User's manual

Hyperz v1.1

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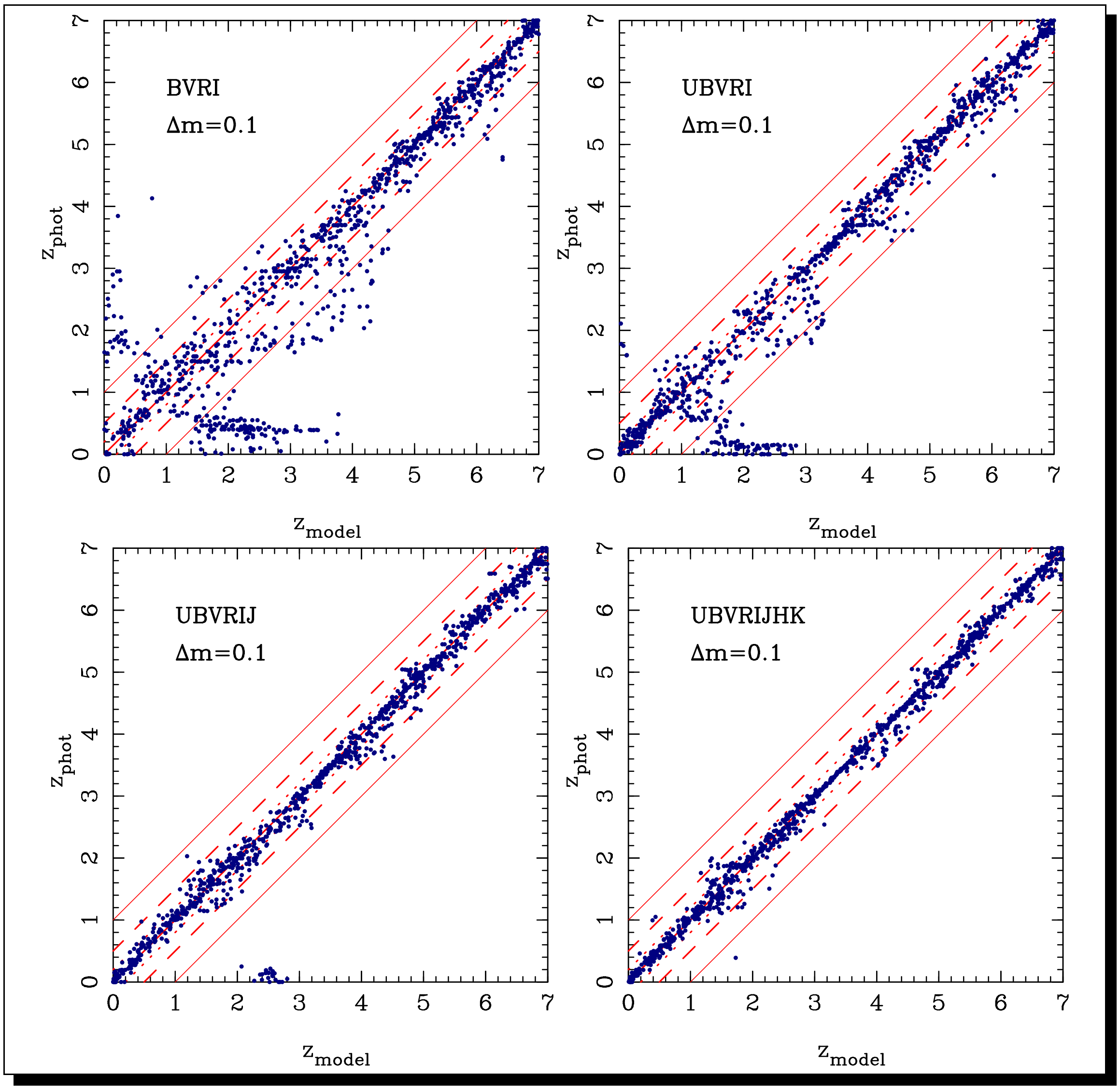

Contents

1 What are photometric redshifts?

The technique of photometric redshifts can boast a relatively long history. Its first applications date back to the sixties, but recently photometric redshifts have experienced a burst of interest because deep multicolour photometric surveys have been carried out, with a large number of objects inaccessible to spectroscopic observations or too time consuming with the available instruments.

Photometric redshifts are an estimate of the redshift of galaxies (or AGNs, quasars) using only large/medium band photometry instead of spectroscopy. The efficiency of the method relies in the identification of spectral breaks, i.e. strong spectral features, still recognizable after the integration of the Spectral Energy Distribution (hereafter SED) below the filter's transmission function. The precision of this estimate is worse than the spectroscopic redshift one, depending on the filters set and on the photometric accuracy, but for many cosmological and extragalactic applications the photometric redshift represents a sufficient information. Thus, the photometric redshift tool can be extensively applied and will rapidly become a crucial tool of observational cosmology. This is the reason inducing us to develop a public code, trying to introduce some improvement in the "classical" method, as the inclusion of the redshift probability distributions and of error bars rather than singular values.

Between the two methods most largely used, the empirical training set (e.g. Connolly et al. 1995, Brunner et al. 1997) and the SED fitting (e.g. Lanzetta et al. 1996, Fernández-Soto et al. 1999) we chose the latter, because of its flexibility when different sets of data are used.

1.1 The SED fitting method

The SED fitting procedure to obtain photometric redshifts is based on the fit of the overall shape of the spectra and on the detection of strong spectral properties. To obtain more secure results, the filter set must be chosen in order to braket some of these features, as the 4000 Å break or the Lyman break at 912 Å. The observed photometric SEDs are compared to those obtained from a set of reference spectra, using the same photometric system. These template SEDs can be either observed or synthetic.

The photometric redshift of a given object corresponds to the best fit of its photometric SED by the set of template spectra, in general through a standard χ^2 minimization procedure. The observed SED of a given galaxy is compared to a set of template spectra:

$$\chi^2(z) = \sum_{i=1}^{N_{\rm filters}} \left[\frac{F_{{\rm obs},i} - b \times F_{{\rm temp},i}(z)}{\sigma_i} \right]^2 , \qquad (1)$$

where $F_{{\rm obs},i}$, $F_{{\rm temp},i}$ and σ_i are the observed and template fluxes and their uncertainty in filter i, respectively, and b is a normalization constant.

A combination of this method with the Bayesian marginalization introducing an *a priori* probability was proposed by Benítez (2000): he demonstrated that in this case the dispersion of z_{phot} can be significantly improved. Despite of this result, we decided to not introduce such type of information, because the application of the Bayesian technique can introduce spurious effects in particular studies. However, this method can be regarded with interest when the goal is some specific application or when one is dealing with poor data, in such a way that the introduction of hints allows to obtain useful results. Alternatively, the photometric redshift estimate can be safely improved introducing the Bayesian inference when prior information is not related to the photometric properties of sources. Examples of such priors that could be combined with the z_{phot} technique are the morphology or the clues inferred from gravitational lensing modeling. In these cases, the user can easily introduce the interesting prior in the Fortran 77 code.

The major advantages of the SED fitting technique are its simplicity and the fact that it does not require any spectroscopic sample. Its weak point is mainly related to the need to choose fiducial spectral templates valid for all objects. We will discuss our choice in the following.

2 The Hyperz package: overview

The public package contains the code to obtain photometric redshifts, called **hyperz** and described in Section 3, as well as a program called **make_catalog**, illustrated in Section 4. The second program is useful to build synthetic photometric catalogues and to carry out tests on the attainable accuracy when recovering the redshift given a filter set and a photometric accuracy (see Bolzonella et al. 2000). There is no difference in the use of **hyperz** between observed and simulated catalogues. Here we report the steps to retrieve and install these programs and the ingredients used to build them. The source files and the binary files containing template SEDs (see later) are available on the web at the address

`http://webast.ast.obs-mip.fr/hyperz`

and mirrored at the addresses `http://www.ifctr.mi.cnr.it/~micol/hyperz` and `http://andorra.astr.tohoku.ac.jp/hyperz` (but check the actual existence of these or new mirrors from the main page). Take care to retrieve the files corresponding to the type of machine you are using: for the source files you have to choose between the IBM version and the default version, working on all other machines. Regarding the binary files, the "big endian" standard works in general under Digital Unix (with the compiler option `-convert big_endian`), SUN, HP, whereas "little endian" binary files have to be downloaded only under Linux system or Digital Unix (without need of compiler options).

2.1 Installation

To extract files, type

```
> gunzip zphot_src_1.1.tar.gz
> tar xvf zphot_src_1.1.tar
> gunzip zphot_big_endian.tar.gz
> tar xvf zphot_big_endian.tar
```

If your machine works with the little endian format for binary files, you have to retrieve the tar file of binary files `zphot_little_endian.tar.gz` instead of the previous one, then

```
> gunzip zphot_little_endian.tar.gz
> tar xvf zphot_little_endian.tar
```

These commands unpack the tar file in a directory named `./ZPHOT/` containing files and subdirectories. Take a look at the `./ZPHOT/src/Makefile` and modify it if needed, according to your compiler and your machine. Now you can compile the Fortran 77 sources typing

```
> cd ./ZPHOT/src
> make hyperz
> make catalog
> make clean
```

In this way you have created the executables **hyperz** and **make_catalog**, that will be automatically copied in the `$HOME/bin` directory (check before "make" and create it if it does not exist). To run the programs from any directory, update your `.login` (`.cshrc`, `.tcshrc` or equivalent) with

```
> source .login
```

after checking the presence of `$HOME/bin` in your login paths.

Both the programs use a parameter file to control input-output data (`zphot.param` and `catalog.param` are the default names). The parameters contained in these files will be detailed in Section 3. Here we will describe one basic ingredient, namely the template SEDs provided with the package, and their handling.

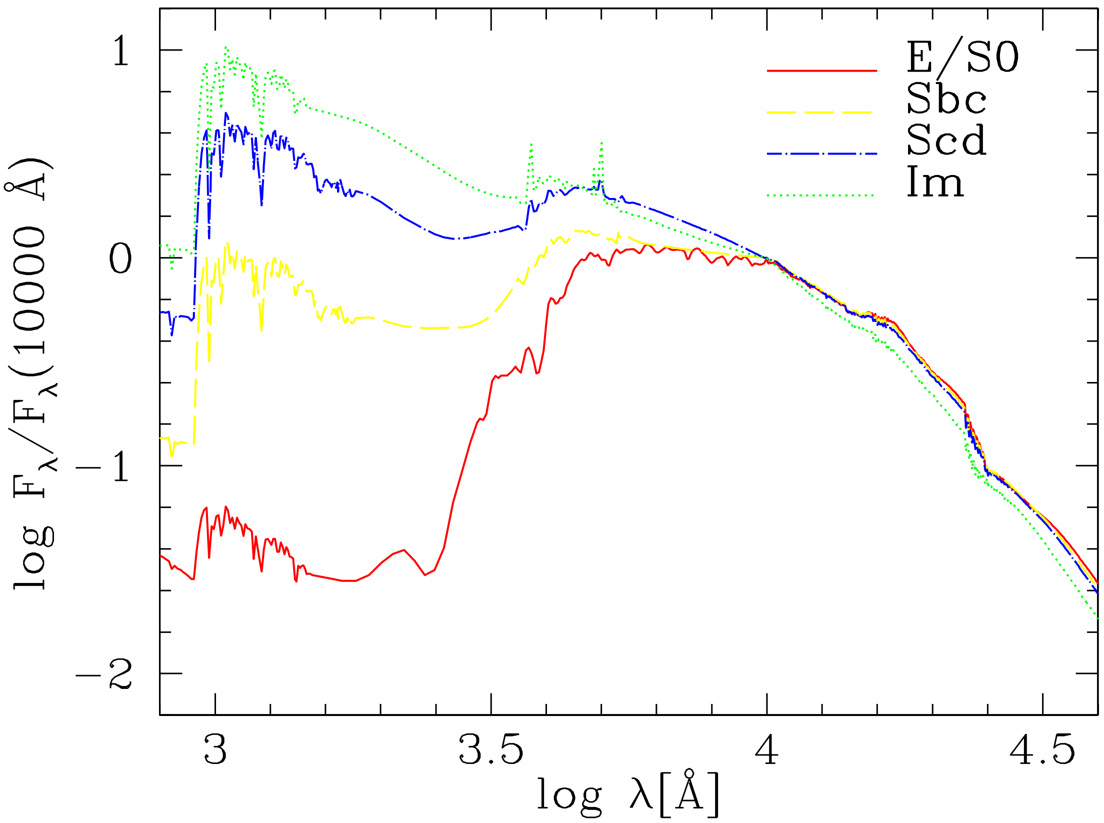

Figure 1: The four CWW mean observed spectra of local galaxies. Because the original data of CWW extend only from 1400 to 10000 Å, we extrapolate the templates at ultraviolet and near-infrared wavelengths using the spectral evolutionary models of Bruzual & Charlot (1993).

