Publications of the Astronomical Society of the Pacific
108: 996–1017, 1996 November

A Data Base for Galaxy Evolution Modeling

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Received 1996 May 23; accepted 1996 July 30

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ABSTRACT. This paper represents a collective effort to provide an extensive electronic data base useful for the interpretation of the spectra and evolution of galaxies. A broad variety of empirical and theoretical data is discussed here, and the data are made fully available in the AAS CD-ROM Series, Vol. 7. Several empirical stellar libraries are part of this data base. They cover the ultraviolet spectral range observed with *IUE*, optical data from different ground-based telescopes, and ground-based infrared data. Spectral type coverage depends on the wavelength, but is mostly complete for types O to M and luminosity classes V to I. A large metallicity range is covered as well. Theoretical libraries of selected spectral indices of cool stars and of stellar continuum fluxes in the temperature range 2000–50,000 K as well as Wolf–Rayet energy distributions are presented. Several libraries of star clusters and early-type galaxies have been selected for this data base. We discuss an extensive set of empirical spectral templates covering the wavelength region from 1200 to 9800 Å, as well as narrow-band line indices in a large number of passbands. Bench-mark spectra of nearby galaxies for model tests are included as well. We compiled numerous evolutionary models and isochrones for stars of all mass ranges of interest, wide metallicity range, and for all evolutionary phases, including the pre-main-sequence phase. The majority of the models have been computed by the Geneva and Padova groups. Evolutionary synthesis models computed by several independent groups are made available. They can be applied to old and young systems, and are optimized with respect to different aspects of input physics. The model predictions include stellar (colors, magnitudes, absorption features) and nebular (emission-line fluxes) properties. Finally, we present models of ionized gas to be used for the interpretation of active galactic nuclei and young star-forming galaxies. The community is encouraged to make use of this electronic data base and to perform a critical comparison between the individual datasets.

1. OVERVIEW

Modeling the stellar content of galaxies, by comparison either with theoretical or with empirical stellar libraries, has come a long way since the earliest interpretations of galaxy spectra as the superposition of spectra of stars were made. Scheiner (1899) was probably the first to make such an attempt. He realized the similarity between the spectrum of M31 and the solar spectrum and concluded that M31 is composed of solar-type stars and must therefore be a distant stellar system.

Since then, progress in observational techniques, theoretical modeling, and computing power has made it possible to perform detailed comparisons between observed and computed properties of even the most distant galaxies. In recent years the availability of large electronic databases has permitted the usage of more and more complex libraries and stellar models to make such comparisons. The goal of this paper is to provide an overview of existing empirical and theoretical libraries and evolution models and to make them available in the most convenient, user-friendly form.

The idea for this project came up during the organization of the conference From Stars To Galaxies: The Impact Of Stellar Physics On Galaxy Evolution, which was held in Porto Elounda Mare (Crete) in October 1995 (Leitherer et al. 1996). Many of the participants felt the need for the publication of a homogeneous data base which would contain many different libraries and models at the same place. The extensive machine-readable tables accompanying this paper, which will be published in the AAS CD-ROM Series, Vol. 7, are intended to fulfill this need. Throughout this paper we will refer to the accompanying electronic material contained in the AAS CD-ROM Series simply as "the CD-ROM."

The plan of the paper is as follows. Each of the authors contributed to the contents of the CD-ROM. We arranged the contributions into individual categories. Empirical stellar libraries are in Sec. 2. These data can be used in combination with existing population or evolutionary synthesis codes to compute spectral energy distributions (SEDs) and spectral features of stellar populations. These observed libraries are complemented by theoretical libraries (Sec. 3). In Sec. 4 we present empirical cluster and galaxy libraries. The purpose of these libraries is to serve as templates for comparison with other galaxies and/or as bench-mark tests for population and evolutionary synthesis models. A variety of stellar evolution models (including isochrones) is discussed in Sec. 5. Most of these models have been published elsewhere, and some are already available electronically, but it will be convenient for the user to have all of them available on one CD-ROM. The majority of the models are suitable for implementation in synthesis codes. Evolutionary synthesis models for old and young systems are presented in Secs. 6 and 7, respectively. These are essentially predictions for the evolution of the spectral energy distribution with time, based upon empirical and theoretical libraries and stellar evolution models. Section 8 presents models of ionized nebulae, with emphasis on the nebular emission. In three of the sets, ionization is provided by the radiation from young massive stars (single stars, or radiation from a cluster of stars formed in a burst). One contribution provides shock models with an application to active galaxies. The philosophy behind this paper is to provide a comprehensive dataset covering as many applications as possible. Most contributions have not been made available electronically before. Some were released before but are included here as well for completeness reasons and for the convenience of the user.

In Table 1 we give a summary of the models discussed in this paper and included on the CD-ROM. All contributions within one section are in alphabetical order. The table lists the short title (column 1), the category as defined in the previous paragraph (column 2), the authors who submitted the data for inclusion on the CD-ROM (column 3), and the corresponding section in this paper (column 4). Column 5 gives the original reference of the work. *This reference* *should be used when a particular dataset is used or referred to, in order to give proper credit to the original authors.* If the CD-ROM as a data base is quoted, the present paper should be referenced.

2. EMPIRICAL STELLAR LIBRARIES

Real galaxies consist of real stars. To make good spectral synthesis models we therefore need access to as large a panchromatic, well-calibrated data base of empirical stellar energy distributions in as wide a range of environments as possible. Despite remarkable recent progress in computing beautifully detailed theoretical stellar energy distributions, it is essential to verify model spectra by comparison to real stars. Theoretical model grids certainly excel on the basis of convenience, homogeneity, and completeness. But they are often viewed as a means to interpolate across gaps in the empirical data bases or to cautiously extrapolate to regimes not available in nearby stellar samples.

Considering their importance for integrated light studies of populations, the available empirical libraries of stellar spectra are somewhat sparse. Probably not more than 3000 flux-calibrated stellar spectra suitable for populations work have been published, and many surveys have restricted applicability, e.g., to only very old or very young systems. After these are broken down into temperature, gravity, and abundance bins (not to mention subclassification for various special features or anomalies), the resulting coverage for fiducial population types near the Sun is notably thin. The coverage for types relevant to other galactic environments (e.g., metal-poor dwarf galaxies or "super"-metal-rich giant ellipticals) is, of course, much poorer.

Given the scope of the challenge, progress in assembling libraries over the last 25 years has been reasonably good, though clearly hampered by the lack of dedicated observing facilities and the disinclination of time allocation committees to support large-scale spectral surveys. Not accidental is the fact that many of the available libraries (as in this dataset) have emerged from the *International Ultraviolet Explorer* satellite, which is the nearest thing we have to a stable, dedicated, spectral survey facility.

Libraries have been constructed in a wide variety of formats. Most modern digital spectra have continuous wavelength coverage with spectral resolutions > 1000, yielding hundreds or thousands of independent spectral points. Continuous coverage is important for evaluating velocity smoothing effects. For population analysis, however, there are strong redundancies in integrated spectra, and it is usually advantageous to use a smaller set of discrete, well-calibrated spectral points which are as sensitive as possible to the important population parameters. To compensate for cosmic dispersion and random observational errors, data for individual objects are often combined to produce a representative group spectrum for a particular type of star. To reduce ambiguity in analyzing integrated light, it is important that signal-to-noise ratios in library spectra be made as large as practicable, with the goal of yielding S/N between 30 and 100 in the final, averaged group energy distributions.

This compilation includes only a few of the published empirical stellar spectral libraries. A summary of representative libraries published prior to 1992 is given in Fanelli et al. (1992), and more recent contributions are reviewed in the papers by Alloin (1996) and Olofsson (1996). Most of these are available in digital form. Overall coverage of the UV/optical/near-IR range (0.12–1.0 μm) is reasonably good, but homogeneous datasets at shorter or longer wavelengths are quite limited. Stars with solar metal abundances are well sampled, but other metallicity regimes require a great deal more work. Users should be alert for inconsistencies within and between the various libraries; some of the known problems are discussed by Worthey (1994) and Silva and Cornell (1992).

2.1 Stellar Libraries in the Infrared and Optical Ranges (Boisson et al.)

A very promising wavelength range not yet fully explored to study the stellar populations in the central part of galaxies is the near-IR range where a cool star spectrum peaks. The H window is particularly well designed for such a study, as the non-stellar contribution (mainly dust) is smaller in the H window than in the K window. Few stellar libraries are up to now available in the near-IR. Each of them being constructed for a specific purpose, they are generally not exhaustive. In particular, very few super-metal-rich (SMR) stars are included.

We present a sample of 37 stars from O to M for luminosity classes I, III, V, including six SMR stars, observed in the *H* band at medium resolution (Dallier et al. 1996). Observations were conducted with the ISIS spectrograph at the CFHT and with IRSPEC at the ESO-NTT. The wavelength range covers 1.573–1.646 μm at the NTT ($R = 1490$ at 1.60 μm) and 1.578–1.642 μm at the CFHT ($R = 2000$ at 1.60 μm). Spectra are in relative fluxes, f_λ, normalized to 1 in the range 1.59290–1.59506 μm.

A library was also constructed in the visible wavelength range (Serote Roos et al. 1996) in order to expand, mainly by the inclusion of SMR stars, existing libraries.

Spectra of 21 stars in the range 4800–8920 Å, covering essentially the late spectral types G, K, M and the luminosity classes I and III, are available. Half of the stars are super-metal-rich. The spectra were obtained at a resolution of 1.25 Å using the Aurelie spectrograph, equipped with a linear array CCD-like detector, attached to the OHP 1.52-m telescope. The spectra of the seven remaining stars, covering the region 5000–9783 Å at a resolution of 8.5 Å, were observed at the CFHT with the Herzberg spectrograph. The spectral types are F, G, K, M, and the luminosity classes III and V. Five stars are SMR. All spectra are in relative fluxes, f_λ, normalized to 100 at 5400 Å.

2.2 An Ultraviolet Group Library (Fanelli et al.)

This library of mean ultraviolet stellar energy distributions is derived from *IUE* spectrophotometry of 216 stars. The spectra cover 1205–3185 Å with a spectral resolution of ~6 Å. They have been corrected for interstellar extinction and converted to a common flux and wavelength scale. Individual stars were combined into standard groups according to their continuum colors, observed UV spectral morphol-

TABLE 1

Overview of the Data Base

Dataset	Catagory[a]	Authors	Section	Reference
Stellar libraries (optical+IR)	emp	Boisson et al.	2.1	Dallier et al. (1996); Serote Roos et al. (1996)
UV group library	emp	Fanelli et al.	2.2	Fanelli et al. (1992)
Far-UV to near-IR library	emp	Fioc and Rocca-Volmerange	2.3	Fioc and Rocca-Volmerange (1996); Rocca-Volmerange et al. (in preparation)
Coudé feed library	emp	Jones	2.4	Jones (1996)
Optical group library	emp	O'Connell	2.5	O'Connell (1973)
IUE library of O- and W-R stars	emp	Robert et al.	2.6	Robert et al. (1993)
IUE atlas of O-type spectra	emp	Walborn et al.	2.7	Walborn et al. (1985)
IUE atlas of B-type spectra	emp	Walborn et al.	2.8	Walborn et al. (1995)
Mg and Fe spectral indices	theor	Chavez et al.	3.1	Chavez et al. (1996b)
Grid of energy distributions	theor	Lejeune et al.	3.2	Lejeune et al. (1996)
CoStar models	theor	Schaerer and de Koter	3.3	Schaerer et al. (1996a,b); Schaerer and de Koter (1996)
Energy distributions of WR stars	theor	Schmutz	3.4	Schmutz (1996)
Cluster and galaxy template	clust	Bica et al.	4.1	this paper
M32, NGC 185, and NGC 205	clust	Hardy and Delisle	4.2	Delisle and Hardy (1996)
Narrow-band indices	clust	Huchra et al.	4.3	Huchra et al. (1996)
Padova library of evolution models	tracks	Bertelli et al.	5.1	Bressan et al. (1993); Fagotto et al. (1994a,b,c); Girardi et al. (1996)
Padova isochrones and SSPs	tracks	Bertelli et al.	5.2	Bertelli et al. (1994)
Geneva library of evolution models	tracks	Meynet and Maeder	5.3	SSMM, SMMS, CMMSS, SCMMS, MMSSC, CMMS
Evolution and nucleosynthesis	tracks	Ødegaard	5.4	Ødegaard (1996a,b)
Spectral indices for SSPs	syn/o	Bressan et al.	6.1	this paper
Energy distributions for SSPs	syn/o	Bressan et al.	6.2	this paper
Models of elliptical galaxies	syn/o	Bressan et al.	6.3	Tantalo et al. (1996)
Galaxy spectral evolution	syn/o	Bruzual and Charlot	6.4	Bruzual and Charlot (1996)
UV spectra for old populations.	syn/o	Dorman and O'Connell	6.5	Dorman and O'Connell (1996)
Spectral evolution model (UV to NIR)	syn/o	Fioc and Rocca-Volmerange	6.6	Fioc and Rocca-Volmerange (1996)
Atlas of synthetic galaxies (UV to NIR)	syn/o	Rocca-Volmerange and Fioc	6.7	Rocca-Volmerange and Fioc (1996)
SSPs for different metallicities	syn/o	Fritze-v. Alvensleben and Kurth	6.8	Fritz-v. Alvensleben and Burkert (1995)
Chemically consistent galaxy evolution	syn/o	Fritze-v. Alvensleben et al.	6.9	Möller et al. (1996)
Grid of evolutionary spectra	syn/o	Traat	6.10	Traat (1996b)
A library for old systems	syn/o	Vazdekis et al.	6.11	Vazdekis et al. (1996a,b)
Models for early-type galaxies	syn/o	Worthey	6.12	Worthey (1994)
Energy distribution for SSPs	syn/y	Bressan et al.	7.1	García-Vargas et al. (1995a)
Calcium triplet synthesis	syn/y	García-Vargas et al.	7.2	García-Vargas et al. (1996b)
Near-IR properties of starbursts	syn/y	Lançon	7.3	Lançon (1996)
Energy distributions for starbursts	syn/y	Leitherer et al.	7.4	Leitherer and Heckman (1995)
Synthesis of young starbursts	syn/y	Mas-Hesse and Cerviño	7.5	Cerviño and Mas-Hesse (1994)
Shock models for active galaxies	photo	Dopita and Sutherland	8.1	Dopita and Sutherland (1995, 1996)
Emission lines from GEHR	photo	García-Vargas et al.	8.2	García-Vargas et al. (1995a,b)
FIR emission line models	photo	Iglesias et al.	8.3	García-Vargas et al. (1996c)
Models for H I regions and starbursts	photo	Stasińska	8.4	Stasińska and Schaerer (1996),[b] Stasińska and Leitherer (1996)[c]

