# README: A Grid of Semi-Empirical MILES SSP Spectra With Variable [$\alpha$/Fe] abundances

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## 1 Introduction

These data are for a new grid of semi-empirical, single-age, single-metallicity stellar population (SSP) model spectra at five different [$\alpha$/Fe] values, generated by A.T. Knowles in work for his Ph.D thesis (Knowles 2019) and for the publication of Knowles et al. [2023]

The details of stellar population computation are presented in Knowles et al. [2023]. Using families of semi-empirical MILES (sMILES) stars presented in Knowles et al. [2021] and the empirical MILES stellar library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011), SSPs are computed for a large range of age, overall metallicity ([M/H]$_{\mathrm{SSP}}$ [1]) and [$\alpha$/Fe] abundance patterns. SSPs are calculated for the same range of [$\alpha$/Fe] as the sMILES stars, from $-0.2$ to $+0.6$ dex in steps of 0.2 dex. The range and sampling of [$\alpha$/Fe] abundance represents an improvement over previously calculated models (e.g. Thomas et al. [2005], Conroy and van Dokkum [2012], Vazdekis et al. [2015]). We summarise the main components of the models in Section 2. The parameter coverage of sMILES SSPs is given in Table 1 and visualised in Figure 1.

Table 1: Age, metallicity, [$\alpha$/Fe] ranges and IMF variations available for the sMILES SSP models. Note here the solar metallicity model is given as [M/H]$_{\mathrm{SSP}}$=0.06.

| Age (Gyr) | [M/H]$_{\mathrm{SSP}}$ | [$\alpha$/Fe] | IMF |
|---|---|---|---|
| 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00, 3.25, 3.50, 3.75, 4.00, 4.50, 5.00, 5.50, 6.00, 6.50, 7.00, 7.50, 8.00, 8.50, 9.00, 9.50, 10.0, 10.5, 11.0, 11.5, 12.0, 12.5, 13.0, 13.5, 14.0 | -1.79, -1.49, -1.26, -0.96, -0.66, -0.35, -0.25, 0.06, 0.15, 0.26 | -0.2 ([$\alpha$/Fe]=0.0 Isochrone) 0.0 ([$\alpha$/Fe]=0.0 Isochrone) 0.2 ([$\alpha$/Fe]=0.0 Isochrone) 0.4 ([$\alpha$/Fe]=0.4 Isochrone) 0.6 ([$\alpha$/Fe]=0.4 Isochrone) | Unimodal ($\Gamma = 0.3 - 3.5$), Bimodal ($\Gamma_{\mathrm{b}} = 0.3 - 3.5$), Universal Kroupa, Revised Kroupa, Chabrier |

[1]
$$[\mathrm{M/H}]_{\mathrm{SSP}} = \log_{10}(\mathrm{Z/X})_{*} - \log_{10}(\mathrm{Z/X})_{\odot}, \quad (1)$$
where Z and X are defined as mass fractions of metals and hydrogen, respectively.