2.2 Template SEDs

In the **hyperz** package we provided both observed SEDs and spectral synthesis models, but the set of template SEDs can be changed by the user. The mean spectra of local galaxies from Coleman, Wu & Weedman (1980, hereafter CWW) are the most popular among the observed SEDs. In Figure 1 we show the four CWW template spectra, extended in the UV and IR regions by means of Bruzual & Charlot spectra with parameters (SFR and age) selected to match the observed spectra at $z = 0$. These SEDs are contained in th files

`./ZPHOT/templates/CWW_E_ext.sed`

`./ZPHOT/templates/CWW_Sbc_ext.sed`

`./ZPHOT/templates/CWW_Scd_ext.sed`

`./ZPHOT/templates/CWW_Im_ext.sed`

In the panorama of synthetic spectra we chose the GISSEL98 (Galaxy Isochrone Synthesis Spectral Evolution Library) spectral evolution library of Bruzual & Charlot

IMF	M_1	M_2	x
Salpeter	0.10	125.	1.35
Scalo	0.10	0.18	−2.60
	0.18	0.42	0.01
	0.42	0.62	1.75
	0.62	1.18	1.08
	1.18	3.50	2.50
	3.50	125.	1.63
Miller & Scalo	0.10	1.00	0.25
	1.00	2.00	1.00
	2.00	10.0	1.30
	10.0	125.	2.30

Table 1: Parameters of Salpeter (1955), Scalo (1986) and Miller & Scalo (1979) laws for the IMF: M_1 and M_2 are the lower and higher mass cutoffs, and x is the parameter of the power law.

(1993), because of its easy implementation, good accuracy, spectral coverage from UV to far-IR, and possibility of spectral evolution to high redshift.

The stellar population synthesis models are based on stellar tracks libraries; then, a spectral energy distribution is assigned to all stars on the evolutionary tracks. Then, the Initial Mass Function (IMF) and the Star Formation Rate (SFR) must be specified to follow the evolution of the integrated spectrum.

2.2.1 Initial Mass Function

The IMF $\xi(M)$ specifies the distribution in mass of a newly formed stellar population and it is frequently assumed to be a simple power law: $\xi(M) = c\,M^{-(1+x)}$. In general, $\xi(M)$ is assumed to extend from a lower to an upper cutoff, chosen to be $M_1 = 0.1\,M_\odot$ and $M_2 = 125\,M_\odot$ in GISSEL. In Table 1 we show the parameters of the three most used IMFs: the Salpeter (1955), Scalo (1986) and Miller & Scalo (1979) laws, in the form used by Bruzual & Charlot in their evolutionary synthesis model.

The different slopes of the three considered laws produce different spectral energy distributions: the Scalo and Miller & Scalo laws are flat at small masses and less rich of massive stars with respect to the Salpeter law, as illustrated in Figure 2. The large number of massive stars in the Salpeter law produces an excess of UV flux, whereas the Scalo law generates too many solar mass stars, making the spectrum too red to match the observed colours.

We adopted the Miller & Scalo law as a good compromise. We also tested the influence of a change in IMF, finding a negligible effect in photometric redshift computation (Bolzonella et al. 2000).

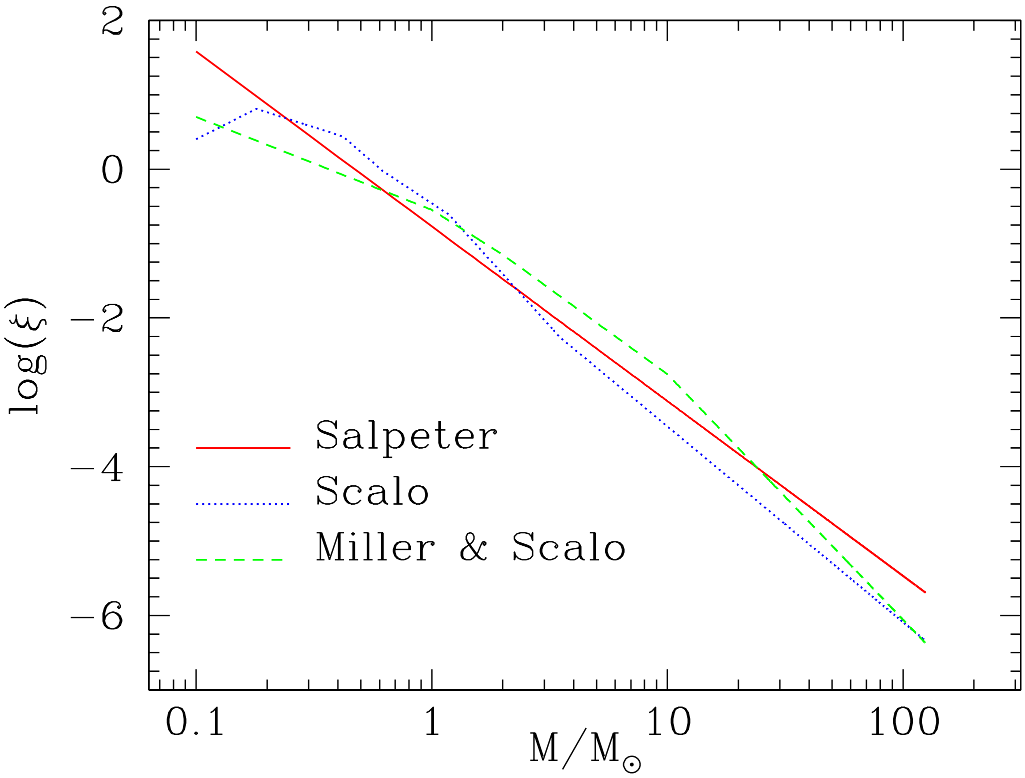

Figure 2: The three IMFs used in the spectral evolutionary models of Bruzual & Charlot (1993).

2.2.2 Star Formation Rate

To build a Composite Stellar Population (CSP) we need the birthrate of stars. The Star Formation Rate depends on the amount of gas converted in stars in the galaxy: $\psi(t) = -\frac{df_{\rm gas}}{dt}$. The Schmidt's (1959) law assumes that the rate of star formation varies with a power n of the density of interstellar gas, $\psi(t) = \psi_0 f^n_{\rm gas} [M_\odot/{\rm yr}]$, with $1 \leq n \leq 2$ (see also Tinsley 1980). Assuming $n = 1$ and a closed-box model (constant total mass) with instantaneous recycling of the gas ejected by the stellar remnants, the Schmidt's law leads to the analytic approximation $\psi(t) \propto \exp(-t/\tau)$, also called μ-model, being $\tau = 1/\psi_0$ the timescale. The integrated spectrum of a stellar population with an arbitrary star formation rate $\psi(t)$ can be obtained from the spectrum of a SSP by means of the convolution integral:

$$f_{\rm CSP}(t) = \int_0^t \psi(t-\tau) f_{\rm SSP}(\tau)\, d\tau$$

assuming that the IMF does not change with time. To reproduce the colours of galaxies of different spectral types, we use the parameters of SFR listed in Table 2: the early galaxies can be matched by a delta burst or by an exponentially decaying SFR with

file	SpT	SFR	Timescale
`./ZPHOT/templates/Burst.ised`	Burst	Single Burst	—
`./ZPHOT/templates/E.ised`	E	Exponential	$\tau = 1$ Gyr
`./ZPHOT/templates/S0.ised`	S0	Exponential	$\tau = 2$ Gyr
`./ZPHOT/templates/Sa.ised`	Sa	Exponential	$\tau = 3$ Gyr
`./ZPHOT/templates/Sb.ised`	Sb	Exponential	$\tau = 5$ Gyr
`./ZPHOT/templates/Sc.ised`	Sc	Exponential	$\tau = 15$ Gyr
`./ZPHOT/templates/Sd.ised`	Sd	Exponential	$\tau = 30$ Gyr
`./ZPHOT/templates/Im.ised`	Im	Constant	—

Table 2: Characteristics of the SFR adopted to match the SEDs of different spectral types of observed galaxies.

$\tau = 1\,$Gyr, S0 and Spiral galaxies are well reproduced by a Schmidt law with timescales ranging from 2 and 30 Gyr, and the Irregulars can be represented by a constant SFR.

In Figure 3 we show the evolution of the SEDs for 6 of the considered spectral types. The CSP are built with the GISSEL98 library, with Miller & Scalo IMF, solar metallicity and different SFRs, as in Table 2. The represented ages range from $10^6\,$yr to $2 \times 10^{10}\,$yr: we can remark that at the younger ages all the SEDs resemble each other, whereas they start to differentiate at ages $\gtrsim 10^7\,$yr, when the 4000 Å break becomes detectable. Moreover it is evident that the size of the 4000 Å break is much more conspicuous for earlier types.

2.2.3 Metallicity

The effect of the metallicity parameter is to produce redder colours by increasing the amount of metals contained in the galaxy. Because the same colour effect can be reproduced changing the age or the reddening of the galaxy itself, the metallicity can be regarded as a secondary parameter in the construction of the reference SEDs. Therefore, we decided to use prevalently the synthesis models with a fixed metallicity, set equal to the solar metallicity: $Z = Z_\odot \simeq 0.02$, with Z the mass fraction of heavy elements in the interstellar gas.

We explored the effect of considering different extreme metallicities provided by GISSEL98 and template SEDs with metallicity evolution. To this goal we used the approximation of the closed-box model, considering the ejection of heavy elements from each generation of stars, without assuming the instantaneous recycling hypothesis. The tests we carried out (Bolzonella et al. 2000) confirm that the metallicity can be regarded as a secondary parameter. In any case, the files containing SEDs with evolving metallicities can be found in the tar files `zphot_big_endian_evol_MiSc.tar.gz` and `zphot_little_endian_evol_MiSc.tar.gz`.