[a] Emp—empirical stellar library; theor—theoretical stellar library; clust—empirical cluster and galaxy library; tracks—stellar evolution models; syn/o—evolutionary synthesis of old systems; syn/y—evolutionary synthesis of young systems; photo–photoionization models.

[b] Models for single-star H II regions.

[c] Photoionization models for starbursts.

ogy, MK luminosity class, and metal abundance. The library consists of 56 groups: 21 dwarf (V), eight subgiant (IV), 16 giant (III), and eleven supergiant (I+II) groups, covering O3–M4 spectral types. A metal-poor sequence is included, containing four dwarf and two giant groups, as is a metal-enhanced sequence with a single dwarf, subgiant, and giant group. More information on the library compilation and descriptions of the behavior of spectral indices characterizing the continuum and strong absorption features are given in Fanelli et al. (1992). Details of the provided spectra are given in the file *FaOCBuWu_uvgrplib_README.*

2.3 A Far-UV to Near-IR Stellar Library (Fioc and Rocca-Volmerange)

The stellar library of the project *PEGASE* (see the description of the file FRV_MODELE/FRV_specstelUVIR.don in Sec. 6.6) is continuous from 220 Å to 10 μm. Its completeness and the identification of spectral types were checked. The published stellar library has a significant coverage of the Hertzsprung–Russell diagram. Spectra from observational atlases (*IUE* atlases, Gunn and Stryker 1983) and near-IR colors from Bessell and Brett (1988) were extended down to the far-UV with models of Kurucz (1993) and Clegg and Middlemass (1987), and up to 10 μm with Engelke's (1992) models. The spectral resolution increases from 10 Å in the far-UV and the visible to 200 Å in the near-infrared. The complete spectra of M giant stars by Fluks et al. (1994) were implemented in the library. To obtain more details on this library, or if there is a need to use the library for evolution models or other purposes, see Fioc and Rocca-Volmerange (1996), or our anonymous account:

ftp.iap.fr in *pub/from_users/pegase/.*

You can also e-mail us at pegase@iap.fr. The present library (May 1996) is being improved with a near-IR spectral library observed with the FTS/CFHT instrument in the *J* band, while *H* and *K* bands have been already published (Lançon and Rocca-Volmerange 1992). It will be installed with a corresponding README file on our anonymous account.

2.4 The Coudé Feed Spectral Library (Jones)

This library contains spectra of 684 stars all observed with the coudé feed telescope and spectrograph at KPNO with grating RC-250 and the TI5 800×800 pixel CCD. The spectra cover the ranges 3820–4500 and 4780–5460 Å at a resolution of 1.8 Å FWHM (~60 km s^{-1}). Each wavelength window was chosen for a specific reason. We wanted to not only include well-studied and universally used features such as the Lick Mg$_2$ and Hβ indices falling in the 5000 Å window, but we were also concerned about being able to identify contributions to the integrated light of a galaxy from its turn-off population, the flux of which will peak, in the optical, in the 4000 Å window, as well as contributing over 50% of the *total* integrated light at those wavelengths. Though somewhat pathological, the two wavelength regions include 14 of the 21 Lick spectral indices (Worthey et al. 1994), all of the 15 Rose indices (Rose 1994), and two new Lick-style Balmer indices (Jones and Worthey 1995). The intended use of the library has been to exploit the intrinsically high line definition of low-luminosity, and hence low-σ (60–100 km s^{-1}), early-type galaxies, which provides a wealth of spectral information not available in giant ellipticals and the bulges of large spirals. However, given the "high" resolution of the library spectra, they can be used in synthesis studies of galaxies at all velocity dispersions, allowing us to compare stellar populations in galaxies over a wide range in luminosity all with the same stellar data base.

Galaxies are made of all types of stars; hence we endeavored to create a library of stellar spectra covering a wide variety of spectral types, luminosity classes, and metallicities. Sample selection was based almost entirely on the availability of atmospheric parameters for the stars. Fortunately several recent studies have increased considerably the number of stars with well-determined atmospheric parameters: Edvardsson et al. (1993) for solar dwarfs, Dickow et al. (1970) for solar giants, Carney et al. (1994) for metal-poor dwarfs, and Pilachowski et al. (1996) for metal-poor giants. These are examples of only the standard evolutionary phases, but the full coverage of the library in atmospheric parameter space is $-2.5<[\mathrm{Fe/H}]<+0.5$, spectral types O–M, and luminosity classes I–V. Although the grid is more coarse in some places, every corner of atmospheric parameter space is anchored with at least a few stars. For example, a series of halo blue stragglers represents the metal-poor upper main sequence. A flux calibration has been attempted, but due to the desire for high resolution and hence the necessity of a narrow slit, *the calibration is only good to ~25%.* A full list of references, a description of the data files, and a discussion of the sample selection and adopted atmospheric parameters can be found in Jones (1996) and the file *Jo_README* on the CD-ROM.

2.5 An Optical Group Library (O'Connell)

This library contains mean absolute spectral energy distributions for 48 common types of stars in the solar neighborhood and two globular clusters derived from spectrophotometry of 156 individual objects. The spectra include 46 selected wavelengths in the range 3300–10,800 Å observed at 20–30 Å resolution. The spectral sequence provides measures of both the continuum and 21 selected absorption features (strong enough to be detectable in integrated light), including Balmer lines, individual metallic features and blends, and molecular bands. For objects with significant reddening, extinction corrections were made according to the Whitford law before combining the SEDs. The standard error of the mean SEDs (averaged over wavelength) of the well-observed groups ranges from 0.01 to 0.04 mag. In most cases, this reflects cosmic dispersion rather than photometric error. Coverage ranges from O5 to M8 spectral types and includes luminosity classes V, IV, III, and I. A small selection of metal poor and "super-metal-rich" stars is included. Further information on production of the library and on the behavior of continuum and line strength indices may be found in O'Connell (1973). Details of the provided spectra are given in the file *OC_opgrplib_README.*

2.6 An *IUE* High-Dispersion Library of O and W-R Stars (Robert et al.)

We present *IUE* high-dispersion spectra of O and W-R stars which are useful for spectral and evolutionary synthesis models of young star-forming regions. The library was described by Robert et al. (1993) and Leitherer et al. (1995) but has not been made available electronically before.

The data presented here are for stellar groups having the same spectral type. There are 31 groups for O stars covering types O3–O9.5 and luminosity classes V–I. The individual spectra were originally discussed by Howarth and Prinja (1989). In addition, four groups representing WNE, WNL, WCE, and WCL stars are included. They are based on St. Louis' (1990) ultraviolet atlas of Wolf–Rayet stars. The identifications of the stars used to construct the 35 groups are in Table 1 of Robert et al.

The spectra have a resolution of 0.75 Å, cover the range 1205–1850 Å, and are normalized to a continuum level of 1.0. All library stars are located within a few kpc of the Sun and have the corresponding ISM metallicity, i.e., solar, or somewhat below. Due to their nature as extreme Population I objects, the library stars are on sight lines of high interstellar gas column densities. Therefore the spectral features are a combination of stellar and interstellar lines. Care must be taken when interpreting the origin of a particular line. Detailed discussions have been given in the above quoted papers.

2.7 *IUE* Atlas of O-type Spectra from 1200 to 1900 Å (Walborn and Nichols-Bohlin)

The *IUE* atlas of O-type spectra (Walborn et al. 1985) contains 101 short-wavelength (SWP), high-resolution observations of 98 stars. They were selected on the basis of high-quality optical spectral classifications, in order to investigate systematically the behavior of the ultraviolet features, including the prominent stellar-wind profiles, and the degree to which they correlate with the optical types. The standard extracted spectrograms from the archive have been rebinned to a constant wavelength resolution of 0.25 Å and uniformly normalized. The plots are arranged in spectral-type, luminosity-class, and peculiar-object sequences. The results show a high degree of correlation between the ultraviolet features, both photospheric and stellar wind, and the optical classifications for the great majority of the O-type stars. This dataset can also be obtained from the National Space Science Data Center (NSSDC).

2.8 *IUE* Atlas of B-type Spectra from 1200 to 1900 Å (Walborn et al.)

The *IUE* atlas of B-type spectra (Walborn et al. 1995) consists of short-wavelength (SWP), high-resolution data from the *International Ultraviolet Explorer* archive. It is designed to complement the widely used O-star atlas from the same source (Walborn et al. 1985; see Sec. 2.7). The atlas presented here completes the OB natural group, extending to type B3 for the main sequence and giants, type B5 at class Ib, and B8 at Ia, which is also the most relevant domain for stellar-wind effects among normal B-type spectra. A number of hypergiants and chemically peculiar supergiants, particularly of types BN/BC (and including three of type O9.7 acquired since the O atlas), are also displayed, as are two peculiar B-type dwarfs and one subgiant with enhanced winds.

A primary objective of this atlas is to chart in detail the systematic decline of the stellar winds in normal stars throughout their two-dimensional (spectral type, luminosity class) domain. As in the O-star atlas, which first demonstrated the strong correlation between the optical spectral types and the UV wind behavior in the majority of the stars, the principal selection criterion was the existence of high-weight optical spectral classifications, to ensure that a consistent reference frame of normal objects is derived. Altogether 86 images have been selected from the *IUE* archive for the atlas. The processing and presentation are as similar as possible to the O-star atlas, with the SWP data (1200–1900 Å range) rectified and rebinned to a uniform resolution of 0.25 Å. This dataset is also available from the NSSDC.

3. THEORETICAL STELLAR LIBRARIES

Empirical stellar libraries cannot always cover the parameter space required to model the spectra of real galaxies. Therefore they need to be supplemented by theoretical stellar libraries. For instance, photoionization models respond rather sensitively to the assumed stellar far-UV radiation field below 912 Å. Yet this important spectral range is essentially inaccessible to direct observations. Grids of model atmospheres are required to fill the gap.

The most widely used set of stellar atmospheres in galaxy evolution modeling is the one published by Kurucz (1992). This set has been made available on CD-ROM before. Chavez et al. (Sec. 3.1) utilized the latest generation of Kurucz's atmospheres for approximately solar-type stars to compute a grid of Mg and Fe indices.

Kurucz's model atmospheres are not optimized for the coolest and hottest temperatures. Lejeune et al. (Sec. 3.2) improved the situation by combining Kurucz models with new atmosphere models optimized for cool stars. For the hottest stars, wind effects become important. A grid of spherically extended non-LTE models is presented by Schmutz (Sec. 3.4). These models are intended to replace Kurucz's models for stars with strong winds, such as W-R stars.

