THE Mg/Fe CHARACTERIZATION OF THE MILES LIBRARY FOR STELLAR POPULATION STUDIES

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Abstract

We have obtained the Mg/Fe abundance ratios for the stars of the spectrum library MILES (Sánchez-Blázquez et al. 2006) in order to include this information into the stellar population models.

The Mg/Fe ratios have been obtained by two methods: (i) compilation from the literature, and (ii) computation from a robust spectroscopic analysis at medium resolution (i.e., the resolution of the MILES's spectra, FWHM = 2.3 Å).

With these two methods, we compiled Mg abundances – which were carefully calibrated to a single uniform scale – for almost 75% of the database. The precision of [Mg/Fe] from the high resolution works is about 0.06 dex and it ranges from 0.08 to 0.15 dex while measured in this work.

These acceptable uncertainties and the good coverage of the stars with [Mg/Fe] around the new MILES's parameter space (T_{eff}, log g, [Fe/H], [Mg/Fe]) will permit us to build up accurate SSP models that will be actually useful to unfold the star formation time scale of different composite systems older than 1 Gyr, opening a new era for the evolutionary stellar population synthesis.

We will be also able to empirically study the dependence of absorption line indices (e.g. Lick System) on the Mg/Fe ratio in order to compute their new fitting functions.

Introduction

Evolutionary stellar population synthesis, i.e. the modeling of spectral energy distributions emitted by evolving stellar populations is a natural approach to studying the stellar content of different galaxies.

A current limitation is that all models using an empirical database of stellar spectra rely on stars from distinct components of our spiral galaxy and their detailed properties are not well characterized. For example, the stars in the different components of the Galaxy show distinct patterns of alpha-elements (O, Ne, Mg, Si, S, Ar, Ca and Ti) reflecting different star formation histories. The models usually only take into account the iron abundance, but stellar spectra may change considerably if the ratio between each other element and Fe is different.

Accounting for well known element abundances will make an empirical spectral stellar library particularly useful for modeling stellar populations with different formations. For instance, [Mg/Fe] depends on the time scale of a stellar formation episode. The greater the ratio, the shorter the burst formation is.

In this work, we present the adopted procedures and results on the compilation from the literature and the necessary computation of Mg abundances in stars of the empirical spectrum library **MILES** (**M**edium-resolution **I**saac Newton Telescope **L**ibrary of **E**mpirical **S**pectra).

This database, which was designed by Sánchez-Blázquez *et al.* (2006), contains flux calibrated optical spectra of high S/N ratio for 985 stars. The coverage of the sample stars in the three-dimensional HR diagram is quite wide. The scales for T_{eff}, log g and [Fe/H] were carefully defined by Cenarro *et al.* (2007). The precision of these photospherical parameters becomes MILES very adequate for stellar population modeling (they are respectively ±100 °K, ±0.2 and ±0.1 dex).

We also show how wide the Mg/Fe coverage is in the new MILES's four dimensional parameter space. As further applications of the MILES library, we succinctly explore our results in order to accurately compute, as soon as possible, the spectra of some single-aged stellar populations (SSP) in a semi-empirical way considering library's stars with specific metallicity and Mg/Fe ratio. Finally, other perspectives are shown too.

Mining Mg abundances and the [Mg/Fe] scale

We looked in the literature for the Magnesium abundances that have already been measured at high spectral resolution for the MILES's stars, and transformed them onto a single scale.

We adopted the Borkova & Marsakov (2005)'s compilation, hereafter BM2005, for defining a consistent scale of the logarithmic solar relative abundance ratio [Mg/Fe], that was based on weighed averages of different measurements at high resolution. The Mg abundances have been measured by different authors taking into account distinct physical assumptions such as local thermodynamical equilibrium (LTE), corrections for non-LTE, atomic line lists and model atmospheres.

The transformation of the abundance ratios from a given work to the uniform scale relies on a statistically representative linear calibration, using MILES's stars in common with the BM2005's sample; as following:

$$[Mg/Fe]_{MILES} = [Mg/Fe]_{BM2005} = A + B \cdot [Mg/Fe]_{work}$$

when A≠0 and/or B≠1 applying a 95% confidence level t-test that considers the parameter errors.