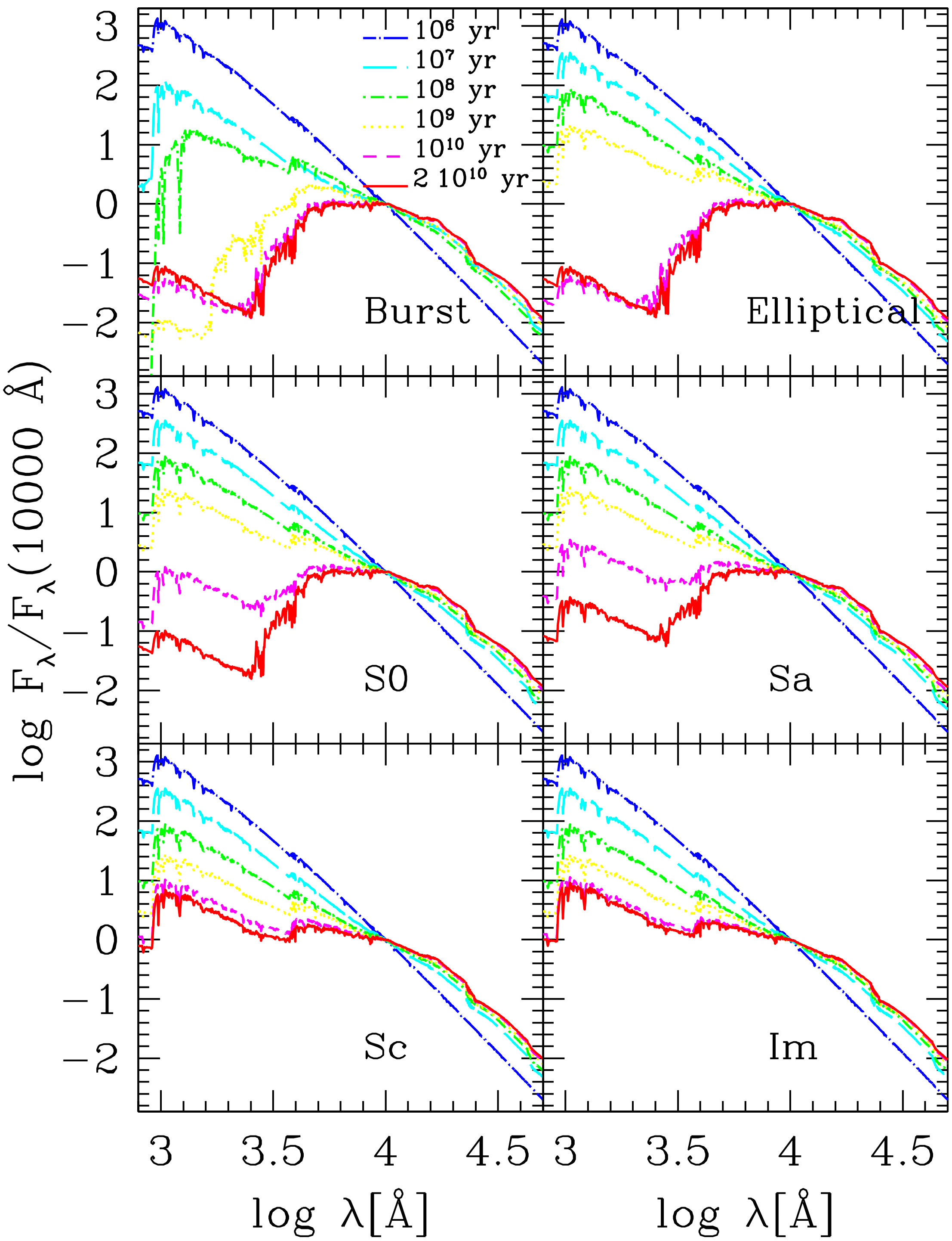

Figure 3: Evolution of the SEDs of different spectral types computed using the spectral evolutionary models of Bruzual & Charlot (1993), with Miller & Scalo IMF, solar metallicity and characteristics of the SFR as shown in Table 1.

2.3 Reddening

Recent studies on high redshift galaxies and star formation obscured by dust have shown the importance of the reddening in the high-z universe. Therefore, another effect that must be taken into account is dust extinction, produced inside the galaxies themselves.

The five reddening laws presently implemented in **hyperz** are:

1. Allen (1976) for the Milky Way (MW);

2. Seaton (1979) fit by Fitzpatrick (1986) for the MW;

3. Fitzpatrick (1986) for the Large Magellanic Cloud (LMC);

4. Prévot et al. (1984) and Bouchet et al. (1985) for the Small Magellanic Cloud (SMC);

5. Calzetti et al. (2000) for starburst galaxies.

The different laws normalized to $k(B) - k(V) = 1$, are presented in Figure 4. The input value is A_V, corresponding to a dust-screen model, with

$$f_{\rm obs}(\lambda) = f_{\rm int}(\lambda) 10^{-0.4 A_\lambda} \,,$$

where $f_{\rm obs}$ and $f_{\rm int}$ are the observed and the intrinsic fluxes, respectively. The extinction at a wavelength λ is related to the colour excess $E(B-V)$ and to the reddening curve $k(\lambda)$ by

$$A_\lambda = k(\lambda) E(B-V) = \frac{k(\lambda) A_V}{R_V} \,,$$

with $R_V = 3.1$ except for the Small Magellanic Cloud ($R_V = 2.72 \pm 0.21$) and Calzetti's law ($R_V = 4.05 \pm 0.80$).

In detail, Allen's law for the MW is computed from the values of $k(\lambda)/R_V$ tabulated in Table 3. At shorter and longer wavelengths we extrapolate the slope from the last available points. For Seaton's law, we adopt the fit presented by Fitzpatrick (1986), that follows the same relation found by the same author for the LMC:

$$\begin{aligned} \frac{E(\lambda - V)}{E(B-V)} &= C_1 + C_2 \lambda^{-1} + \frac{C_3}{\left[\lambda^{-1} - \frac{(\lambda_0^{-1})^2}{\lambda^{-1}}\right] + \gamma^2} \\ &+ C_4 \left[0.539(\lambda^{-1} - 5.9)^2 + 0.0564(\lambda^{-1} - 5.9)^3\right] \end{aligned}$$

with λ in μm. The two laws, for the MW and the LMC, are different in the coefficient values:

	$\lambda_0^{-1}[\mu\mathrm{m}^{-1}]$	$\gamma[\mu\mathrm{m}^{-1}]$	C_1	$C_2[\mu\mathrm{m}]$	$C_3[\mu\mathrm{m}^{-2}]$	$C_4[\mu\mathrm{m}^{-1}]$
MW	4.595	1.051	−0.38	0.74	3.96	0.26
LMC	4.608	0.994	−0.69	0.89	2.55	0.50

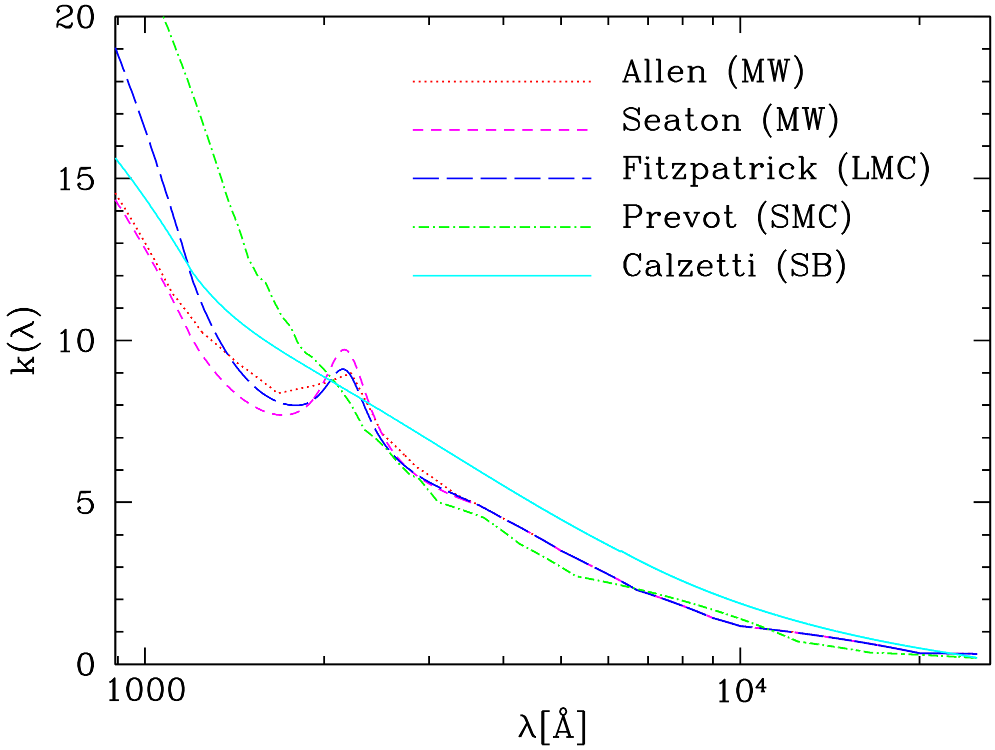

Figure 4: Extinction curves $k(\lambda)$ for the different reddening laws implemented in **hyperz**.

whereas $C_4 = 0$ for $\lambda^{-1} < 5.9\,\mu\mathrm{m}^{-1}$ in any case. Because the validity of these laws is limited to $\lambda^{-1} < 8.3\,\mu\mathrm{m}^{-1}$, i.e. $\lambda > 1200\,$Å, we extrapolated the slope at shorter wavelengths from the 1100 – 1200 Å range. At wavelengths longer than 3650 and 3330 Å respectively for the two quoted laws, we adopt the points from Allen, to avoid $k(\lambda)$ being too flat in the red and near-IR regions.

The points used to compute the law for the SMC are taken from Prévot et al. (1984) and Bouchet et al. (1985) and are listed in Table 3. The peculiarity of this law is the lack of the graphite 2175 Å bump. The non detection of this bump is probably related to the large underabundance of carbon in the SMC. As for Allen's law, we made an extrapolation from the slope computed from the available points.

The most used attenuation curve in high-redshift studies is the law derived by Calzetti et al. (2000). They derived a law as a purely empirical result from a sample of near starburst (SB) galaxies. Again, the most prominent feature of the MW law is absent: this characteristic suggests that starburst galaxies contain SMC-like dust grains, being the 2175Å bump an excellent probe of the type of dust in a galaxy. From Calzetti et al. (2000) we have:

$$k(\lambda) = \begin{cases} 2.659\left(-2.156 + \frac{1.509}{\lambda} - \frac{0.198}{\lambda^2} + \frac{0.011}{\lambda^3}\right) + R_V & 0.12\,\mu\mathrm{m} \le \lambda \le 0.63\,\mu\mathrm{m} \\ 2.659\left(-1.857 + \frac{1.040}{\lambda}\right) + R_V & 0.63\,\mu\mathrm{m} \le \lambda \le 2.20\,\mu\mathrm{m} \end{cases}$$

λ[Å]	$k(\lambda)/R_V$	λ[Å]	$k(\lambda)/R_V$
1000.	4.20	3650.	1.58
1110.	3.70	4000.	1.45
1250.	3.30	4400.	1.32
1430.	3.00	5000.	1.13
1670.	2.70	5530.	1.00
2000.	2.80	6700.	0.74
2220.	2.90	9000.	0.46
2500.	2.30	10000.	0.38
2850.	1.97	20000.	0.11
3330.	1.69	100000.	0.00

λ[Å]	$\frac{E(\lambda-V)}{E(B-V)}$	λ[Å]	$\frac{E(\lambda-V)}{E(B-V)}$	λ[Å]	$\frac{E(\lambda-V)}{E(B-V)}$
1275.	13.54	1810.	7.17	2778.	3.15
1330.	12.52	1860.	6.90	2890.	3.00
1385.	11.51	1910.	6.76	2995.	2.65
1435.	10.80	2000.	6.38	3105.	2.29
1490.	9.84	2115.	5.85	3704.	1.81
1545.	9.28	2220.	5.30	4255.	1.00
1595.	9.06	2335.	4.53	5291.	0.00
1647.	8.49	2445.	4.24	12500.	-2.02
1700.	8.01	2550.	3.91	16500.	-2.36
1755.	7.71	2665.	3.49	22000.	-2.47

Table 3: *Left*: Values of $k(\lambda)/R_V$ for the MW reddening law from Allen (1976). *Right*: Values of $E(\lambda - V)/E(B - V)$ for the SMC reddening law from Prévot et al. (1984) and Bouchet et al. (1985).

with $R_V = 4.05$. Below the validity wavelength range, we obtain the slope of the reddening law by interpolating $k(\lambda)$ at 1100 and 1200 Å. In a similar way, we compute the slope at $\lambda > 22000$ Å from the values at 21900 and 22000 Å.

