Astronomy and Computing 7–8 (2014) 95–100

Contents lists available at ScienceDirect

Astronomy and Computing

journal homepage: www.elsevier.com/locate/ascom

Full length article

BaSTI: An updated, advanced and VO-compliant database of stellar evolution predictions

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ARTICLE INFO

Article history:
Received 29 April 2014
Received in revised form
30 June 2014
Accepted 7 July 2014
Available online 25 July 2014

Keywords:
`elsarticle.cls`
LaTeX
Elsevier
Template

ABSTRACT

Stellar evolution model databases, spanning a wide ranges of masses and initial chemical compositions, are nowadays a major tool to study Galactic and extragalactic stellar populations. We describe here the current status of the widely used BaSTI (A Bag of Stellar Tracks and Isochrones) database. We focus in particular on the efforts devoted to port BaSTI to a VO-compliant environment, the BaSTI Web portal that enables users to retrieve data tables and run a range of web tools to facilitate the theoretical analysis of observations, and planned future developments within the framework of the Italian Virtual Observatory project.

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1. Introduction

Developments in various fields of Physics during the last decade have largely improved our understanding of the structure and evolution of stars. As a consequence, stellar evolution models are now able to match several observational constraints provided by both photometric and spectroscopical analyses of field and clusters stars. At the same time, improvements in the observational facilities are providing a wealth of empirical data on Galactic and extragalactic stellar populations, that require suitable extended sets of stellar evolutionary calculations to be properly interpreted.

Large databases of stellar evolution models, spanning a wide range of stellar masses and initial chemical compositions, are nowadays a fundamental tool to study the properties of stellar populations in both Galactic and extragalactic systems. A reliable library of stellar models has to fulfill some important requirements:

- accuracy—the physics inputs necessary for the stellar evolution calculations have to be updated;
- homogeneity—all models have to be computed using the same evolutionary code and the same treatment of stellar physics;
- completeness—for each chemical composition, the range of stellar masses has to be sampled with a mass spacing appropriate to adequately cover all evolutionary stages and ages;
- reliability—the models have to reproduce as many empirical constraints as possible;
- accessibility—all results have to be easily available to the potential users.

We have accounted for all these criteria to set up a new archive of stellar evolutionary models, named BaSTI (A Bag of Stellar Tracks and Isochrones, see Pietrinferni et al., 2004, 2006, 2009, 2013; Cassisi et al., 2006; Cordier et al., 2007), that covers a wide range of stellar masses, chemical compositions and different choices of important evolutionary parameters (like the mass loss efficiency). The BaSTI database (DB) is a widely used tool for investigating several astrophysical problems.

The work related to the realization of the BaSTI DB represents an important contribution within the Italian Virtual Observatory (VObs.it) initiative (Pasian et al., in preparation), and its main aim has been to make available to the whole scientific community the data stored in the DB. Given that the computations of stellar models are extremely demanding in terms of central processing unit (CPU) time, it was very important to include these simulations in the

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http://dx.doi.org/10.1016/j.ascom.2014.07.002
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Table 1
The main characteristics of the *BASTI* archive.

Mixture	Scaled-solar					α-enhanced			
η	0.0	0.2		0.4		0.2		0.4	
λ_{OV}	0.2	0	0.2	0	0.2	0	0.2	0	0.2
N^O tracks	20	20	20	40	20	20	20	40	20
M_{min} ($M_\odot$)	0.5	0.5	1.1	0.5	1.1	0.5	1.1	0.5	1.1
M_{max} ($M_\odot$)	2.5	2.4	2.4	10	10	2.4	2.4	10	10
N^O isoc.	44	63	44	54	44	63	44	54	44
Age_{max} (Gyr)	9.5	19	9.5	14.5	9.5	19	9.5	14.5	9.5
Photometric System	UBVRIJKL — ACS HST — Strömgren–Walraven Sloan — WFC2–WFC3 (UVIS, IR)								

Virtual Observatory (VO; Hanisch and Quinn, 2003), making the data VO compliant; the core of this effort was done as part of the Euro-VO Data Centre Alliance (EuroVO-DCA) WP4 and WP5 European asset and the Italian Theoretical Virtual Observatory (ITVO) project (Pasian et al., 2006).

