies out of integrated optical spectra. Luckily, other contributions

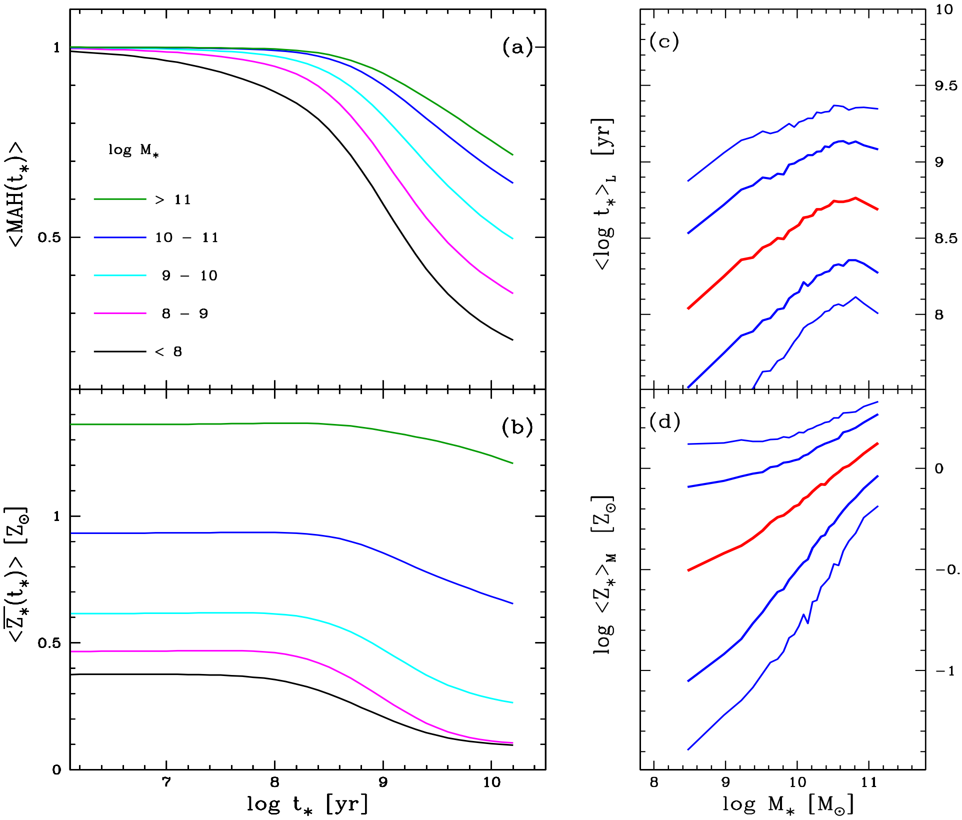

Figure 2. Normalized Mass Assembly Histories *(a)* and evolution of the mean stellar metallicity *(b)* for 84828 star-forming galaxies from the SDSS, averaged over 5 mass intervals. Panels *(c)* and *(d)* show the relation between light and mass-weighted first moments of the $\log t$ and Z distributions and the stellar mass. The lines show the median, 1 and 2 sigma equivalent percentiles in 25 equally populated $M_\star$-bins. (Adapted from Asari *et al.*2007, in prep.).

in this volume expand upon points compressed beyond recognition in these pages. 20 years ago Searle (1986) expressed the reigning skepticism towards this topic, classifying it as "…a subject with bad reputation. Too much has been claimed, and too few have been persuaded.", an opinion shared by many (including myself) up to not long ago. Since then, ingredients and methods have evolved to a point that it became impossible to deny the power of synthesis techniques as a tool to bridge the gap between the fabulous data sets available nowadays and the ever more sophisticated stellar population models. A variety of techniques have been applied in the reconstruction of the mass assembly and even the chemical enrichment histories of galaxies, leading to important constraints for galaxy evolution scenarios.

These optimistic words should not convey the idea that all is done! After all, despite the "long and venerable history" (Searle's words again) of applied population synthesis, fossil methods of the kind discussed in this review have practically re-started from scratch in the past ∼ 3 years. One should thus remain cautious and skeptic until this field reaches full maturity. It is hard to say when this will happen, but some of the hurdles on the way are clear, so lets indulge in a short futurology exercise.

First, as we have seen, there is a strong drive towards full spectral fits. These will gather even more momentum with the imminent release of new $\sim$ Å-resolution evolutionary synthesis models. One does not need a crystal ball to foresee that the combination of new libraries, the proliferation of synthesis methods and the already abundant data will fill up hundreds of journal pages in the new couple of years, reporting results whose compatibility will not be trivial to assess at first. The introduction of α-enhanced libraries (discussed in Coelho's talk), in particular, will add a new and qualitatively different dimension to parameter space, inevitably increasing complexity. Like a spoilt kid with too many toys to chose, this massive overdosis may throw us into a temporary state of confusion, which is why comparative studies (in the spirit of the challenge posed to participants of this meeting) would be highly desirable.

Secondly, the agreement between different methods suggests that we are reaching the limit of information that can be extracted from optical spectroscopy. Indeed, some of the methods are designed to do exactly this! It thus seems unlikely that different methodologies will bring substantial improvements to the t and Z resolutions of currently existing SFH recovery tools. After fitting every single optical pixel, it is clear that progress will require stretching the spectral horizon (say, to the near-IR range explored in Lançon's talk). This brings in new challenges and difficulties, specially for those of us who have grown accustomed to the comparatively easy life of optical astronomy.

Finally, a few words on what seems to be the major fly in the ointment of current fossil methods: Dust. Equation (2.1), used in one way or another by most spectral synthesis codes, pictures a galaxy as a clean system of stars seen behind a sheet of dust. Real galaxies are not quite like that, particularly non ellipticals. At the very least, one should allow the younger populations to be dustier than the others (Charlot& Fall 2000). This has been done in index-methods which compare data to a large library of precomputed models (eg, Kauffmann *et al.*2003), as well as in applications where the number of populations is relatively small (eg., Poggianti *et al.*2001; Mayya *et al.*2004; Solorio *et al.*2005), such that the parameter space can be held under control. However, attempts to retrieve more than one value of A_V from general full spectral synthesis in the optical as the ones described in §3 have stumbled upon less than satisfactory results, with simulations indicating that the extra extinction is not well recovered. This is not surprising given the nasty non-linearities and degeneracies which come together with more complete modeling. Interestingly, single A_V fits of star-forming galaxies in the SDSS find that the line emitting regions are $\sim$ twice as extincted as the stellar population as a whole (Cid Fernandes *et al.*2005), in excellent agreement with detailed studies of nearby galaxies (Calzetti *et al.*2004). This is rather ironic, though, since HII regions are also where the youngest, ionizing populations reside, and thus the result that $A_{V,gas} \sim 2A_{V_\star}$ indicates that the fits should have allowed at least part of the $t < 10$ Myr stars to suffer twice as much extinction as the others! Warnings about such problems have been issued long ago (Witt *et al.*1992), but optical "synthesizers" still have not come up with a fully satisfactory way to deal with them. It is unclear to which extent naive modelling of dust effects is affecting SFH studies of late types in general, but it is clear that the dustier beasts (like LIRGS and ULIRGS) definitely need a more refined treatment. It is also unclear how much improvement can be made with optical data alone. Going back to my previous point (and judging from Bressan's contribution and the GRASIL group work; e.g., Silva *et al.*1998), going beyond optical is inevitable. Combining the kind of detailed optical synthesis discussed here with wider-scale SED modeling involves much more than simply adding more λ's to the fits, and so should keep us busy for a long time.

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