In particular, the application of this law is suggested for the central star-forming regions of galaxies, and then for high-z galaxies. For this reason, Calzetti's law is used to correct the value of the SFR at high-redshift, as seen in the previous chapter. It is evident from Figure 4 that the UV region of the spectrum will be more affected by dust. As a consequence, taking extinction into account is of paramount importance for galaxies at $z \gtrsim 3$, when the rest frame UV emission is shifted to optical wavelengths.

Similarly, but in the opposite way, an extinction curve and a value of the colour excess can be used to deredden the magnitudes of objects seen through the dust of the Milky Way. see next section with parameters description

2.4 Lyman forest

The spectra of high redshift galaxies suffer of a drop in flux below Lyα at $\lambda = 1216$ Å and a further decline below Lyβ, at $\lambda = 1026$ Å. These drops are attributed to absorbing neutral hydrogen clouds at different redshifts between the source and the observer, forming the so-called Lyman forest in the spectra of high redshift objects.

Oke & Korycansky (1982), studying a sample of high redshift QSOs, defined two depression factors, D_A and D_B, characterizing the amount of absorption between Lyα and Lyβ and between Lyβ and the Lyman limit respectively: $D_A = 1 - f_{\rm obs}(\lambda)/f_{\rm int}(\lambda)$, where $f_{\rm obs}(\lambda)$ and $f_{\rm int}(\lambda)$ are the observed and intrinsic fluxes per unit wavelength in the QSO restframe. D_B is defined in the same way as D_A. We adopted the estimates given by Madau (1995) for the attenuation of the continuum due to line blanketing as

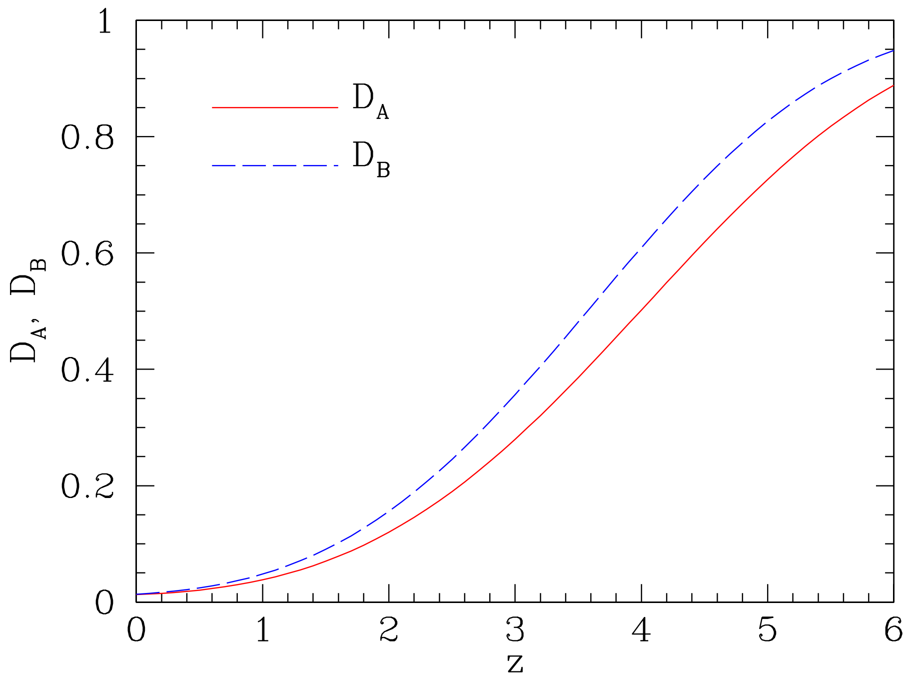

Figure 5: The depression factors D_A and D_B as function of redshift, computed by means of equations 2 and 3 prescribed by Madau (1995).

a function of redshift. He found the flux decrements averaged over all the lines of sight to be

$$\langle D_A \rangle = 1 - \frac{1}{\Delta\lambda_A} \int_{1050(1+z_{\rm em})}^{1170(1+z_{\rm em})} \exp\left[-A_2 \left(\frac{\lambda_{\rm obs}}{\lambda_\alpha} \right)^{3.46} \right] d\lambda_{\rm obs} \tag{2}$$

$$\langle D_B \rangle = 1 - \frac{1}{\Delta\lambda_B} \int_{920(1+z_{\rm em})}^{1015(1+z_{\rm em})} \exp\left[-\sum_{j=3,11} A_j \left(\frac{\lambda_{\rm obs}}{\lambda_j} \right)^{3.46} \right] d\lambda_{\rm obs} \, , \tag{3}$$

where $\Delta\lambda_A = 120(1 + z_{\rm em})$ Å and $\Delta\lambda_B = 95(1 + z_{\rm em})$ Å. The coefficient A_2 relative to the Lyα forest contribution is equal to 3.6×10^{-3}. The main contribution to $\langle D_B \rangle$, representing the flux decrement caused by all Lyman series lines, belongs to Lyβ, Lyγ ($\lambda = 973$ Å) and Lyδ ($\lambda = 950$ Å), whose coefficients are $A_3 = 1.7 \times 10^{-3}$, $A_4 = 1.2 \times 10^{-3}$ and $A_5 = 9.3 \times 10^{-4}$. Figure 5 shows the depression factors D_A and D_B as computed from equations 2 and 3. The fact that $D_B > D_A$ implies that Lyβ and higher order lines contribute significantly to line blanketing. We have applied Madau's prescriptions to compute the opacity of IGM through the mean factors $\langle D_A \rangle$ and $\langle D_B \rangle$, whereas we approximated the Lyman continuum absorption setting $f_{\rm obs}(\lambda) = 0$ for both observed and synthetic SEDs below $\lambda_{\rm L}$, where $\lambda_{\rm L} = 912$ Å is the Lyman limit.

3 Hyperz: Getting started

This code was originally developed by Pelló et al. (1996) and Miralles (1998) . Then, it has been improved, generalized, modified to allow a friendly I/O of data and exhaustively tested (Bolzonella et al. 2000) to reach the present public version.

In the following of this section we will describe the procedure followed by **hyperz** and the meaning of all the parameters involved in the computation.

To start, you simply have to type

```
> hyperz
```

and the program will ask you the name of the main parameter file, which default is `zphot.param`:

```
hyperz photometric redshift code - Version 1.1 (December 11, 2000)
by Micol Bolzonella, Roser Pello', Joan-Marc Miralles
More information at http://webast.ast.obs-mip.fr/hyperz/

Name of parameter file
[default = zphot.param]
```

After entering the name of your parameter file, or pushing "return" if the name corresponds to the default, the program will notify you the status of input files, i.e. the number of SEDs you required, the number of filters and of objects read from the catalogue and eventually it will report error messages in case of problems reading some input file. For instance:

```
Reading parameter file :
There are 5 synthetic spectra
There are 5 filters
There are 1000 objects in the catalogue
Reading reference sed:
ID: Kurucz's model for Alpha Lyrae.  9400K BB interpolation 1.8-200 microns

There are 3303 points in Vega
Reading synthetic spectra :
Type 1 :  /home/mbolzone/ZPHOT/templates/Burst.ised
Type 2 :  /home/mbolzone/ZPHOT/templates/E.ised
Type 3 :  /home/mbolzone/ZPHOT/templates/Sa.ised
Type 4 :  /home/mbolzone/ZPHOT/templates/Sc.ised
Type 5 :  /home/mbolzone/ZPHOT/templates/Im.ised
Building hypercube ...
                      ...  done
```

```
CPU time involved :  384.940002 seconds
I'm working ...
Done !!!
Total CPU time involved :  749.229996 seconds
```

The hypercube computation (see the next section) will take from some seconds to some minutes, the CPU time depending on your template choice, on the number of redshift and reddening steps, in addition to the clock of your machine.

3.1 Procedure

The procedure followed in the code **hyperz** is illustrated in Figure 6. The first step consists in reading the observed magnitudes, with the corresponding errors and the limiting magnitudes for non detected objects. Take care that to obtain reliable results, the photometry must be carried out in all filters within the same aperture, i.e. the flux must be belong to the same physical region. If requested, a dereddening for the Galactic extinction is applied to the photometric catalogue. Hence the magnitudes and the errors are transformed in fluxes. On the other side, there is the handling of the template SEDs. The program builds an *hypercube*, consisting of the fluxes derived from the reference spectra in the following way. If the spectra are taken from the GISSEL library they consist of 221 age records. To save CPU time and memory, **hyperz** provides a rebinning, to reduce the number of considered ages to 51, with the values showed in Table 4. In the "standard" configuration 5 spectral types are considered, corresponding to the Burst, E, Sa, Sc and Im illustrated in the previous section. More SEDs can be redundant. The spectra are reddened following an extinction law chosen from those listed in Section 2.3, and then depressed with the Lyman forest, according to the considered redshift step. At this point, the spectra are convolved with the filter response functions (plus detector if needed, see Section A), to obtain the expected fluxes.

After the *hypercube* construction, the program proceeds with the χ^2 calculation, considering all redshifts, spectral types, ages and absorption values. Minimizing the reduced χ^2 the program finds the better photometric redshift solution and the corresponding SED. Different output files can be chosen by the user, containing different informations, as the best $z_{\rm phot}$, the observed SEDs (mean fluxes and errors), the best-fit integrated SEDs and spectra, the minimum χ^2 as a function of redshift and the secondary solutions.