We used [Mg/Fe] from the BM2005's compilation for 219 stars and collected data for other 89 stars from several high resolution analyses, from which 16 are from duplicated sources. This helped us to evaluate the calibration process and estimate the final errors as well, which are around 0.06 dex. We could not apply the calibration for 23 only stars, because there were not enough stars in common to derive a reliable linear relation.

The typical uncertainty of [Mg/Fe] is: 0.07 and 0.05 dex, respectively for [Fe/H] ≤ -1.0 and > -1.0 dex. The mean error of [Mg/H] is 0.11 dex.

In total, we compiled [Mg/Fe] for 308 MILES's stars covering nearly ⅓ of the library (248 dwarfs and 60 giants), as shown in **Figure 2**. This was extremely useful in defining a representative star reference sample for the calibration process of the Mg abundances measured in this work (next section).

Mg abundances measured at medium resolution

To extend the Mg characterization of the library, a robust spectroscopic analysis was carried out adopting the MILES's spectra.

The Mg abundance measurements done in this work at medium spectral resolution were based on a robust spectral synthesis computed with the MOOG code (Sneden 2002) through an automatic process excluding the bad cases along the process, for example, due to low Signal-to-Noise spectra on the selected regions, and possible chemically peculiar stars.

The MOOG LTE code was fed by linearly interpolated model atmospheres over the MARCS's 2008 grid (Gustafsson *et al.* 2008), and accurate atomic (Vienna Atomic Line Database, VALD) and molecular line lists (Kurucz's database) in order to compute a reliable grid of synthetic spectra for MILES's stars ranging five α/Fe ratios (see **Figure 1** for an example). The linear interpolations were done using the friendly code by Masseron (2008).

We adopted the MARCS models with standard chemical composition that follow suitably the general pattern of our Galaxy for the alpha-enhancement: [α/Fe]=+0.4 as [Fe/H]≤-1.0 and [α/Fe]=0 for [Fe/H]≥0.0 with intermediate values between these fiducial metallicities. The micro-turbulence velocity was fixed as 2.0 km/s.

Two strong Mg features were chosen: MgIλ5528.40Å, hereafter Mg5528, and the strongest line of the Mg b triplet (λ5183.60Å), named here Mg b III; as similarly used in other medium resolution analyses (e.g. Kayser *et al.* 2006).

Two abundance determination methods were applied: one based on pseudo equivalent widths that were carefully defined for each feature, and other one applying line profile fittings by rms minimization inside the feature passband (see **Figure 1**).

After measuring the Mg abundances using each feature or both, calibrating them separately using an extensive control sample (applying representative linear transformations), we computed average values for a great number of dwarfs and giants, respectively 89 and 148. Using the Mg b III only, the determination was possible for 22 dwarfs and 59 giants, and through Mgb5528 we recovered abundances for other 33 dwarfs and 68 giants.

In total, our [Mg/Fe] measurements cover about 40% of the MILES database (419 stars, or 144 dwarfs and 275 giants) with acceptable errors ranging from 0.08 to 0.15 dex; as seen in **Figure 2**.