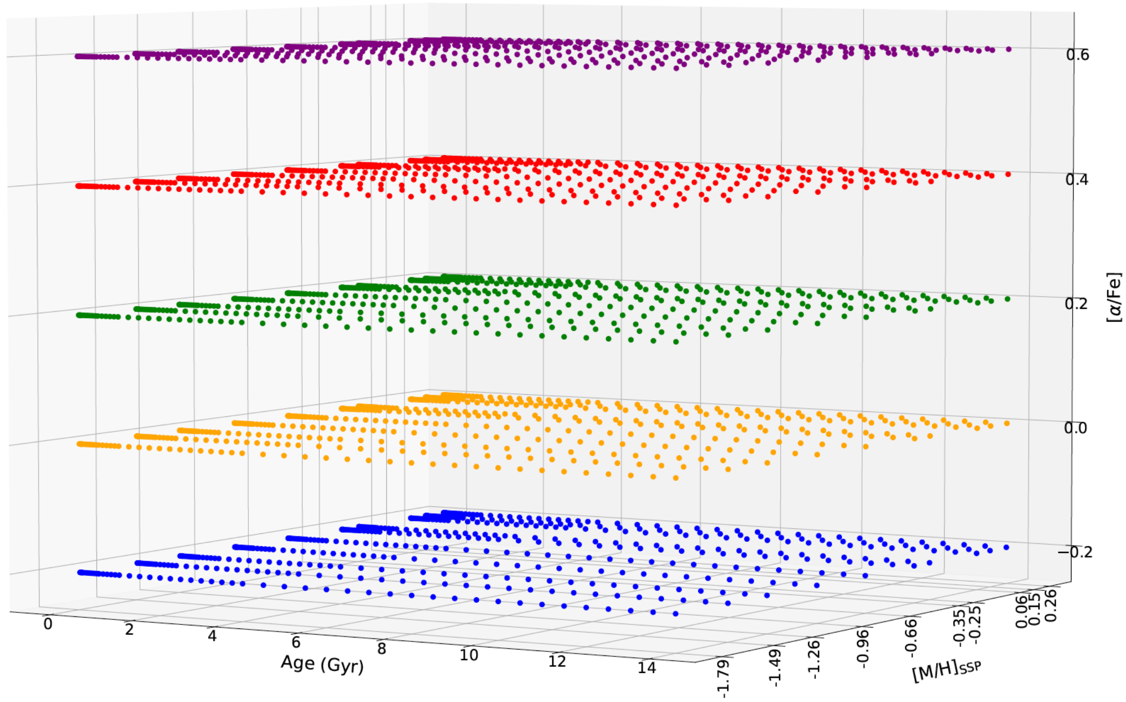


Figure 1: Illustration of age, metallicity ($[M/H]_{SSP}$) and $[\alpha/Fe]$ coverage and sampling of the sMILES SSP grid.

# 2 sMILES SSP Components

## 2.1 IMF

Models are computed for five Initial Mass Function (IMF) types. These include universal and revised Kroupa IMFs (Kroupa 2001) and the unimodal and bimodal IMFs described in Vazdekis et al. [1996] and appendix A of Vazdekis et al. [2003], parameterised by logarithmic slopes $\Gamma$ and $\Gamma_b$, respectively. We compute SSPs for thirteen values of $\Gamma$ and $\Gamma_b$, ranging from 0.3 to 3.5; the same range as those provided previously in Vazdekis et al. [2015][2]. The steps we provide for Unimodal and Bimodal IMFs are 0.3, 0.5, 0.8, 1.3, 1.5, 1.8, 2.0, 2.3, 2.5, 2.8, 3.0, 3.3 and 3.5. A bimodal IMF of $\Gamma_b$=1.3 is similar to the universal Kroupa IMF, whereas steeper slopes (e.g. $\Gamma_b$=3.0) better match the results of massive Early-Type Galaxies (e.g. La Barbera et al. 2016). We also provide SSPs described by a Chabrier [2003] IMF, with a massive star segment logarithmic slope of 1.3. Lower and upper mass cutoffs are set at 0.1 and 100 $M_\odot$, respectively.

## 2.2 Isochrones

We adopt two sets of theoretical isochrones. For SSPs with $[\alpha/Fe]=-0.20$, 0.0 and +0.20 we adopt the scaled-solar isochrones from Pietrinferni et al. [2004]. For SSPs with $[\alpha/Fe]$=+0.40 and +0.60 we use the $\alpha$-enhanced isochrones at $[\alpha/Fe]$=0.40 from Pietrinferni et al. [2006]. Both sets of isochrones, and therefore the resulting sMILES SSPs, are computed for 53 different ages in the range 0.03-14 Gyr (as listed in Table 1). Overall metallicities, defined on the Grevesse and Noels [1993] solar abundance scale, were computed for 10 steps. On this scale, the steps in $[M/H]_{SSP}$ given in Table 1 correspond to absolute metallicity (Z) values of 0.0003, 0.0006, 0.0010, 0.0020, 0.0040, 0.0080, 0.0100, 0.0198, 0.0240 and 0.0300, respectively. The solar metallicity at birth is given as $Z_\odot$=0.0198, which is represented by $[M/H]_{SSP}$=0.06. The reason that the solar metallicity models are provided at $[M/H]_{SSP}$=0.06, as opposed to 0.0, is discussed in detail in Pietrinferni et al. [2004] (their section 5.1). In summary, this difference arises due to the omission of diffusion in the isochrones. Although diffusion processes are known to be present in the Sun, there is evidence suggesting they may be inhibited in other low-mass stars, as discussed in section 2 of Pietrinferni et al. 2004. Further information regarding the isochrones can be found at `http://basti-iac.oa-abruzzo.inaf.it/` and `http://albione.oa-teramo.inaf.it/`.

