SPS-VARIMF User Manual

---

1. Introduction

The **Stellar Population Synthesis for Varying Initial Mass Function (SPS-VARIMF)** model is designed to compute the spectral and photometric evolution of stellar populations across a broad parameter space. This model is explicitly developed to investigate the impact of a non-universal Initial Mass Function **(IMF)** on key galactic properties, including integrated luminosities, stellar masses, and the fractional contributions of stellar remnants. By incorporating IMF variations, SPS-VARIMF provides a more comprehensive framework for studying the evolutionary pathways of galaxies and their observable characteristics.

The model specifically focuses on galaxies in which the IMF evolves as a function of star formation history (SFH) and metallicity, offering a more realistic representation of stellar population synthesis. It produces outputs that include high-resolution spectra and magnitudes in multiple photometric bands, enabling detailed comparisons with observational data.

IMF Variation in SPS-VARIMF

In SPS-VARIMF, the **galaxy-wide IMF (gwIMF)** is allowed to vary at each time step based on the galaxy's star formation rate (SFR) and the gas-phase metallicity at that epoch. The code includes both an **invariant IMF** and the **Integrated Galaxy-wide IMF (IGIMF)** framework, but it can also accommodate any other variable IMF prescription through private communication. This flexibility makes **SPS-VARIMF** a powerful tool for exploring the consequences of IMF variability in different astrophysical contexts.

Metallicity Evolution

The model simulates metal enrichment processes under the assumption of a closed-box system, meaning no gas inflow or outflow is considered. The metallicity evolution is inherently dependent on the adopted **star formation efficiency (SFE)**, which governs the rate of metal production and retention. However, users have the flexibility to assume a constant metallicity if desired, allowing for controlled comparisons and alternative modeling approaches.

Dust Attenuation

An optional dust attenuation component is included in the model, implemented using a **power-law formalism** to account for the wavelength-dependent absorption and scattering of light by interstellar dust. This feature allows users to incorporate the effects of dust on spectral energy distributions (SEDs) and photometric properties, providing a more realistic comparison with observed galaxy spectra.

---

2. Setting Up the Model

Before compiling, ensure that the SPS-VARIMF directory is located in the same parent directory as the following required folders:

- **OUTPUTS**
- **SPECTRA**
- **ISOCHRONS**
- **FILTERS**
- **YIELDS**

2.1 Compiling the Code

The code includes a **Makefile** to facilitate compilation. Before proceeding, ensure that your system has a Fortran compiler installed (e.g., gfortran). You may need to modify the Makefile to specify the correct Fortran compiler for your system

1. **Clean any previous builds** :

   make clean

2. **Compile the program**:

   make

   This will generate an executable file named **main.exe** in the SPS-VARIMF directory.

3. **Running the executable:**

   ./main.exe

2.2 Directory Structure

The program relies on a specific directory layout for its input files:

```
├── ISOCHRONES/
│   ├── Padova/
│   └── PARSEC/
├── SPECTRA/
│   ├── BaSeL3.1/
│   ├── AGB_spectra/
│   ├── post_AGB_spectra/
│   ├── WMBASIC/
│   └── WR_spectra/
│
├── FILTERS/
│
└── YIELD/
```

2.3 Adjust parameters :

To properly configure the SPS-VARIMF model, key simulation parameters must first be defined and initialized in params.f90.

Inorder to adjust optional cases

Dust attenuation (dust_atten):

= 0 : Disabled

= 1 : Enabled (power-law attenuation)

Remnant mass calculation (remnant_cal):

= 0 : Renzini et al. (1993) prescription

= 1 : Spera et al. (2015) prescription

Metallicity evolution mode (Z_MODE):

= 0 : Constant metallicity

= 1 : Metallicity computed at each step from gas enrichment

OB stars count calculation (OB_stars):

= 0 : Do not compute the number of OB stars

= 1 : Compute the number of OB stars

Model Configuration Parameters

Modify the simulation parameters in the **main.f90** program to setup the model. The key parameters include:

Initial Mass Function (IMF) (`imf_type`)

Specifies the type of IMF used in the simulation:

- `2` → **Canonical IMF (Kroupa 2001) –** A standard IMF with fixed power-law slopes.
- `3` → **Integrated Galactic IMF (IGIMF) –** An SFR- and metallicity-dependent IMF.
- `5` → **Top-Heavy IMF –** A flatter IMF favoring high-mass star formation.