Recently, attempts were made in stellar evolution models to relax the artificial separation between the stellar interior and the atmosphere. *Combined* stellar models are particularly relevant in advanced evolutionary stages of massive stars when strong winds invalidate the traditional assumption of a static, grey atmosphere. The first generation of these models is described by Schaerer and de Koter (Sec. 3.3).

3.1 A Grid of Mg and Fe Spectral Indices (Chavez et al.)

We present a grid of the absorption line spectral indices Mg_2, Mg_1, Mg_b, Fe5270, and Fe5335, computed from high-resolution theoretical spectra. The spectra are based on the CD-ROM release of Kurucz's model atmospheres (Kurucz 1993), and numerical codes. The grid covers the effective temperature range 4000–8000 K, surface gravity 1.0–5.0, metallicities, [M/H], from -1.0 to $+0.5$, and microturbulence velocity $\xi=2$ km s^{-1}. Transformation equations of the theoretical grid into the Lick/IDS observational data base are also given.

The collection of indices is supplemented by the corresponding ''pseudo-continuum'' fluxes. Therefore it represents an extremely valuable tool for detailed studies of old stellar populations within the context of populations synthesis (see, e.g., Chavez et al. 1996a). A detailed description is given in Chavez et al. (1996b).

3.2 An Extensive and Uniform Grid of Theoretical Stellar Energy Distributions (Lejeune et al.)

We have assembled a grid of theoretical stellar atmospheres compiling different sets of models published in the literature: (i) Kurucz (1995) models, (ii) Allard and Hauschildt (1995) M-dwarf models, (iii) Bessell et al. (1989, 1991) M giant models, and (iv) Fluks et al. (1994) synthetic spectra for M giants. The grid covers the following parameter ranges: $T_{\rm eff}$: 2000–50,000 K, log g: -1.02 to $+5.5$, and [M/H]: -3.5 to $+1.0$. All the models have been transformed to the same wavelength and flux scale (from 91 Å to 160 μm) as the Kurucz (1995) models.

In the temperature range 3500–50,000 K, the models are identical to those of Kurucz (1995). In the range 2500–3500 K, composite model spectra for M giants with [Fe/H] between -1.0 and $+0.5$ were built by connecting the Fluks et al. (1994) synthetic spectra with the Bessell et al. (1991) models, as described in Lejeune et al. (1996). M-dwarf model spectra covering the temperature range 2000–3500 K were selected from the Allard and Hauschildt (1995) grid.

The resulting dataset is very valuable for the exploration of a large number of properties of individual stars or integrated stellar populations. As a first step toward its application in population and evolutionary synthesis, we have used this grid along with empirical calibrations of stellar colors to derive a complete library of consistently *color-calibrated* theoretical stellar energy distributions (Cuisinier et al. 1996).

3.3 Combined Structure and Atmosphere Models for Massive Stars (Schaerer and de Koter)

The recent ''combined stellar structure and atmosphere models'' (hereafter *CoStar*) for massive stars consistently treat the entire mass losing star from the stellar interior to the outer region of the stellar wind (see Schaerer et al. 1996a,b). In particular, the atmosphere calculations treat H and He in non-LTE, and include line blanketing in a spherically expanding atmosphere.

We have calculated an extensive set of tracks with initial masses between 20 and 120 $M_\odot$ at $Z=0.02$ (solar metallicity) and $Z=0.004$ ($0.2\,Z_\odot$). Details are given in Schaerer and de Koter (1996). We selected 27 models providing a good description of these sequences. They cover the entire parameter space of O3–B0 stars of all luminosity classes (see Schmutz 1996 for similar calculations for W-R stars). Here we provide the theoretical continuous spectral energy distribution predicted by our *CoStar* models in electronic form. The spectral range covers the EUV to far-IR domain.

Our calculations represent the first non-LTE line-blanketed models, which also account for the stellar wind and cover dwarf to supergiant stages of O3 to B0 stars. Of special interest are the ionizing fluxes, which are strongly affected by non-LTE and wind effects (cf. Schaerer et al. 1996b; Schaerer and de Koter 1996). Models of H II regions calculated with the present spectra are provided by Stasińska (see Sec. 8.4). The *CoStar* spectra are also suited for synthesis models of young stellar populations.

3.4 Theoretical Energy Distributions of Wolf–Rayet Stars (Schmutz)

The latest generation of model atmospheres for Wolf–Rayet stars is successful in reproducing the observed line profiles and continuum energy distributions. Therefore it appears to be promising to use theoretical energy distributions of Wolf–Rayet stars for spectral synthesis. The need for the inclusion of realistic Wolf–Rayet model atmospheres in evolutionary synthesis models arises from the important contribution of Wolf–Rayet stars to the far-UV flux in sites of massive star formation. Wolf–Rayet stars can dominate the far-UV energy distribution for a few Myr during the evolution of a population of massive stars. Wolf–Rayet models suitable for inclusion in evolutionary synthesis are presented here.

The flux distributions of Wolf–Rayet star models are arranged in three grids (see Schmutz 1996). Grids 1 and 2 are intended for hydrogen-free Wolf–Rayet stars, with grid 1 for stars with $T_{\rm eff} < 90{,}000$ K and grid 2 for those with higher temperatures. Grid 3 is for transition stars that still contain hydrogen in their atmospheres. The models of grid 3 are line blanketed whereas those of grids 1 and 2 are pure helium models.

A description of the structure of the flux tables has been published in Schmutz et al. (1992) where directions for the use of the models are given as well.

4. EMPIRICAL CLUSTER AND GALAXY LIBRARIES

By definition, the primary goals of most scientists working on population synthesis and galaxy evolution are to be able to measure fundamental properties of stellar populations in galaxies and other systems and predict the evolution of those properties in the cosmological model. The acid test of population models is to be able to reproduce real observations of galaxies and star clusters. Conversely, real data often form the basis for empirical models.

With those aims in mind, this section contains three observational datasets, two sets of spectra for galaxies and star clusters and one set of narrow-band line indices in the Lick system, primarily for extragalactic globular clusters.

4.1 1200–9800 Å Templates of Star Clusters and Early-type Galaxies (Bica et al.)

We present a series of templates built from integrated spectra of star clusters and early-type galaxy nuclei for stellar population analyses. The spectral domain covered is from 1200 to 9800 Å, with a resolution in the range 7–17 Å. They have been collected by ourselves over several years at ESO, OHP, and CFHT in the near-ultraviolet, visible and near-infrared ranges, complemented by *IUE* spectra. For the visible range (~3700–7000 Å), the star cluster spectra (Galactic open and globular clusters, and Large Magellanic Cloud clusters) were discussed by Bica and Alloin (1986a,b), for the near-infrared (~7000–9800 Å) by Bica and Alloin (1987a), and finally for the near-ultraviolet (~3150–4000 Å) by Bica et al. (1994). M31 globular clusters are from Jablonka et al. (1992). References for the galaxy spectra are Bica and Alloin (1987b) for the visible, Bica and Alloin (1987a) for the near-IR, whereas for the near-UV, they were observed in the same runs as the star clusters (Bica et al. 1994), and will be discussed in a forthcoming paper. Galaxy templates in the visible and near-IR have been used in population syntheses, and those of star clusters have been used both to build up a grid of star cluster spectral properties as a function of age and metallicity, and for the visualization of the population syntheses (e.g., Bica 1988; Bica et al. 1990). Star cluster templates in the far-UV (~1200–3200 Å) were given in Bonatto et al. (1995), whereas for early-type galaxies, they are discussed in Bonatto et al. (1996) and Bica et al. (1996). All spectra have been corrected for foreground reddening, as described in the references.

In the present collection we have merged the different wavelength ranges. The templates on the CD-ROM are one-dimensional files, covering the full wavelength range from 1200 to 9800 Å in one file.

4.2 Spectra of M32, NGC 185, and NGC 205 (Hardy and Delisle)

Only a handful of galaxies are sufficiently close to us that their stars can be resolved individually down to the level of an old or at least intermediate-age MS turnoff, even with *HST*. Thus, in only very few cases can we construct color–magnitude diagrams to sufficiently faint magnitudes that something approaching the full history of star formation in these galaxies can be reliably reconstructed from the observations. As soon as we leave the Local Group, spectral synthesis, in its different varieties, becomes the only technique that can be used to derive information on the stellar content of galaxies. Because of the intrinsic difficulty of the subject, its non-uniqueness, and its reliance on stellar evolutionary tools and spectral libraries, it is imperative that the predictions of spectral synthesis be tested on galaxies *for which the answer sought is known in advance or will become known soon through direct observations of their resolved components*. Among the very few galaxies suitable as test benches are three M31 satellites, M32, NGC 185, and NGC 205, for which we provide here flux-calibrated spectral information (Delisle and Hardy 1996). These galaxies are probably of solar or sub-solar metallicity, but are well suited for most available stellar and SED libraries. In addition, at least NGC 185 and NGC 205, are sufficiently diffuse that very deep color–magnitude diagrams are possible. The data on M32 have already been used for a preliminary synthesis effort by Hardy et al. (1994).

These data will be useful for synthesizing the stellar populations of the above galaxies, for which high-spatial-resolution observations will provide independent knowledge of such populations in the near future. In this way synthesis predictions could be confronted with independent results derived from color–magnitude diagrams.

The spectroscopic data furnished here are quite limited in spectral interval and resolution as well as in spatial coverage. They will have to be supplemented by observations conducted in the IR and UV range, and also with observations obtained at spectral classification resolution, i.e., at about 2–3 Å FWHM.

4.3 Narrow-Band Spectral Indices for Globular Clusters and Galaxies (Huchra et al.)

This is a collection of line indices in the Lick system (and others) for a collection of Galactic, M31, M33 and other globular clusters plus bright and dwarf galaxies observed primarily at the MMT over the period 1980–1992 by Huchra, Brodie, Caldwell, Schommer, Christian, and Bothun. The paper describing this catalog of indices is published in Huchra et al. (1996). Here we are providing the data electronically. Table 2 lists the definition of the indices used.

The tables on the CD-ROM list the line indices and errors, multiple measurements for individual objects (plus dispersions and means) to give the reader a sense of the precision and accuracy of individual measures, and index measurements from higher-dispersion spectra. Each of the index tables generally has two lines; the first are the index values and the second are the statistical (calculated from photon counts) errors. An estimate of the external error in each index can be gotten from the multiple measurements given.

5. STELLAR EVOLUTION MODELS

A general review of stellar evolution models has been given by Chiosi et al. (1992). The physics of massive star evolution is discussed in Chiosi and Maeder (1986).

The most widely used stellar evolution libraries are those computed by the Geneva and Padova groups. Both libraries are made available here. They cover a wide range in metallicity and include low-mass, intermediate-mass, and high-mass evolution. The libraries are discussed in Secs. 5.1, 5.2, and 5.3. They are based on the most up-to-date input physics, such as OPAL opacities, stellar mass loss, mixing, and convective overshooting. Differences between the two libraries which are relevant for population synthesis exist. They result from different treatment of various input parameters, and from their observational and theoretical uncertainties. An example is the stellar mass-loss rate, which is varied by a factor of 2 in the Geneva models in order to study its effect on the evolutionary tracks. The influence of different stellar evolution models on evolutionary synthesis models of populations has been discussed by Charlot et al. (1996) and García-Vargas et al. (1996a) for old and young populations, respectively.

Pre-main-sequence evolution has generally been ignored in earlier evolutionary synthesis models. The Kelvin–Helmholtz time scale to reach the main sequence was considered to be short in comparison with the evolutionary time

TABLE 2
Definitions for Line Indices and Colors of Huchra et al. (1996)

Index[a]	*C*1	*I*	*C*2
Suntzeff Indices			
CA	3650.00–3780.0	3910.00–4020.00	4020.00–4130.00
HK	···	3910.00–4020.00	4020.00–4130.00
CN	···	3850.00–3878.00	3896.00–3912.00
Faber and Burstein Indices			
CNR	4082.00–4118.50	4144.00–4177.50	4246.00–4284.75
CH = G band	4268.25–4283.25	4283.25–4317.00	4320.75–4335.75
Hβ	4829.50–4848.25	4849.50–4877.00	4878.25–4892.00
Mg H	4897.00–4958.25	5071.00–5134.75	5303.00–5366.75
Mg$_2$	4897.00–4958.25	5156.00–5197.25	5303.00–5366.75
Mg$_b$	5144.50–5162.00	5162.00–5193.25	5193.25–5207.00
Fe5270 = FE52	5235.50–5249.25	5248.00–5286.75	5288.00–5319.25
Fe 5335	5307.25–5317.25	5314.75–5353.50	5356.00–5364.75
Na I	5863.00–5876.75	5879.25–5910.50	5924.50–5949.25
TiO$_1$	5819.00–5850.25	5939.00–5995.25	6041.00–6104.75
TiO$_2$	6069.00–6142.75	6192.00–6273.25	6375.00–6416.25
Brodie and Hanes Indices			
CNB	3785.00–3810.00	3810.00–3910.00	3910.00–3925.00
H + K	3910.00–3925.00	3925.00–3995.00	3995.00–4010.00
Ca I	4200.00–4215.00	4215.00–4245.00	4245.00–4260.00
G	4275.00–4285.00	4285.00–4315.00	4315.00–4325.00
Hβ	4800.00–4830.00	4830.00–4890.00	4890.00–4920.00
Mg G	5125.00–5150.00	5150.00–5195.00	5195.00–5220.00
Mg H	4740.00–4940.00	4940.00–5350.00	5350.00–5550.00
FC	5225.00–5250.00	5250.00–5280.00	5280.00–5305.00
Na D	5835.00–5865.00	5865.00–5920.00	5920.00–5950.00
Delta	3800.00–4000.00	4000.00–4200.00	···

[a] $C1+C2$ are the continuum bandpasses on either side of I, the index bandpass.

scale of those stars relevant to the properties of the population. New models for massive stars take into account accretion during the pre-main-sequence evolution (Bernasconi, Sec. 5.3). The accretion time is much longer than the Kelvin–Helmholtz time, and this phase becomes relevant for a massive-star population.

