

Fitting galaxy spectra with STECKMAP: a user guide

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STECKMAP stands for (STellar Content and Kinematics via Maximum A Posteriori). It is written in Yorick, and altho some information is available on the official webpage and the tutorials, as well as by typing “info, sfit” (for instance) in the Yorick prompt, the information about the code and its use is rather sparsely distributed. This user guide is an attempt at concentrating this information into one single place and give the user a more efficient and useful experience with the code.

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Chapter 1

What is STECKMAP?

STECKMAP is a software aiming at interpreting galaxy spectra in terms of their stellar populations: star formation history, age-metallicity relation, extinction are constrained. From these, a number of integrated quantities can be further computed, such as luminosity-weighted age and metallicity, and mass-weighted age and metallicity (respectively, LWAge, LWZ, MWAge, MWZ).

To do so, the observed spectrum is projected onto a time-sequence of models of single stellar populations, so as to determine a linear combination of these models, that fit the observed spectrum best (via a penalized χ^2). The weights of the various components of this linear combination indicate the stellar content of the population.

Since in practice observed spectra are altered by the kinematics and the instrumental signature, STECKMAP also determines a broadening function (BF), which is the convolution of the line-of-sight velocity distribution (LOSVD) of the stars and the instrumental point-spread function (PSF). Since the latter is usually well known the BF can be further interpreted in terms of the kinematics of the observed population. This is also done in a Maximum A Posteriori formalism.

Chapter 2

Installing the code

One needs to install Yorick and STECKMAP separately.

2.1 Installing yorick

You will thus need to first install yorick (<http://www.maumae.net/yorick/doc/>). This should in principle be painless, especially using the pre-compiled binary distributions. You should even be able to install it through fink (for Mac) or the linux equivalent. Also yorick is very light (much lighter than the STECKMAP package itself) so you wont have to worry about disk space.

It is important for this version that yorick be installed in the Yorick/ directory such as: `$HOME/Yorick/`

Successful installation should result in the yorick executable to have a full path similar to:

`$HOME/Yorick/yorick-2.1/yorick/yorick` (for yorick-2.1 that is). This note provides few guidelines for installing yorick. Refer to yorick's README for more, as it is more complete. On Macs, yorick can be installed through fink. I recommend using yorick through emacs. This allows for 2 very cool things to happen:

- enables emacs code editing features: colors, indentation, etc... i.e. a helpful coding environment.
- keyboard shortcuts: the buffer you are currently editing can be executed with `Ctrl-X Ctrl-S`.

Follow the yorick.el instructions to set this up. You will need to make a straightforward modification of your `/.emacs`. and inside yorick.el dont forget to provide the full path to the yorick executable (search for the string "yorick-executable-name" and replace the adjacent string "yorick" with the full path to the executable). You can check if yorick is correctly installed by launching it typing

```
bash-3.2$ yorick
  Copyright (c) 2005.  The Regents of the University of California.
  All rights reserved.  Yorick 2.1.05 ready.  For help type 'help'
> include, "demo2.i"
> demo2
```

A cool animation should ensue, greeting you to a successful install of Yorick.

2.2 Installing STECKMAP

You can get the latest package from here: <http://www.aip.de/People/POcvirk/>
Download the latest version. The versions are tagged as:

```
STECKMAP_laptop_ddmmyy.tar
```

or

```
STECKMAP_laptop_ddmmyyyy.tar
```

In your Yorick directory (\$HOME/Yorick/), untar the STECKMAP archive

```
tar -xvf STECKMAP.tar
```

Some routines use the environment variable \$HOME to define absolute paths to some objects, so be sure it is correctly defined by typing in a shell:

```
echo $HOME
```

2.3 Checking the successful installation with an example

Launch yorick by typing "yorick" on the shell command line. Once yorick is launched, load STECKMAP by typing

```
> include, "STECKMAP/Pierre/POP/sfit.i"
```

You will find a couple of example data in Yorick/Pierre/POP/EXAMPLES/. They are provided in order to give the user a taste of what can be done and how to proceed. Follow this small tutorial.