The DB is structured to archive all parameters regarding a stellar model calculation, starting from the initial chemical composition to properties such as type of model, photometric system, heavy element distribution, mass loss, and all parameters regarding the numerical evolutionary code linked to the metadata of the simulation output files. This relational DB offers the possibility of storing and easily searching the obtained data by several set of stellar simulations, and it also gives user-friendly access to a huge amount of homogeneous data such as these tracks and isochrones computed by using our evolutionary code (the Frascati Raphson Newton Evolutionary Code—FRANEC, Pietrinferni et al., 2004).

In its first release, the BaSTI DB was accessible via a dedicated Web portal that provided users with the opportunity of downloading a single tar file containing stellar tracks and/or isochrones of interest. In its later updates, while making the whole DB VO compliant, we decided to give an added-value to the BaSTI archive by developing a new structure: archive +DB+ Web portal.

In Section 2 we briefly discuss the physics inputs adopted in the model computation, and describe the global properties of the stellar simulations stored in the BaSTI DB. In Section 3 we present the WEB database interface. Final remarks and a short discussion concerning the planned developments of BaSTI in the context of Euro-VO will close the paper.

2. The theoretical framework

Our DB has been computed by using an updated version of the FRANEC evolutionary code, improved in many aspects concerning both the numerical scheme for treating the nuclear burnings, and the accuracy of the numerics. Almost all the adopted physics inputs have been updated as well. In particular, the low- and high-temperature radiative opacity tables, electron conduction, and the contribution from plasma-neutrino includethe most recent theoretical predictions (see Pietrinferni et al., 2004 for more details). The nuclear reaction rates have been updated by using the NACRE compilation (Angulo et al., 1999), with the exception of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, that comes from Kunz et al. (2002). As for the Equation of State (EOS), we employ the new EOS by A. Irwin (see Cassisi et al., 2003), that covers the full structure of the models along all relevant evolutionary stages.

All stellar models have been computed by fixing the extension of the convective core during core H-burning both classically (Schwarzschild criterion) and considering a non-negligible overshooting beyond the Schwarzschild boundary ($\lambda_{OV} = 0.2$ Hp). This latter choice reproduces empirical constraints coming from intermediate-age cluster Color–Magnitude Diagrams (CMDs) and field eclipsing binaries.

We have also accounted for mass loss by using the Reimers formula (Reimers, 1975) with the free parameter η set to zero (no mass loss), 0.2 and 0.4, respectively.

The calculations cover 13 different metallicities, namely Z = 0.00001, 0.0001, 0.0003, 0.0006, 0.001, 0.002, 0.004, 0.008, 0.01, 0.0198, 0.03 and 0.04, 0.05, with two different heavy element distributions each: a scaled-solar (Grevesse and Noels, 1993) and an α-enhanced (Salaris and Weiss, 1998) one. We adopted a cosmological He mass fraction $Y = 0.245$ (Cassisi et al., 2003), and a helium-to-metal enrichment ratio $\Delta Y/\Delta Z \approx 1.4$, fixed by the initial solar metal mass fraction obtained from the calibration of the standard solar model.

The chemical compositions listed above correspond to the 'core' simulations stored in the BaSTI DB. To provide a theoretical framework for interpreting the recent empirical evidence of multiple stellar populations in Galactic globular clusters (GGCs), we have recently added to the BaSTI DB models corresponding to both helium and CNO-element enhanced chemical compositions (Pietrinferni et al., 2009). These additional models can be retrieved using the corresponding link that appears on the left hand side of the BaSTI WEB portal (see Fig. 1).

