⋆ ⋆

Pégase

⋆ ⋆

Projet d'**É**tude des **GA**laxies par **S**ynthèse **É**volutive

Version 2.0: September 23, 1999

Michel Fioc — Brigitte Rocca-Volmerange

Institut d'astrophysique de Paris
98 bis boulevard Arago, 75014 Paris, France

E-mail: `pegase@iap.fr`, `fioc@iap.fr`

WWW: `http://www.iap.fr/users/fioc/`

Anonymous ftp: `ftp.iap.fr`
in: `pub/from_users/fioc/PEGASE/PEGASE.2/`

Contents

1 Introduction

The purpose of PÉGASE is the study of galaxies by evolutionary synthesis. This version supersedes our previous model (Fioc & Rocca-Volmerange 1997; contributions in Leitherer *et al.* 1996). The main differences are the implementation of:

- stellar evolutionary tracks with non-solar metallicities;
- the library of stellar spectra of Lejeune *et al.* (1997, 1998);
- radiative transfer computations to model the extinction.

The extension to the far-infrared (Fioc & Dwek, in prep.) and a detailed modeling of the nebular emission (Moy, Rocca-Volmerange & Fioc, in prep.) are in progress. Synthetic spectra computed from standard star formation scenarios fitted on new statistical templates for nearby galaxies (Fioc & Rocca-Volmerange 1999; Fioc & Rocca-Volmerange, in prep.) will be proposed in a near future, as well as their colors, k- and e-corrections.

To be informed of the future developments of PÉGASE, to require specific computations, ask questions, or make comments or suggestions, mail us at `pegase@iap.fr`.

2 Contents of the directory

2.1 List of files

`README.tex`	`IMF_Scalo98.dat`	`stellibLCBcor.dat`
`README.ps`	`Spitzer.dat`	`SunLCB.dat`
`SSPs.f`	`WW.dat`	`VegaLCB.dat`
`calib.f`	`ages.dat`	`King.dat`
`colors.f`	`calib.dat`	`slab.dat`
`scenarios.f`	`dust.dat`	`tracksZ0.0001.dat`
`spectra.f`	`filters.dat`	`tracksZ0.0004.dat`
`IMF_Kennicutt.dat`	`list_IMFs.dat`	`tracksZ0.004.dat`
`IMF_Kroupa.dat`	`list_tracks.dat`	`tracksZ0.008.dat`
`IMF_MillerScalo.dat`	`HII.dat`	`tracksZ0.02.dat`
`IMF_Salpeter.dat`	`BD+17o4708.dat`	`tracksZ0.05.dat`
`IMF_Scalo86.dat`	`stellibCM.dat`	`tracksZ0.1.dat`

2.2 Codes

- `calib.f`: code computing the calibrations of the filters.
- `colors.f`: code computing colors and other quantities.
- `spectra.f`: code computing synthetic spectra of galaxies and other quantities.
- `SSPs.f`: code computing the properties of simple stellar populations (SSPs), i.e. populations of stars formed simultaneously with the same metallicity.
- `scenarios.f`: code used to prepare the input file (star formation scenarios) to `spectra`.

The codes are written in Fortran 77. Though available on most systems, some features are non-standard:

- use of lowercase letters and underscore;
- use of identifiers longer than 6 characters;
- `implicit none`;
- `do while`;
- `do` ... `end do`;
- list-directed input/output in internal files.

Fortran 90 should also work.
To compile and execute the file `name.f` (`name`=`calib`/`colors`/`spectra`/`SSPs`/`scenarios`):

Unix:

```
# f77 name.f -o name
# name
```

VMS:

```
$ for name
$ link name
$ run name
```

You may have to rename `name.f` as `name.for` and change the lowercase letters to uppercase.

2.3 Data files

2.3.1 Stellar evolutionary tracks

Stellar evolutionary tracks for various metallicities (Z) and helium abundances (Y):

- `tracksZ0.0001.dat`: $Z = 0.0001, Y = 0.23$.
- `tracksZ0.0004.dat`: $Z = 0.0004, Y = 0.23$.
- `tracksZ0.004.dat`: $Z = 0.004, Y = 0.24$.
- `tracksZ0.008.dat`: $Z = 0.008, Y = 0.25$.
- `tracksZ0.02.dat`: $Z = 0.02, Y = 0.28$.
- `tracksZ0.05.dat`: $Z = 0.05, Y = 0.35$.
- `tracksZ0.1.dat`: $Z = 0.1, Y = 0.48$.

The names of these files are written in `list_tracks.dat` (read by `SSPs`).

The tracks proposed here come mainly from the "Padova" group. At $Z = 0.1$, pseudo-tracks for masses larger than $9\,M_\odot$ have been computed from the corresponding masses in the $Z = 0.02$ and $Z = 0.05$ sets. For stars undergoing the helium flash, the zero-age main sequence tracks are connected to the zero-age horizontal branch tracks assuming a Reimers law for the mass loss along the first giant branch with $\eta = 0.4$. The same law is used to describe the mass loss during the early asymptotic giant branch phase (EAGB). Pseudo-tracks are then computed for the thermally pulsing AGB (TPAGB) phase using the equations proposed by Groenewegen & de Jong (1993) with $\eta = 4$ (van den Hoek & Groenewegen 1997). Hydrogen burning post-AGB and CO white dwarf tracks from Blöcker (1995) and Schönberner (1983) are then connected. For low-mass stars becoming helium white dwarfs, but for which the Padova group does not provide the tracks, we use the Althaus & Benvenuto (1997) models. The positions of (unevolving) low-mass stars in the HR diagram come from Chabrier & Baraffe (1997).