STECKMAP is a tool package aiming at constraining the stellar content and kinematics from galaxy spectra. To do so, you need two things:

- DATA
- Models against which to compare your data

The detailed use of the function will be explained in the further chapters. For the moment we just want to check STECKMAP is installed properly.

Data

See the path and name of an example file I set up by typing

```
> fV
```

fV is just a variable storing the path and name of the example file. To make things easier, it is loaded by default. Convert the example file by typing:

```
> a=convert_all(fV)
```

this will create the .pdb file, plot the data, and write the redshdift of the example galaxy if it is supplied in the fits keywords. Otherwise it will just assume 0, as in this case. Note that it will plot the 2d plate and the spectrum obtained by summing the whole 2d spectrum in the spatial direction. This is the default behaviour of `convert_all`.

A model basis is a structure as defined in "Pierre/POP/base.struct.i". This structure contains the sequence of SSPs in time and metallicity. As such, it is a data cube. The structure contains this cube and also the wavelengths, the resolution, the metallicity scale, and the ages of wach element of the basis.

SSP basis

To generate a basis, use the function `bRbasis3`:

```
> b=bRbasis3()
```

This will call `bRbasis3` with all the defaults arguments. To get help and see information about the various arguments and their default values you can type

```
> help, bRbasis3
```

or

```
> info, bRbasis3
```

Here the default is a PEGASE-HR sequence of SSPs with 10 age bins from 10Myr to 20 Gyr with Salpeter IMF and Padova tracks. It is flux-normalized by default (see the STECMAP paper for details). PEGASE-HR has a resolution $R=10000$ and the wavelength coverage is 4000 – 6900 Å. All these values can of course be changed when calling `bRbasis3`.

To have an idea of the looks of the basis you just generated, type

```
> ws
```

this is to clear the display

```
> plb, b.flux(,1),b.wave
```

This will result in a nice plot of the basis for the first metallicity of the basis. It can be printed by typing:


```
> b.met(1)
```

since the metallicities are stored in `b.met`. Note that for computational reasons, the metallicities are renormalized. Hence, you can read the original metallicity of the first constant-metallicity slice of the SSP cube `b.flux(,1)` by typing:

```
> Zrescalem1(b.met(1))
```

it should be 0.05.

Fitting engine

The fitting engine is called with the `sfit` command, which takes as arguments, the data, the basis and a bunch of options. Type

```
> help,sfit
```

to see the current documentation for `sfit`. To fit the data, the structure of which is stored in the variable `a`, using the SSP basis, the structure of which is stored in the variable `b`, type:

```
> x=sfit(a,b,kin=1,epar=3,noskip=1,sav=1)
```

The various options will be explained in the next chapter.

Chapter 3

Fitting your data

3.1 Preparing your data: `convert_all`

Spectra of galaxies come in a variety of forms, 1D (such as SDSS), 2D (typical long-slit spectroscopy), 3D (data cubes), some of them have attached errors and masks (e.g. SDSS), others not. STECKMAP on the other hand will fit only one spectrum at a time. Therefore the first step in the analysis is to convert the available data into a 1D spectrum in a format that STECKMAP understands. This can be done in the majority of cases with the `convert_all` routine. Since even in the case of 3D spectroscopy spectra are collected on a 2D detector and even stored in 2D structures (wavelength, fiber number), `convert_all` can deal at the moment only with 1D and 2D provided spectra. The inputs and options can be obtained as

```
> info,convert_all
func convert_all(filelist,cut=,noplots=log=,z0=,SNR0=,wav=,
wavaxis=,xs=,xe=,hdu=,fsigm=,errorfile=)
```

A typical call looks as follows:

```
> a=convert_all(fV,xs=100,xe=300,z0=500./300000.);
NAXIS2>NAXIS1, assuming AXIS2 wavelength axis
no redshift in fits header... will assume 0 or take user input
no S/N in fits header... will assume 100 or take user input
redshift 0.00166667
>
```

3.1.1 Input

The only mandatory input is the filename of the data file to be ingested `filelist`. This must be a fits file following Note that it can be a list but it is usually more practical to convert and analyse spectra one by one.