Also included on the CD-ROM are stellar evolution models by Ødegaard. These models were calculated independently from Geneva and Padova and are useful for comparison (Sec. 5.4).

5.1 The Padova Library of Stellar Evolution Models (Bertelli et al.)

We present large grids of stellar models computed for different choices of the chemical composition:

$Z=0.0001$, $Y=0.230$ (Girardi et al. 1996),
$Z=0.0004$, $Y=0.230$ (Fagotto et al. 1994a),
$Z=0.004$, $Y=0.240$ (Fagotto et al. 1994b),
$Z=0.008$, $Y=0.250$ (Fagotto et al. 1994b),
$Z=0.02$, $Y=0.280$ (Bressan et al. 1993),
$Z=0.05$, $Y=0.352$ (Fagotto et al. 1994a),
$Z=0.1$, $Y=0.475$ (Fagotto et al. 1994c).

The chemical parameters (Y,Z) obey the helium-to-metal enrichment law $dY/dZ=2.5$, which constitutes a lower limit to the commonly accepted rate (Pagel et al. 1992).

The (initial) masses of the evolutionary tracks span the range 0.6–120 $M_\odot$, except for the set with metallicity $Z=0.1$, whose masses range from 0.6–9 $M_\odot$. Each evolutionary sequence is followed from the zero-age-main-sequence (ZAMS) to the beginning of the thermally pulsing regime of the asymptotic giant branch phase (TP-AGB) for low- and intermediate-mass stars, and to the central C ignition for higher masses.

A detailed description of the physical ingredients of the stellar models presented here can be found in Alongi et al. (1993), Bressan et al. (1993), Fagotto et al. (1994a,b,c) and Girardi et al. (1996). In brief, the key assumptions for the physical ingredients are the following.

(1) With the exception of the models with $[Y=0.475,\ Z=0.1]$ the radiative opacities are from Iglesias et al. (1992, and references therein) and Rogers and Iglesias (1992), assuming the abundances by Grevesse (1991). For the set with $[Y=0.475,\ Z=0.1]$ the classical opacities of Huebner et al. (1977) are adopted because the new ones by Iglesias et al. do not yet extend to such a high value of the metal content. In all the calculations, the molecular opacities are from Bessell et al. (1989, 1991).

(2) The nuclear reaction rates are from Caughlan and Fowler (1988). It is worth recalling that the rate of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ is lower than in previous estimates. The network of nuclear reactions involves 17 elements, ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{18}O, ^{20}Ne, ^{22}Ne, ^{24}Mg, and ^{25}Mg. The rates of neutrino energy losses are from Munakata et al. (1985).

(3) The models are calculated taking convective overshoot into account according to the formalism of Bressan et al. (1981), Bertelli et al. (1985), Alongi et al. (1991, 1993), and Bressan et al. (1993). The mean free path of convective elements is 0.5 H_p (where H_p is the local pressure scale height).

(4) The models of low- and intermediate-mass stars are calculated at constant mass, whereas those of massive stars are followed in presence of mass loss by stellar winds. Specifically, massive stars with initial mass $M \geqslant 12\ M_\odot$ are evolved including the effect of mass loss by stellar winds from the ZAMS stage. The mass-loss rates are from de Jager et al. (1988) for all evolutionary stages remaining below the so-called de Jager limit. We adopt the scaling factor with metallicity derived by Kudritzki et al. (1989). If a star happens to cross the de Jager limit, the mass loss rate is increased to $10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. For the W-R stages, which are defined to start when the surface abundance of hydrogen is smaller than $X=0.3$ (WNL stars), we apply the mass-loss rate of Langer (1989).

5.2 The Padova Library of Isochrones and SSPs (Bertelli et al.)

In this section we present the libraries of isochrones and integrated magnitudes and colors for SSP calculated with the stellar models of Sec. 5.1.

The isochrones of each set (at given chemical composition, cf. Sec. 5.1) span a wide range of ages. They are presented both in the theoretical and observational planes of the *UBV* passbands of Buser and Kurucz (1978), the *RI* Cousins passbands of Bessell (1990), and the *JHK* passbands of Bessell and Brett (1988). For each isochrone we list the current mass, the bolometric magnitude, the absolute visual magnitude in the Johnson system, and the colors $(U-B)$, $(B-V)$, $(V-R)$, $(V-I)$, $(V-J)$, $(V-H)$, and $(V-K)$. In addition, we give the indefinite integral of the initial mass function (IMF) by number over the mass (FLUM). This quantity allows the reader to derive the luminosity function. The adopted IMF is the Salpeter (1955) law with $\alpha=2.35$ (in number). See Bertelli et al. (1990, 1994) for full details.

In the range of low- and intermediate-mass stars and hence old and intermediate ages, the effect of mass loss by stellar winds passing from the tip of the red giant branch (RGB) down to the horizontal branch (HB), or the red clump as appropriate, and all along the thermally pulsing regime of the AGB phase (TP-AGB) are taken into account. More precisely, the rate of mass loss during the RGB phase is adopted according to the Reimers (1975) relationship with $\eta=0.45$, whereas the rate of mass loss during the TP-AGB phase is based on the semi-empirical formalism of Marigo et al. (1996), which incorporates the mass-loss prescription of Vassiliadis and Wood (1993). With these assumptions the initial/final mass relation (M_i-M_f) of the isochrones matches the observational one by Weidemann (1987). These isochrones are shortly referred to as the VW isochrones.

The library of integrated magnitudes and colors of the SSPs covers the same range of ages and chemical composition as for the isochrones. Furthermore the same IMF is used. The technical procedure is the same as in Bressan et al. (1994), Silva (1995), and Tantalo et al. (1996). Two grids of SSPs are presented depending on some specific assumptions on either the mass-loss rates or the library of stellar spectra.

The first grid is the one used by Tantalo et al. (1996). These SSPs extend the ZAMS to 0.15 $M_\odot$ with the aid of the VandenBerg (1985) models for stars with mass lower than 0.6 $M_\odot$. The rate of mass loss during the RGB and TP-AGB phases is according to the Reimers (1975) relationship with $\eta=0.45$. These SSPs are computed with the new library of stellar spectra described in Silva (1995) and Tantalo et al. (1996); see also Sec. 6.2, in which the metallicity–$T_{\rm eff}$ relation of Bessell et al. (1989, 1991) is introduced using the $(V-K)$ color as a temperature indicator. These SSPs are shortly referred to as SIL-SSP.

The second set makes use of the VW isochrones. Therefore the main difference with respect to the previous set is in the rate of mass loss during the TP-AGB phase, whereas the rate of mass loss for the RGB stages is the same $(\eta=0.45)$. These SSPs are shortly designated as VW-SSP.

For both sets of SSPs the integrated magnitudes and colors are in the Johnson–Cousins photometric system. The listed quantities are

(i) absolute visual and bolometric magnitudes (M_V and $M_{\rm bol}$);
(ii) bolometric corrections BC; and
(iii) colors $(U-B)$, $(B-V)$, $(V-R)$, $(R-I)$, $(V-J)$, $(V-K)$, $(V-L)$, $(V-M)$, $(V-N)$, and $(1550-V)$.

Finally, we present extensive tabulations as function of gravity, $T_{\rm eff}$, and metallicity of a quantity named *bolometric correction* ($\mathrm{BC}_{\Delta\lambda}^{HST}$) that would enable the reader to transfer the luminosity and $T_{\rm eff}$ of a star (or point along an isochrone) into magnitudes and colors in various passbands of the refurbished *HST* WFPC2, i.e., F170W, F218W, F255W, F300W, F336W, F439W, F450W, F555W, F606W, F702W, F814W, and F850LP, and of the old *HST* FOC, i.e., F150W +F130LP, F175W, F220W, and F342W. For all details about the calculations of the theoretical magnitudes by convolving the spectral energy distributions with different metallicity, $T_{\rm eff}$, and gravity with the passband transmission, response of the camera, and telescope configuration for each passband, the reader should refer to Chiosi et al. (1996). In brief, the procedure is as follows:

(i) First, from a spectral energy distributions of given $\log T_{\rm eff}$, gravity ($\log g$), and chemical composition, we calculate the quantity

$$N_{\Delta\lambda}=\int_{\lambda_{\rm min}}^{\lambda_{\rm max}}(F_\lambda(\lambda)/(hc/\lambda))\Gamma_{\Delta\lambda}(\lambda)d\lambda, \qquad (1)$$

where F_λ is the spectral energy distribution of the source, $\Gamma_{\Delta\lambda}(\lambda)$ is the product of the filter transmission $T_{\Delta\lambda}(\lambda)$ and the response function $R_{\Delta\lambda}(\lambda)$ of the telescope assembly and detector in use, and all other symbols have their usual meaning (h is the Planck constant and c is the speed of light). According to its definition, $N_{\Delta\lambda}$ is the number of photons emitted per unit of time by an ideal source with $L=L_\odot$ and detected by the filter in use. This quantity is then scaled to that received by a collector of unit area when the source is located at the distance of 10 pc. Finally, large grids of $N_{\Delta\lambda}$ are computed at varying $T_{\rm eff}$, gravity, and chemical composition.

(ii) Second, we define

$$\mathrm{BC}_{\Delta\lambda}^{HST}=M_{\rm bol,\odot}+21.1+2.5\log[U_{\Delta\lambda}\times\Sigma\times N_{\Delta\lambda}], \qquad (2)$$

where Σ is the area of the collecting surface, and $M_{\rm bol,\odot}$ is the absolute bolometric magnitude of the Sun, for which we adopt 4.72.

(iii) Finally, the real absolute magnitude $M_{\Delta\lambda}$ of a star of any luminosity, $T_{\rm eff}$, gravity, and chemical compositions is given by

$$M_{\Delta\lambda}=M_{\rm bol}-\mathrm{BC}_{\Delta\lambda}^{HST}. \qquad (3)$$

5.3 Update of the Geneva Library of Stellar Evolution Models (Meynet and Maeder)

We present the complete set of stellar models computed by the Geneva group until now. The Geneva "package" on the CD-ROM contains:

(i) pre-main-sequence evolution with accretion (Bernasconi 1996);
(ii) main-sequence (MS) and post-MS evolution in the range of 0.8–120 $M_\odot$ for:

$Z=0.040$, $Y=0.34$ (Schaerer et al. 1993a; SCMMS),
$Z=0.020$, $Y=0.30$ (Schaller et al. 1992; SSMM),
$Z=0.008$, $Y=0.264$ (Schaerer et al. 1993b; SMMS),
$Z=0.004$, $Y=0.252$ (Charbonnel et al. 1993; CMMSS),
$Z=0.001$, $Y=0.243$ (Schaller et al. 1992; SSMM);

(iii) horizontal branch (HB), post-HB, and AGB star models for various Z and Y (Charbonnel et al. 1996; CMMS);

(iv) models of stars with $M > 15\ M_\odot$ for all above (Z,Y) with mass-loss rates increased by a factor of 2 (Meynet et al. 1994; MMSSC);

(v) a code for calculating isochrones of different ages; and

(vi) complete tables of isochrones calculated for various Z and ages between 3×10^6 and 12×10^9 yr.

Work in progress includes (i) models of low-mass stars between 0.3–1.0 $M_\odot$ for various Z, with an up-to-date equation of state (Charbonnel 1996); (ii) models in the range 0.3–120 $M_\odot$ at $Z=0.10$ (Mowlavi et al. 1996); and (iii) refined models of young starbursts (age <12 Myr), including also pre-MS evolution and providing the emergent spectrum predicted by complete stellar models (Schaerer and Bernasconi 1996). The results will be available in the near future.

