GALAXEV (version 2003)

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1 INTRODUCTION

GALAXEV is a library of evolutionary stellar population synthesis models computed using the new isochrone synthesis code of Bruzual & Charlot (2003). This code allows one to compute the spectral evolution of stellar populations in wide ranges of ages and metallicities at a resolution of 3 Å across the whole wavelength range from 3200 Å to 9500 Å, and at lower resolution outside this range. GALAXEV supersedes all previous releases of our models over the last decade. We strongly recommend to read the above paper in its entirety before using the models. In particular, Table A1 of the appendix gives a qualitative assessment of the spectral predictions of the model for simple stellar populations of various ages and metallicities.

2 CONTENT

The files in the various **bc03.*.tar.gz** archives are organized into four subdirectories.

./bc03/doc
./bc03/models
./bc03/src
./bc03/templates

You need about 150 MBytes of disk space to copy the basic set of files.

2.1 Simple Stellar Populations (SSPs) or instantaneous-burst models

The default distribution provides 26 SSP models computed using the Padova 1994 evolutionary tracks. The **./bc03/models/Padova1994/chabrier** subdirectory contains 13 'standard' (as defined in Section 3 of Bruzual & Charlot 2003) SSP models computed using the Chabrier (2003) IMF with lower and upper mass cutoffs $m_L = 0.1$ M$_\odot$ and $m_U = 100$ M$_\odot$. The SSP models are normalized to a total mass of 1 $M_\odot$ in stars at age $t = 0$. These models are identified by the following file names:

bc2003_hr_m22_chab_ssp.ised_ASCII	bc2003_lr_m22_chab_ssp.ised_ASCII
bc2003_hr_m32_chab_ssp.ised_ASCII	bc2003_lr_m32_chab_ssp.ised_ASCII
bc2003_hr_m42_chab_ssp.ised_ASCII	bc2003_lr_m42_chab_ssp.ised_ASCII
bc2003_hr_m52_chab_ssp.ised_ASCII	bc2003_lr_m52_chab_ssp.ised_ASCII
bc2003_hr_m62_chab_ssp.ised_ASCII	bc2003_lr_m62_chab_ssp.ised_ASCII
bc2003_hr_m72_chab_ssp.ised_ASCII	bc2003_lr_m72_chab_ssp.ised_ASCII
bc2003_hr_m62_chab_ssp_Pickles_Stelib.ised_ASCII	

The **./bc03/models/Padova1994/salpeter** subdirectory contains 13 analogous SSP models computed using the Salpeter (1955) IMF with the same mass cutoffs:

bc2003_hr_m22_salp_ssp.ised_ASCII	bc2003_lr_m22_salp_ssp.ised_ASCII
bc2003_hr_m32_salp_ssp.ised_ASCII	bc2003_lr_m32_salp_ssp.ised_ASCII
bc2003_hr_m42_salp_ssp.ised_ASCII	bc2003_lr_m42_salp_ssp.ised_ASCII
bc2003_hr_m52_salp_ssp.ised_ASCII	bc2003_lr_m52_salp_ssp.ised_ASCII
bc2003_hr_m62_salp_ssp.ised_ASCII	bc2003_lr_m62_salp_ssp.ised_ASCII
bc2003_hr_m72_salp_ssp.ised_ASCII	bc2003_lr_m72_salp_ssp.ised_ASCII
bc2003_hr_m62_salp_ssp_Pickles_Stelib.ised_ASCII	

Table 1. Metallicities of SSP models

Tracks	Key	Z	X	Y	[Fe/H]	Tracks	Key	Z	X	Y	[Fe/H]
Padova 1994[a]	m22	0.0001	0.7696	0.2303	−2.2490	Padova 2000[a]	m122	0.0004	0.7696	0.2300	−1.6469
	m32	0.0004	0.7686	0.2310	−1.6464		m132	0.001	0.7690	0.2300	−1.2486
	m42	0.004	0.7560	0.2400	−0.6392		m142	0.004	0.7560	0.2400	−0.6392
	m52	0.008	0.7420	0.2500	−0.3300		m152	0.008	0.7420	0.2500	−0.3300
	m62	0.02 ($Z_\odot$)	0.7000	0.2800	+0.0932		m162	0.019 ($Z_\odot$)	0.7080	0.2730	+0.0660
	m72	0.05	0.5980	0.3520	+0.5595		m172	0.03	0.6700	0.3000	+0.2883

[a]See Bruzual & Charlot (2003) for references.

Table 1 provides the keys to identifying the metallicities of the different SSP models based on the file names.

Each **bc2003_hr_*** (high resolution) file contains 221 spectra describing the spectral evolution of an SSP at unequally spaced time steps from $t = 0$ to $t = 20$ Gyr. The spectra are defined over 6900 wavelength points from 91 Å to 160 μm. They rely on the STELIB spectral library in the range from 3200 Å to 9500 Å and on the BaSeL 3.1 spectral library outside this range. The **bc2003_lr_*** (low resolution) models are the low resolution counterparts of the high resolution models. They rely on the BaSeL 3.1 spectral library over the entire wavelength range from 91 Å to 160 μm (1221 wavelength points). For solar metallicity, we also provide high-resolution models similar to the **bc2003_hr_m62_*** models above, for which the Pickles library was used instead of the BaSeL 3.1 library to extend the spectra blueward of 3200 Å and redward of 9500 Å (see Section 4.1 and Fig. 9 of Bruzual & Charlot 2003). These files contain 11288 wavelength points, and they are named **bc2003_hr_m62_chab_ssp_Pickles_Stelib** and **bc2003_hr_m62_salp_ssp_Pickles_Stelib** for the Chabrier and Salpeter IMFs, respectively. We refer to Bruzual & Charlot (2003) for more detail about the stellar evolution prescription and the spectral libraries.