3.1.2 Options

<code>hdu=</code>	if fits file contains multiple header data units, specify number of hdu to read.
<code>cut=</code>	filelist is cut at cut-th file, default is 10
<code>log=</code>	log=1 enforces log wave sampling in case fits header information is inaccurate.
<code>noplot=</code>	disables the plotting of the spectrum read (useful when remotely running a batch of spectra on a machine without an active X11 window with nohup for instance. default is noplot=0, so plotting happens.
<code>z0=</code>	if redshift is not provided in fits header, can be given by user as z0=
<code>SNR0=</code>	same as z0 for global signal to noise ratio. Note that ideally it is better to supply a noise spectrum via <code>errorfile=</code> .
<code>errorfile=</code>	specify a name for an error file in order to fill the sigma vector. This will only work for 1D spectra right now.
<code>wavaxis=</code>	possible values are 1 or 2. Useful if data is provided as 2d frame, typical for long-slit spectroscopy. If no value is provided (default) we take as the wavelength axis as the axis with largest dimension.
<code>xs=, xe=</code>	start and end of the stacking in the spatial direction, useful for long slit spectroscopy.
<code>sigm=</code>	sigm=1 forces sigma=1 instead of d/(S/N).

3.1.3 Output

The direct result of the call is a structure containing various informations about the spectrum and the galaxy, and the various filenames of the results files `.res`, the original data file `.fits`, the intermediate data file `.pdb`. This latter file is written by the routine and will be accessed by the fitting routine `sfit`. You can see the content of the result structure by typing:

```
> a
[galStruct(name="NGC4621",filename=
"/Users/Pedro/Yorick/STECKMAP/Pierre/POP/EXAMPLES/NGC4621-1.pdb",result_dir=
"Users/Pedro/Yorick/STECKMAP/Pierre/POP/EXAMPLES/",resfile=
"/Users/Pedro/Yorick/STECKMAP/Pierre/POP/EXAMPLES/NGC4621-1.res",wavesampling=
"LIN",redshift=0.00166667,SNR=100)]
>
```

3.2 Preparing a sequence of SSP models: `bRbasis3`

There are several versions of the routine for generating the SSP basis. The most advanced at the moment is `bRbasis3`. Information can be obtained by typing:

Code	Reference	age range (yr)	[Z/H]
'BC03'	Bruzual & Charlot 2003	$10^5 - 1.710^{10}$	[0.3,-2]
'MILES'	Vazdekis 2010	$2.10^7 - 1.710^{10}$	[0.2,-1.3]
'PHR'	Leborgne et al. 2004	$2.10^7 - 1.710^{10}$	[0.2,-2]
'GD05'	Gonzalez-Delgado et al. 2005	$2.10^7 - 1.710^{10}$	[0.2,-2]

Table 3.1: References of the SSP models available with STECKMAP.

```
> info,bRbasis3
func bRbasis3(ages,&FWHM,&bab,mets=,nbins=,R=,wavel=,N=,basisfile=,dlambda=,
zr=,br=,inte=,navg=,list=,intages=,dirsfr=,filters=,s=)
>
```

A typical call looks as follows:

```
> b=bRbasis3([1.e8,2.e10],wavel=[3500.,7000.],basisfile="MILES",nbins=30);
```

3.2.1 Inputs

The most important input here is the age ranges where the models will be computed. It is given as a 2-vector [age_{min} , age_{max}]. The unit is years.

3.2.2 Options

nbins Number of ages bins of the basis.
wavel Wavelength range of the models (by default the broadest available range is taken).
basisfile Reference of the models to be used. See table 3.1 for a list of the models available with the code.

3.3 Running the fitting engine: sfit

Chapter 4

Interpreting the results

When the option `sav= 1` is given to `sfit`, the results are saved. The various results files are created in the same directory as the initial data file, upon success of the fitting procedure. The `.pdb` file is the result of the `convert_all` procedure. It is a binary file containing the initial data, a wavelength vector, an error spectrum and sometimes a mask if it has been supplied in the proper way (such as when dealing with SDSS data). This chapter describes the other files available.

4.1 Description of the results files

The format of the files is text as follows:

1. variable name
2. length of vector
3. values
4. variable name
5. length of vector
6. ...

