Stellar Populations in the Milky Way and Beyond
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Stellar populations model developments

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Abstract. Significant advancements in current stellar populations synthesis models are needed to enhance their ability to perform detailed spectroscopic analyses. Key improvements include incorporating varying abundance ratios through multiple approaches, such as utilizing empirical stellar spectra and applying theoretical differential corrections to account for abundance ratio variations. The development of spectral libraries with controlled abundance variations, offers a more robust framework for modeling non-solar chemical compositions in unresolved stellar populations. Additionally, extending stellar populations models beyond the optical range into the near-infrared is crucial for studying young stellar populations and galaxies at varying redshift. These advancements will provide more precise diagnostic tools for interpreting the wealth of observational data expected from upcoming large-scale spectroscopic surveys, ultimately refining our understanding of galaxy evolution and chemical enrichment processes.

Keywords. galaxies: stellar content; galaxies: abundances; galaxies: evolution; stars: abundances; stars: fundamental parameters

1. Introduction

Detailed studies of stellar populations based on spectroscopic data have provided strong constraints on galaxy formation and evolution, which are essential for contemporary numerical cosmological simulations within the ΛCDM paradigm. These studies have established that Early-Type Galaxies (ETGs) predominantly host old stellar populations, with their mean ages increasing with galaxy mass and, for the most massive galaxies, approaching the age of the Universe (Renzini 2006). This trend has recently been corroborated by observations from the James Webb Space Telescope (JWST), which have unveiled quiescent galaxies with estimated formation epochs at redshifts $z \sim 10$ (e.g., Carnall *et al.* 2023; Glazebrook *et al.* 2024). Similarly, the mean metallicity of ETGs increases with galaxy mass, reaching supersolar values for the most massive systems (e.g., Thomas *et al.* 2005; Yamada *et al.* 2006). The bulk of stellar populations in these galaxies formed in less than 1 Gyr, as inferred from the observed overabundance of [Mg/Fe] relative to the solar neighborhood abundance pattern (e.g., Worthey *et al.* 1992; Vazdekis *et al.* 2004). This α-element overabundance increases with galaxy mass, suggesting even shorter star formation timescales for more massive galaxies (e.g., de la Rosa *et al.* 2011). Intriguingly, the overabundance of Mg is not mirrored by Ca (e.g., Vazdekis *et al.* 1997), another α-element, highlighting unique abundance ratio patterns, where not all the α-elements are enhanced in lock-step (e.g., Conroy *et al.* 2014). Additionally, certain elements, such as Na, are significantly enhanced in massive galaxies (e.g., Conroy *et al.* 2014; La Barbera *et al.* 2017; Röck *et al.* 2017), but are depleted in dwarf galaxies (e.g., Sen *et al.* 2018). Moreover, the central regions of ETGs exhibit an Initial Mass Function (IMF) skewed toward M-dwarf stars, with deviations from the Milky Way IMF becoming

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more pronounced with galaxy mass (e.g., La Barbera *et al.* 2013; Martín-Navarro *et al.* 2015; van Dokkum *et al.* 2017).

These insights have been made possible through the use of stellar population synthesis models, which compare theoretical predictions with galaxy (and star cluster) observations to infer key stellar population parameters (Tinsley 1980). While much of this progress has been achieved using the optical spectral range, there is now a growing opportunity to explore other critical wavelength regimes, such as the near-ultraviolet (NUV), which is highly sensitive to hot stars from both young and old populations, and the near-infrared (NIR), which probes cool stars. These spectral ranges are providing new constraints and, importantly, enabling unique solutions for stellar population properties that were previously unattainable (e.g., Baldwin *et al.* 2018; Dahmer-Hahn *et al.* 2018; Eftekhari *et al.* 2022).

The advent of next-generation ground- and space-based observing facilities, including large-aperture telescopes and extensive surveys, demands further advancements in stellar population models. This work focuses on describing some of these developments, including new observational spectral libraries, improved treatments of abundance ratio modeling, extensions to the NUV and NIR spectral windows, and the implementation of innovative fitting methods.