For completeness, we also include a parallel set of models computed using the Padova 2000 evolutionary tracks instead of the Padova 1994 tracks. We caution, however, that we do not favor this alternative set of models for the reasons outlined in Section 3.1 and footnote 6 of Bruzual & Charlot (2003). The models are identified with the following file names in the subdirectories **./bc03/models/Padova2000/chabrier** and **./bc03/models/Padova2000/salpeter**.

bc2003_hr_m122_chab_ssp.ised_ASCII   bc2003_lr_m122_chab_ssp.ised_ASCII
bc2003_hr_m132_chab_ssp.ised_ASCII   bc2003_lr_m132_chab_ssp.ised_ASCII
bc2003_hr_m142_chab_ssp.ised_ASCII   bc2003_lr_m142_chab_ssp.ised_ASCII
bc2003_hr_m152_chab_ssp.ised_ASCII   bc2003_lr_m152_chab_ssp.ised_ASCII
bc2003_hr_m162_chab_ssp.ised_ASCII   bc2003_lr_m162_chab_ssp.ised_ASCII
bc2003_hr_m172_chab_ssp.ised_ASCII   bc2003_lr_m172_chab_ssp.ised_ASCII
bc2003_hr_m162_chab_ssp_Pickles_Stelib.ised_ASCII

bc2003_hr_m122_salp_ssp.ised_ASCII   bc2003_lr_m122_salp_ssp.ised_ASCII
bc2003_hr_m132_salp_ssp.ised_ASCII   bc2003_lr_m132_salp_ssp.ised_ASCII
bc2003_hr_m142_salp_ssp.ised_ASCII   bc2003_lr_m142_salp_ssp.ised_ASCII
bc2003_hr_m152_salp_ssp.ised_ASCII   bc2003_lr_m152_salp_ssp.ised_ASCII
bc2003_hr_m162_salp_ssp.ised_ASCII   bc2003_lr_m162_salp_ssp.ised_ASCII
bc2003_hr_m172_salp_ssp.ised_ASCII   bc2003_lr_m172_salp_ssp.ised_ASCII
bc2003_hr_m162_salp_ssp_Pickles_Stelib.ised_ASCII

In addition to the above files, the **./bc03/models/Padova1994/chabrier**, **./bc03/models/Padova1994/salpeter**, **./bc03/models/Padova2000/chabrier** and **./bc03/models/Padova2000/salpeter** subdirectories contain several complementary text (ASCII) files listing useful photometric, spectroscopic and physical properties of the models. As an example, for the standard solar-metallicity model, these files are named:

bc2003_hr_m62_chab_ssp.1color   bc2003_lr_m62_chab_ssp.1color
bc2003_hr_m62_chab_ssp.2color   bc2003_lr_m62_chab_ssp.2color
bc2003_hr_m62_chab_ssp.3color   bc2003_lr_m62_chab_ssp.3color
bc2003_hr_m62_chab_ssp.4color   bc2003_lr_m62_chab_ssp.4color
bc2003_hr_m62_chab_ssp.5color   bc2003_lr_m62_chab_ssp.5color
bc2003_hr_m62_chab_ssp.1ABmag   bc2003_lr_m62_chab_ssp.1ABmag

bc2003_hr_m62_chab_ssp.6lsindx_ffn   bc2003_hr_m62_chab_ssp.7lsindx_ffn
bc2003_hr_m62_chab_ssp.6lsindx_sed   bc2003_hr_m62_chab_ssp.7lsindx_sed
bc2003_hr_m62_chab_ssp.6lsindx_sed_lick_system   bc2003_hr_m62_chab_ssp.7lsindx_sed_lick_system

Tables 2 and 3 below describe the quantities listed in the various ***.?color**, ***.1ABmag** and ***.?lsindx*** files. These quantities are measured in the rest frame of a model galaxy and are given at all model ages (see Section 3.9 below for the computation of magnitudes and colors at different redshifts). In Table 2, for all magnitudes and colors, we indicate in parentheses the sequential numbers of the adopted filters in the reference list given in the file **./bc03/src/filters.log**. The filter response functions themselves are stored in the file **./bc03/src/filterfrm.res**. In the next section, we explain how to add filters to our database and how to modify the filters in use. In the ***.1color** and ***.2color** files, the zero points of the colors are computed in the Vega magnitude system, i.e. by requiring that all colors be zero for the Kurucz (1995, priv. comm.) model atmosphere of α-Lyrae. This model is given in the file **./bc03/src/A0V_KURUCZ_92.SED**. Please note that the spectral indices in the ***.?lsindx*** files in Table 3 are computed only for the high resolution (**_hr_**) models.

3 PROGRAMS

In the subdirectory **./bc03/src** we provide several FORTRAN programs and subroutines which the user may find useful to handle our files.

3.1 Setting up the environment and building the programs

In your **.cshrc** or **.login** file, please define **bc03** as the directory which contains the GALAXEV programs:

setenv bc03 /full_path_to_GALAXEV_src_directory

The variable **$bc03** then contains the full path to the **./bc03/src** directory. Please then do

cd $bc03
source ./.bc_cshrc
make all

in order to define some environment variables and useful aliases and to build the required executables. The compilation options at the beginning of the **Makefile** may have to be changed depending on your FORTRAN compiler.

