AN EMPIRICAL SPECTRAL LIBRARY OF CHEMICALLY WELL CHARACTERIZED STARS FOR STELLAR POPULATION MODELLING

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Abstract

With the goal of assembling a new generation of more realistic simple stellar population models (single-aged, single-metallicity and single-specified abundance pattern), we have obtained magnesium abundances for nearly 80% of the stars in the MILES library, which is a standard reference empirical spectral data base. New and homogeneous spectroscopic observations of carefully selected stars are also in progress to improve the coverage over the parameter space of MILES.

Here we report on: (i) the framework of the Mg abundance determination carried out at mid-resolution, (ii) the parametric improvement of MILES by including new observations, and (iii) the initial planning for the SSP spectral modelling.

Motivation

Semi-empirical stellar population models usually consider only the overall fraction of metals in stars and, therefore, ignore the different chemical abundance patterns that are present in individual stars.

Distinct chemical evolutions have an important influence on the shape of integrated spectra of composite stellar systems. For example, spectral line strengths in dwarf and giant elliptical galaxies differ due to their different histories of star formation (Sansom & Northeast 2008).

A current limitation is that all models using an empirical stellar data base rely on stars from distinct components of our spiral galaxy, whose atmospheres are neither completely nor homogeneously characterized in terms of elemental abundances. Besides this, distinct components of the Galaxy show different abundance patterns. Typically, models only take into account the iron abundance, but stellar spectra may change considerably if the abundance ratios between iron and other metals depart from the unity in a relative scale to the Sun.

Accounting for well-known elemental abundances, including the alpha (O, Ne, **Mg**, Si, S, Ar, Ca and Ti) and iron peak elements (V, Cr, **Fe**, Co, Ni, Mn and Cu), will make an empirical stellar library particularly useful for modelling of spectral energy distribution (SED) emitted by evolving stellar populations. For instance, whilst **Mg** is produced via carbon burning in massive stars and ejected into the interstellar medium mainly through type II supernovae (like those alpha-elements), the **Fe** peak elements come basically from type Ia supernovae. Consequently, the Mg/Fe ratio will depend on the time scale of a star forming episode and, therefore, the greater the ratio **[Mg/Fe]**, the shorter the star burst is.

In this poster contribution, we present the procedures and preliminary results from our project for building a new set of semi-empirical simple stellar population (SSP) models based on the MILES data base. We have improved the chemical characterization of the stars in the library as well as we are also currently expanding it with additional homogeneous spectroscopic observations.

The MILES library

The **M**edium-resolution **I**saac Newton Telescope **L**ibrary of **E**mpirical **S**pectra (**MILES**) contains good-quality flux-calibrated optical spectra (λλ3525–7500 Å) for 985 stars with a uniform FWHM resolution of 2.5 Å (Sánchez-Blázquez *et al.* 2006, Falcón-Barroso *et al.* 2011).

The parametric coverage of sample stars in the 3-D Hertzsprung Russell diagram is quite wide: 2800 ≤ T_{eff} ≤ 50400 K, 0.0 ≤ log g ≤ 5.0, and –2.7 ≤ [Fe/H] ≤ +1.0 dex.

The photospheric parameter scales were carefully homogenized from data of several high-resolution spectroscopic analyses (Cenarro *et al.* 2007). The parameters are accurate enough for many purposes: σT_{eff} = 100 K, σ(log g) = 0.2, σ[Fe/H] = 0.1 dex.

MILES is regarded nowadays as the standard empirical stellar library in the field and represents a substantial improvement over previous works. MILES is available to the community through a user-friendly webpage (*http://miles.iac.es*).