4.1.1 Stellar content

These are the files: `res-SAD`, `res-MASS`, `res-SFR` and `res-AMR`. They look like this (here for the `res-MASS` file):

Ages (Myr)	10				
10.0000	23.2692	54.1455	125.992	293.173	
682.190	1587.40	3693.75	8595.06	20000.0	
Masses in each time bin	10				
39.4829	17.2968	5.35236	2.45517	0.997133	
5.72450	251.843	2432.88	16218.1	39665.3	

The variables relative to the stellar content all refer to a time axis, which can be seen as lookback time or the age of the stellar component. It is always given first in these files. The (Myr) indicates the time axis is in Myr. Then comes the field of interest, here the masses. Here is a short description of the content of each file:

- **res-SAD:** The Stellar Age Distribution, i.e. the contribution in flux of each component to the observed spectrum. It is normalized so that the sum of the SAD is 1. It is the basic quantity STECKMAP is working with (rather than masses or SFR). In a typical STECKMAP run the SAD is shown in the top plot of the results panel.
- **res-AMR:** The Age-Metallicity Relation. This gives the metallicity $Z(i)$ of each component i of age $age(i)$, hence defining effectively an age-metallicity relation. In extragalactic astronomy, the metallicity is usually understood as a total abundance of metals, i.e. the fractional mass of everything which is not H or He. With this convention, in the models used here the metallicity of the sun is 0.02. Some authors will use 0.019 instead, but in practice this does not make a huge difference in the interpretation of the results, in particular as long as one does not embark into computing abundances of individual elements. In a typical STECKMAP run the AMR is shown as the middle plot of the results panel.
- **res-MASS:** This file gives the stellar mass as a function of the age. Note that it is understood as an “initial mass”, i.e. the mass the given component had at the time of its birth. No mass loss is taken into account here. The masses for each time bin i are simply computed as:

$$mass(i) = \frac{sad(i)}{M/L(age(i), Z(i))} \quad (4.1)$$

where $M/L(age, Z)$ is the mass to light ratio of a stellar population of age age and metallicity Z . Again since no mass loss is taken into account this refers to the *initial mass*, i.e. it only accounts for the dimming of the population, not for the decrease/recycling of its stellar mass. The masses are given in principle in solar masses but the normalization is arbitrary: the relative masses (i.e. between the various bins) are correct but the actual normalization results from the fact that sad is normalized to unity, i.e. $\sum_i sad(i) = 1$.

- **res-SFR:** The Star Formation Rate (SFR) as a function of lookback time. It is obtained as:

$$SFR(i) = \frac{mass(i)}{\Delta t(i)}, \quad (4.2)$$

where $\Delta t(i)$ is the duration or extent of the age bin i . Note that this is *not* $t(i+1) - t(i)$ but is rather computed as like $\Delta t(i) = t(i+1/2) - t(i-1/2)$. The SFR is given in M_{\odot}/yr but is not physically normalized. As

for the masses, the relative variations are correct but not their absolute values, and the actual normalization is essentially inherited from that of the masses *mass*.

4.1.2 Kinematics

The broadening function of the data results from the convolution of the LOSVD and the instrument's PSF or LSF. However, I will often abusively call it the LOSVD, and talk about kinematics eventhough I should be talking about kinematics + instrumental characteristics. The broadening function is stored in the **res-LOSVD.txt** file. It begins as follows:

```
v (km/s)      369
              -1003.75      -998.323      -992.892      -987.460      -982.029
              -976.597      -971.165      -965.733      -960.301      -954.869
              ...
```

This describes the velocity range (in km/s) on which the LOSVD has been computed. Next come the actual values of the broadening function for each of these velocities:

```
g(v)          369
              1.57828e-06      1.62290e-06      1.65155e-06      1.65992e-06      1.63955e-06
              1.61256e-06      1.54141e-06      1.47136e-06      1.33613e-06      1.13671e-06
              ...
```

The LOSVD or BF $g(v)$ is normalized to unity, i.e. its sum is equal to 1.