2. Stellar Populations Models

Modern stellar population models primarily rely on single-burst stellar populations (SSPs), which assume single-age and single-metallicity star clusters. These SSPs serve as the fundamental building blocks for understanding the more complex stellar populations observed in galaxies. The core ingredients of these models include: *i)* isochrones, incorporating the latest advances in stellar evolution, including evolved phases; *ii)* stellar spectral libraries, which can be empirical or theoretical; and *iii)* a prescription for the Initial Mass Function (IMF), such as those proposed by e. g., Salpeter (1955); Scalo (1986); Kroupa (2001); Chabrier (2001); Vazdekis *et al.* (1996).

These models predict observables such as:

i) Photometric properties (e.g., fluxes, colors, mass-to-luminosity ratios, and surface brightness fluctuations) (e.g., Tinsley 1980; Arimoto & Yoshii 1986; Buzzoni 1989, 1993; Bruzual & Charlot 1993; Bressan *et al.* 1994; Worthey 1994; Vazdekis *et al.* 1996; Kodama & Arimoto 1997; Leitherer *et al.* 1999; Maraston 1998; Liu *et al.* 2000; Blakeslee *et al.* 2001; Maraston 2005; Cerviño *et al.* 2013).

ii) Line-strength indices (e.g., Lick indices, Rose indices, Ca II triplet) (e.g., Peletier 1989; Worthey 1994; Vazdekis *et al.* 1996; Tantalo *et al.* 1998; Thomas *et al.* 2003; Schiavon 2007).

iii) Low-resolution spectra (e.g., Bruzual & Charlot 1993; Bressan *et al.* 1994; Kodama & Arimoto 1997; Leitherer *et al.* 1999; Maraston 2005; Conroy *et al.* 2009; Eldridge & Stanway 2009).

iv) Spectra at moderately high resolution (e.g., Vazdekis 1999; Vazdekis *et al.* 2003, 2010, 2012, 2016; Leitherer *et al.* 1999, 2010, 2014; Schiavon *et al.* 2000, 2002; Bruzual & Charlot 2003; Le Borgne *et al.* 2004; González-Delgado *et al.* 2005; Coelho *et al.* 2007; Buzzoni 2009; Lee *et al.* 2009; Percival *et al.* 2009; Maraston & Strömbäck 2011; Maraston *et al.* 2020; Conroy *et al.* 2012, 2018; Meneses-Goytia *et al.* 2015; Röck *et al.* 2015; Stanway & Eldridge 2018; Verro *et al.* 2022b; Byrne & Stanway 2023; Park *et al.* 2025).

v) Surface brightness fluctuation spectra (e.g., Mitzkus *et al.* 2018; Vazdekis *et al.* 2020).

While these models generally show good agreement, significant differences remain, which can lead to variations in results between models and across spectral ranges. These discrepancies are particularly pronounced when incorporating the NIR spectral range and

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comparing model predictions with observed galaxy spectra (e.g., Baldwin *et al.* 2018) or stellar clusters (e.g., Eftekhari *et al.* 2022).

3. Models Predicting SSP Spectra with Varying Abundance Ratios

To model the impact of varying abundance ratios, different approaches have been adopted:

i) Base models using empirical stars: These models rely on stars that follow the abundance pattern of the Milky Way (e.g., Vazdekis 1999; Vazdekis *et al.* 2003, 2010, 2012, 2016; Schiavon *et al.* 2002; Bruzual & Charlot 2003; Le Borgne *et al.* 2004; Maraston & Strömbäck 2011; Maraston *et al.* 2020). These models employ scaled-solar isochrones, making them self-consistent around solar metallicity but α-enhanced at lower metallicities. However, the effects of stellar spectra on SSP predictions are far more significant than those of isochrones (e.g., Vazdekis *et al.* 2015).

ii) Models based on theoretical stellar spectra: This approach uses synthetic stars with varying abundance ratios, primarily α-elements, integrated along isochrones (e.g., Coelho *et al.* 2007; Lee *et al.* 2009; Percival *et al.* 2009; Moura *et al.* 2019; Rennó *et al.* 2020; Byrne & Stanway 2023; Park *et al.* 2025). Most such models are not fully self-consistent, as they generally employ scaled-solar isochrones.