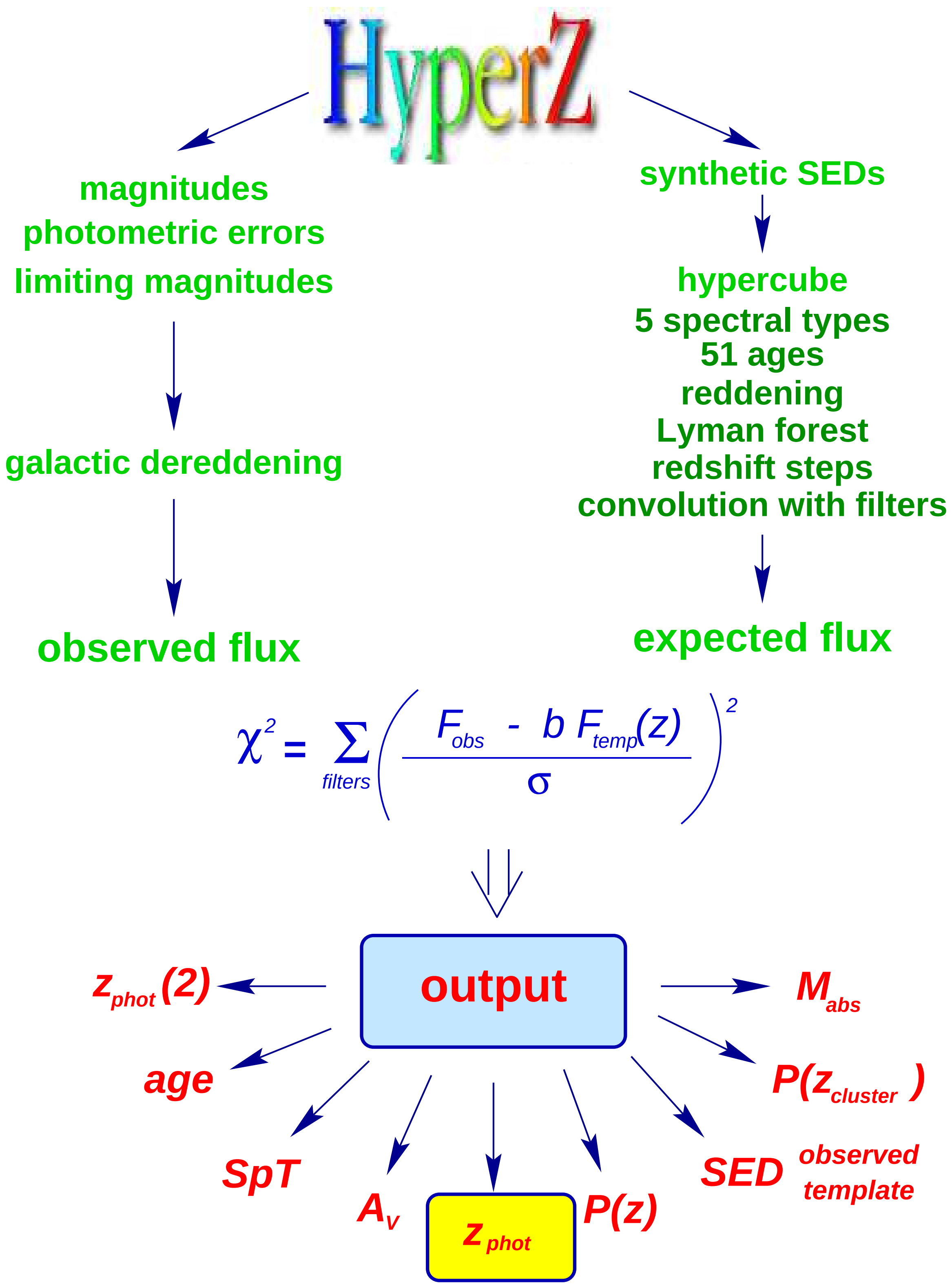

Figure 6: Flow-chart representing how **hyperz** works in its standard configuration.

n	age [Gyr]	n	age [Gyr]	n	age [Gyr]	n	age [Gyr]
1	0.00032	14	0.02630	27	0.50880	40	8.50000
2	0.00100	15	0.03000	28	0.71870	41	9.50000
3	0.00158	16	0.03300	29	1.01519	42	10.5000
4	0.00251	17	0.03600	30	1.43400	43	11.5000
5	0.00398	18	0.03900	31	1.70000	44	12.5000
6	0.00631	19	0.04500	32	2.00000	45	13.5000
7	0.01000	20	0.05250	33	2.30000	46	14.5000
8	0.01148	21	0.06405	34	2.60000	47	15.5000
9	0.01318	22	0.09048	35	3.50000	48	16.5000
10	0.01514	23	0.12780	36	4.50000	49	17.5000
11	0.01738	24	0.18053	37	5.50000	50	18.5000
12	0.01995	25	0.25500	38	6.50000	51	19.5000
13	0.02291	26	0.36020	39	7.50000		

Table 4: Ages corresponding to the 51 records selected from the 221 available in the GISSEL library.

3.2 Parameters

In this section we will describe in detail the input and output files involved in the procedure of **hyperz**, with an exhaustive description of all parameters contained in `zphot.param` and an example of these files.

3.2.1 Inputs

The file `zphot.param` contains the following input parameters for **hyperz**:

- `AOVSED`: the file-path containing the spectrum of Vega;
- `FILTERS_RES`: the file-path containing the filter transmission functions;
- `FILTERS_FILE`: the file containing information about filters. The first column is the identification number of each filter in the file `FILTER.RES`. The user can check it in the file `filters.log` (see Section A). If the user wants a combination of several filters, e.g. n_1 (filter) and n_2 (detector), write $n_1\&n_2$ in the first column. When the magnitude system is different from the standard Vega or AB, the second column contains the correction (in magnitudes): $m_{\rm Vega} = m_{\rm cat} + m_{\rm corr}$. When the magnitude system is the standard Vega or AB, $m_{\rm corr} = 0$. The user can specify the magnitude system AB using the `MAG_TYPE` parameter. See Fukugita et al. (1995) for typical correction values. Also, when using the Thuan-Gunn system (based on the standard BD+17 4708):

$$
\begin{array}{rclcl}
g(\text{Vega}) & = & g(\text{TG}) & + & 0.201 \\
r(\text{Vega}) & = & r(\text{TG}) & - & 0.401 \\
i(\text{Vega}) & = & i(\text{TG}) & - & 0.672 \\
z(\text{Vega}) & = & z(\text{TG}) & - & 0.762
\end{array}
$$

The third column is the rule applied in the case of undetected objects:

0. This filter will not be taken into account in the computation.

1. The flux in this filter is set to $F_{\rm obs} = 0$ with an error corresponding to the flux deduced from the limiting magnitude in the fourth column, i.e. $\Delta F_{\rm obs} = F_{\rm lim}$.

2. The flux in this filter and the associated 1σ error are set equal to $F_{\rm lim}/2$.

3. The flux in this filter and the associated error are computed from the limiting magnitude $m_{\rm lim}$ and from the error $\Delta m_{\rm lim}$ given in columns four and five, respectively.

Undetected objects in a filter i are characterized by a magnitude $m(i) > 90$ [in general $m(i) = 99$, following the convention of the photometric software `SExtractor` (Bertin & Arnouts 1996)]. "Out of field" objects, for which the photometry is not available, must be characterized by a magnitude $m(i) < 1$ (in general $m(i) = 0$); in this way the filter "out of field" is not taken into account in the χ^2 minimization procedure.

The fourth column gives the limiting magnitude $m_{\rm lim}(i)$ in each filter i. The fifth column is the error value in magnitudes, $\Delta m_{\rm lim}(i)$, that will be attributed to undetected objects when option 3 is selected in column three. Lines beginning with a # or blank lines are not considered.

- `TEMPLATES_FILE`: the name of the file containing the path of templates that the user wants to use and their type (`BC` = Bruzual & Charlot, binary, `AS` = ASCII); the user can select or unselect a template by placing or removing a # as the first character in the `spectra.param` file. The correct path of templates must be checked by the user.

  The present library consists of 8 synthesis template SEDs with solar metallicity and Miller & Scalo IMF presented in Section 2.2.1, and 4 spectra from CWW and extended in UV and near-IR with the GISSEL98 library. This set of templates can be changed by the user.

- `FILT_M_ABS`: the filter number (to be checked in the file `filters.log`, as before) for the absolute magnitude estimate (Vega magnitudes; with k-correction only).

- ERR_MAG_MIN: the value of the photometric error which is set if the input error from the catalogue is < ERR_MAG_MIN, to avoid too small and non-realistic photometric errors. It is worth to note that SEDs computed from a catalogue are "absolute", in the sense that errors should include ALL the possible sources (air-mass, photometric zero-points, background noise, etc.).

- Z_MIN and Z_MAX: the limits of the redshift range the user wants to investigate. These parameters are connected to CATALOG_TYPE: if CATALOG_TYPE = 0, these limits are set for all the objects in the catalogue; if CATALOG_TYPE = 1, the limits are set individually for each object.

- Z_STEP: the step in redshift used in the first estimate of best fit. After the first minimization, the candidate solutions are refined with a step Z_STEP/10 to search for smaller χ^2.

- ZSTEP_TYPE: the option for the type of step in redshift: if ZSTEP_TYPE = 0 the step is constant and equal to Z_STEP, if ZSTEP_TYPE = 1 the step is evolving as Z_STEP $\times(1+z)$. The latter is preferable if the user wants to better investigate the low redshifts region without increasing the total number of steps and consequently the CPU time.

- CATALOG_TYPE: must be set to 0 if the input catalogue has the format:

  $$\texttt{id},\ [m(i), i=1, n_{\rm filt}],\ [\Delta m(i), i=1, n_{\rm filt}]$$

  where id is the identification number, $m(i)$ are the observed magnitudes, $\Delta m(i)$ are the corresponding photometric errors and $n_{\rm filt}$ the number of filters. CATALOG_TYPE must be set to 1 if the format is

  $$\texttt{id},\ z_{\rm min},\ z_{\rm max},\ [m(i), i=1, n_{\rm filt}],\ [\Delta m(i), i=1, n_{\rm filt}]$$

  with a redshift range $(z_{\rm min}, z_{\rm max})$ that can be different for each object. In the latter case the values of Z_MIN and Z_MAX are not taken in account.

- CATALOG_FILE: the name of the input photometric catalogue.

- MAG_TYPE: the type of magnitude used in the catalogue: 0 for standard magnitudes (Vega system or others, see FILTERS_FILE), 1 for AB magnitudes.

- REDDENING_LAW: the law for internal reddening (see Section 2.3):

  0. No reddening

  1. MW from Allen (1976);

  2. MW from Seaton (1979);

  3. LMC from Fitzpatrick (1986);

4. SMC from Prévot et al. (1984) and Bouchet et al. (1985);

5. Starburst galaxies from Calzetti et al. (2000).

- `AV_MIN`, `AV_MAX` and `AV_STEP`: the values of the maximum and minimum absorption in the V band (in magnitudes) and the value of the computation step to cover the range. If `REDDENING_LAW` $= 0$, these values are not taken in account.

- `AGE_CHECK`: the option for the control of age as a function of redshift: if this parameter is set equal to `y` or `Y` the program checks that the age of the template is less than the age of the universe (for a cosmological model assigned with `H0`, `OMEGA_M` and `OMEGA_V`) at the redshift under consideration.

- `PROB_THRESH`: the minimum value of the probability (inferred from the reduced χ^2 analysis) for the study of secondary maxima. The range of permitted values is 0 – 100.

- `OUTPUT_FILE`: the name of output files (without extension).

- `SED_OBS_FILE`, `SED_TEMP_FILE`, `LOGPHOT_FILE`, `ZPHOT_FILE` and `CATPHOT_FILE` are the options `y/n` for the output files containing:

  – `OUTPUT_FILE.obs_sed`: the observed SEDs, given as the mean integrated fluxes through the photometric system, and the corresponding errors (units selected by `OUTPUT_TYPE`).

  $$\texttt{id},\ [F_{\rm obs}(i), i = 1, n_{\rm filt}],\ [\Delta F_{\rm obs}(i), i = 1, n_{\rm filt}]$$

  – `OUTPUT_FILE.temp_sed`: the best fit integrated SEDs (same units).

  $$\texttt{id},\ [F_{\rm temp}(i), i = 1, n_{\rm filt}]$$

  – `OUTPUT_FILE.log_phot`: the best fit parameters as a function of the redshift, with steps defined by `Z_STEP`:

  $$\texttt{id},\ z_{\rm step},\ \chi^2_\nu(z_{\rm step}),\ P(\chi^2_\nu),\ \texttt{SpT},\ \texttt{age [Gyr]},\ A_V$$

  where $z_{\rm step}$ is the redshift step, $\chi^2_\nu(z_{\rm step})$ is the minimum reduced χ^2 corresponding to the considered redshift, $P(\chi^2_\nu)$ is the probability associated to the value of χ^2_ν and the degrees of freedom involved (see Table 5), `SpT`, `age [Gyr]` and A_V are the spectral type, the age and the reddening of the SED corresponding to the minimum χ^2. The χ^2_ν is defined by χ^2/ν, where ν is the number of degrees of freedom. Because we are interested in only one parameter (the photometric redshift), the degrees of freedom are $n_{\rm filt} - 1$, subtracting the degree of freedom lost with the normalization b in equation 1.