A detailed discussion of the physical ingredients can be found in SSMM, CMMSS, MMSSC, and CMMS. Therefore only a brief summary is given here. (i) The new radiative opacities by the OPAL group have been used (Rogers and Iglesias 1992; Iglesias et al. 1992; Iglesias and Rogers 1993). (ii) At low $T_{\rm eff}$, i.e., below 6000 K, radiative opacities by Kurucz (1991) also including the main molecular lines have been accounted for. (iii) The initial composition (Y,Z) has been chosen consistently with a relation of the form $Y = Y_p + dY/dZ\,\delta Z$, where Y_p is the primeval helium content and dY/dZ is the relative helium-to-metal enrichment. Y_p is taken equal to 0.24 and dY/dZ has been chosen equal to 3, except for $Z=0.04$ where dY/dZ was taken equal to 2.5. (iv) The mass-loss rates are taken as given by de Jager et al. (1988) for stars throughout the HR diagram, except the Wolf–Rayet stars. We adopt a scaling of mass-loss rates with metallicity as given by the models of Kudritzki et al. (1991), i.e., $\dot M$ is proportional to $Z^{0.5}$. For Wolf–Rayet stars, there is no indication yet for a dependence of $\dot M$ values on initial Z. However, we adopt the $\dot M$ versus mass relation found by Langer (1989) for WNE and WC stars, i.e., $\dot M = (0.6-1.00)\times10^{-7}\ (M/M_\odot)^{2.5}$ in solar masses per year, respectively. For WNL, the average mass-loss rate of $4\times10^{-5}\ M_\odot\ {\rm yr}^{-1}$ is adopted (cf. Conti 1988). These mass-loss rates were enhanced by a factor of 2 during the pre-W-R and the WNL phases in MMSSC. (v) Extensive comparisons of models and observations have suggested the presence of moderate overshooting of about 0.2 H_p. (vi) The detailed treatment of the partial ionization for the heavy elements has been included. (vii) The optically thick wind of W-R stars is treated in the framework of the modified Castor et al. theory (Castor et al. 1975; Kudritzki et al. 1989). This enables us to satisfactorily calculate the $T_{\rm eff}$ and radii of W-R stars.

5.4 Models for the Evolution and Nucleosynthesis of Massive Stars (Ødegaard)

Detailed nucleosynthesis calculations of very massive stars up to advanced stages have been performed. The computations include a nuclear network with 174 species linked by 1742 nuclear reactions. The computations have been done with a dynamical stellar evolution code and include semi-convection and overshooting. The large nuclear network and the diffusion equation are solved at each time step. A more detailed description of the computations can be found in Ødegaard (1996a,b).

Surface abundances of 95 selected species from H to Ge are presented. We also give the evolutionary tracks of the stars. The model predictions include stellar mass, mass-loss rate, luminosity, $T_{\rm eff}$, core temperature and density, mass of convective core, abundances of ^{4}He, ^{12}C, and ^{16}O in the core, and the accumulated mass loss of each nuclear species.

6. EVOLUTIONARY SYNTHESIS MODELS: OLD SYSTEMS

In the early days of galaxy evolution, modeling old stellar populations such as, e.g., elliptical galaxies, seemed much easier to describe than, for instance, young populations like spiral, irregular, or starburst galaxies. The reasons were that from optical and near-IR broadband colors early-type galaxies (E's and S0's) seem to form a very homogeneous class of objects, and gaseous emission as well as dust absorption are unimportant as compared to late type or starburst galaxies. With the extension of the accessible spectral range to the UV, X, sub-mm, and radio regions, as well as with the availability of higher spatial resolution for spectroscopy, this situation has changed dramatically; e.g., in the UV, elliptical galaxies show a variety of spectral properties that keep challenging stellar evolution models, and many of the former "old, red, and dead" E/S0 galaxies nowadays show evidence for intermediate age populations or at closer look even reveal some central ongoing star formation. Cold gas detected near the centers of several E/S0 galaxies as well as hot gas seen as X-ray coronae prove that these galaxies are not entirely gas-free. The classical picture of a monolithic initial collapse scenario for the formation of ellipticals is questioned by detections of intermediate age sub-populations, peculiar core kinematics, and of obvious old spiral–spiral merger remnants well advanced on their way to becoming E/S0 galaxies.

The optical and near-IR light of old stellar populations is dominated by low-mass stars in their late and luminous stellar evolutionary phases. The correct description of their stellar evolutionary tracks including the lifetimes of the various stages are of crucial importance. We know by now that the range of stellar metallicities in ellipticals is large. While low to average luminosity ellipticals reveal significantly subsolar abundances in their integrated spectra the nuclear regions of high-luminosity E's contain a significant population of high-metallicity stars.

The method of *population synthesis* uses some minimization scheme to isolate from a complete library of observed or theoretical stellar spectra those constituents and their respective proportions that contribute to the spectral energy output of an observed galaxy. The use of isochrone spectra instead of individual star spectra makes sure that some form of IMF is realized in the solution. If distinctive spectral features are used, this method can give a very precise—though not necessarily unique—*status quo* description of a composite stellar population. *Evolutionary synthesis* aims at modeling the complete evolutionary path of a stellar system to the presently observed state. Assuming some kind of star-formation history, the spectral evolution of a galaxy is followed from the birth of the first stars, thus directly offering cosmological applications. Pieces of input physics can either be a complete set of stellar evolutionary tracks, an IMF, and a library of color calibrations or stellar spectra. Simple stellar populations (=single burst and single metallicity) and early-type galaxies with their discontinuous or strongly declining star formation histories in general lead to luminosities, colors, and SEDs strongly fluctuating in time. Two approaches are used to cure this problem; one keeps the IMF as a free parameter and smooths the resulting luminosity and color evolution in an appropriate way, and the other uses smoothly interpolated isochrones which already incorporate some IMF. Every composite stellar population with any kind of star-formation history, such as, e.g., a burst of given strength at some stage of evolution, can be expanded into a series of SSPs of different ages.

Some of the models presented here also follow the chemical enrichment history of composite stellar populations and use stellar tracks and spectra for various metallicities to consistently account for the enrichment history of successive stellar generations. Open problems here are the poorly known He-to-metal evolution (dY/dZ) and the influence of non-solar abundance ratios.

6.1 A Grid of Spectral Indices for Single Stellar Populations (Bressan et al.)

We present the narrow-band indices for single stellar populations (SSPs) with metallicities ranging from $Z=0.0004$ to 0.1 (where $Z_\odot=0.02$). Brief and detailed descriptions of the SSP models can be found in Sec. 5.2 and in Bressan et al. (1994), Silva (1995), and Tantalo et al. (1996), respectively.

The narrow-band indices are calculated by means of the empirical calibrations of Worthey (1992) and Worthey et al. (1994), who give the index strength as a function of stellar atmospheric parameters ($\Theta_e = 5040/T_{\rm eff}$, $\log g$, and [Fe/H]). The definition of the spectral indices strictly follows that of Worthey (1992). In brief, all the indices are constructed by means of a central passband and two pseudo-continuum passbands on either side of the central band (see Worthey et al. 1994 for details). The continuum flux is interpolated between the midpoints of the pseudo-continuum passbands.

The integrated indices for SSPs are obtained as follows:

(1) First, for every combination of $T_{\rm eff}$, g, and [Fe/H], we derive the flux in the continuum passband using the library of stellar spectra of Bressan et al. (1994) and Tantalo et al. (1996). See also Sec. 6.2.
(2) Second, for the same values of $T_{\rm eff}$, g, and [Fe/H], we calculate the flux in the central passband with the analytic fits of Worthey et al. (1994).
(3) Third, we get the integrated $F_{I\lambda}$ and $F_{C\lambda}$ as described in Bressan et al. (1996).
(4) Fourth, knowing the integrated fluxes, we apply the definition of each index to derive the integrated index.

The following indices are considered: CN$_1$, CN$_2$, Ca4227, G4300, Fe4383, Ca4455, Fe4531, Fe4668, Hβ, Fe5015, Mg$_1$, Mg$_2$, Mg$_b$, Fe5270, Fe5335, Fe5406, Fe5709, Fe5782, NaD, TiO$_1$, TiO$_2$.

Each set (fixed metallicity) contains the temporal evolution of all the indices as indicated.

6.2 Library of Spectral Energy Distributions for SSPs (Bressan et al.)

We present the spectral energy distributions (ISEDs) for the two sets of SSPs named SIL-SSP and VW-SSP (see Secs. 5.1 and 5.2 for the chemical parameters and other physical ingredients).

6.2.1 SIL-SSPs

The ISEDs of the SIL-SSPs have been calculated using the spectral library adopted by Silva (1995) and Tantalo et al. (1996). The main body of the spectral library is from Kurucz (1992), extended to the high- and low-temperature ranges. For stars with $T_{\rm eff}>50{,}000$ K, pure blackbody spectra are assigned. For stars with $T_{\rm eff} < 3500$ K the new catalog of stellar fluxes by Fluks et al. (1994) is adopted (see Silva 1995 for details). We use the metallicity–$T_{\rm eff}$ relation of Bessell et al. (1989, 1991), with the $(V-K)$ color as temperature indicator. An interpolation is made between the $T_{\rm eff}$ of Bessell et al. (1989, 1991) and the $(V-K)$ colors given by Fluks et al. (1994) for spectral types from M0 to M10.

6.2.2. VW-SSPs

The ISEDs of the VW-SSPs have been calculated dropping the metallicity effect adopted in the previous case.

6.3 Spectrophotometric Models of Elliptical Galaxies (Bressan et al.)

In this section we present a few chemo-spectrophotometric models of elliptical galaxies, taken from Tantalo et al. (1996). In brief, these models aim to simulate the collapse of a galaxy made of two components, luminous material and dark matter, by taking into account the infall of primordial gas into the potential well of dark matter. They also include the effect of galactic winds powered by supernova explosions and stellar winds from massive, early-type stars as the key physical phenomenon responsible for the color–magnitude relation of elliptical galaxies. These models are labeled by the asymptotic mass that should be reached by the luminous component $M_L(T_G)$ at the present age T_G in the absence of galactic winds (see Tantalo 1994 and Tantalo et al. 1996 for details). The following values of $M_L(T_G)$ are considered: 3×10^{12} 1×10^{12} 1×10^{11}, and $5\times10^{10}\,M_\odot$. The rate of star formation is $\Psi(t)=\nu G(t)^k$, where $G(t)$ is the current gas fraction and ν is an efficiency parameter. The IMF is the Salpeter law normalized to the fraction ζ of stars above 1 $M_\odot$. The infall time scale τ is the same for all the models, i.e. 0.1 Gyr. For each model we give the temporal evolution of the ISED and integrated colors in the Johnson–Cousin system. Finally we give a summary table containing the key parameters of the models, namely, the efficiency ν of star formation, the fraction of the IMF ζ above 1 $M_\odot$, the asymptotic mass $M_L(T_G)$ in units of $10^{12}\ M_\odot$, the age at the onset of galactic winds (t_{gw} in Gyr), the fraction of gas $G(t)$ and stars $S(t)$, and the metallicity $Z(t)$ at the same epoch, the mean metallicity $\langle Z(t) \rangle$ of the stellar component, the rate of star formation $\Psi(t)$, the gravitational binding energy Ω_g of the gas, the total thermal energy E_g of the gas together with the separate contributions from Type I and II supernovae and stellar winds. All these quantities refer to the epoch of galactic winds.

6.4 A Library of Galaxy Spectral Evolutionary Models (Bruzual and Charlot)

Isochrone synthesis spectral evolution models for simple stellar populations of metallicity $Z=0.0004$, 0.004, 0.008, 0.02, 0.05, and 0.10 are included in this contribution. The models are based on the Padova group evolutionary tracks and the Lejeune et al. (1996) model atmosphere compilation described in Sec. 3.2. The evolving spectra include the contribution of the stellar component in the range from the EUV to the FIR; the age varies from 0 to 20 Gyr and various IMFs are considered. For the $Z=0.02$ case, models built from empirical stellar libraries of low and high resolution (in the optical range) are included. Programs are provided to compute composite stellar populations from the included single stellar populations. This is the natural extension and update of the models by the same authors that are currently available (for solar metallicity only).

A detailed description of these models can be found in Bruzual and Charlot (1996).

