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Stellar evolution@EURO-VObs

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Abstract. Stellar evolutionary models are a fundamental tool for addressing many astrophysical issues. For such a reason, it is of fundamental relevance to make them available to the whole scientific community in an easy and direct way. We briefly review the main ingredients requested for computing stellar models and show some illustrative scientific cases concerning the comparison between model predictions and suitable empirical evidence. We discuss also some problems related to the implementation of stellar models library inside the Virtual Observatory, and report about our experience with the our BaSTI stellar model repository.

Key words. Stars: evolution - Stars: horizontal-branch - Hertzsprung-Russell (HR) and C-M diagrams - Galaxy: Globular Clusters - Galaxies: stellar content

1. Introduction

Stellar evolution models are pivotal ingredients in order to understand the evolutionary properties of the various Stellar Populations present in both resolved and unresolved stellar systems, so that they play a fundamental role in assessing the 'nature' and the contribution of the different blocks that contribute to build the galaxies.

During the second half of the last century, stellar evolution theory has allowed to properly understand the 'meaning' of the various branches observed in the Color Magnitude Diagram (CMD) of both galactic globular clusters (GGCs) and open clusters. This notwithstanding for a long time these theoretical predictions were accounted for with an uncritical approach. They were used at face value without accounting for theoretical uncertainties and their effect in deriving estimates about cluster age and distances. More recently, this approach to the theoretical framework drastically changed and more critical assessments were adopted. The motivations at the base of this change have to be searched both in the will of providing reliable estimates of the systematic uncertainties affecting this kind of comparison and in the relevant advances made in the observational techniques and in the 'Physics' applied to stellar models.

On the observational side, in recent years, the impressive improvements achieved for both

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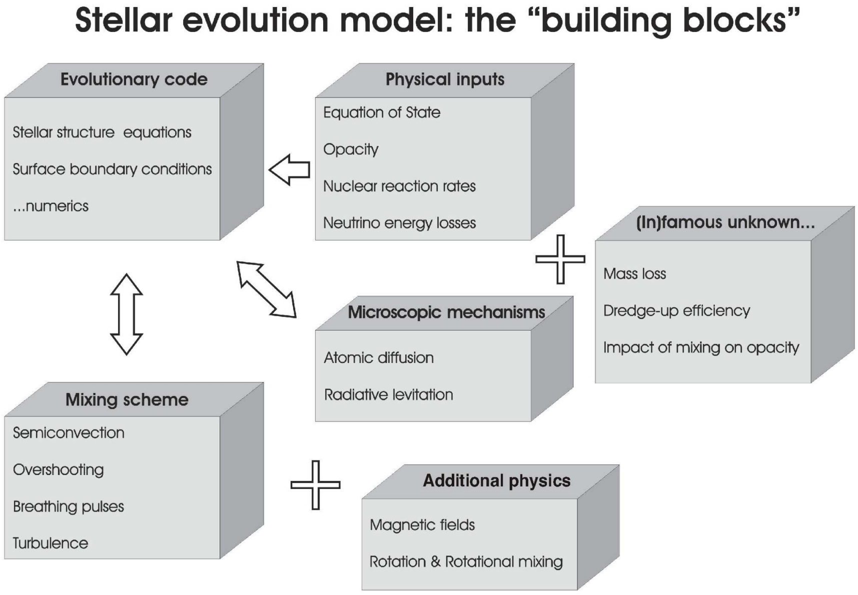

Fig. 1. A qualitative view of the main 'blocks' needed for 'building' a stellar model.

photometric and spectroscopic observations, has allowed to collect data of an unprecedented accuracy, which provide at the same time a stringent test and a challenge for the accuracy of the models.

On the theoretical side, even if significant improvements have been achieved in the determination of the Equation of State (EOS), opacities, nuclear cross sections, neutrino emission rates that are all fundamental physical inputs for solving the stellar structure equations, residual uncertainties do exist still as it is clearly testified by the not negligible differences still existing among evolutionary results provided by different theoretical groups. At the same time, models computed with this updated physics have been extensively tested against the latest observations, and this has also contributed to increase the awareness that it is no more possible to neglect physical processes as radiative levitation, rotation, magnetic fields, considered secondary physical mechanisms until few years ago.