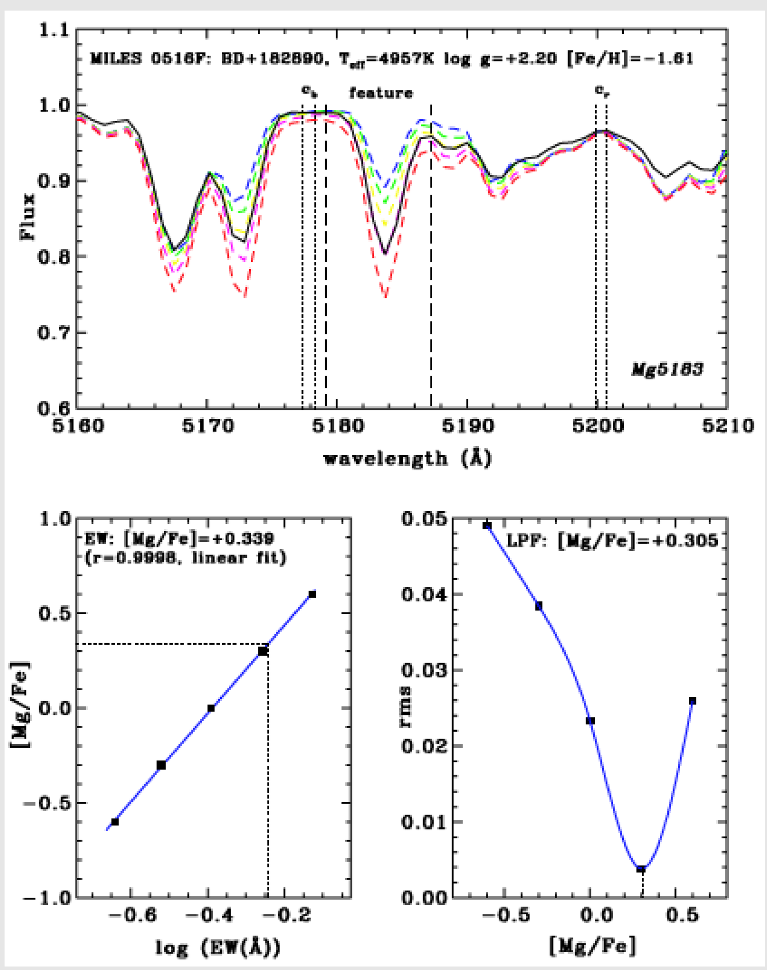

Fig. 1 – Example of spectral synthesis for the Mg5183 feature. The observed spectrum is represented by the solid black line and the theoretical ones by colourful dashed lines. [Mg/Fe] is obtained through two methods: EW and LPF (respectively illustrated in the bottom-left and bottom-right plots).

Acknowledgements

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A. Milone dedicates this work to his daddy whose decease completes thirty years this week.