6.5 Ultraviolet Spectra for Old Stellar Populations (Dorman and O'Connell)

This contribution comprises spectral energy distributions for use in modeling the integrated spectral properties of galaxies, for $1000<\lambda<10{,}000$ Å. The data cover stellar populations for $2<t<20$ Gyr, and for the following metallicity/helium abundance combinations:

(1) [Fe/H]$=-1.48$, $Y=0.236$ ($Z=0.0006$, [O/Fe]=0.60),
(2) [Fe/H]$=-0.47$, $Y=0.248$ ($Z=0.006$, [O/Fe]=0.23),
(3) [Fe/H]$=+0.00$, $Y=0.270$ ($Z=0.0169$),
(4) [Fe/H]$=+0.38$, $Y=0.270$ ($Z=0.04$),
(5) [Fe/H]$=+0.43$, $Y=0.340$ ($Z=0.04$), and
(6) [Fe/H]$=+0.58$, $Y=0.270$ ($Z=0.06$).

We provide the following data: (i) SEDs computed from isochrones at intervals of 2 Gyr; (ii) "evolutionary fluxes" [$\dot{n}_0(t)$ in the notation of Dorman et al. (1995, hereafter DOR95)], which are used to compute the relative contribution of horizontal-branch stars to the main-sequence/red-giant component, (iii) integrated SEDs for each of the HB/post-HB tracks computed by Dorman et al. (1993), and (iv) integrated SEDs for the four post-AGB sequences due to Schönberner (1979, 1983). It is intended that the post-AGB sequences represent the end stages of evolution for those HB sequences that terminate on the AGB rather than being taken to completion on the white dwarf cooling track; generally, this corresponds to the HB mass range that makes up the red HB clump.

The isochrones are a revised version of those used in DOR95, computed by a new program (Dorman 1996) specifically designed to handle the high-metallicity isochrones accurately. As well, the table of $\dot{n}_0(t)$ given in DOR95 Table 6 is superseded by the values presented here. The SEDs are computed using three sources for the emergent flux at a point on the HR diagram: the Kurucz (1993) synthetic fluxes, the non-LTE hot ($T>40{,}000$ K) model atmospheres of Clegg and Middlemass (1987), and fluxes selected from the Gunn and Stryker (1983) scans for M giants for $T<3926$ K. The post-AGB SEDs are computed with solar metallicity Kurucz fluxes. These spectra are described in greater detail in Dorman and O'Connell (1996). The isochrones themselves are available from the author on request.

The isochrone spectra are given in an arbitrary unit which is a multiple of the solar V-band luminosity/Å. The HB and later evolution are integrated over the evolutionary track, and thus their units are of energy/Å. A full description of how to combine the evolutionary phases to produce stellar populations of arbitrary HB morphology is given in DOR95. To compare with similar work or observation, the simplest method is to normalize the synthetic spectra at the V band or other convenient bandpass.

6.6 The Codes and Input Data of the Spectral Evolution Model PEGASE for Starbursts and Evolved Galaxies from the Far-UV to the Near-IR (Fioc and Rocca-Volmerange)

The project PEGASE (Projet d'Etude des GAlaxies par Synthèse Evolutive) has been designed to reproduce the SED (stellar and nebular continua, emission lines) of starburst galaxies and of evolved galaxies of the Hubble sequence with an optional metal-dependent extinction. The innovation of this model is the extension to the near-infrared in a way consistent with the optical and the ultraviolet. This allows any multispectral analysis from 220 Å to 10 μm.

The integration algorithm is based on isochrones derived from stellar tracks of the Padova or Geneva groups connected to the TP-AGB phase (Groenewegen and de Jong 1993) and the post-AGB phase until the stage of white dwarfs (Schönberner 1983; Blöcker 1995). Other input data for bolometric corrections, parameters of nebular emission, and filter characteristics are included as well. The code for the evolution of an instantaneous burst and the code to compute galaxy spectra are in FORTRAN 77 running under UNIX and VMS. A large variety of parameters of star formation (initial mass function and star-formation rate) are made available to users.

Our stellar library is also made available in this paper since it is a basic element of the model (see Sec. 2.3). The project PEGASE is new, taking advantage of the experience of our previous models (Rocca-Volmerange et al. 1981; Guiderdoni and Rocca-Volmerange 1987; Lançon and Rocca-Volmerange 1996). *The innovation is to present the code itself and all input data—in particular our stellar library and that of Jacoby et al. (1984)—published and usable in an easily manageable form.* Each file is clearly identified and submitted for publication. Further improvements of any block will be announced on

ftp.iap.fr in *pub/from_users/pegase/.*

Final output data are synthetic spectra of starbursts or evolved galaxies, their colors in most of the classical UV to near-IR (including J,H,K,L,M filters) photometric systems and other data (M/L_V, M/L_B, numbers of SNII, equivalent widths of the main emission lines, gas fraction, number of Lyman continuum photons) while many others can be easily computed. Metallicity-dependent extinction, nebular components and ejecta by stars are optional. Directions to compute synthetic spectra, colors, and other output data are presented in the file FRV_README.

6.7 An Atlas of Synthetic Spectra and Colors Computed with the Spectral Evolution Model PEGASE for a 1-Gyr Starburst and Eight Types of Evolved Galaxies from the Far-UV to the Near-IR: *k* and *e* Corrections in Three Cosmologies (Rocca-Volmerange and Fioc)

Synthetic energy distributions, continuous from 220 Å to 10 μm, are published for a 1-Gyr starburst and eight spectral types of galaxies of the Hubble sequence.

SEDs are the sum of the stellar emission plus the nebular continuum and of emission lines with a time resolution starting with 1 Myr and slowly increasing. The spectral resolution is identical to that used in our stellar library (Sec. 2.3): 10 Å in the visible and 200 Å in the near-IR. Colors and various output data (M/L_V, M/L_B, numbers of SNII, equivalent widths of main emission lines, gas fraction, number of Lyman continuum photons) are listed at the same time steps. Details on the templates are given in the RVF_README file.

Tables of k and $(k+e)$ corrections from the spectral atlas for a 1-Gyr starburst and eight spectral types of the Hubble sequence are computed in three cosmologies defined by $(H_0, \Omega_0, \Lambda_0)$ values of (50, 0.1, 0.0), (50, 1.0, 0.0), and (75, 0.1, 0.9) through a large variety of filters (including Johnson–Cousins *UBVRIJHKLM*, DENIS filters, *HST* filters, Foca 2000 Å filter). Predictions of apparent magnitudes and colors of high-redshift galaxies can be derived from these corrections (Rocca-Volmerange and Guiderdoni 1988). Other models can be computed by request at the PEGASE address: pegase@iap.fr.

6.8 Single Stellar Populations of Different Metallicities (Fritze-v. Alvensleben and Kurth)

Using the new set of stellar evolutionary tracks from the Geneva group (cf. Sec. 5.3) we have repeated our photometric evolutionary synthesis modeling of SSPs exactly as described in Fritze-v. Alvensleben and Burkert (1995). Metallicities presented here are $Z=0.001$, 0.004, 0.008, 0.020, 0.040. Stars with $m<0.8\ M_\odot$ are from the compilation of Einsel et al. (1995). Some stellar absorption indices are modeled on the basis of the Gorgas et al. (1993) calibrations for all individual stellar evolutionary stages as described in Einsel et al. (1995) and Möller et al. (1996). Color calibrations for *UBVRI* in the Johnson system are as described in Einsel et al., $(V-K)$ colors for cold stars are from Ridgway et al. (1980) and Fluks et al. (1994).

For each SSP we provide the evolution of luminosities in *UBVRIK* and of some stellar absorption indices.

6.9 Chemically Consistent Galaxy Evolution (Fritze-v. Alvensleben et al.)

Using the same input physics as described in Sec. 6.8 we present here evolutionary synthesis models for:

(i) a Hubble Sequence of galaxies E/S0, Sa, Sb, Sc, Sd/Im for solar metallicity; and

(ii) a Hubble Sequence of galaxies E/S0, Sa, Sb, Sc, Sd/Im calculated in a chemically consistent way.

Galaxies of various spectral types are characterized by semiempirical star-formation histories as described in Fritze-v. Alvensleben and Gerhard (1994) and Möller et al. (1996). Our models also follow the chemical enrichment of the ISM through stellar winds, PNe, Type I and II SNe, explicitly accounting for the respective time delays. SNI contributions are based on the carbon deflagration CO–wd binary scenario (Matteucci 1991). Our second model sequence describes the spectral and photometric evolution of a Hubble sequence of galaxies in a chemically consistent way. This means that within the framework of a simplified closed-box one-zone model we take into account the successive enrichment of the ISM out of which later generations of stars are born; i.e., we follow successive generations of stars on individual tracks appropriate for their initial metallicities. The photometric aspects of this chemically consistent treatment were presented by Einsel et al. (1995), the chemically consistent spectral evolution is described in Möller et al. (1996).

Solar metallicity models are calculated for a Scalo IMF from 0.15 to 85 $M_\odot$ as in Fritze-v. Alvensleben and Gerhard and use tracks including He flash. Chemically consistent models use a Salpeter IMF from 0.15 to 120 $M_\odot$ and tracks without He flash, since He flash tracks are only available for two of the five metallicities.

For each set of models we provide the evolution of luminosities in *UBVRIK* and of some stellar absorption indices (cf. Sec. 6.8).

6.10 Grids of Theoretical Evolutionary Spectra of Stellar Populations (Traat)

The Traat (1992, 1996a,b) evolutionary population/galaxy models produce spectral energy distributions, broad- and narrow-band colors, and magnitudes and mass-to-light ratios for both *"initial-burst"* stellar populations and populations with continuous star formation. Age and composition are arbitrary, with the limitations set in practice by properties of the input stellar track/isochrone sets. Stellar evolution sources are basically either Padova or Geneva tracks or isochrones. The conversion from stellar luminosities and temperatures to spectral flux distributions is currently based on Kurucz (1993) model atmospheres, with the prospect of their replacement in the cool star region $T_{\mathrm{eff}}\leqslant 4500$ K by the new Uppsala release in the future. Both the stellar tracks and atmospheres cover a wide metallicity range, allowing the study of composition effects on the resulting spectra and photometry. See Traat (1996b) for more details on these spectro-photometric models.

The data files of the present CD-ROM distribution rely on Padova *isochrones* with eight metallicities 0.0001, 0.0004, 0.001, 0.004, 0.008, 0.02, 0.05, and 0.1. The computed model spectral fluxes are scaled to the *unit mass of stars* ever formed in the bright star interval 0.6–120 $M_\odot$ and represent pure integrated stellar light, no nebular component/absorption has been included. The star-formation rate has been parameterized as a power of the gas volume density (as introduced by Schmidt 1959), with index s and time scale t_0. In this parameterization, the single-generation (''initial-burst'') populations are independent of the star-formation rate and its power index and form the limiting case of $t_0=0$.

The models are chemically homogeneous. The data set for each Z value includes: a number of power-law IMFs of different slopes, the corresponding single-generation populations, populations with continuous/continuing star formation for those IMFs with six values for t_0 and four values for the star-formation rate exponent: $s=0$ (constant SFR), $s=1$ (exponentially declining), $s=1.5$, and 2 (initially faster, later slower than the exponential SFR). A detailed description of the layout of tables is given in an accompanying README file on the CD-ROM.

6.11 A Spectrophotometric Population Synthesis Library for Old Stellar Systems (Vazdekis et al.)

We present the results of a new stellar population synthesis model designed to study old stellar systems such as the early-type galaxies by Vazdekis et al. (1996a). It provides for six optical and near-infrared colors and 25 absorption line indices (including the Lick system). It can synthesize single age, single-metallicity stellar populations or follow the galaxy through its evolution from an initial gas cloud to the present time. The model incorporates the latest stellar spectral libraries and the isochrones of the Padova group transformed to the observational plane by our own method. In another paper (Vazdekis et al. 1996b) we discuss in detail the application of this model to a new set of data for three early-type *standard* galaxies.

Our goal here is to present the obtained synthetic colors and line strengths electronically. First we give the synthetic observables as well as $(M/L)_V$ for single-age, single-metallicity, stellar populations, for a range of age, metallicity, and for two different IMF shapes. Second, we present these same observables obtained with our full chemo-evolutionary population synthesis model, where we vary the star-formation rate, the age, and the IMF shape.

6.12 Evolutionary Population Models for Early-Type Galaxies (Worthey)

The Worthey (1994) evolutionary population models give integrated $UVBR_CI_CJHKLL'M$ colors and magnitudes, SBF magnitudes, spectral energy distributions, and Lick/IDS spectral index strengths for populations of arbitrary age, and (assumed scaled-solar) abundance [Fe/H]. The ages range from 1 to 18 Gyr, and abundances from −2.0 to +0.5 dex. Helium abundance Y is a free parameter. The underlying stellar evolution is that of VandenBerg (VandenBerg 1985; VandenBerg and Bell 1985; VandenBerg and Laskarides 1987). The stellar fluxes used to compute integrated flux are mostly theoretical (Kurucz 1992; Bessell et al. 1989, 1991), and explicitly include the effects of metallicity on the spectral shape and colors. See Worthey (1994) for details.