A careful discussion of the uncertainties affecting stellar models for low-mass stars was early addressed by Chaboyer (1995), who investigated the reliability of theoretical predictions concerning H-burning structures presently evolving in GGCs and, in particular on the accuracy of age predictions. Such an investigation has been extended to later evolutionary phases by Cassisi et al. (1998, 1999), Castellani & Degl'Innocenti (1999), and Gallart et al. (2005). A discussion of the drawbacks of stellar models for low-mass stars and their impact on the most used age, distance and chemical composition indicators has been also provided by Cassisi (2005 and references therein).

In this contribution, we briefly discuss the main ingredients that are necessary for computing a stellar models, and show what are the main outputs provided by stellar model computations. We discuss also very few illustrative examples of the kind of comparisons that can be performed between empirical evidence and evolutionary stellar models. The importance to include stellar model predictions in the framework of the Virtual Observatory, as well as some open issue related to this effort are also discussed.

2. Stellar models: the 'building blocks'

From the point of view of people using stellar models, they provide: i) evolutionary lifetimes that can be compared with suitable star counts; ii) bolometric luminosity and effective temperature that once converted in useful magnitudes and colors in various photometric systems by using color-T_{eff} relations and Bolometric Correction scales, can be compared with empirical data, and iii) predictions about the surface chemical abundances that can be tested against spectroscopic measurements.

However, any user before accounting for these theoretical predictions should ask himself this fundamental question: How much accurate and reliable are the predictions coming out from stellar models?

It is clear that the reliability of a stellar model depends mostly on the accuracy of the adopted physical inputs as well as on the physical processes accounted for as: atomic diffusion, levitation, rotation.

In Figure 1, we show a qualitative picture showing the most important 'building blocks' that are required in order to construct a stellar model.

The equations that describe the physical behavior of any stellar structure are well known since long time and a detailed discussion on their physical meaning can be found in many books such as Cox & Giuli (1968), Kippenhan & Weigart (1990) and Salaris & Cassisi (2005). The solution of these equations is no more a problems - thanks also to the advances in computer programming and computer science: updated stellar evolution codes, once the physical scenario has been homogeneously fixed, provide results quite similar.

However, in order to solve the stellar structure differential equations outer boundary conditions have to be provided: one can rely on some empirical relation for the thermal stratification as that provided by Krishna-Swamy (1966) or a fully theoretical law as the so-called gray (or Eddington) approximation, or alternatively one can adopt the predictions given by suitable model atmospheres.

The meaning and role played by the various 'ingredients' listed in Fig. 1 has been extensively discussed in the literature (see for instance Castellani 1999).

Before closing this section, we wish to comment a bit on Fig. 1. As already stated, this picture has only a qualitative purpose. In the 'block' *"(in)famous unknown..."* we put: mass loss efficiency, dredge-up efficiency and the impact of mixing on opacity. When referring to the dredge-up efficiency we are considering the process occurring during the Asymptotic Giant Branch (AGB). In any case, for all the 'ingredients' listed in this block we are not yet able to predict their efficiency from fundamental principles and indeed we still rely on - quite approximate - parametrization of the various processes.

In the block *"Additional physical processes"*, we include the presence of magnetic fields and the occurrence of rotation and rotational-induced mixing. It is clear that in the implementation of both processes in an evolutionary code, due to our poor knowledge of the physics at work would require a sizable number of assumptions and free parameter. The reason for which we do not include them in the *"(in)famous unknown..."* block is due to the evidence that we are always forced to account for mass loss and the 3^o dredge-up in order to explain the Horizontal Branch morphology (HB) and the evolution of AGB stars; whereas we really need to account for magnetic field and rotation only to interpret some specific observational features related, for instance, to the evolutionary properties of VLM stars and HB stars.

3. The stellar evolution 'market'

In the previous section, we have discussed the main physical ingredients that affect the accuracy of stellar model predictions. Once the physical framework has been set, it is possible to start stellar model computations. These numerical computations can provide a huge amount of physical data about the structural and evolutionary properties of stars for various chemical compositions and mass ranges.

The various data that are provided by stellar models, can be used in many different astrophysical applications, such as the study of individual stars and/or binary systems, the interpretation of spectroscopic measurements, the analysis of the evolutionary properties of galactic stellar systems, and - when used in combination with suitable Population Synthesis tools (see Salaris et al. , these proceedings) - the investigation of the properties of unresolved stellar systems. In the next section, we will give few illustrative examples of these applications.

