A LARGE STELLAR EVOLUTION DATABASE FOR POPULATION SYNTHESIS STUDIES. III. INCLUSION OF THE FULL ASYMPTOTIC GIANT BRANCH PHASE AND WEB TOOLS FOR STELLAR POPULATION ANALYSES

DANIEL CORDIER
Ecole Nationale Superieure de Chimie de Rennes, Campus de Beaulieu, Rennes, France; daniel.cordier@ensc-rennes.fr

ADRIANO PIETRINFERNI[1] AND SANTI CASSISI[2]
INAF—Astronomical Observatory of Collurania, Teramo, Italy; pietrinferni@oa-teramo.inaf.it, cassisi@oa-teramo.inaf.it

AND

MAURIZIO SALARIS[3]
Astrophysics Research Institute, Liverpool John Moores University, Birkenhead, UK; ms@astro.livjm.ac.uk

ABSTRACT

Stellar evolution tracks and isochrones are key inputs for a wide range of astrophysical studies; in particular, they are essential to the interpretation of photometric and spectroscopic observations of resolved and unresolved stellar populations. We have made available to the astrophysical community a large, homogenous database of up-to-date stellar tracks and isochrones and a set of programs useful in population synthesis studies. In this paper we first summarize the main properties of our stellar model database (BaSTI) already introduced by Pietrinferni and coworkers. We then discuss an important update of the database, i.e., the extension of all stellar models and isochrones until the end of the thermal pulses along the asymptotic giant branch. This extension of the library is particularly relevant for stellar population analyses in the near-infrared or longer wavelengths, where the contribution to the integrated photometric properties by cool and bright asymptotic giant branch stars is significant. A few comparisons with empirical data are also presented and briefly discussed. We then present three Web tools that allow an interactive access to the database and make it possible to compute user-specified evolutionary tracks, isochrones, stellar luminosity functions, and synthetic color-magnitude diagrams and integrated magnitudes for arbitrary star formation histories. All these Web tools are available at the BaSTI database official Web site.

Key words: astronomical data bases: miscellaneous — galaxies: stellar content — stars: AGB and post-AGB — stars: general

Online material: color figures

1. INTRODUCTION

The interpretation of photometric and spectroscopic observations of resolved and unresolved stellar populations is nowadays a fundamental tool to investigate the formation and evolution of galaxies. Large grids of stellar evolution models and isochrones are a necessary ingredient in this kind of analysis, together with appropriate tools to predict synthetic color-magnitude diagrams (CMDs)—and hence star counts along the various observed CMD branches—integrated magnitudes, and spectra of stellar populations with an arbitrary star formation history (SFH). To this purpose Pietrinferni et al. (2004, 2006) published a huge and homogeneous database of stellar evolution models that covers the relevant chemical composition range of stellar populations in galaxies of various morphological types, and allows one to choose among different treatments of core convection and stellar mass loss employed in the model calculations. These models are available on the World Wide Web as downloadable files from the BaSTI (Bag of Stellar Tracks and Isochrones) database,[4] together with three Web tools that allow user-friendly manipulation of the stellar evolution library. Thanks to these tools one can compute user-specified isochrones, interpolate among evolutionary tracks

to obtain the evolution for a mass value not contained in the grid, determine the differential and cumulative luminosity functions from a set of isochrones, and finally, compute synthetic stellar populations with an arbitrary SFH and determine their integrated magnitudes and colors.

This paper describes comprehensively the BaSTI database, and in particular how to run the various Web tools, the necessary inputs, and their outputs. Section 2 describes the stellar evolution library, with particular emphasis on the most recent extensions not included in Pietrinferni et al. (2004, 2006); §§ 3–5 describe the individual Web tools that allow the computation of user-specified isochrones, models, luminosity functions, and synthetic CMDs. Section 6 contains our final conclusions, and the Appendix contains some more technical details about the implementation of the Web tools.

2. STELLAR EVOLUTION MODELS AND ISOCHRONES

We have computed stellar evolution models for 11 different metallicities, namely, $Z = 0.0001, 0.0003, 0.0006, 0.001, 0.002, 0.004, 0.008, 0.01, 0.0198, 0.03,$ and 0.04, assuming two different heavy-element distributions: the scaled-solar one by Grevesse & Noels (1993) and the α-enhanced one with $\langle[\alpha/\mathrm{Fe}]\rangle = 0.40$ by Salaris & Weiss (1998). As for the initial He-mass fractions, we employed a value of $Y = 0.245$ for the cosmological He (see, e.g., Cassisi et al. 2003). To reproduce the solar initial He abundance obtained from the calibration of the solar model, we assume an

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[1] Also at Universitá di Teramo, Teramo, Italy.
[2] Also at Instituto de Astrofisica de Canarias, La Laguna, Tenerife, Spain.
[3] Also at Max-Planck-Institut für Astrophysik, Garching, Germany.
[4] See http://terri1.oa-teramo.inaf.it/BASTI.

He-enrichment law equal to $\Delta Y/\Delta Z \sim 1.4$. For each initial chemical composition we have computed stellar evolutionary tracks with mass in the range $0.5\ M_\odot \leq M \leq 10\ M_\odot$ and a fine mass spacing. Mass loss from the stellar surface is accounted for using the Reimers (1975) law and two values of the free parameter η, namely, $\eta = 0.2$ and 0.4. For stars that develop convective cores during the central H-burning phase we have computed models with and without overshoot from the Schwarzschild boundary of the central convective regions.

All evolutions, with the exception of the least massive stars whose central H-burning timescale is longer than the Hubble time, have been computed from the pre-main-sequence phase until the C ignition or until the first thermal pulse along the asymptotic giant branch (AGB), depending on the initial stellar mass. Full details of these calculations can be found in Pietrinferni et al. (2004, 2006). Very recently we have extended the evolution of low- and intermediate-mass objects through the entire thermal pulse (TP) phase, until the end of the AGB stage. To this purpose we have used the synthetic-AGB technique (Iben & Truran 1978). Our simplified treatment of the TP-AGB phase satisfactorily reproduces several integrated properties (see below) of stellar populations in the near-IR bands, which are greatly affected by the presence of TP stars. Given that the purpose of this library of stellar models is to provide a reliable tool to be employed in stellar population synthesis studies, we feel confident that the following simplified treatment of the AGB evolution is adequate for our purposes. For each stellar model of a given initial chemical composition and mass, we started the synthetic AGB evolution at the beginning of the TP phase, where the stellar evolution calculations were terminated. The first model of the synthetic TP-AGB evolution is characterized by the total mass M, carbon-oxygen core mass M_{CO}, luminosity L, effective temperature T_{eff}, and surface chemical composition (X_f, Y_f, Z_f) of the last fully evolutionary model.