3.2 Transforming from ASCII to binary files

The spectral evolutionary models produced by our code are stored as binary files to save disk space and time when later reading the files. In this distribution, we have written the files as text (ASCII) files to make them universally readable. However, since our programs assume that the input files are in binary format, we provide a program (**bin_ised**) which makes the transformation from text to binary format transparent to the user. Another program (**ascii_ised**) performs the conversion from binary to ASCII format. To run these programs, just type the name of the program followed by the name of the input file. For example, use

bin_ised bc2003_hr_m62_chab_ssp.ised_ASCII

to create the binary file **bc2003_hr_m62_chab_ssp.ised**, or

ascii_ised bc2003_hr_m62_chab_ssp.ised

to create the ASCII file **bc2003_hr_m62_chab_ssp.ised_ASCII**.

3.3 Extracting individual spectra

The program **galaxevpl**, launched by the alias command **gpl**, reads the binary ***.ised** files and allows the user to interactively extract one or several (up to 24) individual spectra at selected ages (in Gyr). The selected spectra are written in a multicolumn file suitable for plotting. The user can specify the wavelength range in which the spectra are written to the file, the flux units, choose a normalization option and change the default output file name. By default, the spectra are output as luminosity per unit wavelength in units of $L_\odot$ Å^{-1}, with $L_\odot = 3.826 \times 10^{33}$ ergs s^{-1}.

3.4 Handling the filter file

The filter response functions are stored in the text file **filterfrm.res**. The script **build_filterbin** transforms this file into a binary file, named **FILTERBIN.RES**, that is used as input by programs requiring access to the filter response functions. The filters included in this distribution are listed in the file **filters.log**. The program **seefilter** allows the user to extract the response functions of one or more filters selected according to the filter sequence numbers in **filters.log**. This program writes as output a two-column text file listing the requested response functions and a short text file listing some characteristics of the filters (e.g., wavelength range, effective wavelength). The program **zeropoint** computes the zero points of colors defined by any combination of the filters listed in **filters.log**, as specified by the filter sequence numbers. The zero points are computed in the Vega magnitude system, i.e. by requiring that all colors be zero for the Kurucz (1995, priv. comm.) model atmosphere of α-Lyrae. This model is given in the file **A0V_KURUCZ_92.SED**.

The procedure to add new filters has been simplified with respect to previous distributions of our software package. New filter response functions can be appended to the existing file **filterfrm.res** in free format, i.e., two columns of text with the wavelength λ (**in Å**) in the first column and the response function in the second column. Before the first record of a new filter, please add a line with a '#' as its first character. A filter description is optional starting on the third character of this line. Simple inspection of the existing **filterfrm.res** file will clarify this point. We recommend that new filters be *appended* to the existing list and not inserted at other positions, since the current sequence numbers would otherwise change and possibly affect previous assignments of filters in various programs.

Table 2. Content of the *.?color and *.1ABmag files.

File	Column	Quantity	Description
*.1color	1	log age (yr)	log model age in yr
	2	Mbol	absolute bolometric magnitude
	3	Umag	U(12) absolute magnitude
	4	Bmag	B(14) absolute magnitude
	5	Vmag	V(15) absolute magnitude
	6	Kmag	K(57) absolute magnitude
	7	14−V	1400(22) − V(15) color
	8	17−V	1700(23) − V(15) color
	9	22−V	2200(24) − V(15) color
	10	27−V	2700(25) − V(15) color
	11	U−J	U+(1) − J+(2) color
	12	J−F	J+(2) − F+(3) color
	13	F−N	F+(3) − N+(4) color
	14	U−B	U(12) − B(13) color
	15	B−V	B(14) − V(15) color
*.2color	1	log age (yr)	log model age in yr
	2	Rmag	R(84) absolute magnitude
	3	J2Mmag	2MASS J(120) absolute magnitude
	4	Kmag	K(57) absolute magnitude
	5	V−R	V(15) − R(84) color
	6	V−I	V(15) − I(85) color
	7	V−J	V(15) − J(55) color
	8	V−K	V(15) − K(57) color
	9	R−I	R(84) − I(85) color
	10	J−H	J(55) − H(56) color
	11	H−K	H(56) − K(57) color
	12	V−K'	V(15) − K'(86) color
	13	V−Ks	V(15) − Ks(107) color
	14	J−H	2MASS J(120) − 2MASS H(121) color
	15	J−Ks	2MASS J(120) − 2MASS Ks(122) color
*.1ABmag	1	log age (yr)	log model age in yr
	2	Mbol	absolute bolometric magnitude
	3	g_AB	SDSS g(116) absolute AB magnitude
	4	(u−g)AB	SDSS u(115) − SDSS g(116) AB color
	5	(g−r)AB	SDSS g(115) − SDSS r(116) AB color
	6	(g−i)AB	SDSS g(115) − SDSS i(116) AB color
	7	(g−z)AB	SDSS g(115) − SDSS z(116) AB color
*.3color	1	log age (yr)	log model age in yr
	2	B(4000)	Amplitude of 4000 Å break (Bruzual 1983)
	3	B4_VN	Amplitude of 4000 Å narrow break (Balogh et al. 1999)
	4	B4_SDSS	Amplitude of 4000 Å break (Stoughton et al. 2002)
	5	B(912)	Amplitude of Lyman discontinuity
	6	NLy	log rate of H-ionizing photons (s^{-1})
	7	SNR/yr/Lo	supernova rate (per year per solar luminosity)
	8	PNBR/yr/Lo	planetary nebulae birth rate (per year per solar luminosity)
	9	N(BH)	number of black holes
	10	N(NS)	number of neutron stars
	11	N(WD)	number of white dwarfs
	12	M(Remnants)	total mass in stellar remnants
*.4color	1	log age (yr)	log model age in yr
	2	Mbol	absolute bolometric magnitude
	3	Bmag	B(14) absolute magnitude
	4	Vmag	V(15) absolute magnitude
	5	M*/Lb	Stellar mass-to-B(14) light ratio ($M_\odot/L_{\odot,B}$)
	6	M*/Lv	Stellar mass-to-V(15) light ratio ($M_\odot/L_{\odot,V}$)
	7	M*	Total mass in stars at this age ($M_\odot$)
	8	Mgas	Mass returned to the ISM by evolved stars at this age ($M_\odot$)
	9	Mgalaxy	Sum of M* and Mgas ($M_\odot$)
	10	SFR/yr	Star formation rate ($M_\odot$/yr)
*.5color[a]	1	log age (yr)	log model age in yr
	2	Mbol	absolute bolometric magnitude
	3	b(t)*'s/yr	evolutionary flux (Renzini & Buzzoni 1986)
	4	B(t)/yr/Lo	specific evolutionary flux (Renzini & Buzzoni 1986)
	5	Turnoff_mass	main-sequence turnoff mass at this age ($M_\odot$)
	6	BPMS/BMS	bolometric flux ratio of Post-MS to MS stars