Isochrones (`isoc_type`)

Determines the stellar evolution tracks used:

- `1` → **Padova (2007)**
- `2` → **PARSEC (2022)**

Spectral Library (`spec_type`)

Specifies the spectral database used for stellar populations:

- `1` → **BaSeL spectral library** (default)
- `2` → **Miles spectral library** *(in progress, not yet available)*

Star Formation History (SFH) (`sfh_type`)

Defines how the galaxy forms stars over time:

- `0` → **Single Stellar Population (SSP) –** All stars form in a single burst.
- `1` → **Constant Star Formation Rate (SFR) –** Stars form at a steady rate over time.
- `2` → **Exponentially Declining SFR –** Star formation rate decreases exponentially.
- `4` → **Delayed-Tau SFH –** A rising SFR phase followed by exponential decline.

Additional SFH Parameters:

- **e-folding timescale (`tau`)** (for `sfh_type = 2` and `4`):
  - Range: `0.001 – 1000.0` Gyr
- **Star formation start and truncation time (`Tstart`, `Ttrunc`)**:
  - Default: `Tstart = 0.0`, `Ttrunc = 0.0`
  - Defined in **Gyr**, based on the age of the universe.

Metallicity (`zmet_ini`)

Specifies the initial metallicity index:

- Choose a value from **1–22**, corresponding to metallicity values in **Table 1**.
- (`Z_MODE=0`) **Constant metallicity** throughout the simulation (`zmet = zmet_ini`).
- (`Z_MODE=1`) **Self-enrichment**: Metallicity evolves over time due to stellar feedback.

Galaxy Mass (`M_galaxy` or `M_UCD`):

Defines the total stellar mass formed over time:

- `M_galaxy` → Total stellar mass of a galaxy (in solar masses).

- `M_UCD` → Monolithic formation of **ultra-compact dwarf galaxies (UCDs)**, following a top-heavy IMF.

Star Formation Efficiency (f_star):
Determines how efficiently gas converts into stars:

f_star=M_galaxy/M_gas

- Valid range: **`0 < f_star < 1`**

---

3. Initial Mass Function (IMF) and galaxy-wide IMF (gwIMF)

3.1 The Initial Mass Function (IMF)

The **Initial Mass Function (IMF)** describes the mass distribution of stars formed in a single star formation event within a region approximately **1 parsec** in size. As a fundamental property of stellar populations, the IMF determines the relative abundance of stars of different masses, directly influencing the rate of supernova explosions and subsequent stellar feedback, chemical enrichment processes, and the overall luminosity of stellar populations and unresolved objects.

As a result, the IMF plays a central role in many astrophysical fields, including galaxy evolution, stellar dynamics, and cosmology. For simple stellar populations (SSPs), the IMF can be chosen to be either an invariant canonical IMF or a metallicity- and density-dependent top-heavy IMF. The canonical IMF represents a universal, fixed mass distribution, while the top-heavy IMF accounts for environmental dependencies, leading to an increased fraction of high-mass stars in metal-poor and high-density regions.

This flexibility allows the model to be applied to **monotonically forming stellar populations**, such as star clusters, where all stars are assumed to form in a single burst. Additionally, a **top-heavy** IMF may be appropriate for specific objects such as ultra-compact dwarf galaxies (UCDs), where observational and theoretical studies suggest that variations in the IMF may influence their mass-to-light ratios and stellar populations.

3.2 Galaxy-Wide Initial Mass Function (gwIMF)

The **Galaxy-Wide Initial Mass Function (gwIMF)** is the integrated IMF across an entire galaxy, rather than an IMF specific to an individual star-forming region. It defines the total stellar mass distribution, the formation rates of massive stars, supernova occurrence, and the photometric and chemical properties of galaxies.