The TP-AGB phase is then followed by increasing (after a given time step dt) M_{CO} and L according to equations (5)–(7) in Wagenhuber & Groenewegen (1998), which contain a term mimicking the effect of the hot bottom burning, when appropriate. The hydrogen mass fraction in the envelope (an input of eq. [6] of Wagenhuber & Groenewegen 1998) is approximated as $1 - (Y_f + 0.01) - Z_f$ all along the TP evolution. During a time step the mass of the envelope $(M - M_{CO})$ is reduced not only by the growth of M_{CO} but also by mass-loss processes, accounted for by using the mass-loss formulae of Vassiliadis & Wood (1993). For any given value of M and M_{CO}, the effective temperatures are computed using the relationships in Wagenhuber (1996) that are plotted in Figure 8 of Wagenhuber & Groenewegen (1998). To ensure continuity, the zero points of the equations describing the evolution of L, M_{CO}, and T_{eff} have been adjusted to reproduce the corresponding values of the last fully evolutionary model, at the beginning of the TP phase. The synthetic evolution is stopped when the models have started to evolve off the AGB, at constant luminosity, toward their white dwarf cooling sequence. The full models have been used to compute isochrones for ages ranging between 30 Myr and 19 Gyr. We provide separately models and isochrones with and without the inclusion of the TP-AGB phase, in case users wish to use their own description of the TP-AGB evolution, employing either fully evolutionary calculations or synthetic AGB models with different choices about, e.g., mass loss and/or the core mass-luminosity relationship. To this purpose we provide, as mentioned below, tables with He and CO core mass, as well as the luminosity and effective temperature at the beginning of the TP-AGB phase.

The reader is referred to Pietrinferni et al. (2004) for a detailed discussion about the normalization of the individual evolution-

TABLE 1
Initial Chemical Composition of the Model Grid

Z	Y	[Fe/H] (Scaled-Solar Mixture)	[Fe/H] (α-Enhanced Mixture)
0.0001	0.245	−2.27	−2.62
0.0003	0.245	−1.79	−2.14
0.0006	0.246	−1.49	−1.84
0.0010	0.246	−1.27	−1.62
0.0020	0.248	−0.96	−1.31
0.0040	0.251	−0.66	−1.01
0.0080	0.256	−0.35	−0.70
0.0100	0.259	−0.25	−0.60
0.0198	0.273	+0.06	−0.29
0.0300	0.288	+0.26	−0.09
0.0400	0.303	+0.40	+0.05

ary tracks (the concept of the key point and normalized points between two successive key points) and isochrone computation. Here we simply mention two changes with respect to the discussion in Pietrinferni et al. (2004). The first change is the inclusion of two additional key points along the red giant branch (RGB), one to mark the maximum luminosity during the RGB bump and another to mark the minimum RGB bump luminosity (key points 6 and 7). A total of 370 normalized points are distributed between key point 6 and its predecessor, 30 points are distributed between key points 6 and 7, and 400 points are distributed between key point 7 and the following one, the tip of the RGB. Due to the TP-AGB extension, we have added an additional key point (number 17) after the beginning of the TP phase to mark the termination of the AGB phase, when the model evolution turns to the blue. A total of 250 normalized points cover the TP-AGB phase, between key points 16 and 17. The resulting isochrones have a total of 2250 points.

The main characteristics of the stellar model database are summarized in Tables 1 and 2. Table 1 lists the grid of initial chemical compositions; Table 2 summarizes the available sets of models and isochrones. For a given heavy-element mixture (either scaled-solar or α-enhanced) we have computed models for 11 Z-values (Table 1) using both $\eta = 0.2$ and 0.4 for the evolution until the TP-AGB phase. For each value of η we have computed models with and without overshoot from the central convective core (in the appropriate mass range). The extension of the overshooting region λ_{OV} is $0.2 H_p$ (H_p is the local pressure scale height at the Schwarzschild convective boundary), decreasing to zero when the convective cores vanish, as described in Pietrinferni et al. (2004). For each choice of the metal mixture, Z, η, and convective core extension we specify the number of tracks available, their mass range, the number of isochrones available, and their age range. Note that for masses above $\sim 2.4\ M_\odot$ the evolution with $\eta = 0.4$ is identical to the case of $\eta = 0.2$ (because of the negligible amount of mass lost during their evolution, according to the Reimers' law).

Broadband magnitudes and colors of the stellar evolution tracks and isochrones are predicted using color-T_{eff} transformations and bolometric corrections based on an updated set of model atmospheres described in Pietrinferni et al. (2004) and Cassisi et al. (2004). The evolutionary results are available in the photometric filters listed in Table 2. Additional filters will be added with time. It is worth pointing out that, for the first time, we have homogeneous transformations for both scaled-solar and α-enhanced mixtures even for supersolar metallicities. At present, the transformations for the *Hubble Space Telescope* (*HST*) ACS filters are available only for a scaled-solar chemical composition.

TABLE 2
Summary of the BaSTI Model and Isochrone Database

η	λ_{OV}	No. Tracks	M_{min} ($M_\odot$)	M_{max} ($M_\odot$)	No. Isochrones	Age_{min} (Myr)	Age_{max} (Gyr)
			Scaled-Solar Mixture				
0.2........................	0	20	0.5	2.4	63	30	19
	0.2	20	1.1	2.4	44	30	9.5
0.4........................	0	40	0.5	10	54	30	14.5
	0.2	20	1.1	10	44	30	9.5
			α-Enhanced Mixture				
0.2........................	0	20	0.5	2.4	63	30	19
	0.2	20	1.1	2.4	44	30	9.5
0.4........................	0	40	0.5	10	54	30	14.5
	0.2	20	1.1	10	44	30	9.5

Note.— Color-T_{eff}: *HST* ACS *UBVRIJHKL*.

For the TP-AGB section of the models and isochrones, broadband colors and magnitudes have been computed by supplementing the transformations used up to the beginning of the TP phase with the Westera et al. (2002) ones for RGB and AGB stars with $T_{eff} < 3750$ K. To ensure continuity, the bolometric corrections and colors of Westera et al. (2002) have been shifted to match the other sets of transformations when $T_{eff} = 3750$ K. Along the TP-AGB phase, when the $(J - K)$ colors reach $(J - K) = 1.2$ mag, we use the $(J - K)$–T_{eff} and $(H - K)$–T_{eff} relationships by Bergeat et al. (2001) that are appropriate in the carbon star regime. Models and isochrones extended along the TP-AGB phase are at the moment transformed only to the *UBVRIJHKL* system.