The distribution on the CD-ROM includes several ''flavors'' of model grid: (i) Five power-law IMFs plus Miller and Scalo (1979) are provided. For the power-law IMFs the lower-mass cutoff was chosen so that $M/L_V=2.5$ for globular-cluster-like populations (with a reasonable accounting of stellar remnants; Worthey 1996), so output M/L values differ from the tabulation in Worthey (1994) by a constant factor plus a small perturbation caused by the fact that a small amount of low-mass starlight is missing. (ii) Also included are four schemes for how helium abundance tracks overall abundance. (iii) One model grid without helium burning and later stages of stellar evolution is included for those interested in adding HB, AGB, early-AGB, post-AGB stages, or other stages of evolution by themselves. (iv) The models as tabulated in Worthey (1994) are also included unaltered.

Each model (at one age and [Fe/H]) is stored in a FITS file with ascii table extensions. One ''flavor'' is made of a grid of FITS files covering the range of age and [Fe/H]. A FORTRAN program is provided that reads the data using Pence's FITSIO routines (also included), interpolates in the model grid to arbitrary age and metallicity, and combines populations in any combination the user specifies. Multicolor color–magnitude diagrams are also available in the FITS file ascii extensions.

7. EVOLUTIONARY SYNTHESIS MODELS: YOUNG SYSTEMS

The early phase in the evolution of a stellar population ($t<50$ Myr) is dominated by the properties of massive stars. Several models have been constructed to address issues such as the relative contributions of stellar and nebular emission, effects of stellar winds, or the properties of Wolf–Rayet stars and red supergiants. The evolutionary time scales of massive stars are often not long in comparison with the age of the population so that aspects of star formation and stellar evolution are often closely connected.

We are including three model sets which make predictions over a wide spectral range and for various properties of the population: Bressan et al. (Sec. 7.1), Leitherer et al. (Sec. 7.4), and Mas-Hesse and Cerviño (Sec. 7.5). The three models use three different sets of stellar evolution models, aiding the user in realizing how stellar evolution affects the synthetic spectrum (see also García-Vargas et al. 1996a). Bressan et al. have computed energy distributions for single stellar populations of different chemical composition with the latest set of Padova tracks (see Sec. 5). The same stellar population was used to compute a grid of synthetic calcium triplet equivalent widths for starbursts containing red giants and supergiants (Sec. 7.2). The models of Leitherer et al. are based on Maeder's (1990) multi-Z models, in combination with extended model atmospheres for Wolf–Rayet stars. The models of Mas-Hesse and Cerviño use the Geneva models described in Sec. 5 and give numerous properties of the stellar population, in addition to the energy distributions.

The spectral evolution model PEGASE by Fioc and Rocca-Volmerange (Secs. 6.6. and 6.7) is discussed in the section on old systems. It can, however, be applied to galaxies forming young, massive stars as well.

A relatively new field to explore in evolutionary synthesis work of young systems is the infrared. Dedicated modeling in this spectral region is presented by Lançon in Sec. 7.3. These models are particularly useful in systems with high dust content where only the infrared provides access to the underlying stellar population.

7.1 Energy Distributions for Single Stellar Populations (Bressan et al.)

We present spectral energy distributions for instantaneous star bursts formed according to a Salpeter-type IMF for ages between 1 and 350 Myr. All clusters have a mass of $1\times10^6\ M_\odot$. The description of the isochrones (Padova group) and the stellar atmospheres used in the modeling can be found in García-Vargas et al. (1995a).

However, in the models presented here, the IMF parameters are slightly different from those given in the indicated paper. The spectra have been computed assuming a *standard* Salpeter IMF: $\alpha=2.35$, $m_{\rm low}=1\ M_\odot$, $m_{\rm up}=100=M_\odot$. Together with this standard set of models we also present two complementary sets of models computed with non-standard IMFs. These are models corresponding to $\alpha=3.30$, $m_{\rm low}=1\ M_\odot$, $m_{\rm up}=100\ M_\odot$, and to $\alpha=2.35$, $m_{\rm low}=1\ M_\odot$, $m_{\rm up}=30\ M_\odot$.

7.2 Calcium Triplet Synthesis (García-Vargas et al.)

We present theoretical equivalent widths for the sum of the two strongest lines of Calcium triplet, CaT, in the near-IR (λλ8542, 8662 Å). We have used the spectral energy distributions presented by Bressan et al. in Sec. 7.1. The stellar CaT equivalent widths have been calculated according to the calibrations given by Díaz et al. (1989). The nebular contribution has been included. Tables with the synthetic line strengths, both stellar and nebular fluxes, at representative wavelengths in the ultraviolet, optical, near-IR and thermal IR are given. Details of the evolutionary synthesis code can be found in García-Vargas et al. (1996b).

We have calculated the CaT equivalent width for SSPs (instantaneous burst, Salpeter-type IMF, $\alpha=2.35$, $m_{\rm low}=1\ M_\odot$, $m_{\rm up}=100\ M_\odot$, $M=10^6\ M_\odot$), three metallicities ($Z=0.004$, 0.008, and 0.02), and ages between $\log t=6.00$ (yr) and $\log t=8.55$ (yr) (with a logarithmic step in age of 0.05). Four models representative of the bulge population of ages 5, 10, 12, and 15 Gyr are also included.

Several combined-population models have been computed with different mass percentages of young (2.5–4.5 Myr, capable to ionize), intermediate (around 9 Myr, rich in RSG) and old (bulge) populations. The equivalent width of Hβ in emission has also been synthesized. The tables contain sufficient information to allow the user to calculate any other required combination.

7.3 Evolution of Near-IR Properties of Starburst Regions (Lançon)

Starburst regions are often so heavily obscured with dust that studying them at infrared wavelengths represents a definite advantage. Near-IR spectra allow us to explore deeply embedded stellar sources and the influence of these stars on the surrounding interstellar medium, by comparisons with the predictions of evolutionary population synthesis models. The stellar energy distribution in this wavelength range is specifically sensitive to the evolving contribution of red supergiants, while the near-IR emission lines reveal ionizing stars and shocks.

The files provided present the predicted evolution of the stellar energy distribution between 1.4 and 2.5 μm for various starburst scenarios and upper mass limits of the stellar initial mass function, up to an age of 200 Myr. Selected integrated properties (total mass in stars, luminosities with and without the contribution of ionized gas, recombination lines) are also listed as functions of time. This work is the result of a collaboration with B. Rocca-Volmerange (Institut d'Astrophysique de Paris). It makes extensive use of a library of near-IR empirical stellar spectra (Lançon and Rocca-Volmerange 1992) which is continuously being further developed (contact: lancon@astro.u-strasbg.fr). Details and applications of the models can be found in Lançon (1996), Lançon et al. (1996), and in Lançon and Rocca-Volmerange (1996).

7.4 Spectral Energy Distributions for Massive-Star Populations (Leitherer et al.)

We present the results of an extensive grid of evolutionary synthesis models for populations of massive stars. The parameter space has been chosen to correspond to conditions typically found in objects like giant H II regions, H II galaxies, blue compact dwarf galaxies, nuclear starbursts, and infrared luminous starburst galaxies. The models are based on the most up-to-date input physics for the theory of stellar atmospheres, stellar winds, and stellar evolution.

Observable properties of a population of stars are computed for the two limiting cases of an instantaneous burst and a constant star-formation rate over a time interval of 1–25 Myr, in steps of 1 Myr. Three choices of the initial mass functions are studied: a Salpeter- and a Miller–Scalo-type IMF with upper mass limits of 100 $M_\odot$, and a Salpeter IMF truncated at 30 $M_\odot$. Metallicities of 0.1 $Z_\odot$, 0.25 $Z_\odot$, $Z_\odot$, and 2 $Z_\odot$ are considered.

The output products are spectral energy distributions covering the wavelength range 50 Å to 9 μm. The files included on the CD-ROM give fluxes (i) for stars only, (ii) for nebular emission, and (iii) for gas and stars combined. The contamination of the stellar ultraviolet, optical, and near-infrared continuum by nebular emission has been discussed by Olofsson (1989), Mas-Hesse and Kunth (1991), and Leitherer and Heckman (1995). Under typical starburst conditions the nebular continuum is not negligible. Depending on the wavelength, addition of the nebular continuum leads to significantly redder or bluer broadband colors than obtained from a pure stellar continuum.

The spectral energy distributions were previously used to compute the galaxy properties published by Leitherer and Heckman (1995). The energy distributions themselves were not published in that paper, only derived quantities such as colors and magnitudes.

7.5 Evolutionary Synthesis for Young Starbursts (Mas-Hesse and Cerviño)

We have computed evolutionary synthesis models for young starbursts (i.e., from 0 to 20 Myr). The models are based on evolutionary tracks from Schaerer et al. (1993a,b, and references therein) for six different metallicities ($Z_\odot/20$, $Z_\odot/5$, $Z_\odot/2.5$, $Z_\odot$, $2\ Z_\odot$, and $Z_\odot$ with enhanced mass-loss rate). They have been performed for several IMF slopes (-1, -2.35 [Salpeter], and -3) with mass limits between 2 and 120 $M_\odot$ and for two star-formation regimes, an instantaneous burst, and for a constant star formation.

Stellar inputs are from a compilation described in Mas-Hesse and Kunth (1991) based on Kurucz and Mihalas atmosphere models, together with observational values and the atlas from Jacoby et al. (1984). We have considered only solar metallicity atmosphere models for all models. The files on the CD-ROM contain all the parameters we have synthesized: stellar populations: O, B, A stars of V, III, and I luminosity classes, WN and WC Wolf-Rayet stars, and other spectral types; ionizing flux and related parameters (nebular continuum, Hβ emission line strengths); spectral energy distributions in the range 1200 Å–3.6 μm and the radio (~6 cm) emission; the ratio of the Si IV λ1400 and C IV λ1550 absorption-line equivalent widths; Hβ emission-line equivalent widths; the Wolf-Rayet bump equivalent width and its ratio to the Hβ luminosity; and the effective temperature $T_{\rm eff}$.

More details can be found in Mas-Hesse and Kunth (1991) and Cerviño and Mas-Hesse (1994). The models are currently being completed by including the effect of evolution in binary systems. Preliminary results can be found in Cerviño and Mas-Hesse (1996) and in Cerviño et al. (1996).

8. MODELS FOR THE EMISSION SPECTRA OF IONIZED GAS

Ionized gas is a prevalent and readily observable component of the interstellar medium in galaxies. Gas in this state is both a good absorber, especially in the ultraviolet where many resonance transitions are found (e.g., Spitzer and Jenkins 1975), and an emitter of line and continuum radiation over much of the electromagnetic spectrum. The production of ionized gas requires power, and thus this phase of the ISM traces the effects of energetic processes within galaxies. The emission spectrum depends on local properties of the ionized gas and therefore can be used to measure parameters such as abundances, temperatures, and pressures. Excellent texts on this subject include Spitzer (1978) and Osterbrock (1989).

Because a number of different physical processes can make ionized gas, a variety of modeling techniques have been developed to calculate the emitted spectra of various types of astrophysical plasmas. Shock models consider cases where the dominant power is provided by the mechanical energy of gas flows, e.g., in stellar winds or outflows, or supernova explosions. The results from such models depend both on the structure of the shock and the medium into which it is propagating. Factors such as abundances, the degree of gas clumping, magnetic fields, and transport of ionizing radiation produced by the shock enter into the models. An important early set of shock models was calculated by Raymond (1979) for a variety of standard astrophysical situations. In Sec. 8.1 we present a series of modern shock emission models computed by Dopita and Sutherland, which can be applied to circumstances such as the presence of supernova remnants in a variety of astrophysical settings.

H II regions are perhaps the most dramatic examples of ionized gas structures associated with the evolution of the stellar populations of galaxies. These objects are relatively dense gas clouds which are photoionized by nearby, young OB stars. Giant and supergiant H II regions exist with sizes of ~1 kpc or more in the disks of otherwise normal galaxies (e.g., the Tarantula Nebula in the 30 Doradus complex of the Large Magellanic Cloud). Because H II regions depend on OB stars for their photoionization, they can be used to trace the locations and levels of star-forming activity in galaxies. Their bright optical/UV/IR emission spectra also have been exploited for studies of intrinsic properties of the ISM, and especially of abundances of He (as a cosmological test) and elements such as C, N, O, Ne, S, and Ar which are products of stellar nucleosynthesis.