In its simplest form, the gwIMF is often assumed to be universal, meaning it follows a single, invariant functional form across all galaxies, regardless of their star formation history (SFH) or metallicity. This assumption has been widely used in stellar population synthesis models and cosmological simulations. However, observational and theoretical evidence suggests that the IMF may vary systematically with environmental conditions such as **star formation rate (SFR)** and **gas-phase metallicity**.

One of the most well-established non-universal IMF frameworks is the **Integrated Galaxy-wide Initial Mass Function (IGIMF) theory (** Weidner et al. 2013; Kroupa et al. 2013; Yerabkova et al. 2018, Zonoozi et al. 2018, Yan et al. 2021, Zonoozi et al. 2025). In this approach, it is assumed that all stars form in embedded clusters (Kroupa & Weidner 2003; Dinnbier et al. 2022)**,** making the gwIMF an integral over all embedded clusters formed at a given time.

In this model, the IMF in individual star clusters depends on local conditions such as SFR and metallicity, leading to a systematically varying gwIMF across different galaxies. This variation impacts mass-to-light ratios, supernova feedback, and chemical enrichment, making the IGIMF approach more realistic for modeling galaxy evolution. This self-regulated star formation process, as implemented in SPS-VARIMF, ensures that the gwIMF is dynamically responsive to galactic conditions, providing a more realistic representation of stellar populations in galaxies.

3.3 The gwIMF in SPS-VARIMF

The SPS-VARIMF model allows users to explore both **universal** and **non-universal** (IGIMF-based or other variable IMF formulations) to investigate their impact on galactic properties. This implementation allows for a more realistic representation of stellar populations, significantly impacting predictions of stellar feedback, supernova rates, metal enrichment, and photometric evolution in galaxies.

The program supports:

- **Canonical IMF**: A Kroupa-like IMF with fixed slopes (alpha1 for low-mass stars, alpha2 for high-mass stars).
- **IGIMF**: An IMF that varies with SFR and metallicity.
- **Top-Heavy IMF**: A flatter IMF for extreme environments.

Subroutines such as IMF_NORM, IGIMF_NORM, and IMF_TOPHEAVY handle IMF normalization and computation of stellar remnants.

The GWIMF code[1] is used to compute the galaxy-wide initial stellar mass functions based on IGIMF theory for different adopted star formation rate or metallicity.

Implications of IGIMF:

- **Low SFR galaxies** have steeper gwIMFs (i.e., they form fewer high-mass stars), leading to reduced supernova rates and weaker chemical enrichment.
- **High SFR galaxies** have a flatter gwIMF, allowing for enhanced formation of massive stars and higher chemical enrichment rates.
- The IGIMF naturally explains observed trends in galaxy evolution, such as the **mass-metallicity relation** and variations in the Hα-to-UV ratio in star-forming galaxies.

This framework is implemented in the SPS-VARIMF model, allowing users to explore how IMF variations affect galaxy properties, such as stellar populations, chemical evolution, and feedback processes and how underlying IMF influence key galactic observables and compare them to empirical data.

1 https://github.com/ahzonoozi/GWIMF

4. Stellar Evolution Tracks and Isochrones

We provide an option to use **isochrones** based on **Padova** or **PARSEC** models[2]. These theoretical models describe stellar evolution in terms of luminosity, temperature, and internal structure, making them essential for stellar population studies, galactic evolution research, and star clusters.

Covering a wide range of stellar masses (0.1 $M_\odot$ to 350 $M_\odot$) and metallicities, they enable simulations of stellar populations across different galactic environments, from metal-poor early-universe stars to younger, metal-rich clusters. These models incorporate updated physics, including mass loss, convection, and opacity adjustments, ensuring high accuracy for astrophysical applications.

This code allows users to include isochrones from **Padova** or **PARSEC** models. These isochrones are computed for ages ranging from about 1 Myr to 14 Gyr and across various metallicities from Z=0.0001 ([Fe/H]=-2.2) up to Z=0.06 ([Fe/H]=+0.5). The corresponding metallicity indices are listed in Table 1, facilitating the modeling of stellar populations in different galactic environments.