  – `OUTPUT_FILE.z_phot`: the best fit redshift and corresponding parameters for each object:

ν	$P = 0.99$	0.95	0.90	0.75	0.68	0.50
1	0.00016	0.00393	0.0158	0.1015	0.170	0.455
2	0.0100	0.0515	0.105	0.288	0.386	0.693
3	0.0383	0.117	0.195	0.404	0.503	0.789
4	0.0742	0.178	0.266	0.481	0.576	0.839
5	0.111	0.229	0.322	0.535	0.626	0.870
6	0.145	0.273	0.367	0.576	0.663	0.891
7	0.177	0.310	0.405	0.608	0.691	0.907
8	0.206	0.342	0.436	0.634	0.713	0.918
9	0.232	0.369	0.463	0.655	0.732	0.927
10	0.256	0.394	0.487	0.674	0.747	0.934

Table 5: Values of the reduced χ^2 corresponding to the probability $P(\chi^2|\nu)$ of exceeding the value χ^2 by chance, as a function of the number of degrees of freedom ν.

`id`, $z_{\rm phot}$, χ^2_ν, $P(\chi^2)$, `SpT`, $N_{\rm age}$, `age [Gyr]`, A_V, b $z_{\rm inf}(99\%)$, $z_{\rm sup}(99\%)$, $z_{\rm inf}(90\%)$, $z_{\rm sup}(90\%)$, $z_{\rm inf}(68\%)$, $z_{\rm sup}(68\%)$, $z_{\rm wm}$, $P(\chi^2_{\rm wm})$, $M_{\rm abs}$, $z_{\rm phot}(2)$, $P[\chi^2(2)]$

where $z_{\rm phot}$ is the redshift corresponding to the minimum χ^2, $N_{\rm age}$ is the age record number, as listed in Table 4, followed by the other SED characteristics corresponding to the best fit spectrum. $z_{\rm inf}$ and $z_{\rm sup}$ are the extrema of confidence intervals defined by the $\Delta\chi^2$ method, being the number of "interesting parameters" equal to 1, i.e. the photometric redshift. In this case the values of $\Delta\chi^2$ defining the confidence intervals at 99%, 90% and 68% are 1.00, 2.71 and 6.63 respectively (Avni 1976). The other quantities are the weighted mean $z_{\rm wm}$, computed in the confidence interval at 99% around the main solution, the associated probability, the Vega absolute magnitude $M_{\rm abs}$ in the `FILT_M_ABS` filter. $z_{\rm phot}(2)$ and $P[\chi^2(2)]$ are the secondary solution and its χ^2 probability.

If the user switches on the `Z_CLUSTER` option three columns are added: the absolute magnitude in the `FILT_M_ABS` filter if the object is at `Z_CLUSTER`, the probability at `Z_CLUSTER` and the apparent magnitude in the redshifted filter closest to `FILT_M_ABS` (used to estimate the absolute magnitude).

- `OUTPUT_FILE.cat_phot`: the best fit and secondary solutions (if any) for each object. `CATPHOT_FILE` contains `ZPHOT_FILE`, and it has the same format, without the columns regarding the secondary solution and the cluster option, and with an additional column to display the solution rank.

Note that looking at the `OUTPUT_FILE.log_phot` file the user can find that the secondary maximum has a higher probability than the first one. This is because of the refinement around the χ^2 minima: the main photometric redshift and the secondary solution are written after the refinement, whereas the file `OUTPUT_FILE.log_phot` contains probabilities before the refinement, with the step `Z_STEP`. After refinement, some solutions can change their rank in the solution classification.

- `OUTPUT_TYPE` : selects the flux units for the output SEDs in files with extension `.spe`, `.temp_sed` and `.obs_sed`:

  0. 2×10^{-17}erg/cm^2/s/Å;

  1. μJy;

  2. AB magnitudes.

- `OMEGA_M`: the matter density parameter; used if the age check is switched on and for absolute magnitude computation.

- `OMEGA_V`: the cosmological constant density parameter; used if the age check is switched on and for absolute magnitude computation.

- `H0`: the Hubble constant; used if the age check is switched on and for absolute magnitude computation.

- `Z_CLUSTER`: optional parameter; if the user selects this option, the program computes the probability of each object to lie at `Z_CLUSTER` and writes it in the `.z_phot` file.

- `M_ABS_MIN`: optional parameter; the minimum absolute magnitude (bright).

- `M_ABS_MAX`: optional parameter; the maximum absolute magnitude (faint).

- `MATRIX`: optional parameter. The user can choose `y/Y` or `n/N` (default is `n`): if the user selects `y/Y` the program will write for each object a file `#id.m` containing the χ^2 value over the parameter space:

  `id`, z, `SpT`, $N_{\rm age}$, `age [Gyr]`, A_V, χ^2.

  If the catalogue contains more than 100 objects the program asks to confirm, because these are large files.

- `SPECTRUM`: optional parameter as `MATRIX`. If the user chooses `y/Y` (default is `n`), files named `#id.spe` containing the spectrum of the best fit model $\lambda, F(\lambda)$ are written for each galaxy.

- `EBV_MW`: optional parameter. The colour excess $E(B-V)$ for the galactic dereddening of data (default is `EBV_MW` $= 0$). The reddening law used for the dereddening is number 1 (Allen 1976).

The file `OUTPUT_FILE.out_phot` is a fixed output, summarizing the main parameters used running **hyperz**:

- the name of the photometric catalogue file;
- the name and associated number of template files;
- the characteristics of filters:
  - `n` is the number of filter in the file `FILTER.RES`;
  - `wl_eff` is the effective wavelength of the filter, computed as:

    $$\lambda_{\rm eff} = \frac{\int \lambda R(\lambda)\, d\lambda}{\int R(\lambda)\, d\lambda}\,,$$

    where $R(\lambda)$ is the filter transmission normalized at $R_{\rm max} = 1$;
  - `surface` is the integral of the normalized filter transmission:

    $$S = \int R(\lambda)\, d\lambda\,;$$

  - `bandpass1` is the effective bandpass computed with a Gaussian approximation:

    $$\Delta\lambda = 2\sqrt{\frac{\int (\lambda - \lambda_{\rm eff})^2 R(\lambda)\, d\lambda}{S}}\,;$$

  - `conv_AB` is the conversion between AB and Vega magnitudes (see Section A):

    $$m_{\rm Vega} = m_{\rm AB} - \texttt{conv\_AB}\,;$$

  - `mag_lim` is the limiting magnitude (selected in `FILTERS_FILE`);
  - `nd` is the non detection law (selected in `FILTERS_FILE`);
- the range and step in redshift;
- the range and step in A_V and reddening law;
- the range of absolute magnitudes and the filter used to compute it;
- the cosmological parameters.

The user must check the maximum number of steps in redshift and reddening and the maximum number of templates and filters in the file `~/ZPHOT/src/dimension.dec`. The program will stop if the user requests a number exceeding the maximum. If the user wants to change some dimensions (because of problems of memory in the user's machine if the size of the executable is too large or if the user wants to increase the array dimensions), he/she must edit the file and recompile the program.

Here we report an example of the parameter files `zphot.param`, `UBVRI.param`, `spectra.param` and of the photometric catalogue `UBVRI.cat`:

```
::::::::::::::
zphot.param
::::::::::::::

A0VSED          ~/ZPHOT/filters/A0V_KUR_BB.SED # Vega SED
FILTERS_RES     ~/ZPHOT/filters/FILTER.RES     # filters' transmission
FILTERS_FILE    ~/ZPHOT/filters/UBVRI.param    # filters' file
TEMPLATES_FILE  spectra.param                  # models file
FILT_M_ABS      91                             # filter for absolute magnitude
ERR_MAG_MIN     0.05                           # err_min
Z_MIN           0.00                           # minimum redshift
Z_MAX           6.00                           # maximum redshift
Z_STEP          0.20                           # step in redshift
ZSTEP_TYPE      0                              # 0 step = Z_STEP
                                               # 1 step = Z_STEP*(1+z)
CATALOG_TYPE    0                              # cat.type
                                               # 0 z/cat
                                               # 1 z/obj
CATALOG_FILE    ~/ZPHOT/models/UBVRI.cat       # cat file
MAG_TYPE        0                              # 0 standard Vega mag, 1 AB mag
REDDENING_LAW   5                              # reddening law
                                               # 0 no reddening
                                               # 1 Allen (1976) MW
                                               # 2 Seaton (1979) MW
                                               # 3 Fitzpatrick (1983) LMC
                                               # 4 Prevot (1984) Bouchet (1985) SMC
                                               # 5 Calzetti (2000)
AV_MIN          0.00                           # Av_min
AV_MAX          1.20                           # Av_max
AV_STEP         0.20                           # Av_err
AGE_CHECK       y                              # check age gal. < age universe
PROB_THRESH     10.00                          # prob. thresh. for second. max. (0,100)
OUTPUT_FILE     UBVRI                          # name of output files (no extension)
OUTPUT_TYPE     0                              # 0 2.E-17 erg/cm^2/s/A, 1 microJy, 2 mag_AB
SED_OBS_FILE    n                              # file .obs_sed
SED_TEMP_FILE   n                              # file .temp_sed
LOGPHOT_FILE    n                              # file .log_phot
CATPHOT_FILE    n                              # file .cat_phot
ZPHOT_FILE      y                              # file .z_phot
H0              50.                            # Hubble constant
                                               # used to compute absolute magnitude and
                                               # ages if AGE_CHECK = y
```

```
OMEGA_M        1.                             # density parameter (matter)
                                              # used to compute absolute magnitude and
                                              # ages if AGE_CHECK = y
OMEGA_V        0.                             # density parameter (Lambda)
                                              # used to compute absolute magnitude and
                                              # ages if AGE_CHECK = y
###################### cluster option        ##########################
#Z_CLUSTER     1.                             # redshift of cluster

###################### optional parameters   ##########################
#M_ABS_MIN     -28.                           # minimum absolute magnitude (bright)
#M_ABS_MAX     -9.                            # maximum absolute magnitude (faint)
MATRIX         n                              # file .m for each object
SPECTRUM       n                              # file .spe for each object
EBV_MW         0.                             # E(B-V) for galactic dereddening
```

```
::::::::::::::
UBVRI.param
::::::::::::::

12     0.00   1   30.0   0.5
108    0.00   1   30.0   0.5
111    0.00   1   29.0   0.5
112    0.00   1   28.0   0.5
113    0.00   1   27.0   0.5
```

```
::::::::::::::
spectra.param
::::::::::::::

~/ZPHOT/templates/Burst.ised         BC
~/ZPHOT/templates/E.ised             BC
#~/ZPHOT/templates/S0.ised           BC
~/ZPHOT/templates/Sa.ised            BC
#~/ZPHOT/templates/Sb.ised           BC
~/ZPHOT/templates/Sc.ised            BC
#~/ZPHOT/templates/Sd.ised           BC
~/ZPHOT/templates/Im.ised            BC
#~/ZPHOT/templates/CWW_E_ext.sed     AS
#~/ZPHOT/templates/CWW_Sbc_ext.sed   AS
#~/ZPHOT/templates/CWW_Scd_ext.sed   AS
#~/ZPHOT/templates/CWW_Im_ext.sed    AS
```

```
::::::::::::::
UBVRI.cat
::::::::::::::

1     24.660 25.239 24.588 23.581 22.745 0.051 0.052 0.051 0.050 0.050
2     99.000 99.000 29.498 25.686 23.100 1.000 1.000 0.336 0.054 0.050
3     28.018 27.582 25.930 25.241 24.309 0.175 0.122 0.056 0.051 0.050
4     28.524 26.291 24.674 24.140 23.493 0.349 0.060 0.051 0.050 0.050
5     99.000 99.000 27.048 25.204 24.048 1.000 1.000 0.087 0.052 0.050
```