iii) Based on empirical stars corrected with theoretical differential spectral corrections: This method applies synthetic differential corrections to empirical stellar spectra to simulate varying levels of α-enhancement (e.g., Cervantes *et al.* 2007; Walcher *et al.* 2009; Conroy *et al.* 2012, 2018; Vazdekis *et al.* 2015; La Barbera *et al.* 2016; Knowles et al. 2023). At solar metallicity, the empirical stars naturally lead to scaled-solar SSPs, and these differential corrections are applied to the empirical stars to bring them to varying levels of α-enhancement and thus modify the resulting model predictions. At low metallicity, the empirical stars naturally lead to α-enhanced SSPs, and the differential corrections are employed to predict, e.g., scaled-solar SSPs. In general, these models make use of scaled-solar isochrones for all metallicity regimes, although there are notable exceptions (Vazdekis *et al.* 2015; Knowles et al. 2023). This method can be extended to account for individual elements rather than varying elements in lockstep (e.g., Conroy *et al.* 2018). Note that these differential spectral corrections can be obtained from individual stars (e.g., Knowles *et al.* 2021) or from the SSPs computed with theoretical stars with varying abundances (e.g., Vazdekis *et al.* 2015). This approach minimizes uncertainties from theoretical spectra, such as incomplete molecular line lists, but is constrained by the parameter coverage of the empirical stars (e.g., Coelho *et al.* 2007; Vazdekis *et al.* 2015).

3.1. *sMILES Stellar Library and SSPs*

The MILES library (Sánchez-Blázquez *et al.* 2006) is one of the most widely used empirical stellar libraries for optical spectral range studies. Knowles *et al.* (2021) recently extended this library with different α-enhancement values for all the stars. This extension employed new theoretical stellar libraries with varying abundance ratios computed using ATLAS9 model atmospheres, the ASSϵT radiative transfer code (1D, LTE), and opacity distribution functions (ODFs) from Mészáros *et al.* (2012). It adopted the solar abundances from Asplund *et al.* (2005) and line lists from Allende Prieto *et al.* (2018). All α-elements were enhanced uniformly. Molecular line lists included H_2, CH, C_2, CN, CO, NH, OH, MgH, SiH, SiO, and TiO. A temperature- and gravity-dependent microturbulence was adopted.

These corrections influence not only line features (e.g., Mg and Fe) but also continuum shapes, particularly at blue wavelengths. For instance, a comparison with PHOENIX models revealed differences of up to $\sim 20\%$, especially at short wavelengths for typical

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giant and solar-like stars (Knowles *et al.* 2021). Notably, these differences also affect measured line-strength indices, particularly Mg*b*, some hydrogen lines, and molecular bands such as $C_2$4668 (Knowles *et al.* 2021).

Differential corrections derived from these models were applied to the MILES stars, creating the sMILES libraries with $-0.2 \leq [\alpha/\mathrm{Fe}] \leq 0.6$. These differential corrections were implemented in the Vazdekis *et al.* (2015) code to compute new SSPs with similar abundance ratio levels. The abundance ratios of the observed stars were adopted from Milone *et al.* (2011). These new sMILES SSP models, published in Knowles et al. (2023), were compared with those of Vazdekis *et al.* (2015), where the differential corrections were applied to the computed SSP spectra rather than to the individual stars, as done in these new models.

Perhaps the most striking difference is the impact on the Hβ (Trager *et al.* 1998) and Hβ_o (Cervantes & Vazdekis 2009) indices. While Hβ virtually does not change in strength when increasing this abundance ratio from scaled-solar to $[\alpha/\mathrm{Fe}] = 0.4$ using the Vazdekis *et al.* (2015) models, Hβ_o decreases by $\sim$0.3 Å. In contrast, for the sMILES models, Hβ increases by $\sim$0.25 Å, while Hβ_o barely varies. This result demonstrates that these differential corrections are still model-dependent, though less so than we computing the SSPs with the theoretical stellar spectra themselves. Another notable aspect is that the finer abundance variation steps adopted in the sMILES models, compared to those in Vazdekis *et al.* (2015), have revealed that the impact on the indices is not entirely linear.

3.2. *New Abundance Ratio Determinations in Library Stars*

Although several approaches have been considered for determining the abundance ratios of the empirical stars whose spectra are intended to be varied by applying differential corrections, the most appropriate method is to have their abundances directly measured, particularly for the elements being varied. A recent effort in this direction has been made by García-Pérez *et al.* (2021) for the MILES library and its new extension, which includes $\sim$200 additional stars observed with the same telescope and instrumental setup using the IDS at the INT 2.5m. These stars were specifically selected to expand the range of abundance ratios as much as possible for a given metallicity value (see García-Pérez *et al.* 2021 for details). The comparison between these new α-abundance estimates and the determinations from Milone *et al.* (2011) shows reasonably good agreement.