For each chemical composition, models span the mass range $0.5 \leq M/M_\odot \leq 10$, with a very fine mass spacing. All models – with the exception of the least massive ones whose central H-burning timescale is longer than the Hubble time – have been evolved from the Pre-Main Sequence phase to C-ignition, or until the first thermal pulses along the asymptotic giant branch, depending on mass. The main characteristics of our archive are listed in Table 1. The model calculations have been used to compute stellar isochrones for a wide range of ages, ranging from 30 Myr to the upper limit listed in Table 1.

For each chemical composition we also have computed additional He-burning models with He-core mass and envelope chemical profile fixed by a Red Giant Branch (RGB) progenitor having an age of ~13 Gyr at the RGB tip, and a range of values of the total stellar mass. These Horizontal Branch (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 types of pulsating variable stars.

Luminosities and effective temperatures of the models have been transformed to magnitudes and colors for several photometric filters – see Table 1 – by using color-T_{eff} transformations and bolometric corrections obtained from an updated set of calculations of stellar model atmospheres and spectra.

The BaSTI WEB portal allows also to retrieve tables – both in ASCII and html format – for each chemical composition containing selected properties of the computed stellar models, taken at specific evolutionary stages. By using the whole theoretical framework associated to the BaSTI DB, we have also developed a new set of low- and high-resolution integrated synthetic spectra of simple stellar populations (SSPs—single age, single metallicity populations) for both scaled-solar and α—enhanced metal mixtures