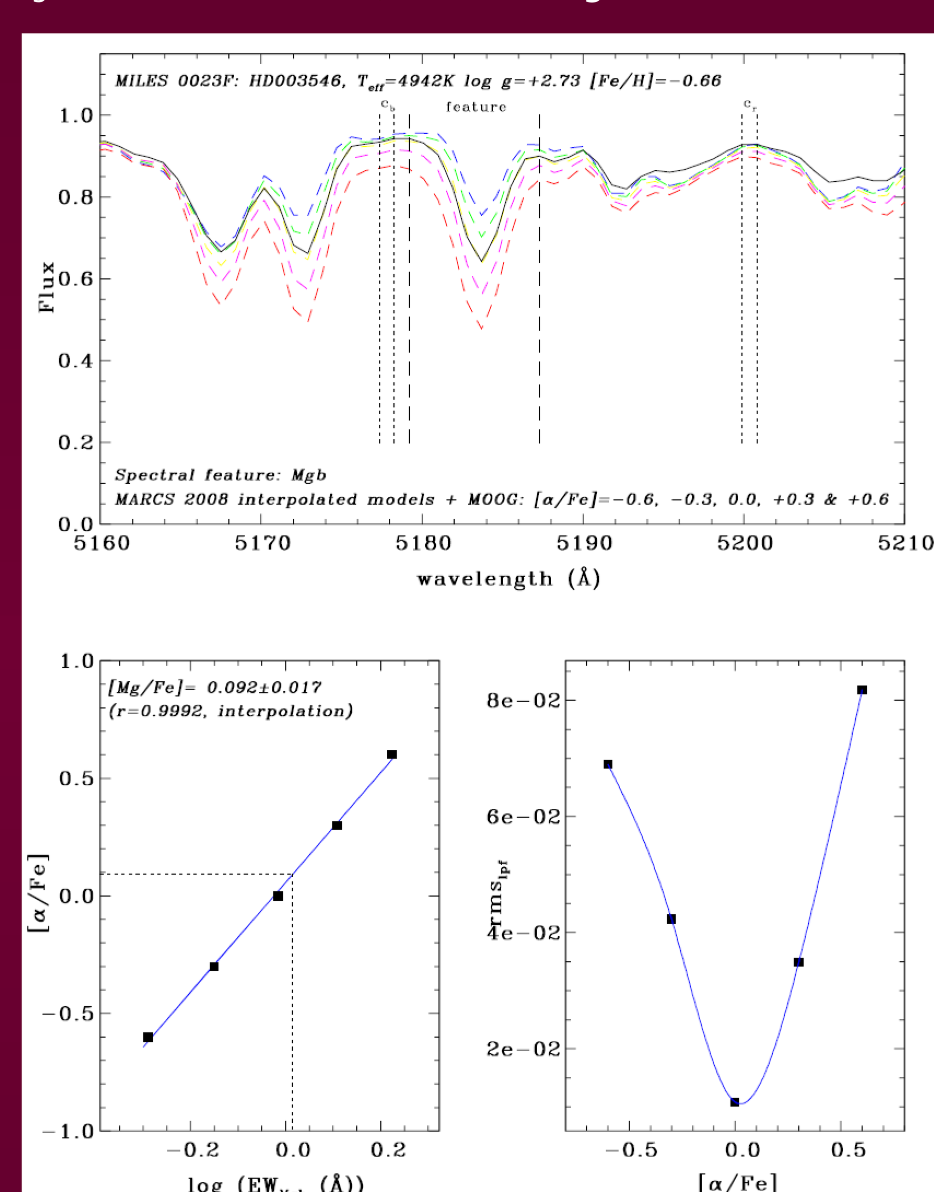

Fig. 1 – Spectral synthesis for a giant on the Mg b feature showing a passband and two pseudo continuum windows focusing on its strongest line. The observed spectrum is represented by the solid black line and the synthetical ones, computed for five [α/Fe], by the colourful dashed lines. The abundance ratio at medium resolution is obtained through a linear relationship between it and the logarithm of the equivalent width and through the best line profile fitting (bottom graphs). The average ratio has to be calibrated to that uniform scale.