All models described above have been computed under the assumption that a star of a given mass and initial chemical composition loses during its evolution a fixed amount of mass, determined by the adopted mass-loss law. An isochrone for an old population will therefore display on the CMD a clumpy horizontal branch (HB) phase, comprising stars all with essentially the same total mass, because of both the constant mass of their progenitor and the constant value of the mass lost along the previous RGB phase. If one wants to simulate the extended HBs observed in Galactic globular clusters, a spread in the amount of mass lost by the RGB progenitor has to be accounted for. To this purpose, for each chemical composition we have also computed additional large sets of core-He-burning models, with the He core mass and envelope chemical profile fixed by a RGB progenitor having an age of ∼13 Gyr at the RGB tip, and a range of values of the total stellar mass, to simulate the effect of a spread in the mass lost along the RGB. These HB models (∼30 for each chemical composition) constitute a valuable tool to perform synthetic HB modeling and to investigate pulsational and evolutionary properties of different kinds of variable stars.

Users can directly download from the BaSTI database evolutionary tracks and HB models as single files or as tar gzipped archive files, selecting among the following options (11 initial chemical compositions for each choice): scaled-solar, α-enhanced, canonical (no overshoot), noncanonical (overshoot included), $\eta = 0.2$, $\eta = 0.4$, TP-AGB excluded, and TP-AGB included. We have included on the Web site appropriate "README" files and also provide tables (both in ASCII and HTML format) summarizing the main properties of the theoretical models (not including the TP-AGB phase) and also providing the CMD location of the zero-age HB and the central He exhaustion stages. These two

latter sets of tables can be found at the pages containing the $\eta = 0.4$ models. A large number of precomputed isochrones for each of the individual options described before, spanning the full age range allowed by the computed models, can be downloaded as tar gzipped archive files.

The models and isochrones contained in BaSTI have been extensively tested in Pietrinferni et al. (2004, 2006) and already employed in a number of investigations (e.g., Gallart et al. 2005). We conclude this section by showing a few tests for the TP-AGB extension that we introduce in this paper. We first tested our isochrones against near-IR surface brightness fluctuation (SBF) magnitudes, which are very sensitive to the brightness and evolutionary timescales of AGB stars (see, e.g., Liu et al. 2000; Cantiello et al. 2003; Mouhcine et al. 2005; Raimondo et al. 2005).

We considered the *J*- and *K*-band SBF magnitudes determined by González et al. (2004) for a sample of Magellanic Cloud superclusters. A supercluster is obtained by co-adding individual clusters belonging to the same SWB class (see Searle et al. [1980] for the definition of the SWB classes, which are essentially age ranges). González et al. (2004) also provide the mean metallicity and age of the objects grouped in each supercluster. The original SBF magnitudes were on the Two Micron All Sky Survey system and have been transformed to the Johnson system following Bessell & Brett (1988) and Carpenter (2001).

Figures 1 and 2 display the observed SBF absolute magnitudes in *K* and *J* [González et al. (2004) assume $(m - M)_0 = 18.50 \pm 0.13$ for the Large Magellanic Cloud (LMC) and $(m - M)_0 = 18.99 \pm 0.05$ for the Small Magellanic Cloud (SMC)] of six superclusters, whose age range is covered by our models, as a function of age. Different symbols correspond to different mean metallicities; the three youngest superclusters all share the same metallicity. Horizontal error bars correspond to the age spread around the mean supercluster ages, as given by González et al. (2004).

We have compared these data with the SBF magnitudes obtained from our isochrones for the appropriate mean metallicities of the individual superclusters. Note that for each individual value of *Z* considered, we have plotted the theoretical SBF magnitudes only in the age range spanned by the one (or more) supercluster with that mean value of *Z*. We employed the BaSTI models with $\eta = 0.2$, including overshooting in the appropriate age range. For the lowest metallicity (oldest) supercluster we also display the results obtained with $\eta = 0.4$. Theory is able to
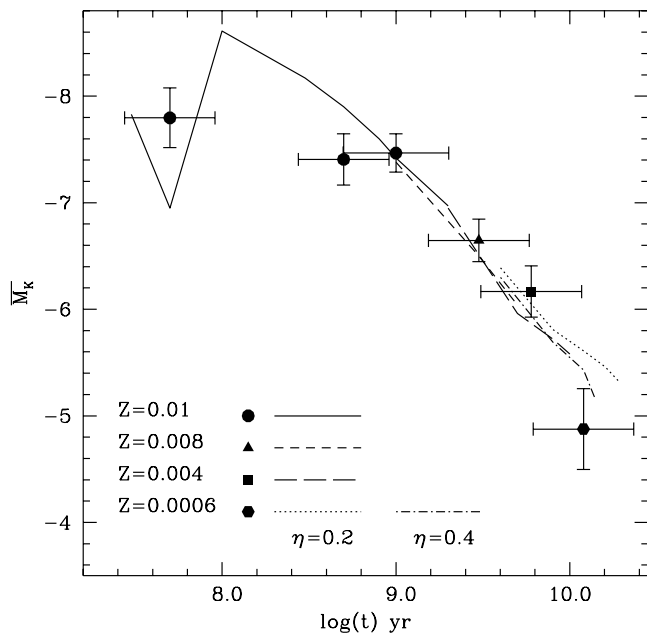
FIG. 1.—Run of the K-band SBF magnitudes of Magellanic Cloud super-clusters as a function of their age. Theoretical SBF magnitudes for the appropriate metallicity and age range (denoted with different line styles) of the individual superclusters (superclusters of different metallicities are denoted with different symbols) are also displayed. These theoretical values are obtained from the scaled-solar isochrones including overshooting and with $\eta = 0.2$, extended along the TP-AGB phase. At $Z = 0.0006$ we also display values obtained with $\eta = 0.4$ (dash-dotted line; see text for details).

FIG. 3.—Same as Fig. 1, but for the integrated $(H - K)$ and $(J - K)$ colors of Magellanic Cloud superclusters (see text for details).

fit the data points within the observational errors, the only exception being the J-band SBF of the oldest supercluster.