4.1.3 Spectra

A number of spectra are available in the **res-spectra.txt** file. In order of appearance are the wavelength range (in Angstrom), the data, the best fitting model, the weight vector, and, if the option `epar=3` has been used, the non-parametric extinction curve (maybe calling it non-parametrically adjusted continuum (i.e. NPAC would make more sense...)). Although these are readily plotted in a usual STECKMAP run, this results file should allow the user more flexibility in displaying/examining his fit.

4.2 How to improve your fit ?

4.2.1 Masking bad pixels/emission lines

4.2.2 Dependence on hyperparameters

4.3 Assessing the significance of the results

It is natural and wise to wonder about the significance of our results. There are at least 3 types of errors we should care about:

- Noise in the data: photon noise, read-out noise, background noise...
- Methodological errors: although authors of spectral inversion methods do not like to think about it there can be systematic effects due to the method itself and the choices that have been made in terms of interpolating between the ssp models, their normalization etc.... Perhaps the best way to investigate these is to use different methods in simple, controlled experiments, as was done in [1].
- Theoretical uncertainties: the ssp models are at the core of galaxy spectra inversion techniques, and they are not perfect (uncertainties in the stellar parameters and coverage of stellar libraries, uncertainties in stellar tracks...). A good way to investigate the effect of these is to always analyse a given spectrum with a collection of models rather than just one model. Several popular models are already plugged in the distributed version of STECKMAP (see table 3.1), and can be used simply by changing the parameter `basisfile` in the `brbasis3` call. This approach was also used in [1].

In the following we will focus on the methods available in STECKMAP to tackle the first item and some of the second, via MonteCarlo experiments.

4.3.1 Robustness of the results: running Monte Carlo experiments

Here we understand Monte Carlo experiments as: rerunning the inversion on the dataset with a randomized element. The randomized element in STECKMAP can either be the noise in the data or the first guess (i.e.e the starting point of the minimization method).

4.3.2 Robustness wrt noise in the data

Here we want to invert mock data, which will be either the original data with a different realization of the noise, or the best model we have of that data, with noise added according to the noise vector. The relevant options for `sfit` are listed in Tab. 4.1

A typical call will look like:

```
x=sfit(a,b,kin=1,noskip=1,sav=1,nMC=5,dMC=''bestmodel'',MC_noise=''yes'')
```

4.3.3 Robustness wrt first guess choice

All iterative optimization methods require a starting point, which is usually referred to as the *first guess*. In the case of SFH reconstruction from spectra, scientists aim at designing a method and an implementation of it, that will be as little as possible sensitive to the first guess. Ideally, we would like STECKMAP to give always the same answer, no matter what the first guess was. In STECKMAP,

nMC=	number of MC experiments to be performed
dMC=	determines the mock data to be used for the MC experiments. Two choices are possible only: dMC='bestmodel' will create a mock spectrum by taking the best model (corresponding to the derived solution SAD, AMR, BF etc...) and noising it using the noise spectrum. The latter has been provided by the user during the conversion with <code>convert_all</code> . See Sec. 3.1.1 for the specifications of the noise spectrum or global signal to noise ratio. dMC='data'. In this case the mock spectrum will be the original data with noise added according to the noise spectrum or the global SNR. Note that with dMC='bestmodel' we expect $\chi^2 \approx 1$ for the MC runs, while in the case dMC='data', we expect $\chi^2 \approx 2$ because the original data already contains noise.
MC_noise=	'yes': mock data is noised according to noise spectrum or global SNR
MC_noise=	'no': mock data is not noised (if mock data is the original data then no extra noise is added, same for best model)

Table 4.1: Options for `sfit` for performing MonteCarlo experiments to test the robustness of the results with respect to noise in the data.

the default first guess is a flat distribution for all fields. This flat first guess has 2 good properties.

- Convergence: the method usually converges to a good solution (in the χ^2 and regularization sense), which is NOT TRUE for all first guesses: in fact, it is fairly easy to come up with a first guess that leads to a secondary minimum with a very bad χ^2 , or which leads to divergence of the minimization method.
- Uniformity

From my own experience using STECKMAP I acquired confidence in the fact that the flat first guess *usually* does a good job. However there is no proof that it is always the best or that it will not sometimes lead to misfits or secondary minima. Note that this is true for all available methods [?, ?]. To cope with this, many authors note the fact that in order to make sure that they reach a “global” minimum and not a secondary minimum, they have to run the fitting engine several times, using a family of first guesses.