[2] `http://research.iac.es/proyecto/miles/pages/ssp-models.php`

## 2.3 Stellar Libraries

Both sMILES and empirical MILES libraries are used in the SSP calculations. The stellar parameters adopted ($T_{\rm eff}$, log g, [Fe/H] and [Mg/Fe]) were those of Cenarro et al. [2007] and Milone et al. [2011]. For stars missing [Mg/Fe] estimates, approximations ([Mg/Fe] values of 0.0, 0.2 or 0.4) were made from both Milone et al. [2011] (their figure 10) and a Milky Way pattern based on Bensby et al. [2014] (their figure 15). We use [Mg/Fe] as a proxy for overall [$\alpha$/Fe] in the MILES and resulting sMILES stars. Some MILES stars were removed from the sample, as they were found not to be representative of their tagged stellar parameters (see sections 2.2 of Vazdekis et al. 2010 and 2.3.1 of Vazdekis et al. 2015), resulting in a final sample of 925 stars.

The final sMILES library consists of families of 801 spectra for five [$\alpha$/Fe] abundances of −0.2, 0.0, +0.2, +0.4 and +0.6 dex. The 124 stars that could not be differentially corrected, due to their stellar parameters falling outside of the range of the theoretical stellar grid presented in Knowles et al. [2021] (mainly at $T_{\rm eff}$ >10000K or $T_{\rm eff}$ <3500K), were used only empirically in each family of stars and corresponding SSP calculation. This allows for young and old stellar populations to be modelled with sMILES SSPs.

The underlying theoretical and the semi-empirical stellar libraries presented in Knowles et al. [2021] are publicly available on the UCLanData repository (`https://uclandata.uclan.ac.uk/178/`) and MILES website (`http://research.iac.es/proyecto/miles/pages/other-predictionsdata.php`), respectively.

sMILES SSPs are calculated at MILES resolution (FWHM=2.5 Å) and wavelength coverage (3540.5 − 7409.6 Å). Example sequences of models in age and metallicity are shown in the top and middle panels of Figure 2, respectively. The bottom panel of Figure 2 shows spectral ratios of different [$\alpha$/Fe] SSP models relative to the [$\alpha$/Fe]=0.0 case.