Figure 3 compares the dereddened integrated $(J - K)$ and $(H - K)$ colors provided by González et al. (2004) for the six superclusters—transformed to the Johnson system as done for the SBF—with theoretical predictions from the same models employed for the SBF analysis. Theoretical colors appear consistent with their observational counterparts; the mean difference be-
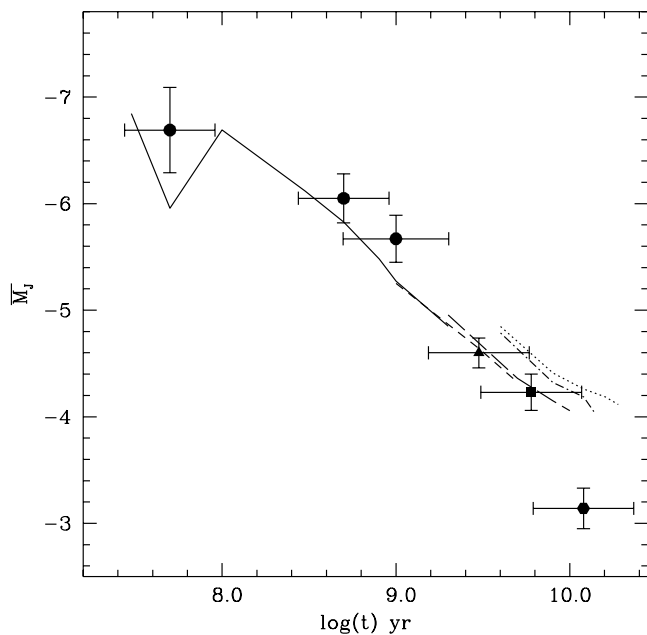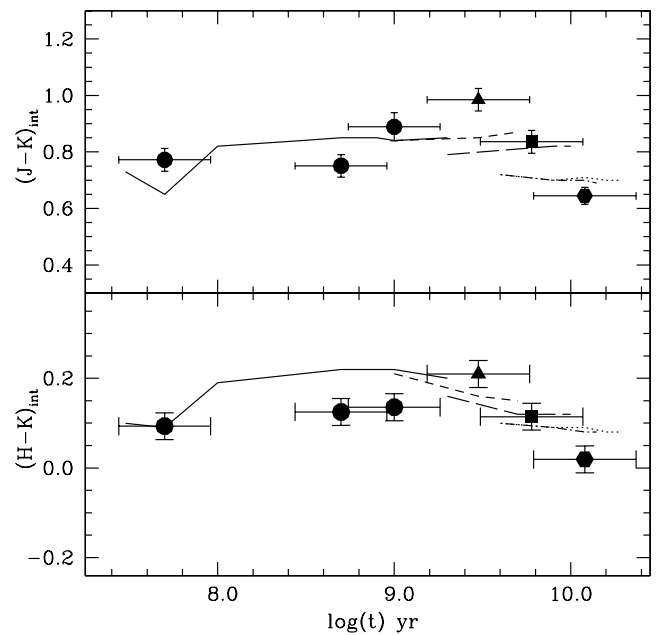
tween theory and observations is equal to ~ 0.03 mag in both $(J - K)$ and $(H - K)$. This value can be considered a reasonable estimate of the accuracy of our predicted integrated near-IR colors. Finally, Figure 4 compares the combined $[K, (J - K)]$ CMDs of AGB stars in a sample of LMC clusters with theoretical isochrones. The individual stars have been co-added according to the SWB class of the parent clusters. Reddenings are from Frogel & Cohen (1982), and we use an LMC distance modulus $(m - M)_0 = 18.50$. The metallicities and ages of the theoretical isochrones are selected on the basis of the SWB class, following

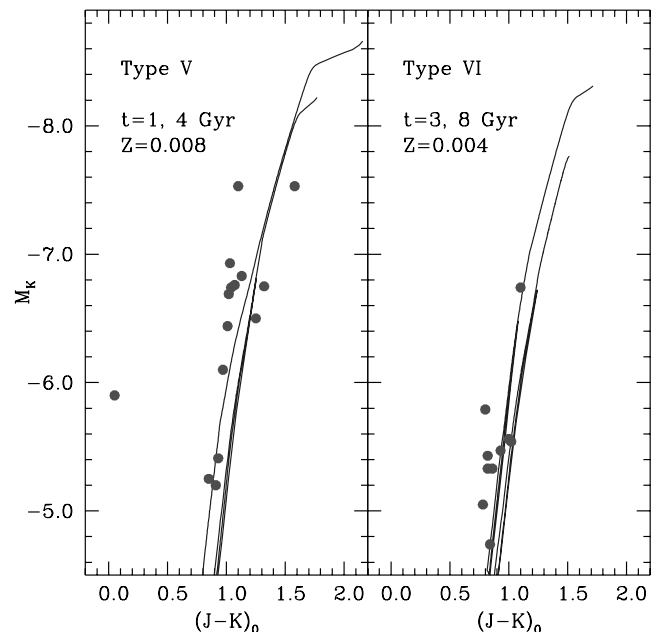FIG. 2.—Same as Fig. 1, but for the J-band SBF magnitudes (see text for details).

FIG. 4.—Cumulative $[K, (J - K)]$ CMDs of AGB stars in a sample of LMC clusters. Theoretical isochrones for the appropriate age and metallicity range are also displayed (see text for details). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 5.— Web interface for the tool dedicated to isochrones and evolutionary tracks. [*See the electronic edition of the Journal for a color version of this figure.*]

again González et al. (2004). One can see a good overlap between the theoretical AGB sequences and the observed near-IR CMDs.

3. ISOCHRONE MAKER AND TRACK INTERPOLATION PROGRAM

We have created a dedicated World Wide Web interface that allows the direct computation of isochrones for any given choice of age, for the chemical compositions and age ranges listed in Tables 1 and 2. It also enables the user to compute interpolated evolutionary tracks in the mass range 0.5–10 $M_\odot$ for any chemical composition in the grid. A linear interpolation on a point-by-point basis between two neighboring evolutionary tracks stored in the database is performed to determine the track for the specified mass. The mass spacing of the tracks included in BaSTI is small enough that a linear interpolation is sufficient to guarantee

a high accuracy. Once the track is computed, it is immediately transposed in the chosen photometric system.

The use of this interface is particularly simple: first of all one has to go to the BaSTI Web site[5] and click on the link "Isochrones— Tracks" in the "Web Tool" section; a page like the one displayed in Figure 5 will appear. The user has now to choose among a number of options:

1. The output type, i.e., isochrone or interpolated evolutionary track.

2. The heavy-elements mixture, i.e., scaled-solar or α-enhanced.

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[5] See http://terri1.oa-teramo.inaf.it/BASTI. In case of network and/or technical problems with this official Web site, the user can connect to D. C.'s personal Web site, http://astro.ensc-rennes.fr, where the BaSTI Web tools have been mirrored in the "BaSTI Web Tools" section.

3. The photometric system of interest; at the moment we allow a choice between the standard *UBVRIJHKL* filters and the *HST* ACS ones.

4. Core convection treatment, i.e., with or without convective core overshoot.

5. The initial chemical composition (Y, Z).

Once these input parameters are fixed, the next screen allows the choice of the isochrone age (in megayears) or the track initial total mass in solar units. Outputs (in the same format as the tracks and isochrones stored in the database) are directly sent to the user's browser.