Spectra emitted by H II regions are strongly dependent on the distributions of matter and radiation within the ionized medium. This factor is often quantified via the ''excitation parameter,'' that is, the ratio of density of ionizing photons at a typical point in a nebula to the local mean electron density. This parameter determines the basic properties of an H II region. Thus, for example, in a nebula that is ionized by hot O stars, when the excitation parameter is small the lower stages of ionized metals such as O will be dominant. The presence of low ionization levels in an H II region therefore does not necessarily imply ionization by cooler OB stars.

The Lyman continuum spectral energy distributions of the ionizing stars are also an important factor in determining the ionization structures and therefore the spectra of H II regions. However, the emitted spectrum depends only in a rather subtle way on the chemical composition of the ionized gas. When the abundances of the most common ''metals'' (e.g., CNO) are low, the nebula lacks coolants, and will have a higher electron temperature than a more metal-rich H II region with the same density distribution and ionizing radiation field. The main metallicity diagnostics are the rather weak, temperature-sensitive emission lines.

The interpretation of physical characteristics of H II regions from their spectra is a mature field, and as a result many of the inevitable pitfalls in modeling complex objects have been discovered. The extensive literature in this field should be consulted before undertaking any quantitative analysis of emission line spectra from H II regions or the related, lower-density diffuse ionized gas (DIG) components of galaxies.

One of the most widely used photoionization modeling codes is CLOUDY which was written by Gary Ferland. In Sec. 8.2 García-Vargas et al. present models for giant H II regions where photoionization is provided by young stellar clusters which were calculated with CLOUDY. This work is extended to the infrared via models by Iglesias et al. in Sec. 8.3.

In Sec. 8.4, Stasińska presents another set of models for H II regions with full spectral coverage for the line emission, computed with her photoionization code PHOTO, and using as an input the radiation field from a young cluster as well as from single stars. The main differences between the sets of García-Vargas et al. and Stasińska are in the ionizing radiation field (arising from a different set of stellar evolutionary tracks and a different set of model atmospheres), and also in the geometry adopted for the nebula.

8.1 Shock Models for Active Galaxies (Dopita and Sutherland)

A fast, radiative shock in interstellar space is a powerful source of ionizing photons. An early attempt to investigate the effects of radiative transfer in thermally unstable cooling flows or fast radiative shocks was given by Binette et al. (1985). Hybrid models for fast shocks with an externally imposed photoionizing field have been extensively discussed, e.g., by Contini and Viegas-Aldrovandi (1987, and references therein), and these have been extensively applied to the interpretation of narrow emission-line regions of active galaxies.

An accurate treatment of the internal radiative transfer in fast shocks was accomplished in the code MAPPINGS II (Sutherland and Dopita 1993). Sutherland et al. (1993) applied this to the interpretation of the optical spectra of the filaments associated with the radio jet of Cen A.

The files given in the present contribution are the models used in the papers by Dopita and Sutherland (1995, 1996) where full details can be had. There are two points that must be emphasized if these models are to be used successfully.

First, in order to compute the spectrum of a fast shock, we have to compute two contributions: (i) the spectrum produced by the cooling/recombination region of the shock itself; (ii) the spectrum produced in the photoionized precursor H II region, which for shock velocities greater than 200 km s^{-1} can be treated as an equilibrium H II region.

Second, the parameters which determine the spectrum are shock velocity, pre-shock density, and magnetic pressure in the pre-shock gas. These models presented here run from 150 to 500 km s^{-1}. All models are plane-parallel, steady flow. The pre-shock hydrogen density for all models is 1.0 cm^{-3}. This density is low enough that all models are in the low density limit. In this case, cooling lengths, time scales, etc., scale as (1/density) and luminosity scales directly as density. These scaling factors can be used to estimate other shock structures up to a density of about 10 cm^{-3} for magnetic parameter < 1.0, and up to about 100 cm^{-3} for magnetic parameter >1.0. The magnetic parameter is $(B/\mu G)/(n/1.0\ cm^{-3})^{0.5}$. This determines the degree of magnetic pressure support in the recombination region of the shock, where the downstream photons produced in the hot plasma are absorbed. This makes a *big* difference to the output spectrum.

In the use of these models, the user should be aware that the cooling is thermally unstable, and that *real* shocks have a complex 3-D structure with condensations. This will help to make the shock structures "leaky" to the photon field in the downstream direction. The line intensities of species such as [N I] and [O I] are almost certainly overestimated in the models, and the spectrum will also tend to fluctuate in time, which is not accounted for in these steady-flow models. See Dopita and Sutherland (1995, 1996) for a more detailed discussion of these effects.

8.2 Predicted Emission Lines from Giant H II Regions (García-Vargas et al.)

We have computed theoretical models of the emission-line spectra of giant extragalactic H II regions (GEHR) in which a single star cluster is assumed to be responsible for the ionization. Ionizing clusters, of different masses and metallicities, were constructed assuming that they formed in a single burst and with a Salpeter initial mass function. Their evolution was then followed in detail up to an age of 5.4 Myr, after which they lack the high-energy photons needed to keep the regions ionized.

The integrated spectral energy distribution of every cluster has been computed for a set of discrete ages representative of relevant phases of their evolution and have been processed by the photoionization code CLOUDY, in order to obtain the corresponding emission-line spectra of the ionized gas at optical and infrared wavelengths.

A wide range of initial compositions, spanning from about 1/20 (Z=0.001) to 2.5 $Z_\odot$ (Z=0.05), and total masses, between about $1-6\times10^4$ $M_\odot$ have been considered. Gas and stars are assumed to have the same metallicity and this has been taken into account both in the stellar evolution and atmosphere models and in the nebular gas producing a consistent set of models. In this contribution, we give the synthetic emission-line spectra of the ionized regions in electronic form. The models themselves are discussed in detail in García-Vargas et al. (1995a,b).

8.3 FIR Emission-Line Models for Star-Forming Regions (Iglesias et al.)

We calculated a grid of photoionization models which can be suitable to interpret the coming ISO observations. We also include the strongest optical emission lines. We present the synthetic emission-line spectra, emphasizing the FIR emission lines' importance in high-metallicity environments where the cooling of the gas is mainly driven through them.

We have assumed a shape for the ionizing spectrum, and it has been processed by the photoionization code CLOUDY, under certain conditions (ionization parameter, electron density, and metallicity), in order to obtain a grid of computed emission-line spectra of the ionized gas at optical and infrared wavelengths.

TABLE 3
Data Structure on the CD-ROM

Dataset	Section	Number	Format	Identifier
Stellar libraries (optical + IR)	2.1	70	fits	DaSeBoJo*
UV group library	2.2	2	fits	FaOCBuWu*
Far-UV to near-IR library	2.3	1	ascii	FRV_specstelUVIR.don
Coudé feed library	2.4	1	tar	Jo_coude.tar
Optical group library	2.5	2	ascii	OC*
IUE library of O- and W-R stars	2.6	52	ascii	RoLeHe*
IUE atlas of O-type spectra	2.7	4	ascii	WaNiPa*
IUE atlas of B-type spectra	2.8	4	ascii	WaPaNi*
Mg and Fe spectral indices	3.1	4	ascii	ChMaMo*
Grid of energy distributions	3.2	1	tar	LeBuCr.tar
CoStar models	3.3	4	ascii	Sc1*
Energy distributions of WR stars	3.4	4	ascii	Sc*
Cluster and galaxy templates	4.1	19	ascii	BiAlBo*
M32, NGC 185, and NGC 205	4.2	4	fits	DeHa*
Narrow-band indices	4.3	2	ascii	HuBrCaChScBo*
Padova library of evolution models	5.1	3	tar	PD1*
Padova isochrones and SSPs	5.2	5	tar	PD2*
Geneva library of evolution models	5.3	417	ascii	Ge*
Evolution and nucleosynthesis	5.4	8	ascii	Oe*
Spectral indices for SSPs	6.1	2	tar	PD3*
Energy distributions for SSPs	6.2	2	tar	PD4*
Models of elliptical galaxies	6.3	2	tar	PD5*
Galaxy spectral evolution	6.4	1	tar	BrCh_gissel96.tar
UV spectra for old populations	6.5	1	tar	DoOC_data.tar
Spectral evolution model (UV to NIR)	6.6	18	ascii	FRV*
Atlas of synthetic galaxies (UV to NIR)	6.7	52	ascii	RVF*
SSPs for different metallicities	6.8	1	tar	FAKu.tar
Chemically consistent galaxy evolution	6.9	1	tar	FAMoLo.tar
Grid of evolutionary spectra	6.10	10	tar	Tr*
A library for old systems	6.11	11	ascii	VaCaPeBe*
Models for early-type galaxies	6.12	1	tar	Worthey.tar
Energy distributions for SSPs	7.1	780	ascii	BrGaDi*
Calcium triplet synthesis	7.2	15	ascii	GaMoBr*
Near-IR properties of starbursts	7.3	15	fits	ALRV*
Energy distributions for starbursts	7.4	25	ascii	LeHeGo*
Synthesis of young starbursts	7.5	349	ascii	CeMH*
Shock models for active galaxies	8.1	84	ascii	DoSu*
Emission lines from GEHR	8.2	2	ascii	GaBrDi*
FIR emission-line models	8.3	2	ascii	IgGaBr*
Models for H II regions and starbursts	8.4	98	ascii	St*

The assumed ionizing continuum has a power-law-type spectrum (slope of −1.5, −2.0, −2.5), or an instantaneous burst (ages: 2.0, 3.5, 4.5, 5.0 Myr and IMF parameters: $\alpha = 2.35, m_{\rm low} = 1\,M_\odot, m_{\rm up} = 100\,M_\odot$). A more complicated way of star formation, including models with some SFR and others with a certain burst duration, as well as a discussion of the dust effect, will be published in a forthcoming paper. Densities are 100, 500, 1000, and 10,000 $\rm cm^{-3}$. Ionization parameters are taken in the range $10^{-1.5}$–10^{-4} (step 0.5 in log u), and metallicities 0.5 $Z_\odot$, $Z_\odot$, and 2.5 $Z_\odot$.

The selected optical emission lines are: [O II]3727 (3726 +3729), [O III]4363, [O III]5007, [O I]6300, [S II]6716, [S II]6731, and [S III]9532. The listed infrared lines are [S IV]10.5, [Ne II]12.8, [S III]19, [O IV]25.9, [O III]51.8, [N III]57, [O I]63.2, [O III]88.3, [N II]121.9, [O I]145.5, and [C II]157.7.

8.4 Grids of Photoionization Models for Single-Star H II Regions and for Evolving Starbursts: Optical, UV, and IR Line Emission (Stasińska)

We present three grids of photoionization models using the code PHOTO (Stasińska 1990) with atomic data updated as in Stasińska and Leitherer (1996). The ionizing fluxes are provided by the *CoStar* model atmospheres of Schaerer and de Koter (1996), by the Kurucz (1992) model atmospheres, and by the stellar population synthesis models for evolving starbursts computed by Leitherer and Heckman (1995). The models are built for various metallicities (solar and subsolar) and cover a wide parameter space in ionizing conditions. They provide the intensities of about 100 lines in the optical, UV and IR, together with ionization fractions for the most important ions, mean electron temperatures for a selection of ions, equivalent widths of hydrogen and helium emission lines, as well as a few other parameters useful for diagnostics of H II regions. The single-star photoionization models will be presented in Stasińska and Schaerer (1996) and the photoionization models for nebulae surrounding evolving starbursts are presented in Stasińska and Leitherer (1996). Models with higher metallicities will be available in the future. All these models can also be retrieved by anonymous ftp from ftp.obspm.fr in the directory /pub/obs/grazyna/cd-crete.

9. DISTRIBUTION ON CD-ROM

The products described in this paper are available in electronic form on the AAS CD-ROM Series, Vol. 7. In addition, *some* of the products are also available via anonymous ftp from the authors (only if indicated in the corresponding section). A summary of the data structure on the CD-ROM is given in Table 3. The first two columns of this table give the identifications of the products in Secs. 2–8. In column 3 we list the total number of files on the CD-ROM for each dataset, including the README file. The file format is in column 4. The files are either in compressed tar format or in compressed (gzip) ascii or fits. The fits format does not refer to the README files, which are in ascii. All file names are preceded by the character string in column 5. This should make it easy for the user to locate a particular dataset. The CD-ROM also contains the file README_FIRST. This is a high-level description of the data structure of all the files on the CD-ROM, going beyond the limited detail provided in Table 3. Users should first inspect the README_FIRST file and then select individual datasets, including the README files of those datasets.

Users are encouraged to direct questions and suggestions on the dataset to the authors. Descriptions and discussions are provided in the quoted literature. A critical comparison of a large number of models can be found in the conference proceedings edited by Leitherer et al. (1996).

Support for this work was provided by NASA Grant No. GO-3591 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA Contract No. NAS5-26555.

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