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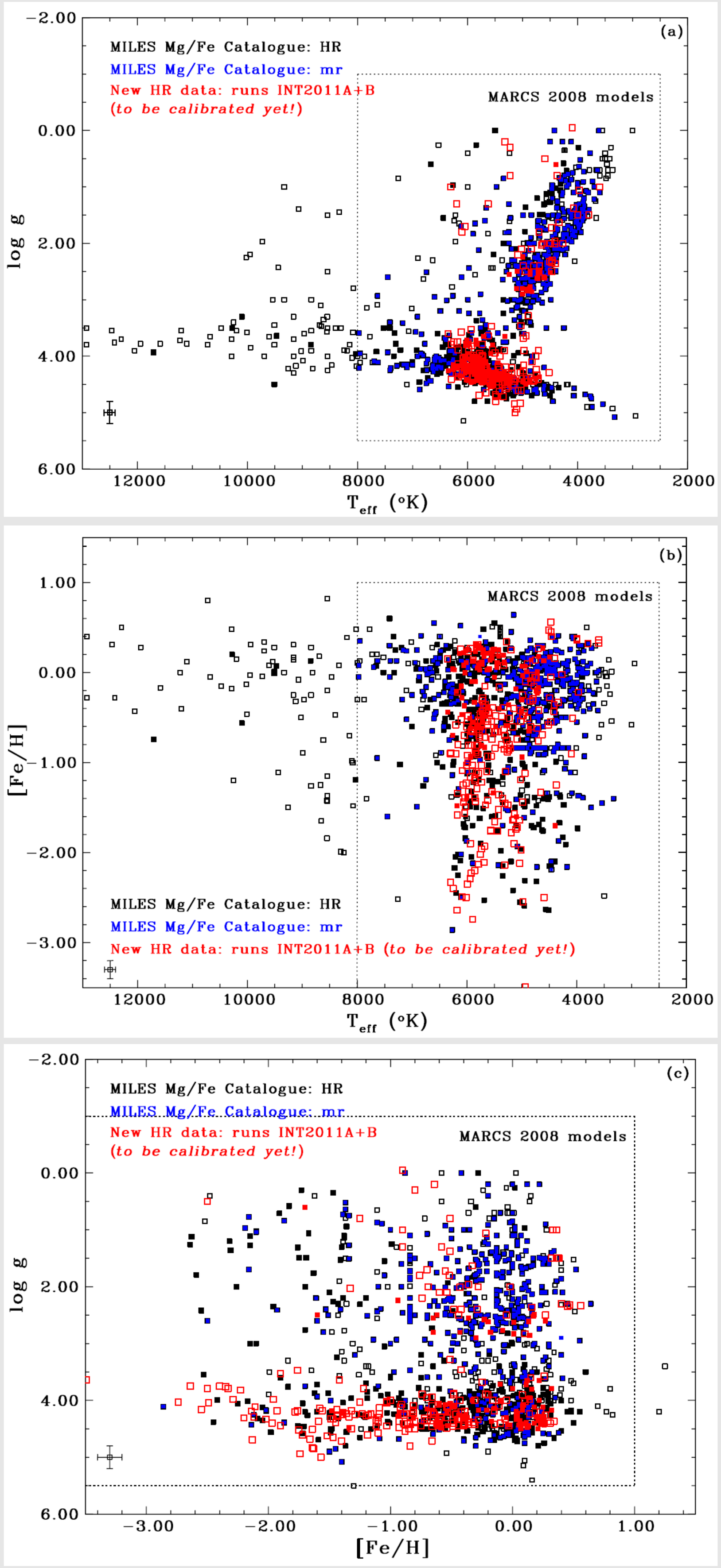

Fig. 2 – Distribution of MILES stars together with the new data from the INT2011A+B observing runs over the parameter space: **(a)** a modified projection of the H-R diagram, **(b)** [Fe/H] vs. T_{eff}, and **(c)** log g vs. [Fe/H]. The open black squares represent stars that have no [Mg/Fe] whilst the filled symbols show stars with measured ratios. The stars observed in INT2011A are designed as filled red squares and the stars that will be still observed as open red squares.

The MILES Mg/Fe catalogue

We collated magnesium and iron abundances from high-resolution (HR) studies in the literature, ensuring that the iron abundances were on the same scale as those originally assigned to MILES stars. Abundance ratios Mg/Fe were transformed onto the [Mg/Fe] scale having as a reference the wide catalogue of Borkova & Marsakov (2005, hereafter BM2005). A spectroscopic analysis at mid-resolution was also carried out to extend the Mg characterization of the library's stars by applying spectral synthesis with the MOOG LTE code (Sneden 2002) through an automatic process excluding poorly matched spectra (Milone, Sansom & Sánchez-Blázquez 2011).

We calibrated [Mg/Fe] to correct systematic differences and guarantee data homogeneity across multiple sources. For the abundance ratios compiled from HR analyses, we chose a subset of stars in common between each data source and BM2005. We used a more extended control sample to calibrate the mid-resolution measurements: 309 MILES stars (255 dwarfs, being 219 from BM2005, and 51 giants from HR studies).