4. LUMINOSITY FUNCTION PROGRAM

The isochrones stored in the BaSTI database, or obtained with the Web tool described in § 3, can be used as input for the tool described here, which computes the luminosity functions (e.g., differential and cumulative star counts as a function of the magnitude in a given wavelength band) of single-age, single-metallicity stellar populations.

To run this Web tool the user has to provide four parameters: the number of isochrones whose luminosity functions are needed (maximum 20), the photometric filter (in the *UBVRIJKLH* system), the initial mass function (IMF) exponent, and the size of the magnitude bins within which the star counts are performed (e.g., 0.15 mag; these bins have to be larger than 0.05 mag). We adopt for the IMF a form of the type $dN_*/dM = CM^{-\alpha}$, where dN_* is the number of stars formed with mass between M and $M + dM$ and C is a normalization constant whose value is fixed by imposing the total number of stars populating the isochrones to be equal to 10^6. A value of α equal to 2.35 corresponds to the Salpeter (1955) IMF.

One has then to choose between the options of computing the luminosity functions only until the RGB tip, along the whole isochrone until the early AGB, or including also the TP-AGB phase. Star counts are then computed analytically by convolving the IMF with the distribution of the initial stellar mass values along the isochrones. For example, the number of stars N between two consecutive points $i - 1$ and i along a chosen isochrone is given by $N = C/1 - \alpha(M_i^{1-\alpha} - M_{i-1}^{1-\alpha})$.

As a final step one has to upload the isochrone files and submit the job. Results are directly sent to the user's Internet browser as ASCII data divided into several sections, each of them corresponding to one individual isochrone. The input parameters are recalled: metallicity, IMF exponent, age, etc. The data themselves are displayed in three columns: the mean magnitude of the bin and the differential (where N denotes the star counts per magnitude bin as a function of the magnitude) and cumulative (where $N+$ denotes the sum of the star counts from the faintest bin to the actual one as a function of the magnitude) luminosity functions.

5. SYNTHETIC CMD CODE

The computation of synthetic CMDs is often required to interpret observations of resolved or unresolved stellar populations. The simplest form of a synthetic CMD is an isochrone that represents the sequence occupied by stars all formed at the same time and with the same initial chemical composition. Clearly, an isochrone does not directly contain information about the number of stars populating the various CMD branches, nor the effect of photometric errors and reddening, and cannot represent composite stellar populations comprising multiple generations of stars. To include these effects one needs a synthetic CMD generator. On the BaSTI Web site the user can access the SYNTHETIC MAN

code, which is an evolution of the version briefly described in Pietrinferni et al. (2004). This code computes the magnitudes and colors of objects belonging to a synthetic stellar population with an arbitrary SFH. The program employs a grid of isochrones with ages between 30 Myr and 14 Gyr (we employ 49 isochrones extended until the end of the TP-AGB phase for each of the 11 metallicities included in our model grid).

The SYNTHETIC MAN code is based on a Monte Carlo algorithm that allows one to include in a simple way observation-related effects such as the reddening /distance/metallicity dispersion and photometric errors and to identify on a star-by-star basis the various types of pulsating stars that may be present in the synthetic population. Synthetic CMDs and observation-related effects can also be efficiently determined by means of analytical integrations, as done in Dolphin (2002). It is worth noting that Skillman et al. (2003) applied three different methods to determine the SFH of the galaxy IC 1613. One of them is the analytical technique by Dolphin (2002), and another is a Monte Carlo method similar to the one we implemented. A comparison of the results with the different techniques shows striking agreement.

The general structure of the SYNTHETIC MAN code is as follows. A SFH file has to be specified first. The SFH contains a grid of N ages t_i (the upper limit for N is set to 200), increasing with increasing running index i (the present time is assigned $t = 0$), and for each age one has to specify a scale factor SF_i proportional to the relative number of stars formed at that time. Also, the metallicity (parameterized by [Fe/H]) of the stars formed at that age has to be given ([Fe/H]$_i$), together with a 1 σ Gaussian spread around this value. The scale factor and [Fe/H] for ages in the range $t_i \leq t < t_{(i+1)}$ are then assumed to be equal to SF_i and [Fe/H]$_i$, respectively. In other words, the SFH is considered to be a sequence of step functions. The scale factor and [Fe/H] at $i = N$ are not considered and can be set to any arbitrary value; the last point in the SFH file is important only because it provides the upper age limit for the simulated stellar population. If one or more single burst stellar populations are needed, one or more pairs of identical ages (i.e., $t_i = t_{(i+1)}$) need to be included in the SFH file.

After the SFH is read by the code, the following cycle starts, running along the SFH index from $i = 0$ to $i = N$. The age difference between two generic t_i and $t_{(i+1)}$ values is computed, and for each star formed in this time interval (the number of stars formed in a generic time interval is determined from the input SFH) a random value of the stellar age $t_i \leq t < t_{(i+1)}$ is drawn with a flat probability distribution, together with a mass M selected randomly according to a user-specified IMF (the default mass range goes from 0.1 to 120 $M_\odot$, although a different lower mass limit can be specified by the user) and a random value of [Fe/H] assigned according to the value of [Fe/H]$_i$ plus the 1 σ spread given in the SFH. With the three specified values of t, M, and [Fe/H] the program interpolates quadratically in age, metallicity, and then mass among the isochrones in the grid to determine the star luminosity, effective temperature, actual value of the mass (in principle different from the initial value because of mass loss), and photometric properties in the *UBVRIJHKL* system.

For each generated mass an additional random number determines whether the star is a member of an unresolved binary system (the percentage of unresolved binaries has to be specified as an input); if this is true, the mass of the second component is selected randomly following Woo et al. (2003), and the fluxes of the two unresolved components are properly added.

Once the photometric properties of an object (single or belonging to an unresolved binary system) are determined, the depth effects

TABLE 3
VARIABLE TYPE INDEX AND SOURCES USED IN THE POPULATION SYNTHESIS PROGRAM

Variable Type Index	Variable Type	Source for Instability Strip Boundaries
0..	No variable	
1..	Fundamental RR Lyrae	Marconi et al. (2003), Di Criscienzo et al. (2004)
2..	First-overtone RR Lyrae	Marconi et al. (2003), Di Criscienzo et al. (2004)
3..	Fundamental anomalous Cepheid	Marconi et al. (2004)
4..	First-overtone anomalous Cepheid	Marconi et al. (2004)
5..	Fundamental classical Cepheid	Bono et al. (2000)

of the synthetic stellar population are simulated probabilistically according to a uniform stellar distribution with a user-specified total depth (in magnitudes). After depth effects are included, the individual magnitudes are modified by adding the effect of extinction (another input parameter; we have employed the extinction ratios from the Asiago Database on Photometric Systems [see Moro & Munari 2000] and $R_V = 3.1$) and then further perturbed according to a Gaussian distribution to simulate the photometric errors, with a user-specified 1 σ width. The star [Fe/H] value is also perturbed according to a Gaussian error with user-specified 1 σ width to mimic the effect of spectroscopic observational errors. As an additional option, the code can search for variable stars, according to their location with respect to the boundary of RR Lyrae and Cepheid instability strips; pulsation periods are then determined. Table 3 shows literature references for the relevant types of variables.