2.3.2 Initial mass functions

Some initial mass functions (IMF) are already defined analytically in `SSPs.f`:

- `ln`: lognormal IMF (Miller & Scalo 1979).
- `RB`: Rana & Basu (1992).
- `Fe`: Ferrini (1991).

Others are given in specific files:

- `IMF_Kennicutt.dat`: Kennicutt (1983).
- `IMF_Kroupa.dat`: Kroupa *et al.* (1993).
- `IMF_MillerScalo.dat`: Miller & Scalo (1979).
- `IMF_Salpeter.dat`: Salpeter (1955).
- `IMF_Scalo86.dat`: Scalo (1986).
- `IMF_Scalo98.dat`: Scalo (1998).

These files are listed in `list_IMFs.dat`.

2.3.3 Filters and calibrations

Filters: The passbands of the filters are provided in the file `filters.dat`. Since you may want to change it to add new filters, we detail its content here. The structure of `filters.dat` is the following:

- 1^{st} line: number of filters (N_{filters}).
- N_{filters} blocks, one for each filter, containing:
  - 1^{st} line:
    - the number of wavelengths ($N_{\mathrm{wavelengths}}$);
    - the type of transmission (see below);

    * the type of calibration (see below);
    * a code between quotes (`'...'`) identifying the filter and used in `calib.dat`;
    * reference, comments (optional).
  - $N_{\text{wavelengths}}$ lines containing:
    * the wavelength in Å;
    * the transmission at this wavelength.

Type of transmission:

- `0`: the shape of the transmission curve ($T_\lambda = T_\nu$) corresponds to the *energy* transmitted.
- `1`: the shape of the transmission curve corresponds to the *number of photons* transmitted.
- `2`: used for

$$D_{4000} = \frac{\displaystyle\int_{4050\text{Å}}^{4250\text{Å}} F_\nu \, \mathrm{d}\lambda}{\displaystyle\int_{3750\text{Å}}^{3950\text{Å}} F_\nu \, \mathrm{d}\lambda} \qquad \text{(Bruzual 1983).}$$

Type of calibration:

- `0`: used for D_{4000}.
- `1`: standard system

$$m(\star) = -2.5 \log_{10} \frac{\displaystyle\int F_\lambda(\star)\, T_\lambda \, \mathrm{d}\lambda}{\displaystyle\int F_\lambda(\text{Vega})\, T_\lambda \, \mathrm{d}\lambda} + 0.03 \qquad \text{(i.e., the magnitude of Vega is 0.03).}$$

- `2`: AB system; used for the SDSS filters (u', g', r', i', z')

$$m_{\text{AB}}(\star) = -2.5 \log_{10} \frac{\displaystyle\int F_\nu(\star)\, T_\nu \, \mathrm{d}\nu}{\displaystyle\int T_\nu \, \mathrm{d}\nu} - 48.60 \qquad (F_\nu \text{ in erg.s}^{-1}.\text{cm}^{-2}.\text{Hz}^{-1}).$$

- `3`: Thuan & Gunn system; used for the Thuan & Gunn filters (u, v, g, r)

$$m_{\text{TG}}(\star) = -2.5 \log_{10} \frac{\displaystyle\int F_\lambda(\star)\, T_\lambda \, \mathrm{d}\lambda}{\displaystyle\int F_\lambda(\text{BD} + 17^\circ 4708)\, T_\lambda \, \mathrm{d}\lambda} + 9.50.$$

- `4`: used for the WFPC2 filters ($F300W$, $F450W$, $F606W$, $F814W$) and the ultraviolet filters at 1650 Å, 2500 Å and 3150 Å

$$m_{-21.10}(\star) = -2.5 \log_{10} \frac{\displaystyle\int F_\lambda(\star)\, T_\lambda \, \mathrm{d}\lambda}{\displaystyle\int T_\lambda \, \mathrm{d}\lambda} - 21.10 \qquad (F_\lambda \text{ in erg.s}^{-1}.\text{cm}^{-2}.\text{Å}^{-1}).$$

- `5`: used for the FOCA filter at 2000 Å

$$m_{-21.175}(\star) = -2.5\log_{10}\frac{\int F_\lambda(\star)\,T_\lambda\,\mathrm{d}\lambda}{\int T_\lambda\,\mathrm{d}\lambda} - 21.175 \qquad (F_\lambda \text{ in erg.s}^{-1}.\text{cm}^{-2}.\text{Å}^{-1}).$$

Calibrations: The calibrations of the filters are computed by the code `calib.f` and written in `calib.dat`. The structure of this file is the following:

- 1st line: caption of the file.
- One line for each filter containing:
  - the name of the filter;
  - the corresponding index used in `colors`;
  - the apparent flux of Vega in erg.s^{-1}.cm^{-2}.Å^{-1}: $\int F_\lambda(\text{Vega})\,T_\lambda\,\mathrm{d}\lambda / \int T_\lambda\,\mathrm{d}\lambda$;
  - the "area" of the filter in Å: $\int T_\lambda\,\mathrm{d}\lambda$;
  - the mean wavelength in Å: $\bar{\lambda} = \int \lambda\,T_\lambda\,\mathrm{d}\lambda / \int T_\lambda\,\mathrm{d}\lambda$;
  - the effective wavelength of Vega in Å: $\int \lambda\,F_\lambda(\text{Vega})\,T_\lambda\,\mathrm{d}\lambda / \int F_\lambda(\text{Vega})\,T_\lambda\,\mathrm{d}\lambda$;
  - the AB-magnitude of Vega;
  - the Thuan & Gunn-magnitude of Vega (`99.999` if undefined);
  - the "monochromatic" luminosity of the Sun in erg.s^{-1}.Å^{-1}: $\int L_\lambda(\odot)\,T_\lambda\,\mathrm{d}\lambda / \int T_\lambda\,\mathrm{d}\lambda$.

The AB-magnitude m_{AB} may be computed from the standard magnitude m (in the Vega-system) as: $m_{\mathrm{AB}}(\star) = m(\star) + m_{\mathrm{AB}}(\text{Vega})$ and the same for the Thuan & Gunn-magnitude. You may also directly modify the type of calibration in `filters.dat` to change the default ones used in `colors.f`.

2.3.4 Other files

- `stellibCMcor.dat`: stellar library of Clegg & Middlemass (1987); $T_{\text{eff}} > 50000\,K$.
- `stellibLCBcor.dat`: stellar library of Lejeune *et al.* (1997, 1998; corrected version (BaSeL-2.0)); $T_{\text{eff}} \leq 50000\,K$..
- `ages.dat`: ages at which the synthetic spectra will be written.
- `HII.dat`: used to compute the nebular emission (continuum and lines).
- `dust.dat`: extinction properties of graphites and silicates (Draine & Lee 1993; Laor & Draine 1993).
- `slab.dat`: results of the radiative transfer code for an homogeneous slab model for both stars and dust (Fioc 1997); used to model the extinction for disk galaxies.
- `King.dat`: results of the radiative transfer code for a spheroidal geometry, where the stars are distributed according to a King profile and the dust to a power $\frac{1}{2}$ of the King profile (Fioc & Rocca-Volmerange 1997); used to model the extinction for elliptical galaxies.
- `VegaLCB.dat`: spectrum of Vega (Lejeune *et al.* 1997; computed by R.L. Kurucz).

- `BD+17o4708.dat`: spectrum of the F subdwarf BD+17°4708 (Oke & Gunn 1983) used to calibrate the Thuan & Gunn (1976) photometric system.
- `SunLCB.dat`: spectrum of the Sun (Lejeune *et al.* 1997; computed by R.L. Kurucz).
- `Spitzer.dat`: table 5.4 of Spitzer (1978, p. 113).
- `WW.dat`: stellar yields of Woosley & Weather (1995).

3 Computing synthetic spectra

3.1 Preliminaries

Stars ▷ Except for the star formation rate, which takes also into account substellar objects, "star", "stellar", etc., refer only to luminous stars to the exclusion of stellar remnants (old white dwarfs, neutrons stars and black holes) and substellar objects.

Gas ▷ Gas means both the gas strictly speaking and the dust.

Metallicity ▷ All the metallicities are given in mass fraction.

Galaxy, reservoir... ▷ We consider only the baryonic matter (with the constant mass $M_{\rm tot}$) and distinguish two zones:

- The galaxy itself (mass $M_{\rm gal}$). Unless otherwise specified, all the quantities refer only to this zone.
- A reservoir of gas only surrounding the galaxy (mass $M_{\rm res}$).

Initially, both zones contain only gas and we have either

- $M_{\rm gal} = M_{\rm tot}$ and $M_{\rm res} = 0$: the galaxy is already fully constituted;

or

- $M_{\rm gal} = 0$ and $M_{\rm res} = M_{\rm tot}$: the galaxy forms entirely by infall from the reservoir.

In both cases, the reservoir may be replenished by galactic winds occurring in the galaxy. These moreover interrupt the infall.

Normalized quantities [†, ‡] ▷ Some quantities in the following are *normalized* to $M_{\rm tot} = 1M_\odot$. To obtain the value for a given $M_{\rm tot}$, you have either to:

- multiply them by $M_{\rm tot}$ [in $M_\odot$]: quantities denoted by a "†";

or

- to add $-2.5\log_{10} M_{\rm tot}$ [in $M_\odot$]: quantities denoted by a "‡".

Maximal star formation rate ▷ If, at any time t, the *normalized* star formation rate $SFR(t)$ exceeds $SFR_{\rm max}$, its maximal possible value given the amount of gas available, `spectra` sets $SFR(t)$ to $SFR_{\rm max}$ and, the first time it happens, also prints a warning on the screen and in the header of the output file.