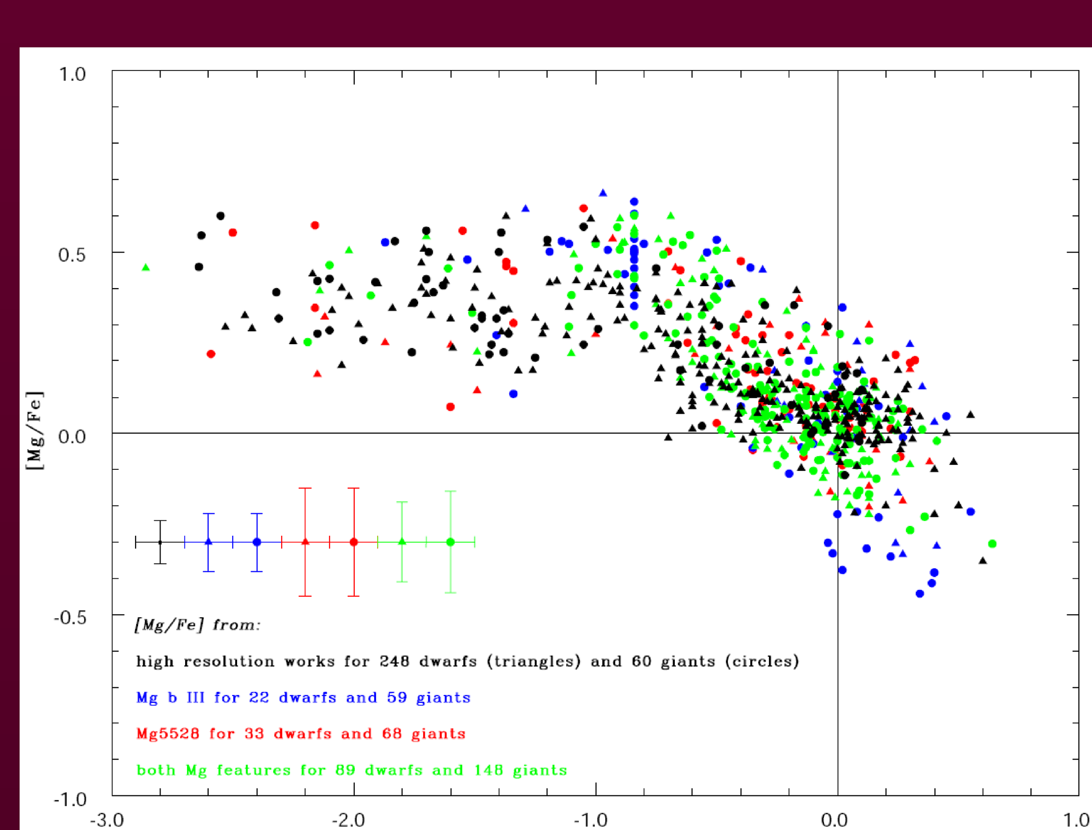

Fig. 2 – Galaxy's pattern of [Mg/Fe] as a function of [Fe/H] statistically and accurately recovered by the collected high resolution abundances and the calibrated measurements done in this work adopting two Mg features.

Age (Gyr)	[Fe/H]	[Mg/Fe]
14±1	-2.00±0.20	+0.40±0.20
6±2	-0.40±0.10	0.00±0.10
6±2	0.00±0.05	0.00±0.10
4±1	0.00±0.10	-0.20±0.10
4±1	*0.00±0.05*	*0.00±0.05*
4±1	0.00±0.10	+0.20±0.10
2±1	0.00±0.10	0.00±0.10
2±1	0.00±0.10	+0.20±0.10
2±1	+0.20±0.10	-0.20±0.1
1.0±0.5	+0.20±0.10	+0.20±0.10
1.0±0.5	+0.40±0.20	-0.20±0.20

Tab. 1 – Several sets of age, metallicity and Mg/Fe ratio, for which new SSP models will be accurately built up using the MILES library.

Conclusions

We have obtained [Mg/Fe] for about ¾ of the MILES library (392 dwarfs and 335 giants, respectively 73% and 76%) that are accurate enough for SSP modeling, opening a new era for that.

The compilation of high spectral resolution Mg abundances in the literature was extremely useful in defining a uniform scale for the Mg/Fe ratio and in obtaining a reference sample for the calibration process of the abundances measured in our work.

The robust spectroscopic analysis was carried out adopting the MILES's spectra based on a LTE spectral synthesis of two Mg features. Two methods were applied through an automatic process: pseudo equivalent width and line profile fitting.

The typical error of [Mg/Fe] from the collected and calibrated high resolution measurements is 0.06 dex, and the uncertainties from our medium resolution analysis range from 0.08 to 0.15 dex, with a weighted average of 0.10 dex (see **Figure 2**).

The coverage of the stars with [Mg/Fe] over the new MILES's four dimensional parameter space is quite good, as shown in **Figure 3**. Specifically, we recovered at medium resolution the Mg abundances for sub-giants and red giants. Unfortunately, a critical point still remains on the extremely cool stars (T_{eff} < 3500 °K). However, we can revisit the bad cases of spectral syntheses to carefully examine the reasons of each of them (e.g. saturation effects, absence of molecular lines) trying to extend more the Mg/Fe coverage.