Once all stars formed between ages t_i and $t_{(i+1)}$ are generated, the next interval ($t_{(i+1)} \le t < t_{(i+2)}$) is considered, and the cycle continues, ending when all stars in the final age bin $t_{(N-1)} \le t < t_{(N)}$ are generated.

As a technical comment, if the value of M for a star generated by the Monte Carlo procedure is too large to be still evolving at its age t or is lower than 0.5 $M_\odot$, the contribution to the total mass of stars formed in the population is taken into account, but the star photometric properties are not determined. The total mass of the objects formed, the total number of the stars whose photometric properties have been determined (in principle different from the total number generated for the reasons mentioned above), and the integrated magnitudes (in the $UBVRIJHKL$ system) of the synthetic population are also computed.

Like all Monte Carlo–based simulations, our program makes extensive use of random numbers. Our random number generator (initially written by James 1990) needs "seeds" to be initialized; these seeds can be either provided by the user or obtained from the True Random Number Service Web site,[6] which derives "true" random numbers from atmospheric electromagnetic noise.

The World Wide Web interface to SYNTHETIC MAN can been found in the BaSTI section "Synthetic Color-Magnitude Diagrams." This software is as simple to use as the others, but a registration is required before its first use. The user receives a notification by e-mail when the computations are completed. In order to get a user identification, one needs to contact S. Cassisi or D. Cordier. In the following we summarize the input parameters for a run of SYNTHETIC MAN.

1. A scale factor for the SFH. As explained before, the SFH contains the relative weight of the star formation episodes in the various age bins. In order to fix the absolute number of objects in each stellar generation, a scale factor has to be chosen. The product of this scale factor times the relative weight in the input

SFH gives the total number of stars created in a generic age bin, with mass between 0.1 (or a user specified lower mass limit) and 120 $M_\odot$. If more than 2×10^6 objects are expected to be formed at a given time step, the program will stop to highlight the excessive amount of computational time needed for the whole simulation.

2. A choice for the mean photometric error. The user can adopt a 1 σ constant error that it is applied to all stars in the simulation, in all nine photometric bands. The size of this constant error (between 0.0 and 1.0 mag) has to be specified. Alternatively, the user can choose to adopt an error varying with the actual star magnitude and/or photometric band. The exact values have to be specified by the user in an appropriate input file. This photometric error input file contains 18 columns and an arbitrary number N of rows (upper limit $N = 200$). The first nine columns display N magnitudes M_λ^i (i running from 1 to N), in order of increasing value, for the $UBVRIJHKL$ photometric bands, respectively. The remaining nine columns are the corresponding 1 σ photometric errors in the $UBVRIJHKL$ filters, respectively (e.g., σ_U, σ_B, and σ_V). The choice of the error for any individual synthetic star proceeds as follows. If M_V^* is the star magnitude in the V band, the program searches for a pair of neighboring tabulated M_V^i magnitudes such that $M_V^i < M_V^* \le M_V^{i+1}$ and assigns to the star σ_V the value tabulated for M_V^{i+1}. If M_V^* is smaller than M_V^1 or larger than M_V^N, the error corresponding to M_V^1 or M_V^N is used, respectively. The same procedure is repeated for all other photometric bands considered.

3. The 1 σ mean spectroscopic error (between 0.01 and 1.0 dex).

4. A choice for the range considered in the stellar mass random extraction. An upper limit of 120 $M_\odot$ is always considered. The user can decide to use a different lower mass limit (larger than 0.1 $M_\odot$) that must then be specified by the user.

5. The total spatial depth of the population (between 0.0 and 10.0 mag).

6. The color excess $E(B - V)$ (between 0.0 and 10.0 mag).

7. The fraction of unresolved binaries.

8. The minimum mass ratio for the unresolved binary systems (between 0.0 and 1.0)

TABLE 4
INDEX FOR THE ISOCHRONE SETS EMPLOYED
BY THE SYNTHETIC MAN CODE

Index	Isochrone Set
1............................	Scaled-solar, no overshooting, $\eta = 0.2$
2............................	Scaled-solar, overshooting, $\eta = 0.2$
3............................	Scaled-solar, no overshooting, $\eta = 0.4$
4............................	Scaled-solar, overshooting, $\eta = 0.4$
5............................	α-enhanced, no overshooting, $\eta = 0.2$
6............................	α-enhanced, overshooting, $\eta = 0.2$
7............................	α-enhanced, no overshooting, $\eta = 0.4$
8............................	α-enhanced, overshooting, $\eta = 0.4$

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[6] See http://www.random.org.

TABLE 5
AVAILABLE STAR FORMATION HISTORIES

Stellar Population	Source
NGC 6822 (global SFH).............	Gallart et al. (1996)
SMC (global SFH)......................	Harris & Zaritsky (2004)
LMC (bar field)..........................	Holtzman et al. (1999)
Local disk....................................	Rocha-Pinto et al. (2000)
Milky Way bulge........................	Mollá et al. (2000)
Sextans A....................................	Dolphin et al. (2003)
LGS3...	Miller et al. (2001)

9. The IMF. The user can adopt a power law of the form M^{-x}. The exponent x must then be specified. Alternatively, the user is allowed to choose the Kroupa et al. (1993) IMF.

10. A choice of the isochrone set to use according to the value of an integer index between 1 and 8. The correspondence between integer value and isochrone set is reported in Table 4.

11. The possibility to search for pulsating variable stars harbored by the synthetic population and compute their periods. An integer value equal to 1 enables the search, and a value equal to 0 prevents the search.

12. The desired SFH. A number of prespecified SFHs for selected galaxies are also provided (see Table 5).

13. As in all simulations based on a Monte Carlo method, our program needs seeds for random number generator initialization. The user can choose the values of the seeds or let the program automatically get seeds from the True Random Number Service Web site.[7] We underline that all computations initialized with the same seeds will lead to identical outputs.