Inclination-dependent quantities [§] ▷ If there is some extinction in the disk geometry, the emission is not isotropic. If you choose to compute the spectra for a specific inclination, the monochromatic luminosity L_λ is then defined as $L_\lambda(\theta_0) = 4\pi\Lambda_\lambda(\theta_0)$, where $\Lambda_\lambda(\theta_0)\,\mathrm{d}\lambda\,\mathrm{d}\omega(\theta_0)$ is the energy radiated between λ and $\lambda + \mathrm{d}\lambda$ and escaping from the galaxy in a solid angle $\mathrm{d}\omega(\theta) = 2\pi \sin\theta\,\mathrm{d}\theta$ having an inclination $\theta = \theta_0$ to the axis of rotational symmetry. Inclination-dependent quantities (monochromatic or in-line luminosities, magnitudes, etc.) are denoted by a "§" in the following. This does not apply to the bolometric luminosity, as computed here ($L_{\mathrm{bol}} \equiv \iint \Lambda_\lambda(\theta)\,\mathrm{d}\lambda\,\mathrm{d}\omega(\theta) \neq \int L_\lambda(\theta_0)\,\mathrm{d}\lambda$), nor to the dust emission, which is supposed to be isotropic (negligible self-absorption). You may also output inclination-averaged spectra ($L_\lambda = \int \Lambda_\lambda(\theta)\,\mathrm{d}\omega(\theta)$) rather than for a specific inclination.

Consistent evolution of the metallicity ▷ Stars are formed with the same metallicity as the ISM.

3.2 Procedure

The synthetic spectra are computed in three steps:

1. run `SSPs`[1] to compute the properties of SSPs of different metallicities;
2. run `scenarios` to prepare the input file to `spectra` containing the parameters of the star formation scenarios;
3. run `spectra`.

3.2.1 `SSPs`

You will be asked:

- The shape of the initial mass function (enter the corresponding number).
- The lower mass of the IMF.
- The upper mass.
- The type of supernovae ejecta.
- If you want to take into account the ejecta due to stellar winds in high-mass stars through a somewhat dubious procedure.
- A prefix (e.g. ***prefix***). The output files corresponding to the tracks `tracksZ*.dat` will be named ***prefix***`_tracksZ*.dat`[2] and will be listed in the file called ***prefix***`_SSPs.dat`.

Default values ▷ Default values are proposed for some quantities. Type `<return>` to select them.

[1] You do not need to run `SSPs` every time if you keep the same IMF and the other parameters asked by `SSPs`.

[2] `spectra` will interpolate between the resulting files. If the metallicity of the stars formed in `spectra` is lower (resp. higher) than the lowest (resp. highest) metallicity of every file, `spectra` does not extrapolate but uses the data of the file with the lowest (resp. highest) metallicity.

3.2.2 `scenarios`

You will be asked:

- the name of the output file, e.g. ***`scenarios.dat`*** (it must be a *new* name);
- the name of the file (***`prefix`***`_SSPs.dat` in the example above) listing the names of the SSP files;
- the fraction of close binary systems (this quantity is used to compute the number and the ejecta of SNIa, assuming the W7 model of Thielemann *et al.* (1986) and the formalism of Greggio & Renzini (1983) and Matteucci & Greggio (1986)).

These data are common to all the star formation scenarios chosen later.

Then for each scenario, you will be asked:

- The name of the file containing the corresponding synthetic spectra (just type `end` to stop).
- The initial metallicity of the interstellar medium (ISM).
- Whether you want to build your galaxy by infall or prefer to start from a galaxy already constituted.

  The infall rate, computed as a function of the time t, is:

  $$M_{\rm tot}\frac{\exp(-t/t_{\rm infall})}{t_{\rm infall}}.$$

  You will have to provide $t_{\rm infall}$ (Myr) and the metallicity of the infalling gas.
- The type of star formation scenario (characterized by an integer) giving *SFR* [†] – the *normalized* star formation rate in $M_\odot$.Myr^{-1} – as a function of the time in Myr, the *normalized* mass of gas $M_{\rm gas}$ [†] in $M_\odot$ and other quantities.
  - Types `0` to `9` are reserved for predefined laws of star formation implemented in `spectra.f`:
    * `0`: instantaneous burst: $SFR(t) = \delta(t)$.
    * `1`: constant star formation rate:
      $$\begin{aligned} SFR(t) &= p_1 \quad \text{if } t \le p_2,\\ &= 0 \quad \text{if } t > p_2. \end{aligned}$$
      $[p_1] = M_\odot.\mathrm{Myr}^{-1}$; $[p_2] = \mathrm{Myr}$.
    * `2`: exponentially decreasing or increasing star formation rate:
      $$SFR(t) = p_2\frac{\exp(-t/p_1)}{p_1}.$$
      $[p_1] = \mathrm{Myr}$; $[p_2] = M_\odot$.
    * `3`: star formation rate proportional to some power of the mass of gas:
      $$SFR(t) = \frac{M_{\rm gas}^{p_1}(t)}{p_2}.$$
      $[p_1] = 1$; $[p_2] = \mathrm{Myr}.M_\odot^{-1}$.
    * `4` ... `9`: not yet defined.