In the meantime, we wish to briefly summarize what are the main outputs of stellar model computations, which can be useful for the whole astrophysical community:

- *evolutionary tracks*: they give us information on how the stars - according to their total mass and chemical composition - distribute in the H-R diagram and in the various observational planes during their evolution with the time;
- *luminosity functions*: these outputs provide predictions about the number of stars which is expected in the various evolutionary stages;
- *isochrones*: they say us how - for a given age - stars of different total mass are distributed in the H-R diagram and the various observational planes.

Figures 2 and 3 show an illustrative example of both evolutionary tracks/isochrones and luminosity functions (Pietrinferni et al. 2004), respectively; while Fig. 4 shows the chemical stratification inside the Sun as predicted by models accounting or not accounting for atomic diffusion.

Along the time, many authors have provided several independent libraries of stellar model predictions, based on different assumptions about both the physical framework (EOS, opacities and so on), and the physical assumptions (canonical and/or non-canonical models, i.e. accounting for diffusive processes and/or convective core overshooting). In Table 1, we

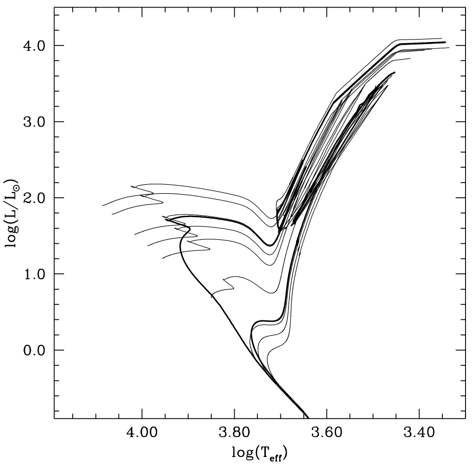

Fig. 2. Evolutionary tracks in the H-R diagram for stellar models with solar chemical composition and mass equal to: 0.8, 0.9, 1.0, 1.5, 2.0, 2.2, 2.4, 2.8 and $3M_\odot$. The two heavy solid lines represent two isochrones for age equal to 600Myr (brighter sequence) and 10Gyr, respectively.

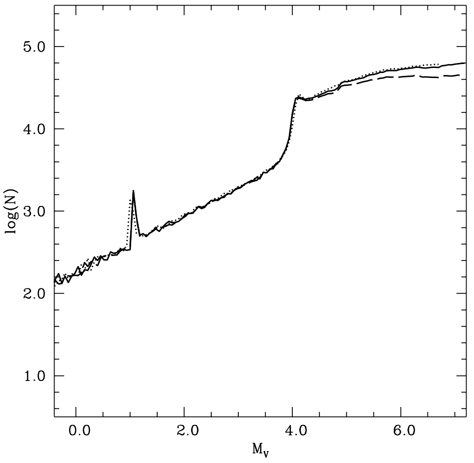

Fig. 3. Selected luminosity functions for a metal rich, old stellar population, t=14Gyr, for various assumptions about the initial He content and the initial mass function. The peak at $M_V \sim 1$ mag, marks the location of the bump along the Red Giant Branch, while the huge increase at $M_V \sim 4$ mag, corresponds to the Sub-Giant Branch region.

provide a - not complete - list of some, most popular and complete stellar model libraries.

Among the various libraries, there exist significant differences that reflect the use of different ingredients and numerical assumptions in the model computations. In addition, the range of stellar masses and chemical compositions covered by the various libraries is not always the same.

It is evident that in order to assess the accuracy of a stellar model library is of pivotal relevance the possibility to perform as many as possible comparisons with the model predictions provided by independent model archives. Therefore, the possibility to have a direct, easy access to the models computed by other authors would be extremely useful.

A problem related to all stellar model archives is that, along the time, the models stored in each archive are usually updated, as a consequence, for instance, of the adoption of more accurate and up-to-date physical ingredients, and it happens very often that the ‘record’ of the previous release of the archive is completely lost. This occurrence does not allow the users of the stellar model predictions to keep track of the ‘evolution’ of the archive and to better understand how the changes in the library would eventually affect their own results. In addition, to keep memory of the previous release of any libraries would also help in investigating how the improvements in the model computations - as due for instance to improvements in the adopted physics - would affect the predicted evolutionary properties.

4. Theory *versus* observations

The comparison between theoretical models and empirical findings is a fundamental step for retrieving the properties of the star or the stellar system under scrutiny. In the same time, this approach is mandatory in order to assess the accuracy and reliability of the theoretical framework. In fact, stellar models ‘builders’ need to check their models by comparing them with empirical evidence in order to see if they are able to reproduce the properties of the real stars. In this context, to have an easy access to both many, independent, stellar model libraries, and a large database of empirical data would be extremely worthwhile.