We linearly interpolated model atmospheres over the MARCS 2008 grid (Gustafsson *et al.* 2008) and used accurate atomic transition data from VALD and Kurucz's compiled molecular data in order to compute synthetic spectra for each individual star ranging 5 different α/Fe ratios. The model atmospheres, with 56 plane-parallel layers each, suitably follow the general chemical pattern of our Galaxy for the α-elements: [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.

Two strong Mg features (the usually strongest line of the Mg b triplet λ5183.60Å, and MgIλ5528.40Å) were analysed through two abundance determination methods: equivalent width (EW), and the line profile fitting (LPF); both applied to the feature passband by using two nearby pseudo-continuum windows (see **Figure 1**).

We have obtained [Mg/Fe] for 752 stars (411 dwarfs and 341 giants) of MILES that are suitable for SSP modelling, i.e. the systematic uncertainty of [Mg/Fe] is 0.1 dex on average over the whole catalogue. The MILES Mg/Fe catalogue provides abundance ratios with their individual errors also showing the sources from where they have been obtained. The weighted average σ[Mg/Fe] is 0.09 dex for the HR values, and 0.12 dex for the mid-resolution (mr) measurements.

The catalogue measurements show fairly flat distributions across the photospheric parameter space covered by the MARCS models. The HR data are distributed along the main-sequence basically from T_{eff} about 4500 up to around 10000 K and on the giant branch mainly from 4000 up to 5500 K (see **Figure 2-a**). The mr measurements have a wide distribution over the H-R diagram. However, there are some deficiencies such as in the low main-sequence, the red giant branch tip and the hottest giants.

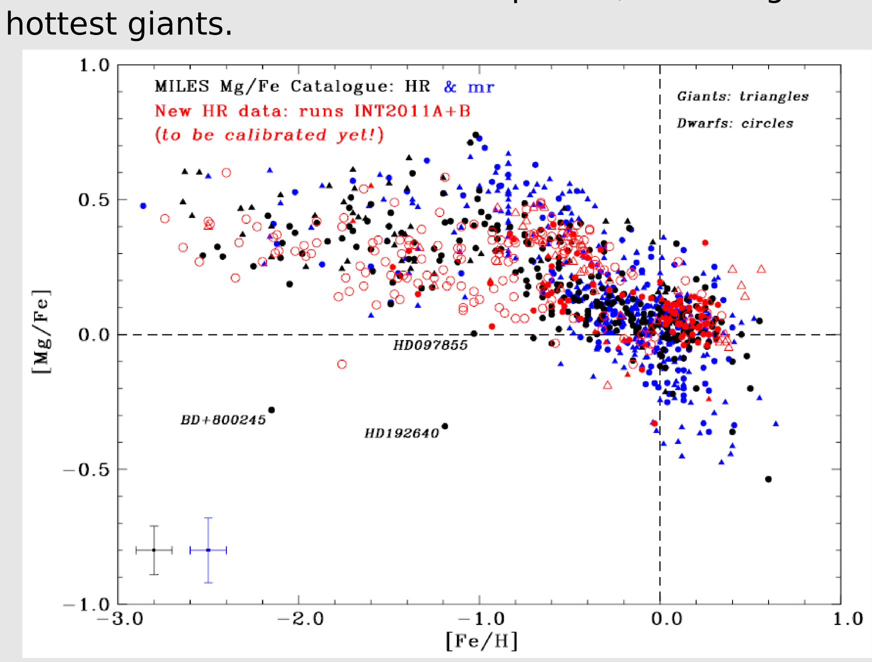

Fig. 3 – [Mg/Fe] as a function of [Fe/H] showing the stars of MILES Mg/Fe catalogue together with new sample of stars represented by red symbols (filled from the INT2011A run and open for INT2011B).