[a] The content of this file is meaningful only for SSP's and is independent of spectral resolution.

Table 3. Content of the *.?lsindx* files.

File	Column	Quantity	Units	Description
*.6lsindx_sed[a]	1	log age (yr)		log model age in yr
*.6lsindx_ffn[b]	2	CN_1	mag	Index No. 1 in Table 2 of Trager et al. (1998)
*.6lsindx_sed_lick_system[c]	3	CN_2	mag	Index No. 2 in Table 2 of Trager et al. (1998)
	4	Ca4227	Å	Index No. 3 in Table 2 of Trager et al. (1998)
	5	G4300	Å	Index No. 4 in Table 2 of Trager et al. (1998)
	6	Fe4383	Å	Index No. 5 in Table 2 of Trager et al. (1998)
	7	Ca4455	Å	Index No. 6 in Table 2 of Trager et al. (1998)
	8	Fe4531	Å	Index No. 7 in Table 2 of Trager et al. (1998)
	9	Fe4668	Å	Index No. 8 in Table 2 of Trager et al. (1998)
	10	Hβ	Å	Index No. 9 in Table 2 of Trager et al. (1998)
	11	Fe5015	Å	Index No. 10 in Table 2 of Trager et al. (1998)
	12	Mg_1	mag	Index No. 11 in Table 2 of Trager et al. (1998)
	13	Mg_2	mag	Index No. 12 in Table 2 of Trager et al. (1998)
	14	Mgb	Å	Index No. 13 in Table 2 of Trager et al. (1998)
*.7lsindx_sed[a]	1	log age (yr)		log model age in yr
*.7lsindx_ffn[b]	2	Fe5270	Å	Index No. 14 in Table 2 of Trager et al. (1998)
*.7lsindx_sed_lick_system[c]	3	Fe5335	Å	Index No. 15 in Table 2 of Trager et al. (1998)
	4	Fe5406	Å	Index No. 16 in Table 2 of Trager et al. (1998)
	5	Fe5709	Å	Index No. 17 in Table 2 of Trager et al. (1998)
	6	Fe5782	Å	Index No. 18 in Table 2 of Trager et al. (1998)
	7	Na D	Å	Index No. 19 in Table 2 of Trager et al. (1998)
	8	TiO1	mag	Index No. 20 in Table 2 of Trager et al. (1998)
	9	TiO2	mag	Index No. 21 in Table 2 of Trager et al. (1998)
	10	Hδ_A	Å	Hδ_A index defined by Worthey & Ottaviani (1997)
	11	Hγ_A	Å	Hγ_A index defined by Worthey & Ottaviani (1997)
	12	Hδ_F	Å	Hδ_F index defined by Worthey & Ottaviani (1997)
	13	Hγ_F	Å	Hγ_F index defined by Worthey & Ottaviani (1997)
	14	D(4000)		4000 Å break as defined by Gorgas et al. (1999)
	15	B4_VN		Amplitude of 4000 Å narrow break (Balogh et al. 1999)
	16	CaII8498	Å	Ca1 Index defined by Díaz et al. (1989)
	17	CaII8542	Å	Ca2 Index defined by Díaz et al. (1989)
	18	CaII8662	Å	Ca3 Index defined by Díaz et al. (1989)
	19	MgI8807	Å	MgI Index defined by Díaz et al. (1989)

[a]Line index strengths computed directly from the high-resolution spectra.
[b]Line index strengths computed using the 'fitting functions' defined in the quoted references. Such functions are not available for indices 15–19, which are therefore not included in the ***.7lsindx_ffn** files.
[c]Line index strengths computed from the spectra degraded to the specific calibration and wavelength-dependent resolution of the Lick system (see Section 4.4 of Bruzual & Charlot 2003).

3.5 Composite stellar populations and attenuation by dust

The program **csp_galaxev**, launched by the alias command **csp**, computes the spectral evolution of composite stellar populations by performing the integration in equation (1) of Bruzual & Charlot (2003), for constant metallicity. The program is interactive and self-explanatory. The user can choose from a series of predefined star formation histories $\psi(t)$ or enter his/her own as an ASCII table. The predefined star formation histories are listed in Table 4.