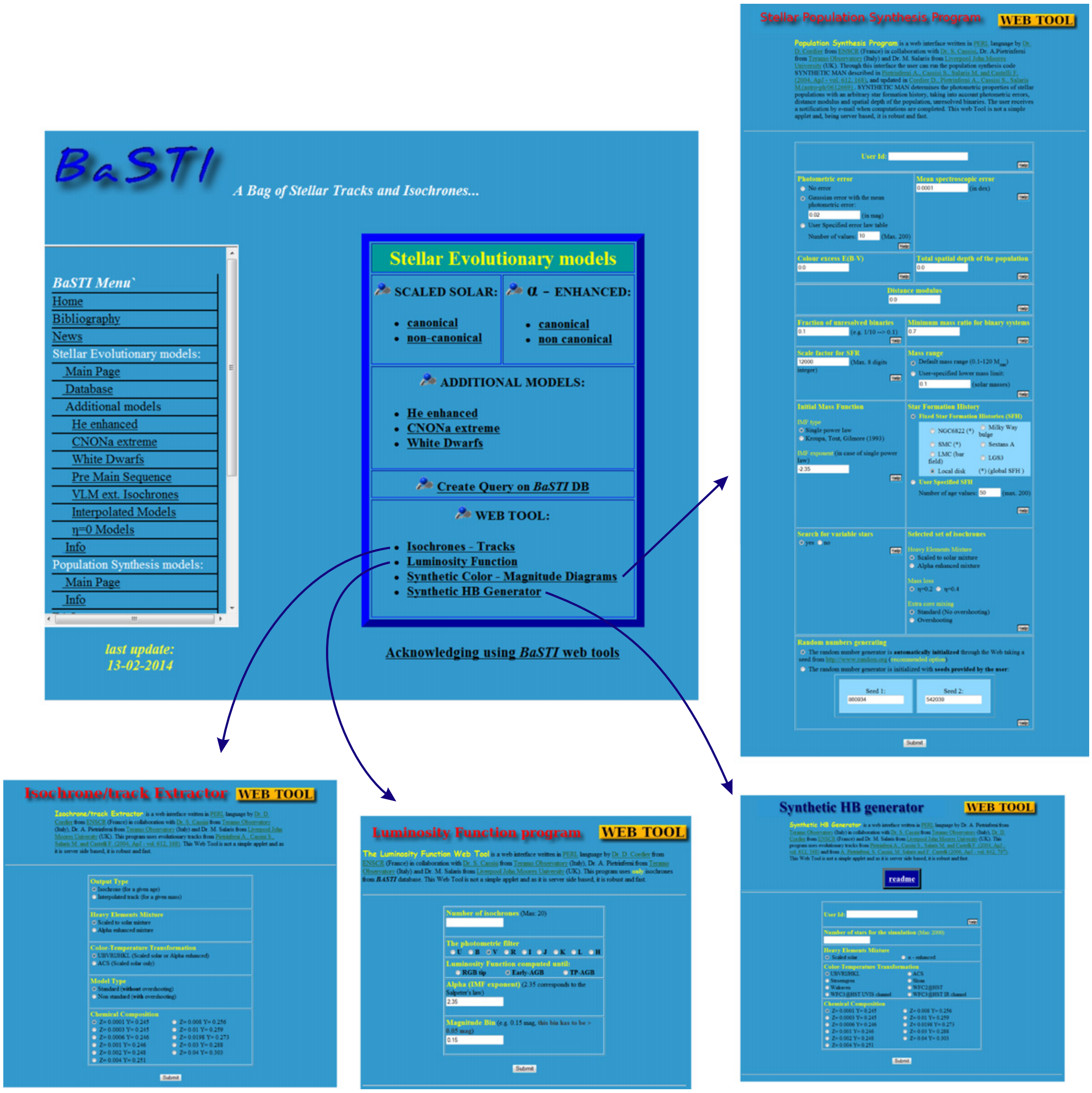

Fig. 1. The main page of the *BaSTI* archive, with the web-tool interfaces.

(see Percival et al., 2009 for more details). This enables a consistent study of the photometric and spectroscopic properties of both resolved and unresolved stellar populations. From our low-resolution spectra it is possible to derive integrate broadband magnitudes and colors in any photometric system. The spectra cover the full wavelength range (9–160,000 nm) and include all evolutionary stages up to the end of asymptotic giant branch evolution. The BaSTI high-resolution spectra are suitable for studying the behavior of line indices, and these spectra have been extensively tested against observational constraints provided by a large sample of Galactic globular clusters (see Percival et al., 2009).

The complete set of synthetic integrated spectra are publicly available via the BaSTI WEB portal following the link *Population Synthesis Models*.

A detailed comparison of both stellar evolutionary predictions and populations synthesis models with other existing theoretical computations and observational data has been shown in Pietrinferni et al. (2004), Pietrinferni et al. (2006), Pietrinferni et al. (2009), Pietrinferni et al. (2013), Cordier et al. (2007), Percival et al. (2009) and Bertelli et al. (2009). A summary of the main model input physics and the parameter space covered by the models for BaSTI and other widely used stellar evolution libraries (i.e. Padua, Yale, Geneva, Victoria) has been presented in Table 1 of Gallart et al. (2005). Although several archives of updated stellar evolutionary models have been presented in the last years (Padua models—Bertelli et al., 2009; Victoria models—VandenBerg et al., 2012), the BaSTI database is the only one that includes stellar models computed with and without assuming the central core overshooting (during the central hydrogen burning stage) and two different values for the mass loss efficiency.

3. The BaSTI archive: web interface/database/interactive and VO tools

The BaSTI Web portal is realized in hypertext mark-up language (HTML) for the static part, while the dynamic portion is written in PHP (Php: Hypertext Preprocessor), a server-side scripting language especially suited for Web development that can be embedded into HTML. The Web server used for our purposes is Apache 2.0, a common choice open-source HTTP server. At present the web interface to access the DB is reachable at the following two URLs:

- Italian Astronomical Archives Center (IA2) Web site.[1]
- INAF-Astronomical Observatory of Teramo.[2]

Together with the theoretical predictions a set of four web interfaces, written in Perl, has been developed. These WEB Tools allow user-friendly manipulations on the stellar evolutionary library. Behind these interfaces there are FORTRAN programs already used in previous published works by our group. This method is powerful and reliable because it is server side based and it uses well known FORTRAN programs (see Cordier et al., 2007 for more details). These web tools (see Fig. 1) are:

- *Isochrone–track maker:* this tool allows to calculate an isochrone/track for a specific age/mass (not included in the DB) for each chemical composition. The algorithm adopted for interpolating among the evolutionary tracks is based on the Equivalent Evolutionary Phases procedure described in Bergbusch and Vandenberg (1992). The user can also choose: heavy element mixture, color–temperature transformation and the model type (with or without overshooting). This tool does not require registration and results are directly sent to the Internet browser.
- *Luminosity function maker:* the tool calculates luminosity functions from a set of isochrones previously downloaded by the user. It is possible to select the heavy element mixture, the photometric filter, the number of isochrones, the number of the stars in the simulation, and the value of the Initial Mass Function exponent (treated as a power-law). It is important to stress that this program runs correctly only with isochrones of this database. As in the case of the isochrone–track maker, results are sent to the user's browser.
- *Synthetic Horizontal-Branch color–magnitude diagram maker:* this tool calculates the photometric properties of HB stars in old stellar populations, employing the tracks provided in the BaSTI archive. At the moment the HB mass distribution is assumed to be Gaussian, while photometric errors are not yet taken into account. The user needs to specify the following parameters: (a) mean HB mass; (b) 1σ dispersion of the Gaussian Distribution; (c) metallicity; (d) heavy element mixture: scaled solar or α-enhanced; (e) the photometric system. The output provides also magnitudes and properties of the objects within the RR Lyrae instability strip (if populated). For stars located in the region of the instability strip where both fundamental and first overtone pulsational mode can be stable, the code provides the fundamental mode pulsation period. The output summarizes also the total number of blue HB stars—those located on the blue side of the RR Lyrae instability strip, red HB stars—those located at an effective temperature lower than the Red Edge of the RR Lyrae instability strip and Asymptotic Giant Branch stars.
- *Synthetic color–magnitude diagram maker:* this population synthesis tool is a synthetic CMD generator. From the BaSTI Web site the user can access the SYNTHETIC MAN(ager). This code computes magnitudes and colors of objects belonging to a synthetic stellar population with an arbitrary Star Formation History (SFH), along all evolutionary phases covered by the model calculations. The program employs the grid of isochrones included in the BaSTI archive. The most important input is the SFH file through which one sets the grid of ages and for each age: the scale factor of the star formation rate (which is proportional to the relative number of stars formed at that time), the metallicity of the stars formed at that age, and the eventual 1σ spread around this value.

The BaSTI Web tool page is freely accessible, and to prevent unauthorized users to run the codes without any scientific purpose, we require a pre-registration to use the last two tools.[3] Pre-registration can be done by sending an e-mail to the people maintaining the BaSTI DB or by using the on-line form accessible from the Web portal.

So far the number of registered users is equal to 88, of which about 58 work in European scientific institutions.

The BaSTI DB (see also Manzato et al., 2009, Sect. 4), accessible via the web portal, includes the metadata of the simulated stellar files and is hosted on an Oracle 10g SQL server. All metadata are stored in tables that are linked to each other by foreign keys on primary keys to avoid any duplication of the information. There is also one auxiliary table to take into account the units used for the different quantities. The metadata of the stored stellar simulation are as follows: all program parameters such as evolutionary code name, version, initial conditions, boundary conditions, EOS, radiative and conductive opacities, nuclear reaction rates, and neutrino losses. In addition, there are also stored the quantities of chemical compositions, such as: global metallicity Z, initial helium abundance Y, iron content [Fe/H], and the corresponding [M/H] value once the heavy elements mixture has been chosen. Additional stored parameters are: the mass loss efficiency, type of model, photometric system, heavy element distribution, and the macro-physics scenario (canonical, overshooting, diffusion, rotation). DB metadata includes also the access details (output filename, file type[4] and full path) to the physical table that stores the output of the simulation.