New data set for MILES

A new set of candidate stars has been compiled from the literature. Their photospheric parameters and Mg abundances were obtained from recent published HR analyses. The whole set contains around one thousand of stars spread over both sky hemispheres. The huge catalogue of stellar parameters PASTEL (Soubiran *et al.* 2010) has been adopted as a main reference to chose the stars. The objective is to carefully select stars in order to have their optical spectra observed and included into MILES to improve the sample distribution.

Optical spectra for 90 stars were collected along 5 nights of March by using the 2.5m Isaac Newton Telescope (INT) with the IDS spectrograph (Observatorio del Roque de Los Muchachos – ORM, Canary Islands, Spain), under the same MILES instrumental conditions.

Besides the March 2011 run (INT2011A), we have also been awarded with other 8 nights from 2 to 9 October 2011 at the ORM (INT2011B) to continue our observations. The idea is to take spectra for 207 more targets that have been categorized as priority classes 0 and 1 like those already observed objects. After excluding spectroscopic binaries, variables and repeated targets, we have got a sample of 445 stars that are observable from the INT/ORM (90 observed in INT2011A). The stars, which have been divided into five priority classes, will relatively fill in gaps over the parameter space as well as they will increase the object density in some other regions of it.

Figure 3 shows the MILES stars' distribution over the plane [Mg/Fe] vs. [Fe/H] in association with the new stellar sample to be incorporated into the library. **Figure 4** presents the same distribution over the projections [Mg/Fe]-T_{eff} and [Mg/Fe]-log g. It is clear that the coverage will be improved in many regions of the parameter space. The photospheric parameters and Mg abundances of the new stellar data set have yet to be calibrated to the MILES system.

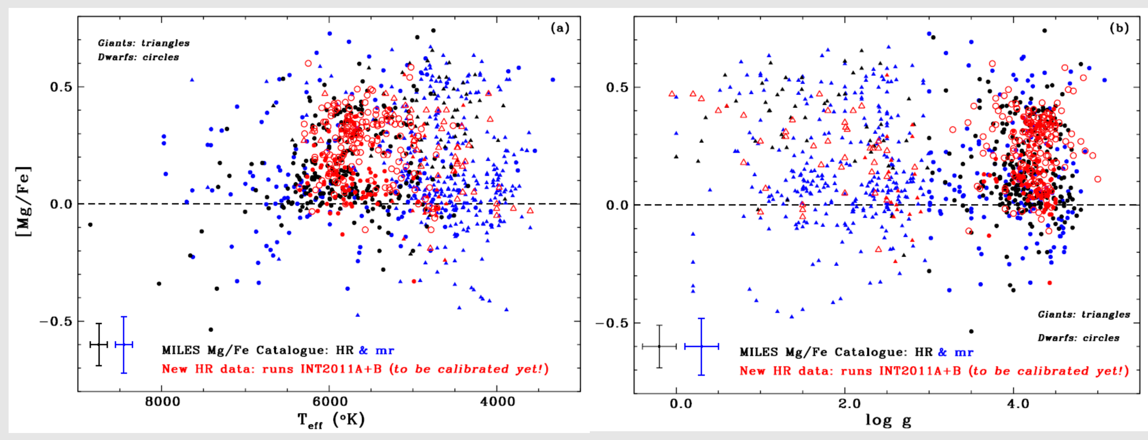

Fig. 4 – MILES stars with measured [Mg/Fe] distributed over two projections: **(a)** [Mg/Fe] vs. T_{eff}, and **(b)** [Mg/Fe] vs. log g. The new data set to be included into the library are also plotted (filled red symbols for the INT2011A run and open red symbols for INT2011B).

Planning the SSP modelling

With the current MILES library it has been possible to construct stellar population models from intermediate- to very-old-age regimes and the metallicity coverage from super-solar to [M/H] = -2.3 (Vazdekis *et al.* 2010). These base models combine scaled-solar isochrones with the abundance pattern of the Galaxy, being self-consistent for solar metallicity. The present work, and in particular, the expansion of the MILES library will allow us to build up SSP models with variable alpha-enhancement for a range in ages and metallicities, assuming magnesium as a proxy of the α-elements.