    You will then be asked the values of the parameters (p_1, p_2, etc.). They must be `real`.
  - Types ≥`10`: you have to implement your star formation law in `spectra.f` (see section 5.2). You will be asked the number of parameters used by this law and the values (`real`) of each one.

  - Types `-1` and `-2` are for files containing the star formation rate as a function of time. You will be asked the name of the file (e.g. *`SFRfile`*):
    * `-1`: *`SFRfile`* must contain on each line the age in Myr and *SFR* separated by blanks.
    * `-2`: *`SFRfile`* must contain on each line the age in Myr, *SFR* and the metallicity of the forming stars separated by blanks. This metallicity may be inconsistent with that of the ISM.

    These quantities must be `real`. The first age in *`SFRfile`* must be 0. and the last must be higher than 20000. The computation of the star formation rate at intermediate ages is performed by `spectra`.

- If the type of star formation scenario is not `-2`, whether you want a consistent evolution or prefer to form stars with a constant metallicity (asked later).

- The fraction (in mass) of the star formation rate used to form substellar objects. These objects lock the mass and are supposed to emit no light.

- If you want galactic winds. Galactic winds expel all the interstellar medium from the galaxy after a given time (asked later) and prevent any further star formation.

- If you want to take into account the nebular emission, i.e. the continuum and lines emitted by the ionized gas in star-forming regions. The emission in the continuum and the hydrogen lines is computed from the number of Lyman continuum photons in the case B of recombination. Typical observed ratios to Hβ are taken for other lines.

  If you hereafter choose to have some extinction, a fraction of the Lyman continuum photons will be absorbed by the dust inside the HII region rather than by the gas. This fraction is computed according to the prescriptions of Spitzer (1978, p. 113) and assuming that 70% of the Lyman continuum photons are absorbed by the gas at solar metallicity.

- If you want to introduce some extinction:

  - `0`: No extinction.
  - `1`: Extinction for a spheroidal geometry.
  - `2`: Extinction for a disk geometry; inclination-averaged.
  - `3`: Extinction for a disk geometry; specific inclination. You will then be asked the inclination in degrees relative to face-on.

  The optical depth is estimated from the mass of gas and the metallicity. The absorption, the albedo and the asymmetry parameter are computed from Draine & Lee (1984) and Laor & Draine (1993) data for a mixture of graphites and silicates depending on the metallicity and fitted on the Magellanic Clouds and the Milky Way (cf. Pei (1992)).

  In the cases `1` and `2`, all the Lyman continuum photons not absorbed by the gas as well as those emitted in the Lyα line are absorbed by the dust as soon as the metallicity of the ISM is non 0.

Default values ▷ Default answers are proposed for some questions. Just type `<return>` to select them. Default names of the output files are created by inserting the number of the scenario between the prefix `spectra` and the suffix `.dat` (see however note 3). For the other questions, the default answers are those defined in `scenarios.f` the first time you answer to a specific question. When you have already answered to this question for a previous scenario, the default is your last choice.

3.2.3 `spectra`

Type the name of the file of scenarios (*`scenarios.dat`* in the example above) when required[3].
The structure of the output files is the following:

- A block describing the evolutionary scenario and ending with a line of asterisks (`*** ... ***`) only.
- One line with:
  - the number of timesteps ($N_{\mathrm{timesteps}}$);
  - the number of wavelengths of the continuum ($N_{\mathrm{continuum}}$);
  - the number of emission lines (N_{lines}).
- A block containing the $N_{\mathrm{continuum}}$ wavelengths (Å) of the continuum (5 per line).
- A block containing the N_{lines} wavelengths (Å) of the emission lines (5 per line).
- $N_{\mathrm{timesteps}}$ blocks (one for each timestep) containing:
  - 1st line:
    - the time (Myr, `integer`);
    - the *normalized* mass of the galaxy [†] ($M_\odot$);
    - the *normalized* mass in stars [†] ($M_\odot$);
    - the *normalized* mass in white dwarfs [†] ($M_\odot$);
    - the *normalized* mass in neutron stars and black holes [†] ($M_\odot$);
    - the *normalized* mass in substellar objects [†] ($M_\odot$);
    - the *normalized* mass in the gas [†] ($M_\odot$);
    - the metallicity of the interstellar medium (mass fraction);
    - the mean metallicity of stars averaged on the mass (i.e., the mean initial metallicity of the stars still alive averaged on their initial mass);
    - the mean metallicity of stars averaged on the bolometric luminosity (i.e., the mean initial metallicity of the stars still alive averaged on their present bolometric luminosity).
  - 2nd line:
    - the *normalized* bolometric luminosity [†] (erg.s^{-1});
    - the optical depth in the V-band (5500 Å) from side to side (through the center for the spheroidal geometry and along the axis of rotational symmetry for the disk geometry);
    - the ratio of the luminosity emitted by the dust to the bolometric luminosity;
    - the *normalized* star formation rate [†] ($M_\odot$.Myr^{-1});
    - the *normalized* number of Lyman continuum photons emitted [†] (s^{-1});
    - the *normalized* SNII rate [†] (Myr^{-1});
    - the *normalized* SNIa rate [†] (Myr^{-1});
    - the mean age of the stars averaged on the mass (Myr);
    - the mean age of stars averaged on the bolometric luminosity (Myr).