The DB project and structure enable a search over a large amount of scientific parameters, with a simple and direct query to find the data that better satisfy the characteristics of a research typology. From the Web portal it is also possible to personalize the SQL (Structured Query Language) query, by making a more complex one and/or filtering on fields like a ratio of two quantities, as it is shown in Fig. 2 as illustrative case: an example of a query for the DB is retrieving a set of simulated isochrones for a given age range and a ratio between mass and metallicity. There is also a Help Web page where the user can read a definition of the used quantities and get an idea of the value by which he/she can search into the archive.

All the evolutionary predictions stored inside the relational DB are in ASCII format as shown in Fig. 3; however they can be immediately transformed in VO-tables, just clicking a button in the Web portal (see the bottom middle panel in 3). This allows to use VO tools like TOPCAT,[5] to analyze the simulation data, and to easily compare the theoretical predictions with observational counterparts. A preview capability for the simulations has been also provided. This has been done by using a STILTS[6]-based online 2D plotting interface (see right bottom panel in Fig. 3, see also Sect. 3 in Molinaro et al., 2010, and Manzato et al., 2008). Besides VO-table translation on web portal, another solution to allow an easy access to BaSTI data directly by VO aware tools has been provided. This alternative approach to retrieve data concerning evolutionary tracks and isochrones consists in a dedicated *Dialog* panel embedded in the TOPCAT application. The dialog – accessible via the *VO* → *BaSTI Data Loader* TOPCAT menu – allows direct search and retrieval of BaSTI simulations from the tool itself. With this solution, and the SAMP (Simple

[1] BaSTI is hosted at the Italian Astronomical Archives Center at the URL http://ia2.oats.inaf.it/index.php/basti-archive-mainmenu-85.

[2] The INAF-OA Teramo BaSTI Web site is at the URL http://www.oa-teramo.inaf.it/BASTI/.

[3] The CPU time required by the other registration-free tools is so short that it is practically impossible to jam up the BaSTI server.

[4] The different types correspond to an isochrone, an evolutionary track or to a summary table.

[5] http://www.star.bris.ac.uk/mbt/topcat/.

[6] http://www.star.bristol.ac.uk/mbt/stilts/.

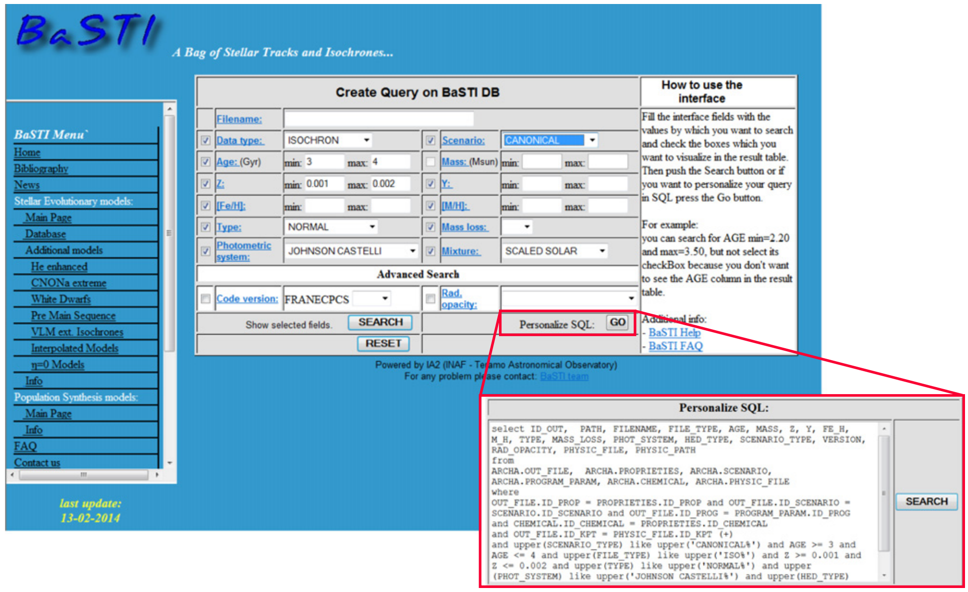

Fig. 2. The web interface for creating a query on *BaSTI* database.