Another effort in this direction has been conducted by Santos-Peral *et al.* (2023) for the X-Shooter Stellar Spectral Library (XSL), as described in the Data Release 3 paper by Verro *et al.* (2022a). This library was obtained using the VLT telescope at a spectral resolution of $\sim$10,000, covering the spectral range $\lambda\lambda$ 0.3 to 2.4 μm. Santos-Peral *et al.* (2023) adopted stellar parameters from Arentsen *et al.* (2019) and used theoretical spectra computed with the TURBOSPECTRUM synthesis code (Plez 2012), MARCS (1D, LTE) model atmospheres, and the Gauguin code (Recio-Blanco *et al.* 2016) to derive Mg and Ca abundances. The MgIb triplet in the V band and the CaII triplet in the I band were used for these abundance determinations. The authors provided [Mg/Fe] and [Ca/Fe] abundances for approximately $\sim$200 XSL stars, representing about one-third of the sample.

4. Increasing the Spectral Resolution: WEAVELIB

Enhancing spectral resolution is a crucial step forward in stellar population synthesis models, particularly for analyzing the spectra of star clusters and low-velocity dispersion galaxies. In this context, a new stellar library, WEAVELIB, is being developed. The

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library is named after the WEAVE multi-object fibre spectrograph, recently commissioned on the 4.2m William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos in La Palma. WEAVE offers several key advantages, including a wide 2-degree field of view and the capability to deploy up to 1000 fibers simultaneously, making it an optimal instrument for constructing extensive spectral libraries.

WEAVELIB will be built using data from both stellar- and galaxy-targeted WEAVE surveys, with the majority of stellar spectra drawn from the Galactic Archaeology (GA) survey. These spectra will have a resolution of $R = 5000$, covering the wavelength range $\lambda\lambda\, 3660 - 9590\,$Å on a relative flux-calibrated scale. Absolute flux calibration is not essential, as the primary objective is to preserve the intrinsic spectral shape of the stars. A key strength of WEAVELIB is the homogeneous determination of stellar atmospheric parameters for all stars included.

The extensive footprint of the contributing surveys (Jin *et al.* 2024) is expected to provide an unprecedented range of stellar parameters, significantly expanding studies of ages, metallicities, and abundance ratios within stellar populations. In particular, the High-Latitude Low-Resolution sub-survey (LR-highlat) of GA will observe approximately 1.5 million sources across 8500 square degrees of the Galactic halo ($10 - 100\,$kpc). This includes stars within the magnitude range $15 < r < 20 - 21$ (Gaia RVS) and an additional 250 square degrees with $r < 20.5$. The survey will cover Gaia Enceladus and Gaia Sausage, including a variety of stellar types such as main-sequence turnoff (MSTO) stars, red giants, extremely metal-poor stars, blue horizontal branch stars, and RR Lyrae variables.

Another GA sub-survey, Disc-Dynamics (LR-disc), will observe approximately 1 million stars spanning the inner, medium, and outer Galactic disc within the magnitude range $15 < r < 19$. LR-disc will cover key Galactic structures, including the inner disc, bar, spiral arms, and outer disc, and will feature a significant sample of red clump giants. Additionally, GA will include a fraction of open clusters.

WEAVELIB may also incorporate spectra from stars originally intended for observation in High-Resolution mode but observed in Low-Resolution mode due to unfavorable weather conditions. Only the highest-quality stellar spectra will be included in WEAVELIB, with an estimated $\sim 15\%$ of MSTO stars and $\sim 20\%$ of giants expected to have a signal-to-noise ratio above 50.

The stellar parameters will be determined using the WEAVE Advanced Processing System (APS), which includes a classifier and a stellar module that utilize the FERЯE algorithm (Allende Prieto *et al.* 2015). This system will provide the effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), metallicity ([M/H]), and ([α/Fe]). The expected precision for the stars to be included in WEAVELIB is approximately 50 to 150 K for $T_{\rm eff}$, 0.1 to 0.25 for $\log g$, and 0.15 to 0.25 for [M/H] and [α/Fe].