[3] If one of the files of spectra you want to create already exists, `spectra` appends one or more "`+`" to the name of the new file and prints a warning on the screen.

- A block containing the *normalized* monochromatic luminosities [†, §] (erg.s^{-1}.Å^{-1}) of the $N_{\mathrm{continuum}}$ wavelengths of the continuum (5 per line).
- A block containing the *normalized* luminosities [†, §] (erg.s^{-1}) of the N_{lines} emission lines (5 per line).

4 Computing colors

To compute colors, luminosities, etc., for a given set of spectra, run colors and type the name of the input file (spectra) when required. You are then asked the name of the output file (colors). If you just type <return>, the name of the output file is created by adding the prefix colors_ to the name of the input file.
The structure of the output file is the following:

- A block describing the evolutionary scenario and ending with a line of asterisks (*** ... ***) only.
- One line giving the number of timesteps ($N_{\mathrm{timesteps}}$).
- Eight blocks consisting each in:
  - one line describing the quantity in each column;
  - $N_{\mathrm{timesteps}}$ lines giving these quantities[4] at each timestep.

The quantities printed in the output file are the following:

- 1[st] block: time Mgal M* MWD MBHNS Mgas Zgas <Z*>mass <Z*>Lbol
  - time: time (Myr, integer).
  - Mgal [†]: *normalized* mass of the galaxy ($M_\odot$).
  - M* [†]: *normalized* mass in stars ($M_\odot$).
  - MWD [†]: *normalized* mass in white dwarfs ($M_\odot$).
  - MBHNS [†]: *normalized* mass in neutron stars and black holes ($M_\odot$).
  - Msub [†]: *normalized* mass in substellar objects ($M_\odot$).
  - Mgas [†]: *normalized* mass in the gas ($M_\odot$).
  - Zgas: metallicity of the gas.
  - <Z*>mass: mean stellar metallicity averaged on the mass.
  - <Z*>Lbol: mean stellar metallicity averaged on the bolometric luminosity.
- 2[nd] block: time Lbol tauV Ldust/Lbol SFR nSNII nSNIa <t*>mass <t*>Lbol
  - Lbol [†]: *normalized* bolometric luminosity (erg.s^{-1}).
  - tauV: optical depth in the V-band.
  - Ldust/Lbol: ratio of the luminosity of the dust to the bolometric luminosity.
  - SFR [†]: *normalized* star formation rate ($M_\odot$.Myr^{-1}).

[4]If no stars have formed yet, all the quantities are set to 0. This happens in particular at $t = 0$ when the galaxy forms by infall.

  - nSNII [†]: *normalized* rate of type II supernovae (Myr^{-1}).
  - nSNIa [†]: *normalized* rate of type Ia supernovae (Myr^{-1}).
  - <t*>mass: mean stellar age averaged on the mass (Myr).
  - <t*>Lbol: mean stellar age averaged on the bolometric luminosity (Myr).

- 3$^{\mathrm{rd}}$ block: time nLymcont L(Ha) W(Ha) L(Hb) W(Hb) LB/LBsol LV/LVsol D4000
  - nLymcont [†]: *normalized* number of Lyman continuum photons emitted (s^{-1}).
  - L(Ha) [†, §]: *normalized* luminosity of the emission line Hα ($\mathrm{erg.s}^{-1}$).
  - W(Ha) [§]: equivalent width of the emission line Hα (Å).
  - L(Hb) [†, §]: *normalized* luminosity of the emission line Hβ ($\mathrm{erg.s}^{-1}$).
  - W(Hb) [§]: equivalent width of the emission line Hβ (Å).
  - LB/LBsol [†, §]: *normalized* blue[5] luminosity ($L_{\mathrm{B}} = \int_{\mathrm{B}} L_\lambda\, T_\lambda\, \mathrm{d}\lambda / \int_{\mathrm{B}} T_\lambda\, \mathrm{d}\lambda$) in units of the solar blue luminosity, (i.e., $L_{\mathrm{B}}/L_{\mathrm{B}}(\odot)$, which is different of $\bar{\lambda}_{\mathrm{B}}\, L_{\mathrm{B}}/L_\odot$ where $L_\odot$ is the bolometric luminosity of the Sun).
  - LV/LVsol [†, §]: *normalized* visual luminosity ($L_{\mathrm{V}}/L_{\mathrm{V}}(\odot)$).
  - D4000 [§]: intensity of the Balmer break (D_{4000}).