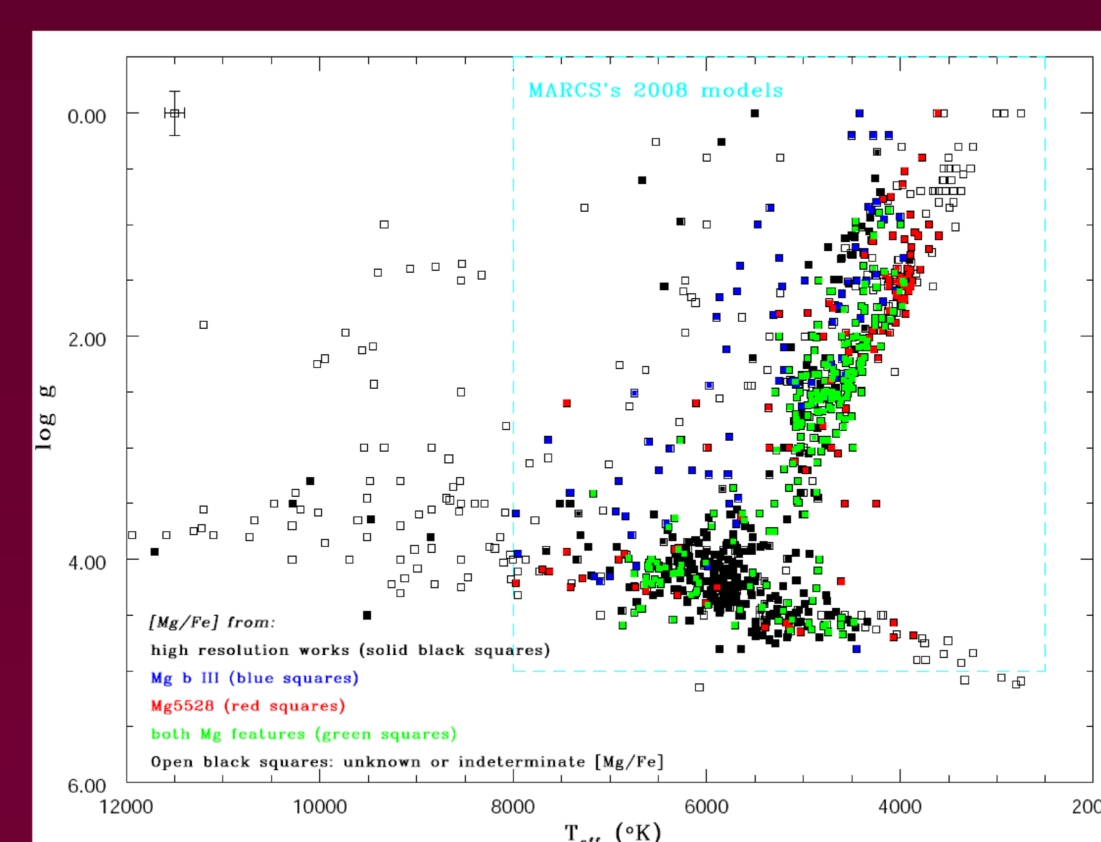

Fig. 3 – The [Mg/Fe] coverage in the new MILES's parameter space: modified HR diagram (*gravity-temperature projection*).