Several techniques to vary the first guess have been implemented in `sfit`. They are activated and controlled using the options of Tab. 4.2. They complete the options given in Tab. 4.1, which affect the mock data. The preferred setup for first guess variation experiments should be : `dMC='data',MC_noise='no'`.

A typical call in order to test 5 random bursts as first guesses, fitting the original data (and not some mock data), will look like:

```
x=sfit(a,b,kin=1,noskip=1,sav=1,nMC=5,dMC='data',fg='RB',MC_noise='no')
```

nMC=	number of MC experiments to be performed
fg=	determines the type of first guess to be used for the MC experiments. Three choices are possible:
fg='flat'	will create a flat first guess. This is the default.
fg='RB'	stands for “random burst”. The first guess for the SAD is a single burst at a random age within the ages of the SSP basis. The width of the burst is 3 age bins. The AMR is flat as well with a random metallicity within the Z range of the SSP basis. The color excess is 0 or the NPEC vector is 1 everywhere, depending on the option chosen to deal with extinction, and the BF is a gaussian centered on 0 km/s.
fg='RG'	stands for “random guess”. All fields are randomized. Not very stable. Prefer the 2 first alternatives.

Table 4.2: Options of `sfit` for performing MonteCarlo experiments to test the robustness of the results with respect to variations of the first guess.

4.3.4 Output of MonteCarlo experiments

The results of each experiments are conveniently stored in the `-res.txt` files, using the same format as the non-MC results, so that for a `nMC=5` run, one has 6 SADs, AMRs, etc... At the moment the corresponding first guesses are not stored in a txt file (altho thats the way it should be!). Here are a few lines of example showing how to recover them. In this example all the fields are concatenated and not properly normalized. It is nonetheless enough to see where the first guess SADs peaks.

```
#include "STECKMAP/Pierre/POP/sfit.i"
a=convert_all(fV,z0=0.0021);
b=bRbasis3(,basisfile="MILES");
x=sfit(a,b,noskip=1,kin=1,nMC=5,dMC="data",fg="RB",MC_noise="no",sav=1,meval=500);
// plot the first guesses (all fields concatenated)
upload,a.resfile(1);
ws,1;
plb,RBs;
```

Chapter 5

Tweaking STECKMAP

In some cases you will want to use STECKMAP in a way that was not initially planned by the author. This chapter gives a few tricks and corresponding yorick codes to do so.

5.1 Adding a constraint on the AMR

5.2 Fitting the spectrum with SSPs + power-law

Bibliography

- [1] M. Koleva, P. Prugniel, P. Ocvirk, D. Le Borgne, and C. Soubiran. Spectroscopic ages and metallicities of stellar populations: validation of full spectrum fitting. *MNRAS*, 385:1998–2010, April 2008.

Appendix A

Common emission lines in the optical

Emission lines of a variety of chemical elements are usually seen in optical spectra of galaxies. Here is a compilation of the most common ones. It is not meant to be exhaustive but will help the user to design masks efficiently. Wavelengths are given in the air (**check that!**).

Emission line	Wavelength (air, Å)	Ref.
H α	6563	(2)
H β	4861	(2)
H γ	4340	(2)
H δ	4101	(2)
H ϵ	3970	(2)
H ζ	3889	(2)
HeI	5876	(1)
[O I]	6300	(1)
[O II]	3727	(1)
[O III]	4363	(1)
[O III]	4959	(1)
[O III]	5007	(1)
[N II]	6584	(1)
[N II]	6548	(1)
[Ne III]	3869	(1)
[S II]	6716	(1)
[S II]	6731	(1)

Table A.1: Common emission lines in optical spectra. References: (1): http://www.mpa-garching.mpg.de/SDSS/DR7/raw_data.html, (2): http://en.wikipedia.org/wiki/Balmer_series