- 4$^{\mathrm{th}}$ block: time Mbol V U-B B-V V-K V-RC V-IC J-H H-K
  - Mbol [‡]: *normalized* bolometric magnitude ($M_{\mathrm{bol}}(\odot) = 4.75$).
  - V, U, B [‡, §]: *normalized* absolute magnitudes in the filters of Buser & Kurucz (1978) [see note 5].
  - RC and IC [‡, §]: *normalized* absolute magnitudes in the R and I Cousins filters (Bessel 1990).
  - J, H and K, as well as L and M (see below) [‡, §]: *normalized* absolute magnitudes in the filters of Bessel & Brett (1988).

- 5$^{\mathrm{th}}$ block: time K-L L-M V-RJ V-IJ JK-V UK-JK JK-FK FK-NK 2000-V
  - RJ and IJ [‡, §]: *normalized* absolute magnitudes in the R and I Johnson filters (Johnson 1965).
  - UK, NK [‡, §]: *normalized* absolute magnitudes in the U and N filters of Koo (1986)
  - JK, FK [‡, §]: *normalized* absolute magnitudes in the J and F filters of Kron (1980).
  - 2000 [‡, §]: *normalized* absolute magnitude in the ultraviolet filter (José Donas, private communication) of the FOCA experiment (Milliard et al. 1991).

- 6$^{\mathrm{th}}$ block: time V-ID ID-JD JD-KD BJ-V BJ-RF V-606 300-450 450-606 606-814
  - ID, JD, KD [‡, §]: *normalized* absolute magnitudes in the I, J and K DENIS filters (Éric Copet, private communication); the passband of the K filter is the one determined at ambient temperature.
  - BJ, RF [‡, §]: *normalized* absolute magnitudes in the B_{J} and R_{F} photographic filters (Couch & Newell 1980).

[5] For the sake of the consistency with the stellar library of Lejeune *et al.* (1997, 1998), the U, B, V filters used in the files of colors are from Buser & Kurucz (1978), not from Bessel (1990). The B filter is always $B3$, except for $U - B$ where we use $B2$, which, as $U3$, is not corrected for the atmospheric absorption.

  - `300`, `450`, `606`, `814` [‡, §]: *normalized* absolute magnitudes in the $F300W$, $F450W$, $F606W$, $F814W$ filters of the WFPC2 instrument on the Hubble Space Telescope.

- 7[th] block: `time u'-g' g'-r' V-r' r'-i' i'-z' u-v v-g g-V g-r`
  - `u'`, `g'`,`r'`, `i'`, `z'` [‡, §]: *normalized* absolute magnitudes in the Sloan Digital Sky Survey filters (Fukugita *et al.* 1996).
  - `u`, `v`, `g`, `r` [‡, §]: *normalized* absolute magnitudes in the Thuan & Gunn (1976) filters.

- 8[th] block: `time 1650-B 1650-2500 3150-B`

  `1650`, `2500` and `3150` [‡, §]: *normalized* absolute magnitudes in Gaussian filters centered on the corresponding wavelengths in Å of the Rifatto *et al.* (1995) data.

Note that not all the filters provided in `filters.dat` are used in the ouput file of `colors`. See section 5.5 if you want to use them.

5 Adaptations

5.1 IMF

You may define your IMF as a series of p continuous piecewise power laws giving the number of stars n as a function of their mass m:

$$\text{if } m \in [m_i, m_{i+1}], \quad \frac{\mathrm{d}n}{\mathrm{d}\ln m} \propto m^{s_i} \qquad (1 \leq i \leq p).$$

Create a file like this (see for example `IMF_Scalo86.dat`):

$$\begin{array}{ll} p & \\ m_1 & s_1 \\ m_2 & s_2 \\ \vdots & \vdots \\ m_p & s_p \\ m_{p+1} & \end{array}$$

and add its name at the end of the file `list_IMFs.dat` (type `<return>` at the end of the file). The lower mass should preferably be larger than $0.09\,M_\odot$ and the upper mass less than $120\,M_\odot$ to be in agreement with the tracks. The continuity of the power laws and the normalization of $\int_{m_1}^{m_{p+1}} \frac{\mathrm{d}n}{\mathrm{d}m} m\,\mathrm{d}m$ to $1\,M_\odot$ are ensured by `SSPs`.

5.2 Star formation rate

You may define your own star formation rate. Search for the lines

```
c      if (typeSFR.eq.n>=10) then
c           SFR(i)=your SFR law (note that i = time in Myr + 1)
c      end if
```

in `spectra.f`. Uncomment and modify them; then, express the *normalized* star formation rate [†] `SFR(i)` at the timestep `i` as a function of the age `time(i)=i-1.`, the *normalized* mass of gas [†] (`sigmagas(i)`) or other quantities. `SFR(i)` may also depend on free parameters `param(1)`, `param(2)`, ... , `param(nparam)` that you will have to provide when running `scenarios`. The maximal number of parameters `nmaxparam` is set to 99 in the declarations at the top of `spectra.f`; it should be enough!

5.3 Changing the output ages of the spectra

`ages.dat` contains the ages in Myr (one per line, `integer`) at which the spectra are printed. You may change these data (do not forget to type `<return>` at the end of the file). If necessary, modify the parameter `nmaxtimesimpr` at the beginning of `spectra.f` (maximal number of printed spectra).