Regarding flux calibration, the goal is to achieve an accuracy of less than 5% by utilizing XP Gaia data, along with spectra from the WEAVE dwarf survey that will be acquired over the observing years. This calibration can be further refined using the newly proposed method by Maíz-Apellániz & Weiler (2024), which employs STIS/HST spectrophotometric data in combination with six Gaia filters.

Finally, it is important to note that stellar spectra from other WEAVE surveys will also contribute to WEAVELIB, particularly those from surveys focused on massive stars. These are expected to observe approximately 200,000 AB stars and 20,000 OB stars, with their atmospheric parameters determined using the CaII Triplet region, following the methods outlined by Simón-Díaz (2010); Holgado *et al.* (2018); Carneiro *et al.* (2019). Additionally, around 100,000 white dwarf candidates will be observed in another WEAVE survey. Stellar spectra from galaxy-targeted surveys, such as WEAVE-StePS or WEAVE-Apertif, will also be considered for inclusion in WEAVELIB.

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4.1. *Developing NIR Spectral Libraries for Young Stellar Populations*

Predicting SSP spectra in the NIR spectral range for young stellar populations remains a challenge, primarily due to the lack of comprehensive stellar coverage, particularly for hot stars, which shine relatively little in these wavelengths. To address this, a new stellar library is being developed to complement existing NIR libraries, such as IRTF (Cushing *et al.* 2005; Rayner *et al.* 2009) and XSL (Verro *et al.* 2022a). This library, the mileS Moderate resolution neAr-infRared sTellar librarY (SMARTY) (Bertoldo-Coelho *et al.* 2024), consists of 31 stars selected from the MILES sample and observed at the Gemini Telescope using GNIRS. The spectra cover the wavelength range 0.9-2.4 μm with a resolution of $R = 1300$.

To further expand this library, the SMARTY team is conducting new observations at the SOAR telescope using TripleSpec. This extended library, named SO-SMARTY, consists of 222 stars selected from the MILES and HST archives. The spectra cover the wavelength range 1.0-2.47 μm with a resolution of $R = 3500$. All selected stars have temperatures above ~ 6000 K. This library will enable the computation of SSP spectra for stellar populations younger than ~ 1 Gyr.

5. Summary

Advancements in stellar population synthesis models are explored, as they play a crucial role in understanding galaxy formation and evolution within the ΛCDM paradigm. These models rely on several key ingredients, including stellar isochrones, stellar spectral libraries, and the IMF prescription. Improving their accuracy requires significant refinements in various aspects, such as the inclusion of new observational spectral libraries, enhanced abundance ratio modeling approaches, and extensions into the NIR spectral window.

A major aspect involves addressing abundance ratio variations in SSPs. Several approaches are considered, including empirical methods based on observed stars, fully theoretical models using synthetic stellar spectra, and hybrid techniques that apply differential theoretical spectral corrections to empirical libraries. The latter is illustrated with the sMILES stellar library, which extends the well-established MILES library. This new dataset provides semi-empirical spectra with different levels of α-enhancements, improving the ability to model non-solar abundance patterns. Additionally, new abundance ratio determinations for empirical stars further enhance the reliability of such approaches.

To improve the spectral resolution of stellar population models, the WEAVELIB project is introduced. This initiative take advantage of high-quality spectra obtained with the WEAVE multi-object spectrograph, significantly refining stellar population analyses. The higher spectral resolution of WEAVELIB is particularly beneficial for studying low-velocity dispersion systems such as globular clusters and dwarf galaxies, where precise spectral features improve the accuracy of age and metallicity determinations.

Moreover, expanding stellar population models into the NIR spectral range is crucial for studying young and intermediate-age stellar populations and galaxies at varying redshifts. Efforts to construct new NIR spectral libraries incorporating empirical spectra, are discussed.

Overall, these improvements in stellar populations modeling contribute to a more accurate interpretation of galaxy properties, providing tighter constraints on their formation histories, chemical compositions, and evolutionary pathways. The integration of high-resolution spectral libraries and refined abundance ratio treatments represents a significant step forward in bridging observations with theoretical models of galaxy evolution.

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