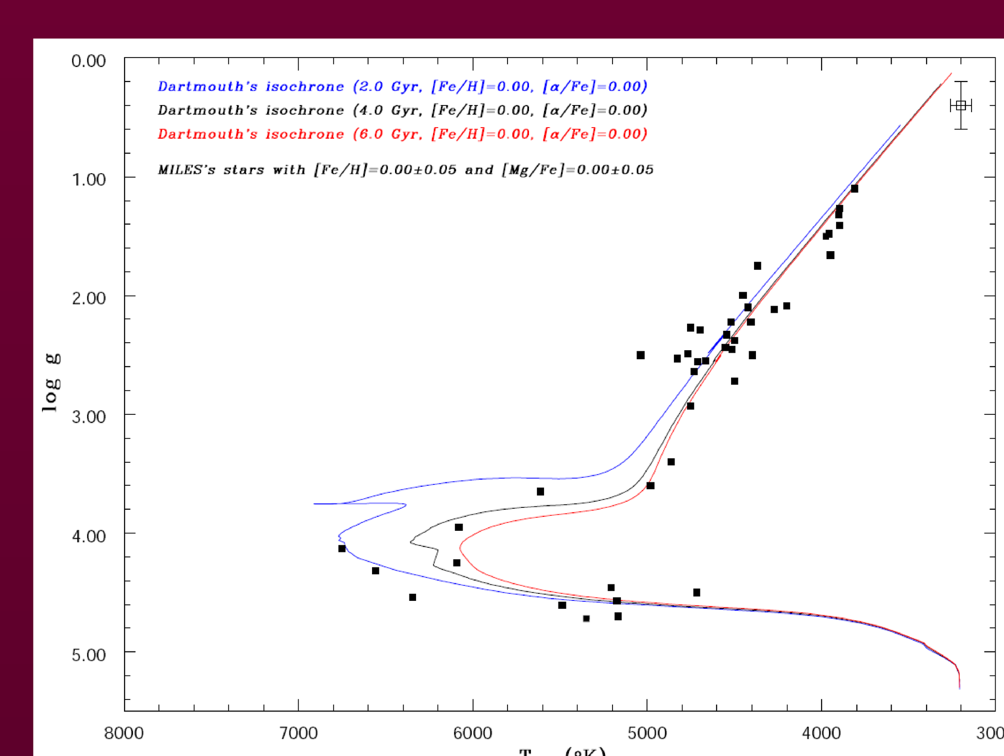

Fig. 4 – Spectacular example of an isochronal fit adopting MILES's stars for the solar chemical composition and around 4 Gyr.

Further applications

*From now on, we are able to semi-empirically compute with greater accuracy the observable properties of several SSPs (older than 1 Gyr), taking into account precise metallicity and Mg/Fe ratio of the stars that must be selected to represent them (see **Table 1**).*

Figure 4 shows a spectacular example of an isochronal fitting for MILES's stars with solar age and chemical composition that will be used to compute the representative SSP spectrum.

We have also started a study of the dependence of absorption line indices on Mg/Fe. Preliminary behaviour of the Lick Hβ as a function of the stellar parameters using pairs of similar dwarfs of [Mg/Fe] is shown in **Figure 5**. We intend to compute empirical fitting functions for the main Lick indices in order to actually improve and extend the SSP models for different alpha-enhancements, to be applied to recover the star formation histories of distinct systems (such as dwarf galaxies and globular clusters).

Moreover, we can test and apply the same approach of this work to obtaining the Calcium abundances for the MILES's stars. Indeed, we have interesting questions about the Calcium-enhancement in several composite stellar systems (e.g. early-type galaxies).

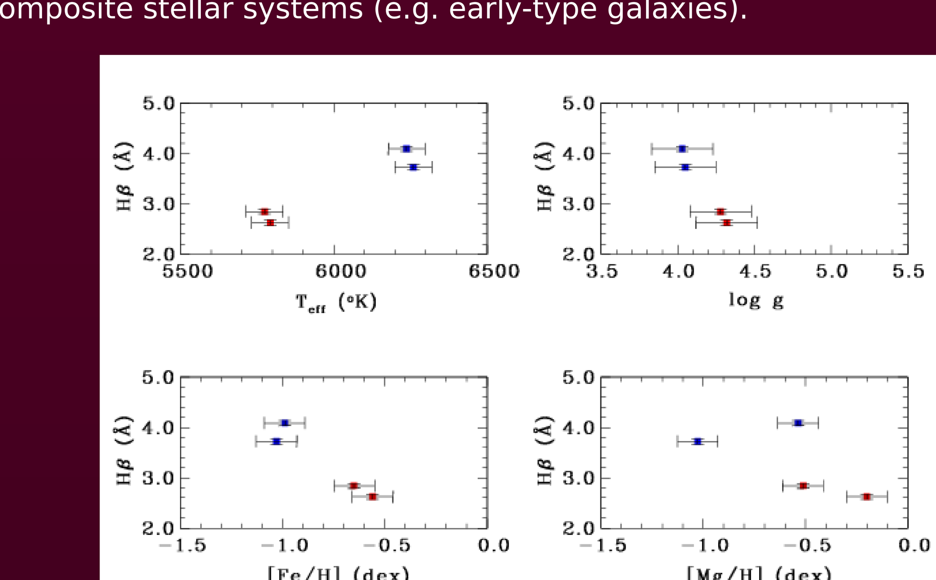

Fig. 5 – Lick Hβ index as a function of the photospherical parameters for two pairs of similar dwarf stars (represented by red and blue symbols) showing different behaviours.

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