The program **csp_galaxev** also includes an option for computing the effects of attenuation by dust on spectral properties according to the simple two-component model of Charlot & Fall (2000). This option requires two input parameters (see section 5 and equation [6] of Bruzual & Charlot 2003): the total effective V-band optical depth $\hat{\tau}_V$ affecting stars younger than 10^7 yr; and the fraction μ of it that is contributed by the 'ambient' (i.e. diffuse) interstellar medium, which also affects the light from older stars ($\mu \approx 0.3$ on average, with substantial scatter). The characteristic timescale of 10^7 yr corresponds to the typical lifetime of a giant molecular cloud. Please note that, because of the different attenuations affecting young and old stars in this model, the effective attenuation curve is a function of time and is *not* a single power-law for composite stellar populations (see figure 5 of Charlot & Fall 2000, to whom we refer for detail). The attenuation curve corresponding to given choices of $\hat{\tau}_V$ and μ can be visualized at any age by comparing the spectra of the attenuated and unattenuated models.

Using option = 0 (SSP) for the star formation history in **csp_galaxev** will not perform the convolution integral in equation (1) of Bruzual & Charlot (2003). However, it will produce the magnitudes and colors through the filters currently in use (see next paragraph) and will add the effects of dust on the spectral properties if required.

The files output by the program **csp_galaxev** have the same format as the SSP files listed in Section 2.1 above, and they follow the same naming convention. The colors computed by this program are defined in the file assigned to the environment variable **RF_COLORS_ARRAYS** in the file **.bc_cshrc**, and hence, they can be changed by the user. In the default release,

Table 4. Analytic expressions for predefined star formation histories in csp_galaxev.

Description	Expression
Instantaneous burst	$\psi(t) = 1\mathrm{M}_\odot\ \delta(t)$
Exponentially declining[a,b]	$\psi(t) = [1\mathrm{M}_\odot\ +\ \epsilon \mathrm{M}_{\mathrm{PG}}(t)\ ]\ \tau^{-1}\ \exp(-t/\tau)$
Single burst of length τ	$\psi(t) = 1\mathrm{M}_\odot\ \tau^{-1}$ for $t \leqslant \tau$; $\psi(t) = 0$ for $t > \tau$
Constant[b]	$\psi(t) = \mathrm{const}$
Delayed[b]	$\psi(t) = 1\mathrm{M}_\odot\ \tau^{-2}\, t\ \exp(-t/\tau)$ $[\psi(t)$ is maximum at $t = \tau]$
Linearly declining[b]	$\psi(t) = 2\mathrm{M}_\odot\ \tau^{-1}\, [1 - (t/\tau)]$ $[\psi(t) = 0$ for $t \geqslant \tau]$

[a]The user has the choice of entering either the e-folding timescale τ or the fraction $\mu_{\mathrm{SFR}} = 1 - \exp(-1\,\mathrm{Gyr}/\tau)$ of the initial mass of gas that is transformed into stars after 1 Gyr (Bruzual 1983). The quantity $\mathrm{M}_{\mathrm{PG}}(t) = 1\mathrm{M}_\odot\ [1 - \exp(-t/\tau)]\ -\ \mathrm{M}_{\mathrm{stars}}\ -\ \mathrm{M}_{\mathrm{remnants}}$ is the mass of gas that has been processed into stars and returned to the ISM at time t. The optional parameter ϵ controls the fraction of $\mathrm{M}_{\mathrm{PG}}(t)$ that can be recycled into new star formation ($0 < \epsilon \leqslant 1$): $\epsilon = 0$ means no recycling; $\epsilon > 1$ simulates gas infall (total galaxy mass $> 1\mathrm{M}_\odot$); $\epsilon < 0$ simulates gas outflow (total galaxy mass $< 1\mathrm{M}_\odot$).
[b]The user can enter an optional parameter t_{cut} such that $\psi(t) = 0$ for $t \geqslant t_{\mathrm{cut}}$.

20 colors are computed in the Vega system, and 4 colors are computed in the AB system (this number can be increased to up to 12 colors in the AB system). The first 9 colors in the Vega system are written to the file ***.1color**, and the remaining 11 colors are written to the file ***.2color**. The colors in the AB system are written to the file ***.1ABmag**. When changing the output colors, please make sure to also change the column headers written in the ***.?color** and ***.1ABmag** files to avoid later confusion. This can be achieved by editing the routine **name_sed.f**. Please see Section 3.6 below for important notes about the normalization of absolute magnitudes and other absolute quantities.

3.6 Mass normalization

The absolute magnitudes and other absolute quantities listed in the ***.?color** files scale with galaxy mass. The SSP models are normalized to a total mass of 1 $M_\odot$ in stars at age $t = 0$ (see Bruzual & Charlot 2003). Most star formation rates proposed as options by the program **csp_galaxev** preserve this normalization in the sense that the total mass of gas transformed into stars tends to 1 $M_\odot$ as time tends to infinity. The exceptions are options 3 and 6. For constant star formation rate (option 3), the mass of the model galaxy increases linearly with time. For star formation histories provided in tabular form (option 6), the normalization is set by the user. All absolute quantities can be scaled a posteriori to arbitrary stellar masses using Column (7) of the ***.4color** file, that lists the actual stellar mass of the model at any age.