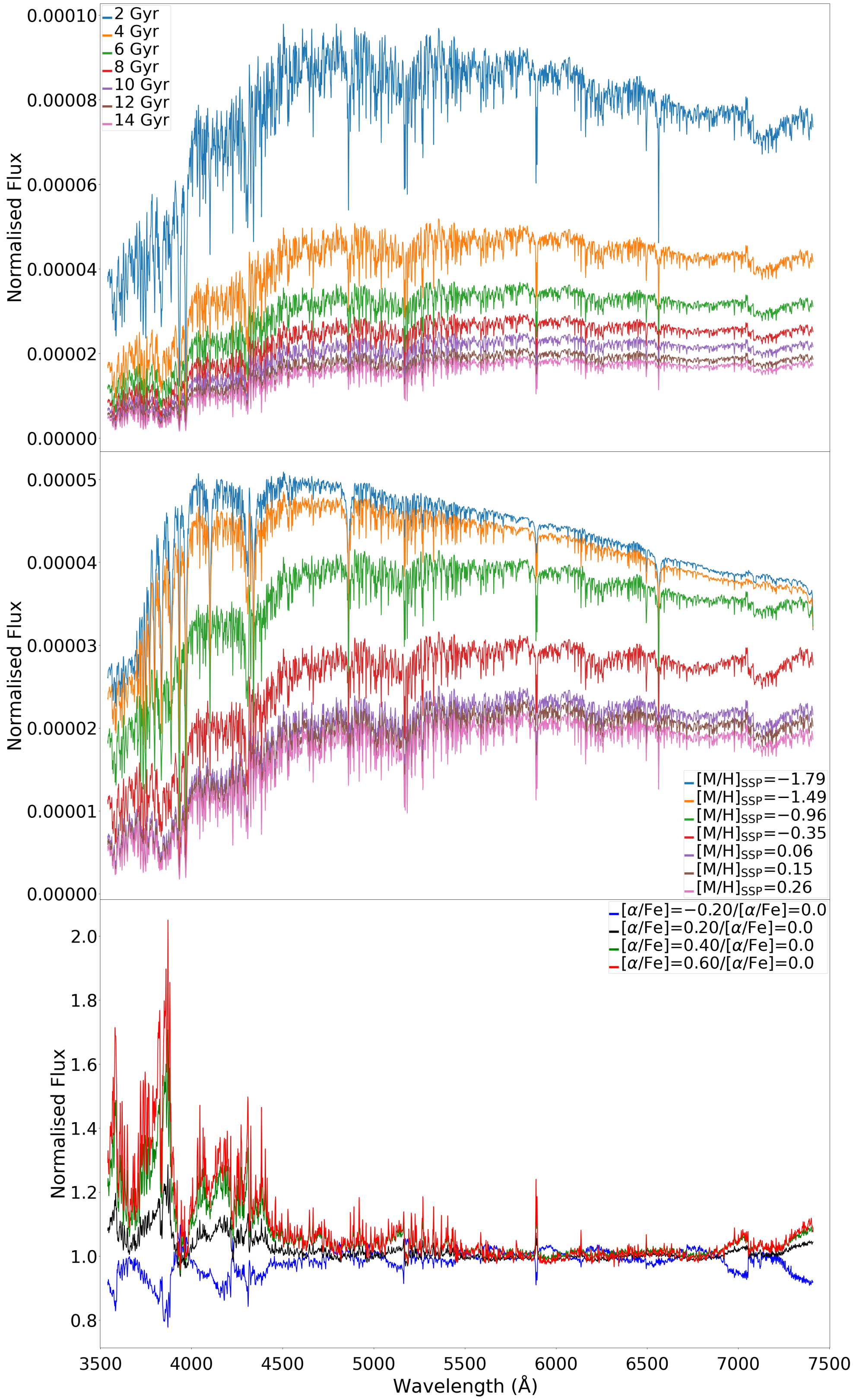


Figure 2: Top panel: sMILES SSP sequence of age for fixed metallicity, [$\alpha$/Fe] ([M/H]$_{\rm SSP}$=0.06, [$\alpha$/Fe]=0.0) and Universal Kroupa IMF in the full MILES wavelength range. Middle panel: sMILES SSP sequence of metallicity for a fixed age, [$\alpha$/Fe] (10 Gyr, [$\alpha$/Fe]=0.0) and universal Kroupa IMF. Bottom panel: sMILES SSP spectral ratios of different [$\alpha$/Fe] models relative to the scaled-solar case, for fixed age, metallicity (10 Gyr, [M/H]$_{\rm SSP}$=0.06) and universal Kroupa IMF populations.

## 3 Data

An SSP can be represented as a probability distribution described by a mean and variance (Cerviño and Luridiana 2006; Vazdekis et al. 2020). For this work, the products we make publicly available are the mean spectra of the stellar population.

The data files here are presented as FITS (Flexible Image Transport System) files, with SSPs first separated into directories indicating the adopted IMF used in the calculation and then into directories identifying the [$\alpha$/Fe] value of the population.