5.4 Introducing other filters

You may include other filters (see section 2.3.3):

- Change the number of filters on the first line of `filters.dat`.
- At the end of the file, write on the same line (with blanks between them):
  - the number of wavelengths defining the passband of the filter;
  - the type of transmission;
  - the type of calibration;
  - the name between quotes;
  - comments (optional).
- Write each wavelength (Å) and the corresponding transmission on one line. Do not forget to type `<return>` at the end of the file.
- Run `calib` to obtain the calibrations of the filters in `calib.dat`.

5.5 Printing other quantities

`colors` may print other quantities:

- *Normalized* absolute magnitudes [‡, §] `mag(j,i)` (magnitude at time `time(j)` in the filter number `i`) and derived colors [§].
- *Normalized* "monochromatic" luminosities [†, §] `fluxfilter(j,i)` (erg.s^{-1}.$Å^{-1}$) or their ratio to the solar luminosity in the filter (`fluxfilter(j,i)/fluxsol(i)`).
- *Normalized* luminosity [†, §] `Lumline(j,i)` (erg.s^{-1}) of the emission line number `i` (see `HII.dat`) at time `time(j)` or its equivalent width [§] `EW(j,i)` (Å). The data for the nebular lines are given in `HII.dat` at lines 84 to 144. Each line contains the wavelength of the emission line, the ratio of its intensity to Hβ, the name and, finally, the index `i` used in `colors.f`.

To do this, add new lines in `colors.f` before the instruction `close(50)` in the following way:

```
do j=1,ntimes
     write(50,format) variable1(j), variable2(j)...
end do
```

6 References

Althaus L.G., Benvenuto O.G., 1997, ApJ 477, 313

Bessel M., 1990, PASP 102, 1181

Bessel M., Brett J., 1988, PASP 100, 1134

Bruzual G., 1983, ApJ 273, 105

Buser R., Kurucz R.L., 1978, A&A 70, 555

Chabrier G., Baraffe I., 1997, A&A 327, 1039

Clegg R.E.S., Middlemass D., 1987, MNRAS 228, 759

Couch W.J., Newell E.B., 1980, PASP 92, 746

Draine B.T., Lee H.M., 1984, ApJ 285, 89

Ferrini F., 1991, in *Chemical and Dynamical Evolution of Galaxies*, F. Ferrini, F. Matteucci, J. Franco (eds.), p. 520

Fioc M., 1997, Ph.D. thesis (Université Paris XI): *Évolution spectrale des galaxies de l'ultraviolet au proche infrarouge — Étude de l'histoire de la formation d'étoiles* (in French; available at `http://www.iap.fr/users/fioc/`)

Fioc M., Rocca-Volmerange, 1997, A&A 326, 950

Fukugita M., Ichikawa T., Gunn J.E., Doi M., Shimasaku K., Schneider D.P., 1996, AJ 111, 1748

Greggio L., Renzini A., 1983, A&A 118, 217

Groenewegen M., de Jong T., 1993, A&A 267, 410

Johnson H.L., 1965, ApJ 141, 923

Kennicutt R.C., 1983, ApJ 272, 54

Koo D.C., 1986, ApJ 311, 651

Kron R.G., 1980, ApJS 43, 305

Kroupa P., Tout C.A., Gilmore G., 1993, MNRAS 262, 545

Laor A., Draine B.T., 1993, ApJ 402,441

Leitherer C. *et al.*, 1996, PASP 108, 996

Lejeune T., Cuisinier F., Buser R., 1997, A&AS 125, 229

Lejeune T., Cuisinier F., Buser R., 1998, A&AS 130, 65

Matteucci F., Greggio L., 1986, A&A 154, 279

Miller G.E., Scalo J.M., 1979, ApJS 41, 513

Milliard B., Donas J., Laget M., 1991 , AdSpR 11, 135

Oke J.B., Gunn J.E., 1983, ApJ 266, 713

“Padova”:

- Bressan A., Fagotto F., Bertelli G., Chiosi C., 1993, A&AS 100, 647
- Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994a, A&AS 104, 365
- Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994b, A&AS 105, 29
- Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994c, A&AS 105, 39
- Girardi L., Bressan A., Chiosi C., Bertelli G., Nasi E., 1996, A&AS 117, 113

Pei Y.C., 1992, ApJ 395, 130

Rana N., Basu S., 1992, A&A 265, 499

Rifatto A., Longo G., Capaccioli M., 1995, A&AS 114, 257

Salpeter E., 1955, ApJ 121, 161

Scalo J.M., 1986, Fund. Cosm. Phys. 11, 1

Scalo J.M., 1998, in *The Stellar Initial Mass Function*, G. Gilmore, D. Howell (eds.) [ASP Conf. Ser. 142], p. 201

Spitzer L., 1978, *Physical Processes in the Interstellar Medium*, Wiley-Interscience

Thielemann F.K., Nomoto K., Yokoi K., 1986, A&A 158, 17

Thuan T.X., Gunn J.E., 1976, PASP 88, 543

van den Hoek L., Groenewegen M., 1997, A&AS 123, 305

Woosley S., Weaver T., 1995, ApJS 101, 181