To construct α-enhanced SSP models, the MILES stars will have to be selectively collected in the 4-D parameter space to suitably follow state-of-the-art alpha-enhanced isochrones. To improve the cross-matching between isochrones and real stars, the [Mg/Fe] values will be taken into account within an interpolation scheme in the 4-D space. This will allow us to integrate stellar spectra along an isochrone, both with the same [Mg/Fe] abundance ratio, in a self-consistent approach.

Figure 5 presents an example of how a cross-matching of MILES stars with an isochrone (from Dotter *et al.* 2008) can be improved by adding the new data set from the INT2011A+B runs. We do hope that the SED and colour modelling of a few SSPs will be directly increased in quality by using the new stellar spectra (see **Table 1**).

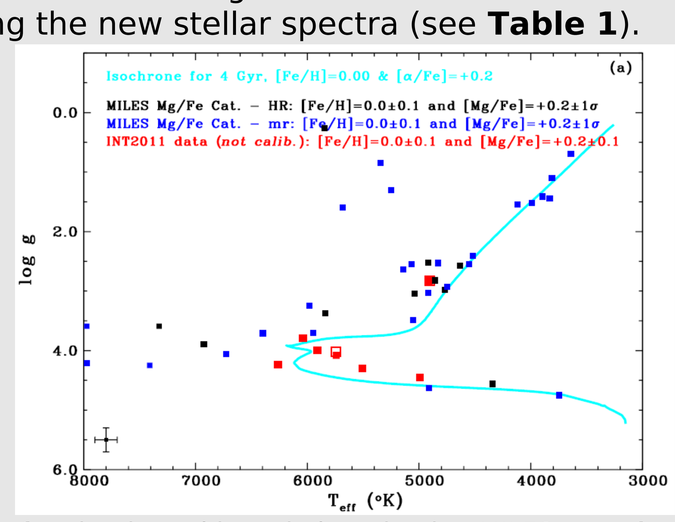

Fig. 5 – Example of an isochronal-based plot adopting MILES stars for 4 Gyr, [Fe/H] = 0.0 dex, and [α/Fe] = +0.2 dex (isochrone from Dotter *et al.* 2008). Filled red squares represent stars from the INT2011A run and open red symbols the stars from INT2011B.

Age (Gyr)	[Fe/H] (dex)	[α/Fe] (dex)
2	+0.2	0.0, +0.2
4	0.0	0.0, +0.2
6	-0.4	+0.2, +0.4
8	-0.6	+0.2, +0.4
10	-0.6	+0.2, +0.4
14	-1.4	+0.2, +0.4
14	-1.2	+0.2, +0.4

Tab. 1 – Set of age and [Fe/H], for which SSP models assuming variable alpha-enhancement can be empirically improved by adding the new stellar data.

Conclusions and perspectives

We have obtained [Mg/Fe] abundance ratios with a precision of ~0.1 dex for about 80% of the MILES stars (*accurate enough for SSP modelling*), either collated from high-resolution studies in the literature or derived from the analysis of the mid-resolution MILES spectra. They are placed on a uniform scale, and are available on demand or accessible from MNRAS.

The coverage of MILES stars with [Mg/Fe] over the 4-D parameter space of the library (T_{eff}, log g, [Fe/H], [Mg/Fe]) is currently being improved by observing spectra for hundreds of stars with known parameters using the same instrumental configuration employed for the original MILES. The intention is to fill in some gaps and increase the density in other regions of the parameter space.

By adopting the extended MILES library, we will be able to compute a set of self-consistent semi-empirical SSP models with variable alpha-enhancement for old ages and metallicities around solar. These SSP models represent a benchmark for the models that take into account such non-solar abundance ratios with the aid of theoretical atmospheres, becoming possible to evaluate the effects of their limitations (e.g. incomplete data on atomic and molecule line lists).