In the top level of the master sMILES_SSP.tar.gz file, the IMF directories are labelled as follows:

- **Bimodal_**$x$ - Bimodal IMF with $\Gamma_b = x$
- **Unimodal_**$x$ - Unimodal IMF with $\Gamma = x$
- **Universal_Kroupa** - Universal Kroupa IMF
- **Revised_Kroupa** - Revised Kroupa IMF
- **Chabrier_1.3** - Chabrier IMF with a massive star segment logarithmic slope of 1.3

Within each IMF directory, the SSPs are separated according to their [$\alpha$/Fe] values:

- **aFem02** - [$\alpha$/Fe]=$-0.2$
- **aFep00** - [$\alpha$/Fe]=0.0
- **aFep02** - [$\alpha$/Fe]=0.2
- **aFep04** - [$\alpha$/Fe]=0.4
- **aFep06** - [$\alpha$/Fe]=0.6

The SSP models within the [$\alpha$/Fe] directories are labelled according to their adopted IMF, metallicity ([M/H]$_{\mathrm{SSP}}$), age, [$\alpha$/Fe] value of the adopted isochrone, the [C/Fe] ([C/Fe]=0.0 for this version of the sMILES SSP grid) and lastly the [$\alpha$/Fe] of the resulting stellar population. We show some examples below.

**sMILES_SSPs/Unimodal/Unimodal_1.3/aFem02/Mun1.30Zp0.06T10.0000_iTp0.00_ACFep00_aFem02.fits** - SSP with a Unimodal IMF of $\Gamma = 1.3$, a metallicity [M/H]$_{\mathrm{SSP}}$=0.06 (solar metallicity), an age of 10 Gyr, with an isochrone [$\alpha$/Fe]=0.0 and a resulting stellar population [$\alpha$/Fe] value of $-0.2$. Note also that the **_ACFep00** in the file name indicates that the stellar population has a [C/Fe] ratio of 0.0.

**sMILES_SSPs/Bimodal/Bimodal_3.0/aFep00/Mbi3.0Zp0.26T05.0000_iTp0.00_ACFep00_aFep00.fits** - SSP with a Bimodal IMF of $\Gamma_b = 3.0$, a metallicity [M/H]$_{\mathrm{SSP}}$=0.26, an age of 5 Gyr, with an isochrone [$\alpha$/Fe]=0.0 and a resulting stellar population [$\alpha$/Fe] value of 0.0.

**sMILES_SSPs/Universal_Kroupa/aFep02/Mku1.30Zm1.79T01.5000_iTp0.00_ACFep00_aFep02.fits** - SSP with a Universal Kroupa IMF, a metallicity [M/H]$_{\mathrm{SSP}}$=$-1.79$, an age of 1.5 Gyr, with an isochrone [$\alpha$/Fe]=0.0 and a resulting stellar population [$\alpha$/Fe] value of 0.2.

**sMILES_SSPs/Revised_Kroupa/aFep06/Mkb1.30Zm0.96T00.0300_iTp0.40_ACFep00_aFep06.fits** - SSP with a Revised Kroupa IMF, a metallicity [M/H]$_{\mathrm{SSP}}$=$-0.96$, an age of 0.03 Gyr, with an isochrone [$\alpha$/Fe]=0.4 and a resulting stellar population [$\alpha$/Fe] value of 0.6.

**NOTE**: The full library, including this file and all the IMF directories, are deposited on the MILES website at: `http://research.iac.es/proyecto/miles/pages/other-predictionsdata.php`.

Here on UCLanData, the Universal Kroupa IMF directory is deposited to allow easier access to one of our sMILES SSP grids.

Any queries can be directed to Adam T. Knowles (adamtknowles@gmail.com).

## 4 Use of these files

Whilst these semi-empirical SSP spectra are made publicly available for anyone to download and use, this is at the users own risk. The author does not guarantee that they are free from errors. If you make use of these data please acknowledge Knowles et al. [2023]. For comparisons with other available SSP models and real galaxy data see Knowles et al. [2023], Knowles [2019] and Knowles et al. [2021].

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