After specifying the input parameters, users can start their computations by clicking the "Submit" button. The calculation may take some time (from a few minutes to hours, mainly depending on the requested number of stars). After the calculation is
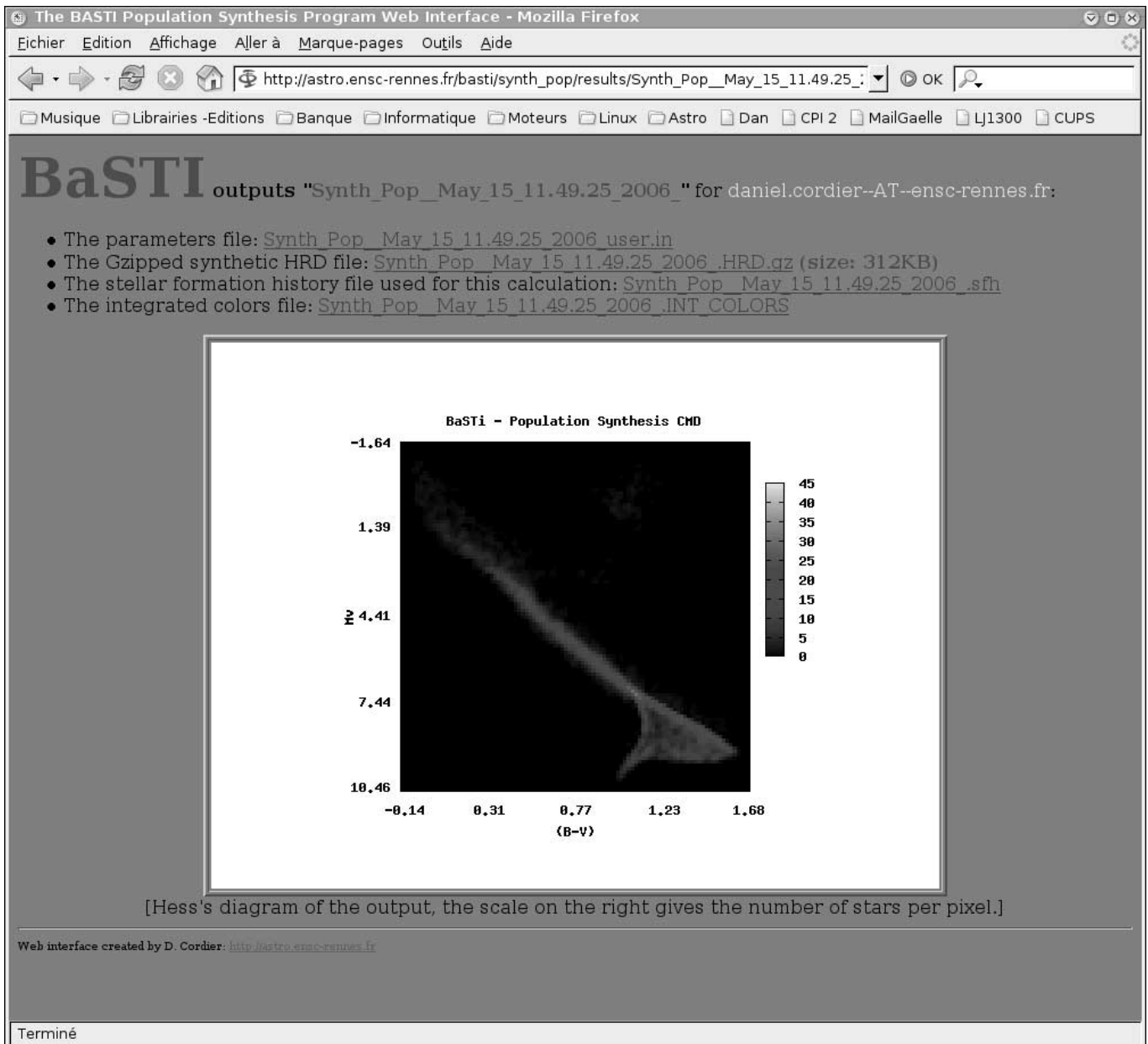
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[7] See http://www.random.org.

FIG. 6.—Example of the output Web page for the SYNTHETIC MAN Web tool. [*See the electronic edition of the Journal for a color version of this figure.*]

completed the user receives an e-mail as notification. As the size of the output files can amount to several megabytes, they cannot be sent by e-mail, and a solution involving a dynamically generated Web page has been found to be preferable. In the output Web page four data files are available:

1. `Synth_Pop_*_user.in`. This ASCII file recalls the parameters used for the calculation.

2. `Synth_Pop_*_.HRD.gz`. This gzipped file contains data for the individual stars, in which one can find the following quantities: identification number, $\log t$ (yr), [Fe/H], the value of the actual mass, $\log L$ ($L_\odot$), $\log T_{\rm eff}$ (K), M_V, $(B - V)$, $(U - B)$, $(V - I)$, $(V - R)$, $(V - J)$, $(V - K)$, $(V - L)$, $(H - K)$, the value of the initial mass, the initial mass of the unresolved binary companion (if present; for stars without a companion this quantity is set to 0.0), logarithm of the pulsation period (in days; if the search for variable is off or if the star is not pulsating, this quantity is set to 99.99), and an index denoting the type of variable (see Table 3 for explanations). This file can be uncompressed with the standard GNU software GUNZIP. As this file can be relatively large, downloading is automatically forced when users click on the link.

3. `Synth_Pop_*_.sfh`. This file contains the SFH data used for the calculations.

4. `Synth_Pop_*_.INT_PROPERTIES`. This file contains the integrated *UBVRIJHKL* absolute magnitudes produced by the stars evolving in the synthetic population, several selected integrated colors, the total number of stars with computed photometric properties, the total mass of stars formed (within the mass range specified in the input file) according to the specified SFH, and a summary of the various types of variable stars found (if the search for variables is off, the values are all equal to zero).

The asterisk denotes a string chosen by the Web tool to avoid the possibility of output files corresponding to a specific simulation being overwritten by those related to a different run. The string is selected according to the time when the numerical run is launched. For example, if the run is launched at 16.51.34 of 2006 May 3, the string will be "`May_3_16.51.34_2006`." An example of the output Web page is displayed in Figure 6. The [V, $(B - V)$] Hess's diagram taking into account all the synthetic objects drawn for the simulation is also automatically displayed, with stars' numbers being encoded with colors. The user should be aware that, for obvious reasons, Web pages displaying program outputs are deleted by the software manager 1 month after the end of the computation.

6. CONCLUSION

In this paper we have presented the content of the BaSTI database for stellar population synthesis studies. In particular, we have discussed the recent extension of the models to the end of the TP-AGB phase and described three Web tools used to compute synthetic CMDs, luminosity functions, and user-specified isochrones and stellar evolution tracks.