3.7 Multiple bursts

The program **add_bursts**, launched by the alias command **add**, allows one to combine two bursts of star formation occurring at arbitrary times with arbitrary amplitudes. The ***.ised** file output by this program can be entered again as input file if adding more than 1 burst is desired. The files output by **csp_galaxev** can also be used as input to **add_bursts**. The files output by **add_bursts** have the same format as the SSP files listed in Section 2.1 above, only with a more refined grid of time steps, and they follow the same naming convention.

The total mass of a model computed with **add_bursts** depends on the absolute amplitudes chosen as input parameters. The mass is *not* normalized by default to 1 $M_\odot$. As is the case for **csp_galaxev**, the colors written by **add_bursts** in the ***.?color** files are controlled by the environment variable **RF_COLORS_ARRAYS**, and hence, they can be changed by the user (see Section 3.5 above). When changing the output colors, please make sure to also change the column headers written in the ***.?color** and ***.1ABmag** files to avoid later confusion. This can be achieved by editing the routine **name_sed.f**.

3.8 Modifying spectral resolution

The program **downgrade_resolution**, launched by the alias command **dgr**, allows the user to degrade the resolution of the model spectra in the high-resolution wavelength range from 3300 to 9300 Å. After being given the name of the input ***_hr_*.ised** file, the program offers the choice of either rebinning the spectra or applying a Gaussian broadening function or a Gaussian stellar velocity dispersion, as detailed below. All the spectra in the output ***.ised** file (renamed automatically to reflect the adopted value of the various parameters) are broadened, and the colors in the ***.1color**, ***.2color** and ***.1ABmag** files and the spectral quantities in the ***.?lsindx_sed** files are computed from the broadened spectra. The output files written by this program have the same format and follow the same naming convention as the SSP files listed in Section 2.1 above, and they can be used as input to other programs in this package. The various options work as follows.

Rebinning the spectra. The user must supply the bin width Δ in Å. The rebinned spectrum is then computed as

$$L_\lambda^{\mathrm{RB}}(\lambda, t) \;=\; \int_{\lambda-\frac{\Delta}{2}}^{\lambda+\frac{\Delta}{2}} d\lambda'\ L_\lambda(\lambda', t)\ . \qquad (1)$$

Applying a Gaussian broadening function. The user must supply the desired output FWHM resolution $\Gamma_{\rm FWHM}$ in Å. The broadened spectrum is then computed as

$$L_\lambda^{\rm GB}(\lambda,t) \;=\; \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{+\infty} d\lambda'\, L_\lambda(\lambda',t)\, \exp\left[-\frac{(\lambda-\lambda')^2}{2\,\sigma^2}\right] \,, \tag{2}$$

where

$$\sigma \;=\; \frac{\left(\Gamma_{\rm FWHM}^2-\Gamma_{\rm stelib}^2\right)^{1/2}}{2.3548} \,. \tag{3}$$

Here, $\Gamma_{\rm stelib}=3$ Å is the FWHM resolution of the STELIB atlas (Bruzual & Charlot 2003). In this option, the user can also choose to transform the original model spectra to the specific calibration and wavelength-dependent resolution of the Lick/IDS system. In this case, $\sigma(\lambda)$ is computed as

$$\sigma(\lambda) \;=\; \frac{\left[\Gamma_{\rm IDS}^2(\lambda)-\Gamma_{\rm stelib}^2\right]^{1/2}}{2.3548} \,, \tag{4}$$

where $\Gamma_{\rm IDS}(\lambda)$ is given in Table 8 of Worthey & Ottaviani (1997).

Applying a Gaussian stellar velocity dispersion. The user must supply the stellar velocity dispersion σ_V in $\rm km\,s^{-1}$. The broadened spectrum is then computed as

$$L_\lambda^{\rm VD}(\lambda,t) \;=\; \frac{1}{\sigma_V\sqrt{2\pi}}\int_{-\infty}^{+\infty} dv\; L_\lambda\left[\lambda\left(1+\frac{v}{c}\right)^{-1},t\right] \exp\left(-\frac{v^2}{2\,\sigma_V{}^2}\right) \,, \tag{5}$$

where v is the stellar velocity and c is the speed of light.

3.9 Redshift dependence of galaxy magnitudes and colors

We consider a galaxy with intrinsic spectral energy distribution $L_\nu(\nu,t)$ at redshift z, expressed in units of luminosity per unit frequency. The apparent magnitude of the galaxy corresponding to the integrated photon flux collected at $z=0$ by a detector with filter response function $R(\nu)$ can be written as

$$m\left[z,t(z)\right] \;=\; -\,2.5\,\log\left[\frac{\displaystyle\int_{-\infty}^{+\infty}\frac{d\nu}{\nu}\,\frac{(1+z)L_\nu\left[\nu(1+z),t(z)\right]}{4\pi d_L^2(z)}\,R(\nu)}{\displaystyle\int_{-\infty}^{+\infty}\frac{d\nu}{\nu}\,C_\nu(\nu)\,R(\nu)}\right] \,, \tag{6}$$

where $d_L(z)$ is the luminosity distance, and $C_\nu(\nu)$ is a fixed reference spectrum that depends on the magnitude system. For Vega-based magnitudes, we take $C_\nu(\nu)$ to correspond to the Kurucz (1995, priv. comm.) model atmosphere of α-Lyrae given in the file **./bc03/src/A0V_KURUCZ_92.SED**. For AB magnitudes, $C_\nu(\nu)$ corresponds to a hypothetical source with constant flux density 3631 Jy ($=3.631\times10^{-20}$ ergs $\rm s^{-1}\,cm^{-2}\,Hz^{-1}$) at all frequencies ν (Oke & Gunn 1983). In this case, equation (6) simplifies to (Fukugita et al. 1996)