5. Spectral Libraries

The program uses the **BaSeL** spectral library as a **primary source** for general stellar spectra. However, for **special types of stars**, spectral data are obtained from specific references.

1. **BaSeL:** General stellar spectra.
2. **TP-AGB (Lancon & Mouhcine 2002):** Spectra for O-rich and C-rich Asymptotic Giant Branch (AGB) stars.
3. **Post-AGB (Rauch 2003):** NLTE spectral models for post-AGB stars.
4. **Wolf-Rayet Stars (Smith et al. 2002):** Spectra for Wolf-Rayet (WR) stars.
5. **OB stars (Eldridge et al. 2017):** High-resolution spectral models for OB stars.

Subroutines such as SPEC_AGB.f90, SPEC_PAGB.f90, and SPEC_WR.f90 process and interpolate these libraries onto the wavelength grid.

6. Star Formation History (SFH)

The SFH defines how the galaxy forms stars over time. Supported types include:

- **Constant SFR**: Star formation proceeds at a constant rate.
- **Exponential Decline**: SFR declines exponentially with time.
- **Delay-Tau Model**: A combination of a rising phase followed by exponential decay.

The SFH subroutine (sfh_gal.f90) calculates the mass fraction and star formation rate over specified time intervals.

2 http://stev.oapd.inaf.it/cgi-bin/cmd

7. Metallicity Evolution

The current implementation uses a **closed-box model** for metallicity enrichment, where all gas remains within the galaxy. The enrichment process is driven by stellar yields, read from the YIELD/ folder. Future updates will incorporate **gas inflow models**.

8. Filters and Photometry

The model computes magnitudes in 143 photometric bands, whose filter profiles are stored in the FILTERS/ folder and the filter order displayed in the FILTER_LIST.dat file. The Filtr.f90 subroutine reads and interpolates these profiles for photometric calculations. Magnitudes are computed in the AB system and utput spectra are provided in units of solar luminosity per hertz ($L_\odot$/Hz).

---

9. Future Enhancements

- **Gas Inflow**: Current metallicity evolution is limited to a closed-box model, meaning no gas inflow or outflow occurs.. Gas inflow will be added to account for external enrichment.
- **Additional SFHs**: Support for more complex SFHs, including bursty star formation.

---

10. Acknowledgments

This program is built upon extensive research in stellar population synthesis and uses publicly available codes and libraries, including Padova, PARSEC, BaSeL, GALAXEV (Bruzual & Charlot), FSPS (Flexible Stellar Population Synthesis), and others. We acknowledge the invaluable contributions of the researchers and developers who have made these resources available to the scientific community.

SPS-VARIMF was developed by **Akram Hasani Zonoozi** at the *Institute for Advanced Studies in Basic Sciences (IASBS)*. For any publications or research that utilize **SPS-VARIMF** , please cite the following reference:

Zonoozi, Haghi, and Kroupa et al. MNRAS, 2025 (https://doi.org/10.1093/mnras/staf091)

“Stellar population synthesis models with a physically varying IMF”

For comments, questions, bug reports, or feedback, please contact:

a.hasani@iasbs.ac.ir
e.h.zonoozi@gmail.com

Table1: Metallicity Index (`zmet_ini`)

Z_index	Z [log(Z/Z⊙)]
1	0.0002 (-1.98)
2	0.0003 (-1.80)
3	0.0004 (-1.68)
4	0.0005 (-1.58)
5	0.0006 (-1.50)
6	0.0008 (-1.38)
7	0.0010 (-1.28)
8	0.0012 (-1.20)
9	0.0016 (-1.07)
10	0.0020 (-0.98)
11	0.0025 (-0.89)
12	0.0031 (-0.79)
13	0.0039 (-0.69)
14	0.0049 (-0.59)
15	0.0061 (-0.49)
16	0.0077 (-0.39)
17	0.0096 (-0.30)
18	0.0120 (-0.20)
19	0.0150 (-0.10)
20	,0.0190 (+0.00)
21	0.0240 (+0.10)
22	0.0300 (+0.20)