In the near future the BaSTI database will be developed following two directions: the extension of the database itself and the development of an online version of our stellar evolution code.

We plan to extend the mass range spanned by our database by adding tracks for very low mass objects (below 0.5 $M_\odot$) and very massive stars (above 10 $M_\odot$), the latter until C-burning ignition.

With a Web-based version of our evolution code, people who are not expert in stellar evolution calculations will be able to compute models with their customized set of parameters (mixing-length value, extension of the overshooting region, metallicity, etc.), avoiding inaccurate interpolation and/or extrapolation

between and/or from existing models. This could also allow for more complex tuning such as opacity tables or nuclear rate table switching, and changes to the equation of state. We think that this Web-based evolutionary code, as well as the BaSTI database, could be relevant tools for the whole scientific community within the ongoing Virtual Observatory project (Pasian 2004).

APPENDIX

BaSTI WEB TOOLS: SOME TECHNICAL ASPECTS

The World Wide Web, originally conceived for document delivery, has evolved into a medium supporting interactive computations. One way for a Web server (in our case APACHE)[8] to interact with data-generating programs is the well-known Common Gateway Interface (hereafter CGI). Input parameters and data provided by the user are passed to our three FORTRAN programs through PERL programs. PERL is probably the most common CGI scripting language, for which a huge collection of modules is available in the Comprehensive PERL Archive Network.[9]

The track/isochrone interpolation program and the luminosity function program are simply driven with a specific PERL interface, and their outputs are directly displayed as an ASCII file that can be saved in the user's hard disk and used by other programs without any difficulty.

The CMD generator is probably, at the moment, our most sophisticated Web-based software. When it is invoked, a computation identification string of characters (CISC) is assigned. The files are handled and stored with this CISC as part of the file name, so even if multiple users from different parts of the world submit simulations at the same time, they can all be processed separately. When the computation is completed, an HTML page is created on the fly, displaying data output files and a pre-visualization made with GNUPLOT. The PERL module NET allows automatic e-mail sending for user notification.

Figure 7 summarizes the BaSTI Web tools' general scheme. Some details have been omitted, such as interaction with the plotting software GNUPLOT and random seeds downloaded from the True Random Number Service Web site.[10] At the moment all calculations are treated after each user's clicking, and consequently, several computations can be running at the same time on our machine, an occurrence that could seriously affect the computation time. Depending on the success of our online programs, we could implement as a new feature a more elaborate computation-managing system that could "queue" the users requests, decreasing individual computation times.

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[8] See http://www.apache.org.
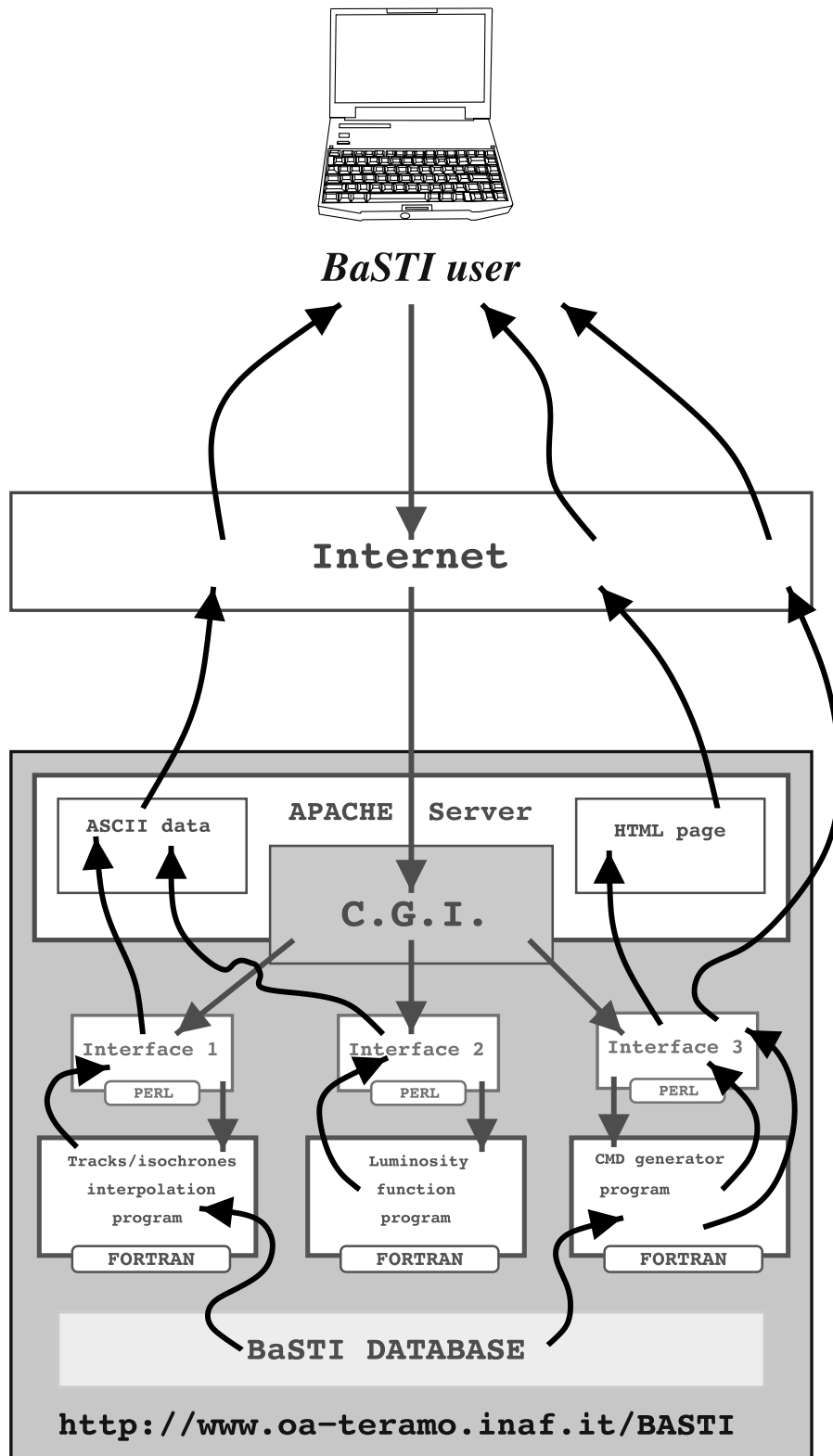[9] See http://www.cpan.org.
[10] See http://www.random.org.

F_{IG}. 7.—Data fluxes in the BaSTI Web tools. Random number generator seeds provided by the True Random Number Service Web site have been omitted. [*See the electronic edition of the Journal for a color version of this figure.*]

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