3.2.2 Outputs

The quantities provided as outputs of **hyperz** have been already described in the previous section. Here we report an example of the `.z_phot` file:

```
::::::::::::::
UBVRI.z_phot
::::::::::::::
1 0.600 0.442 77.86 2 29 1.0152 1.20 0.368E+03 0.541 0.647 ...  -18.90 1.380 0.00
2 3.020 0.032 96.89 1 28 0.7187 1.20 0.159E+05 2.791 3.051 ...  -26.11 5.200 93.50
3 0.200 0.687 60.05 1 30 1.4340 1.00 0.162E+03 0.000 0.277 ...  -14.03 1.940 0.02
4 3.200 0.071 99.09 5 27 0.5088 1.00 0.251E-06 2.899 3.332 ...  -22.94 2.600 37.71
5 4.400 0.019 99.64 1 7  0.0100 1.20 0.110E+02 3.967 4.669 ...  -22.61 2.800 87.07
```

As stated above, the format of this file is the following, ordered by columns: (1) the identification number; (2) the photometric redshift primary solution; (3) its χ^2_ν and (4) the corresponding probability; (5) the number of the spectral type in the order of the `spectra.param` file; (6) the age record; (7) the age in Gyr; (8) the absorption in the V band to be applied at the best fit SED; (9) the normalization factor b of equation 1 needed to minimize the χ^2; (10)-(11), (12)-(13) and (14)-(15) the limits of the confidence intervals at 99%, 90% and 68%; (16) the weighted mean redshift $z_{\rm wm}$; (17) the probability associated to $z_{\rm wm}$ (the columns 12 – 17 here are replaced by dots); (18) the absolute magnitude; (19) the secondary peak of the probability function; (20) the probability of the secondary solution.

One of the most considerable features of **hyperz**, is the possibility of knowing the probability function $P(z)$. This characteristic allows us to describe in an accurate way the results of different tests and to explore the relevance of secondary solutions and then the degeneracy in the parameter space. Moreover, the function $P(z)$ can be used to compute some cosmological quantities properly taking into account the characteristics of the photometric redshift technique. Figure 7 shows an example of SED fitting and the corresponding $P(z)$ for three objects.

4 Make_catalog: Getting started

The public version of the package **hyperz** contains also the program **make_catalog**, useful to build simulated catalogues and to study the accuracy of photometric redshifts as a function of different parameters. The plots in the cover of this manual are an example of this kind of application. Basically, **make_catalog** compute magnitudes using the same template SEDs previously described, and then photometric errors are introduced as Gaussian noise. After a successful installation, the program can be called simply typing `make_catalog` and writing the name of the main parameter file, called by default `catalog.param`.

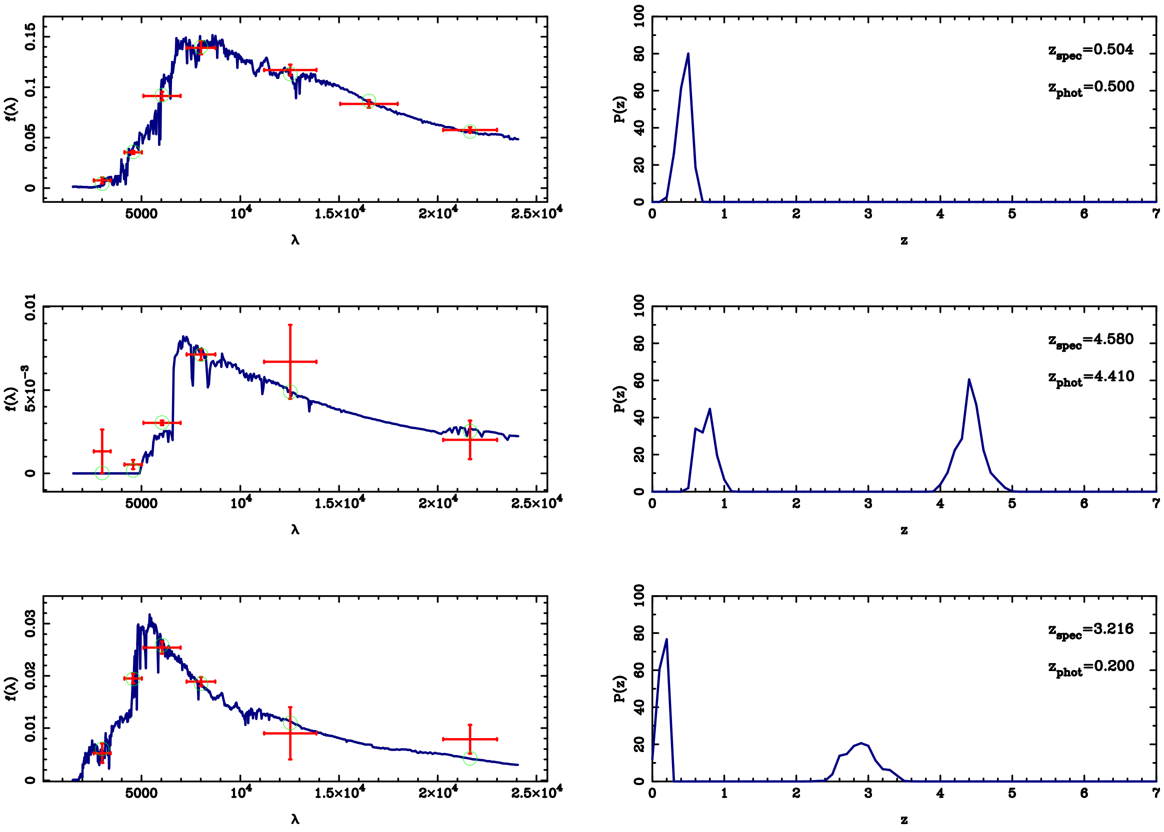

Figure 7: *Left*: The best fit SED (solid line), with superimposed the observed points with error bars (vertical error bars correspond to photometric errors, horizontal error bars represent the surface covered by the filter) and the fluxes derived from the best fit SED (circles). *Right*: The probability functions relative to χ^2 for the three considered objects.

4.1 Parameters

The input parameters contained in `make_catalog` that are different from **hyperz** are:

- `FILTERS_FILE`: the name of the file containing in the first column the identification of filters and in the following columns the information needed to compute photometric errors, according to the error type selected by the parameter `NOISE_TYPE`. In this file lines beginning with a # are not considered.

- `MODEL_CAT_FILE`: the name of file that will contain the random catalogue obtained from the templates. Its format will be:

$$\texttt{id},\ z,\ \texttt{SpT},\ [m(i), i=1, n_{\rm filt}],\ A_V.$$

- `NOISE_CAT_FILE`: the name of file that will contain the random catalogue obtained from the `MODEL_CAT_FILE` adding a random noise. This is the simulated catalogue that can be used as photometric catalogue for **hyperz**. Its format will be:

$$\texttt{id},\ [m(i), i=1, n_{\rm filt}],\ [\Delta m(i), i=1, n_{\rm filt}]$$

- REF_FILTER: the number of the filter (to be checked in the filters.log file) that will have a magnitude in the range between MAG_MIN and MAG_MAX.

- MAG_MIN and MAG_MAX: the magnitudes defining the range of apparent magnitudes attributed to the REF_FILTER.

- N_OBJ: the number of objects in the simulated catalogue.

- Z_FORM: the formation redshift of galaxies.

- Z_MIN and Z_MAX: the limits of the range of redshift where the redshift of the simulated galaxies z have to be selected.

- AGE_RANDOM: the option for the galaxy ages computation. Setting the value 0 the age is assumed to be equal to the age of a galaxy at the redshift z chosen randomly between Z_MIN and Z_MAX, taking into account that galaxy formation occurs at redshift Z_FORM. The value 1 produces ages of galaxies between 0 and the maximum value allowed according to Z_FORM.

- NOISE_TYPE: the type of noise adopted to compute the magnitudes in NOISE_CAT_FILE from MODEL_CAT_FILE: if NOISE_TYPE is 0, random noise with fixed sigma in magnitudes will be applied to magnitudes. Selecting 1, the noise Δm will be computed as a function of m following the approximation

$$\Delta m(m) \simeq \sqrt{\left[2.5 \log\left(1+\frac{1}{S/N}\right)\right]^2 + \mathtt{ERR\_MAG\_MIN}^2}\,, \tag{4}$$

where S/N is the signal to noise ratio, which is given as a function of the apparent magnitude through

$$S/N = (S/N)_0 10^{-0.4(m-m_0)}\,. \tag{5}$$

$(S/N)_0$ is the signal to noise ratio at a given reference magnitude m_0. In the case NOISE_TYPE $= 0$, in the file FILTERS_FILE the column two must correspond to the sigma of the errors distribution; in the second case the columns two and three are the value of $(S/N)_0$ and m_0 respectively. If you chose the latter option, during the run of the program, the limiting magnitudes in each filter will be showed. We assume as limiting magnitudes the value at which the signal to noise ratio fall down 1. You can use these magnitudes in the FILTERS_FILE for **hyperz**. The magnitudes exceeding the limiting magnitudes will be set to 99.

- ERR_MAG_MIN: this a kind of zeropoint error, added quadratically to the error estimate (see equation 4).