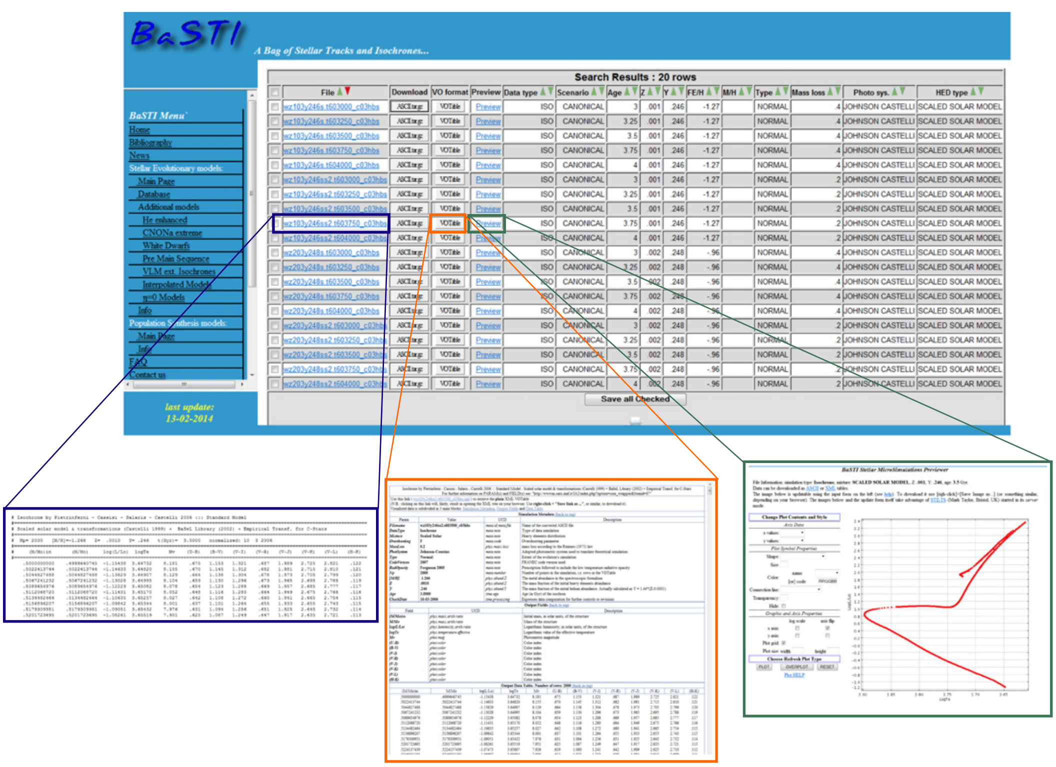

Fig. 3. Output files from *BaSTI* archive.

Application Messaging Protocol) messaging between different tools on researcher's desktop, BaSTI simulations are accessible in the VO framework without the need of downloading the data files in advance to feed the desired application. The TOPCAT dialog solution was intended initially as a work-around approach due to the lack of suitable IVOA standards at the time the BaSTI web interface was developed and is, till then, integrated in the TOPCAT distribution.

At present IVOA standards for theoretical simulations (including *microsimulations*, as are usually named in the VO the stellar ones provided by BaSTI) are more mature and probably it is (or will be) feasible to integrate BaSTI in the VO environment at full potential, by taking advantage of the SimDM and, possibly, SimDAL specifications (the latter one is still under discussion), but in the meantime the solutions described here above are a good start and have already provided important services to the VO community.