$$m_{\rm AB}\left[z,t(z)\right] \;=\; -\,2.5\,\log\left[\frac{\displaystyle\int_{-\infty}^{+\infty}\frac{d\nu}{\nu}\,\frac{(1+z)L_\nu\left[\nu(1+z),t(z)\right]}{4\pi d_L^2(z)}\,R(\nu)}{\displaystyle\int_{-\infty}^{+\infty}\frac{d\nu}{\nu}\,R(\nu)}\right] - 48.60 \,, \tag{7}$$

where $L_\nu\left[\nu(1+z),t(z)\right]$ is in ergs $\rm s^{-1}\,Hz^{-1}$ and $d_L(z)$ is in cm. The *observer-frame* absolute magnitude $M\left[z,t(z)\right]$ is the apparent magnitude obtained by assuming $d_L=10$ pc in equation (6). The *rest-frame* absolute magnitude is the apparent magnitude that the source would have if it were 10 pc away and at rest (i.e., assuming $d_L=10$ pc and $z=0$ in equation [6]). The apparent magnitude in equation (6) can also be computed in terms of the luminosity $L_\lambda(\lambda,t)$ emitted by the galaxy per unit wavelength. Using $L_\lambda(\lambda,t)\,d\lambda=L_\nu(\nu,t)\,d\nu$ and $\lambda\nu=c$, this is

$$m\left[z,t(z)\right] \;=\; -\,2.5\,\log\left[\frac{\displaystyle\int_{-\infty}^{+\infty}d\lambda\,\lambda\,\frac{L_\lambda\left[\lambda(1+z)^{-1},t(z)\right]}{(1+z)4\pi d_L^2(z)}\,R(\lambda)}{\displaystyle\int_{-\infty}^{+\infty}d\lambda\,\lambda\,C_\lambda(\lambda)\,R(\lambda)}\right] \,, \tag{8}$$

The program **cm_evolution**, launched by the alias command **cmev**, computes the redshift dependence of galaxy magnitudes and colors in filters selected by the user from their sequential numbers in the reference list given in the file **./bc03/src/filters.log**. The user can also modify the cosmological model (H_0, Ω, Ω_Λ) and specify the age of the galaxy today. The input ***.ised** file can be any of the files originally included in the package or produced by the various programs. If the user enters only one filter number, the output is written to a file named ***.magnitude_FN1**, where **N1** stands for the

Table 5. Magnitude definitions.

Symbol	Definition	Description
t_z	$t(z)$	age of the galaxy at redshift z
t_g	$t(z=0)$	age of the galaxy today
$M_{\rm ev}(z)$	$M(z,t_z)$	observer-frame absolute magnitude of galaxy with evolving spectrum $L_\lambda(\lambda,t_z)$ at redshift z
$M_{\rm rf}(z)$	$M(0,t_z)$	rest-frame absolute magnitude of galaxy with evolving spectrum $L_\lambda(\lambda,t_z)$ at redshift z
$M_{\rm ne}(z)$	$M(z,t_g)$	observer-frame absolute magnitude of galaxy with non-evolving spectrum $L_\lambda(\lambda,t_g)$ at redshift z
$d_L(z)$	$d_L(z)$	cosmological luminosity distance, a function of H_0, Ω and Ω_Λ (Mattig 1958; Peebles 1993)
$\mathrm{dm}(z)$	$5\ \log\left[d_L(z)/(10\ \mathrm{pc})\right]$	cosmological distance modulus, a function of H_0, Ω and Ω_Λ (Mattig 1958; Peebles 1993)
$m(z)$	$M(z)\ +\ \mathrm{dm}(z)$	apparent magnitude of galaxy at redshift z, where $M(z)$ is any of $M_{\rm ev}(z)$, $M_{\rm rf}(z)$ or $M_{\rm ne}(z)$
$C_{1,2}$	$m_1(z)\ -\ m_2(z)$	photometric color through filters 1 and 2 [also equal to $M_1(z)\ -\ M_2(z)$]
$k(z)$	$M_{\rm ne}(z)\ -\ M_{\rm ne}(0)$	k correction: magnitude difference between a galaxy at redshift z with spectrum $L_\lambda(\lambda,t_g)$ and a galaxy with identical spectrum at $z=0$. No spectral evolution included.
$e(z)$	$M_{\rm ev}(z)\ -\ M_{\rm ne}(z)$	e (evolutionary) correction: magnitude difference between a galaxy at redshift z with spectrum $L_\lambda(\lambda,t_z)$ and a galaxy with spectrum $L_\lambda(\lambda,t_g)$ observed at the same redshift
$[e+k](z)$	$M_{\rm ev}(z)\ -\ M_{\rm ne}(0)$	$(e+k)$ correction: magnitude difference between a galaxy at redshift z with spectrum $L_\lambda(\lambda,t_z)$ and a galaxy with spectrum $L_\lambda(\lambda,t_g)$ observed at redshift $z=0$
$k_{C_{1,2}}(z)$	$k_{M_1}(z)\ -\ k_{M_2}(z)$	color k-correction: $k_M(z)$ denotes the magnitude k-correction defined above
$e_{C_{1,2}}(z)$	$e_{M_1}(z)\ -\ e_{M_2}(z)$	color e-correction: $e_M(z)$ denotes the magnitude e-correction defined above
$[e+k]_{C_{1,2}}(z)$	$[e+k]_{M_1}(z)\ -\ [e+k]_{M_2}(z)$	color $(e+k)$-correction: $(e+k)_M(z)$ denotes the magnitude $(e+k)$-correction defined above