Here we report an example of the parameter files. The `catalog.param` file with all the parameters, and the filter's parameter file `filter_UBVRI.param`, with the two possible choices to compute the photometric noise:

```
::::::::::::::
catalog.param
::::::::::::::

A0VSED          ~/ZPHOT/filters/A0V_KUR_BB.SED # Vega SED
FILTERS_RES     ~/ZPHOT/filters/FILTER.RES     # filters' transmission
FILTERS_FILE    filter_UBVRI.param             # filter's file
TEMPLATES_FILE  spectra1.param                 # templates
MODEL_CAT_FILE  ~/ZPHOT/models/UBVRI.model     # random catalogue
NOISE_CAT_FILE  ~/ZPHOT/models/UBVRI.cat       # catalogue with noise
REF_FILTER      113                            # reference filter
MAG_MIN         22.                            # minimum apparent magnitude in REF_FILTER
MAG_MAX         25.                            # maximum apparent magnitude in REF_FILTER
N_OBJ           1000                           # number of objects
Z_FORM          10.                            # formation redshift
Z_MIN           0.                             # minimum redshift
Z_MAX           6.                             # maximum redshift
AGE_RANDOM      0                              # 0 age = age of universe - T(z_form)
                                               # 1 age = random between 0 and T(z)-T(z_form)
REDDENING_LAW   5                              # reddening law
                                               # 0 no reddening
                                               # 1 Allen (1976) MW
                                               # 2 Seaton (1979) MW
                                               # 3 Fitzpatrick (1983) LMC
                                               # 4 Prevot (1984) Bouchet (1985) SMC
                                               # 5 Calzetti (2000)
AV_MIN          0.0                            # minimum A_v
AV_MAX          1.2                            # maximum A_v
NOISE_TYPE      1                              # 0 random with fixed sigma in magnitudes
                                               # 1 dm(m)
ERR_MAG_MIN     0.05                           # minimum error (if NOISE_TYPE=1)
H0              50.                            # Hubble constant
OMEGA_M         1.                             # density parameter (matter)
OMEGA_V         0.                             # density parameter (Lambda)
RAND_SEED       3010                           # seed for random generator (max 4 figures)


::::::::::::::
filter_UBVRI.param
::::::::::::::

# n.filter sigma       (if NOISE_TYPE=0)
# 12       0.1
# 108      0.1
# 111      0.1
# 112      0.1
# 113      0.1
# n.filter s/n   mag0  (if NOISE_TYPE=1)
12         10.   27.0
108        10.   27.5
111        10.   27.5
```

```
112          10.   27.5
113          10.   28.0
```

The `UBVRI.cat` have been shown in the previuos chapter, whereas the model catalog, containing the SED characteristics, looks like this example:

```
::::::::::::::
UBVRI.model
::::::::::::::

1 0.515 5 6.641 24.617 25.217 24.576 23.537 22.729 0.578
2 5.209 7 0.486 99.000 99.000 28.886 25.752 23.181 0.396
3 0.230 3 9.204 27.559 27.588 25.958 25.119 24.196 0.766
4 3.183 5 1.167 28.435 26.258 24.680 24.142 23.524 0.956
5 4.342 4 0.699 99.000 40.169 27.079 25.269 24.045 1.070
```

A Filters and Photometric systems

The **hyperz** package provides also the response functions of the filters, contained in the file `./ZPHOT/filters/FILTER.RES`. This file is an extension of the file provided in the GISSEL library by Bruzual & Charlot (1993) and at this stage it includes 193 filters. You can add your own filters appending their transmission functions at the end of the file according to the following format: the first line must contain the number of points forming the transmission function (compulsory, no more than 10000 points are accepted) and the name of the filter (optional). The subsequent lines must contain in the first column the number of the point, in column two the wavelength in Å and in column three the value of the transmission. Take care that if your response function contains more than 200 points, the program will proceed with a rebinning to include only 200 points, because otherwise the integration would be too CPU time consuming. Notice that the points must be ordered by increasing wavelengths. Moreover, do not care about the normalization of the transmission functions, because this operation will be performed internally in **hyperz**. In Figure 8 we illustrate the transmission functions of the most used filters, corresponding to the records # 12, 91, 92, 93, 94, 162, 76, 75, 77, 131, 122, 123, 124, 121.

Two reminder files are included in the package, even if they are not used during the computation: `./ZPHOT/filters/filters.log` contains the list of the filters contained in `./ZPHOT/filters/FILTER.RES`, their record number and the number of points composing their transmission function; `./ZPHOT/filters/filters.dat` contains a description of the filters by means of their $\lambda_{\rm eff}$, their surface S, their width, computed as described in Section 3.2, and the conversion between Vega and AB magnitudes..

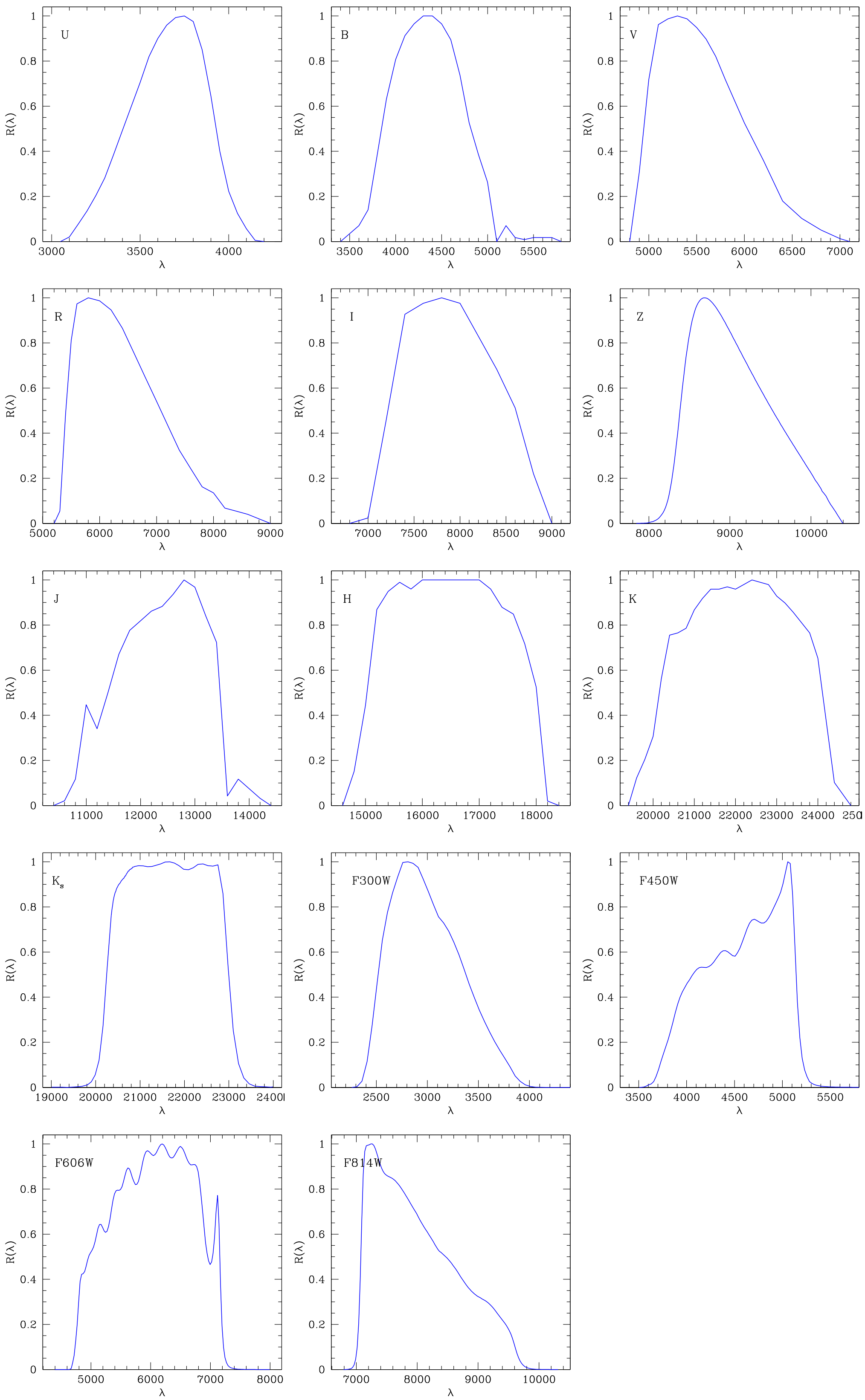

Figure 8: Normalized filter's transmission functions of some of the most used filters.

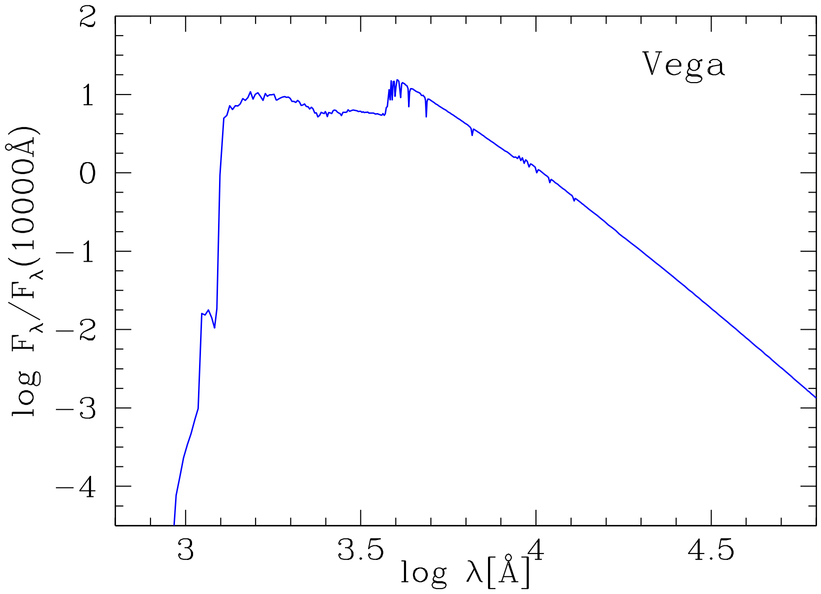

Figure 9: Spectral Energy Distribution of αLyrae (Vega). Data from GISSEL library.

The program **hyperz** works with "standard" Vega magnitudes, as well as with AB magnitudes. The first photometric system is calibrated on the Vega Spectral Energy Distribution shown in Figure 9 and taken from the Bruzual & Charlot (1993) library. In the formulae we have

$$m_{\rm Vega} = -2.5 \left[\log \int R(\lambda) f(\lambda)\, d\lambda - \log \int R(\lambda) f_{\rm Vega}(\lambda)\, d\lambda \right] ,$$

where $f(\lambda)$ is in unit of $\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$. AB magnitudes are defined in such a way that the zero point is set equal for all filters and are directly related to the flux $f(\nu)$: $m_{\rm AB} = -2.5 \log f(\nu) - 48.60$, where $f(\nu)$ is given in $\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$, and thus AB magnitudes can be monochromatic. An object having a flat spectrum will have equal magnitudes in all the filters. The conversion between Vega and AB magnitudes for a given filter is computed using the equation:

$$\mathrm{conv_{AB}} = m_{\rm AB} - m_{\rm Vega} = m_{AB}(\mathrm{Vega}) = -2.5 \log \frac{\int R(\nu) f_{\rm Vega}(\nu)\, d\nu}{\int R(\nu)\, d\nu} - 48.60 \, .$$

B FAQ

Q: I have the photometry measured in 3 filters. Can I compute photometric redshifts?
A: There are no technical problems running **hyperz** with only 3 filters, but the results will be not very reliable. If you look at the probability functions probably you will find multiple solutions and extended "plateaux".

Q: Do I need near-IR or UV to compute photometric redshifts?
A: No, you don't need specifically near-IR or UV. But then the accuracy in several redshift zones, especially at $z > 1$, is going to be severely decreased. You can check Bolzonella et al. (2000) for a complete study.

Q: Do I need to have the photometry in all the filters for each object?
A: If your object was in the field but not detected, then you have to set its magnitude $m > 90$ and choose between the different options that **hyperz** provides to deal with such case. If your object was not in the field, then set its magnitude $m < 1$ and **hyperz** will not consider it in the computation.

Q: Do I need to cite you if I write a paper using this code?
A: It will be greatly appreciated to include a note saying that your results were obtained using the publicly available software **hyperz**, to refer to the paper Bolzonella M., Miralles J.-M. & Pelló R. (2000) and to include the http address where you downloaded it.

Q: I have an unsolvable problem, who can I contact?
A: You can contact either Micol at `micol@ifctr.mi.cnr.it`, Roser at `roser@ast.obs-mip.fr` or Joan-Marc at `jmiralle@eso.org`.

Q: When are you going to release a new version?
A: If you want to be informed of new releases, bug fixes or improvements, just email to any of us.

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