Finally, besides the BaSTI VO framework just depicted, it is worth citing a couple of other tentative solutions tested by the IA2 team: a TAP (Table Access Protocol) endpoint and an S3 (Simple Self-described Service) test. The first one simply exposes a snapshot of the BaSTI metadata DB through an IVOA TAP service; this service is hosted at the Heidelberg GAVO (German

Astrophysical VO) TAP portal.[7] It allows to search the BaSTI metadata with custom queries directly within the VO framework. The second was a support to a simple IVOA protocol that never reached the status of recommendation but whose goal was exactly to expose *microsimulations*. It can be surfed programmatically both for isochrones[8] and stellar tracks;[9] unfortunately it lacks a suitable client application to be used with.

4. Final remarks

In these last five years, a large effort has been devoted to port the BaSTI stellar evolution database to a VO-compliant environment. This repository of stellar model predictions has been largely used as a test-case for the integration and interoperability between VO and computational Grid facilities (see Pasian et al., 2008; Taffoni et al., 2008, in preparation).

From a scientific point of view, this effort has resulted in a major – and largely recognized – success. BaSTI is currently the most updated and complete library of stellar evolutionary models, and provides the whole scientific community with a set of tools that significantly facilitate the analysis of observations of stellar populations, providing 'on demand' specific stellar evolution predictions such as isochrones, luminosity functions and synthetic CMDs. As a consequence of the high scientific value of the stored data, as well as of the high level – in terms of user friendly and quick data access – of the technological environment developed 'around' the original BaSTI Library, this database is becoming nowadays a standard in the field. It is considered within the Euro-VO as one of the best examples of micro-simulations data transferred to the framework of the VO.

Bearing in mind that the main aim of the International VO Alliance is to make both observational and theoretical data more easily accessible to the whole scientific community, it is worthwhile to evaluate the 'popularity rating'of the BaSTI database within the scientific community; since February 2004 (when it first went online), it has received about 34,000 visits, and for at least 80% of the cases, scientific data have been downloaded and/or analyzed online.

We have received a very positive feedback from the BaSTI users, reinforcing our firm belief that we are going in the right direction. However, the most clear evidence that our work is really providing a useful and powerful tool to the whole community is represented by the following considerations:

- the BaSTI archive is extensively used by almost all groups working in the field of stellar populations and evolution of galaxies, either directly via the tools and data we provide, or as a fundamental input in their own population synthesis codes;
- the scientific papers presenting the BaSTI database published since the 2004, have collected more of 1200 citations to date (ADS source);
- the archive is also used as a tool to teach stellar evolution at university level courses.

The planned future developments of the BaSTI archive in the framework of the Italian Virtual Observatory initiative VObs.it, are the following:

1. we wish to include all relevant data describing the physical structure of the computed stellar models. This information is not commonly provided in stellar evolution databases, and is crucial, e.g., for asteroseismological studies;
2. we wish to improve the graphical treatment of the stored data by providing new and more efficient tools for improving the access to the data as well as the interoperability among various (theoretical and observational) resources;
3. we wish to continue using BaSTI as a benchmark for testing IVOA Theory access protocols and standards. This effort is a fundamental requirement to facilitate and improve the inclusion of micro-simulations data inside the VO;
4. allowing the use of distributed computing facilities (e.g. the Grid) for calculations of stellar models fully compatible with the models already included in the BaSTI database. This will be accomplished by working also on our own numerical evolutionary code, to take full advantage of the grid computing architecture. The successive step will be to allow the possibility of performing evolutionary model computations 'on demand', by using a dedicated Grid and Web portal.

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7 See, e.g. http://dc.zah.uni-heidelberg.de/__system__/dc_tables/list/form.

8 http://albione.oa-teramo.inaf.it/PHPmetadata/BaSTIisochron.php?format=metadata.

9 http://albione.oa-teramo.inaf.it/PHPmetadata/BaSTItrack.php?format=metadata.