Table 6. Content of the *.magnitude_FN1, *.magnitude_FN2, and *.color_FN1_FN2 files[a]

File	Column	Quantity	Units	Description
*.magnitude_FN1	1	z		redshift (z=0 entry in table corresponds to a distance of 10 pc)
*.magnitude_FN2	2	LTT	Gyr	light travel time from z to $z=0$
	3	t_z	Gyr	age of galaxy at redshift z
	4	dm	mag	cosmological distance modulus in magnitude units
	5	$M_{\rm rf}$	mag	$M_{\rm rf}(z)$ in selected filter (Vega system)
	6	$M_{\rm ne}$	mag	$M_{\rm ne}(z)$ in selected filter (Vega system)
	7	$M_{\rm ev}$	mag	$M_{\rm ev}(z)$ in selected filter (Vega system)
	8	$m_{\rm ev}$	mag	apparent magnitude $M_{\rm ev}(z)\ +\ \mathrm{dm}(z)$ in selected filter (Vega system)
	9	$M_{\rm rf,AB}$	mag	$M_{\rm rf}(z)$ in selected filter (AB system)
	10	$M_{\rm ne,AB}$	mag	$M_{\rm ne}(z)$ in selected filter (AB system)
	11	$M_{\rm ev,AB}$	mag	$M_{\rm ev}(z)$ in selected filter (AB system)
	12	$m_{\rm ev,AB}$	mag	apparent magnitude $M_{\rm ev}(z)\ +\ \mathrm{dm}(z)$ in selected filter (AB system)
	13	$(e+k)$	mag	$(e+k)$-correction in selected filter
	14	k	mag	k-correction in selected filter
*.color_FN1_FN2	1	z		redshift (z=0 entry in table corresponds to a distance of 10 pc)
	2	LTT	Gyr	light travel time from z to $z=0$
	3	t_z	Gyr	age of galaxy at redshift z
	4	dm	mag	cosmological distance modulus in magnitude units (Table 5)
	5	$C_{\rm rf}$	mag	color $M_{1,\rm rf}(z)-M_{2,\rm rf}(z)$ (Vega system)
	6	$C_{\rm ne}$	mag	color $M_{1,\rm ne}(z)-M_{2,\rm ne}(z)$ (Vega system)
	7	$C_{\rm ev}$	mag	color $M_{1,\rm ev}(z)-M_{2,\rm ev}(z)$ (Vega system)
	8	$C_{\rm rf,AB}$	mag	color $M_{1,\rm rf}(z)-M_{2,\rm rf}(z)$ (AB system)
	9	$C_{\rm ne,AB}$	mag	color $M_{1,\rm ne}(z)-M_{2,\rm ne}(z)$ (AB system)
	10	$C_{\rm ev,AB}$	mag	color $M_{1,\rm ev}(z)-M_{2,\rm ev}(z)$ (AB system)
	11	$(e+k)$	mag	color $(e+k)$-correction in selected filters
	12	k	mag	color k-correction in selected filters

[a]See Table 5 for the definitions of the various quantities.

filter number. In case color evolution is selected by entering two filter numbers, the output is written to three files, named ***.magnitude_FN1**, ***.magnitude_FN2** and ***.color_FN1_FN2**, where **N1** and **N2** stand for the filter numbers. A function procedure **fmag** is provided to allow the user to easily compute these quantities in his/her own code. A sample program **zmag**, launched by the alias command **zmag**, illustrates the use of the function **fmag**. These programs are thoroughly documented. Table 5 summarizes the definitions of various quantities computed by the programs, and Table 6 lists the content of the output files.

3.10 Miscellaneous tips

When a ***.ised** file name is required as input by a program, the extension may be omitted when entering the file name. For example, entering **bc2003_hr_m62_salp_ssp** is equivalent to entering **bc2003_hr_m62_salp_ssp.ised**. It is important *not to rename* ***.ised** *files with different extensions*, otherwise the programs will not recognize them.

When a parameter has a preassigned default value in a program, this is indicated between brackets [ ]. Hitting the 'return' key is equivalent to adopting the default value assigned to the parameter.

4 TEMPLATE SPECTRA

The **$bc03/templates** directory contains the library of 39 template spectra used by Tremonti (2003) to fit the continua and measure emission-line fluxes in SDSS galaxy spectra (see also Kauffmann et al. 2003a; Kauffmann et al. 2003b; Tremonti et al. 2003; Brinchmann et al. 2003). These spectra were selected to provide good coverage of SDSS-DR1 galaxies in the plane defined by $D_n(4000)$ and Hδ_A. These indices are good indicators of the star formation history of a galaxy (Kauffmann et al. 2003a). The library includes 13 template spectra for each of the three metallicities $Z = 0.004$, 0.02 and 0.05. The spectra correspond to 10 instantaneous-burst models with ages of 0.005, 0.025, 0.10, 0.29, 0.64, 0.90, 1.4, 2.5, 5, and 11 Gyr; a constant star formation model with an age of 6 Gyr; and two models with exponentially declining star formation histories with timescales $\tau_{\rm SFR} = 5$ Gyr and 9 Gyr and an age of 12 Gyr. The template spectra have been normalized to $L_\lambda(5500\text{Å}) = 1$.

5 FUTURE UPDATES

Please send email to both **bruzual@cida.ve** and **charlot@iap.fr** if you encounter difficulties in running the models or if you have suggestions for improving GALAXEV.

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