In the following, we briefly discuss few illustrative cases of a comparison between stellar models and empirical data.

4.1. Very-Low-Mass stars

For many years, the computation of reliable models for Very-Low-Mass (VLM) stars has been severely challenged by the lack of robust predictions about the thermal and opacitive properties as well as of suitable outer boundary conditions (Chabrier & Baraffe 2000).

In these last decade, on the theoretical side, the situation largely improved thanks to the recent availability of appropriate EOS, radiative opacity, and outer boundary conditions (Allard et al. 1997). From the observational point of view, thanks to the superb photometric capabilities of the Hubble Space Telescope, a ‘pletora’ of empirical data for such objects were collected (see King et al. 1998). A plain evidence of the remarkable improvements achieved on this issue is represented by the nice fit to the faint MS of the GGC NGC 6397 performed by VLM models by both Baraffe et al. (1998) and Cassisi et al. (2000). Firm constraints for the theoretical framework are also provided by different types of empirical data as those given by the Mass-Luminosity and Mass-Radius diagrams.

Therefore it seems that we can now be fully confident about the accuracy and reliability of VLM models; however unfortunately this is not yet the case. The existence of shortcomings in these models appears when taking into account empirical constraints represented by CMDs of intermediate- and metal-rich VLM stars. Fig. 5 shows the comparison between VLM models and empirical optical data for the largest sample of field subdwarfs with known parallaxes: while models for metal-poor composition finely reproduce the corresponding empirical sequence, the solar composition one clearly does not match the data for $M_V > 11$ mag. This evidence could be considered as a proof for a problem in the evolutionary models, however, Fig. 6 shows the comparison at longer wavelengths between the

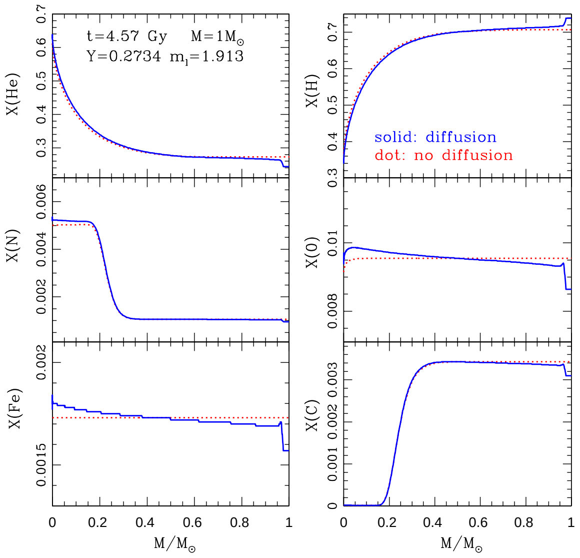

Fig. 4. An example of the stellar model predictions about the chemical stratification inside a given star: the trend of selected chemical elements inside a Solar Standard Model, i.e. a $1M_\odot$ model with solar chemical composition that - at the present age of the Sun - reproduces its radius and luminosity, as provided by stellar models accounting (solid line) or not accounting (dotted line) for atomic diffusion.

Table 1. Most popular libraries of stellar model predictions

Name	Reference
Basti	Pietrinferni et al. (2004, 2006), Cordier et al. (2007)
Geneve	Lejeune & Schaerer (2001)
Granada	Claret, Paunzen & Maitzen (2003)
Padua	Bertelli et al. (1994, 2008), Girardi et al. (2000)
Victoria-Regina	Vandenberg, Bergbusch & Dowler. (2006)
Dotter	Dotter et al. (2007)
Yonsei-Yale	Yi et al. (2001)

same solar metallicity VLM models and empirical data for field stars in the Bulge (Zoccali et al. 2000). It is worth noting that the same models that in the optical CMD do not fit the data, in the Near-Infrared bands nicely reproduce the peculiar shape of the MS.

This result points out that the source of the shortcoming showed in Fig. 5 has not to be searched in the evolutionary models but really in the adopted color - T_{eff} relation: a drawback seems to exist in the evaluation of the opacity contribution at wavelength $\lambda \leq 1\mu m$ in the computation of the model atmospheres.

This kind of results strongly suggest that evolutionary models for VLM stars have already attained a significant level of accuracy in reproducing empirical constraints, and that a big improvement has to be expected in the adopted color - T_{eff} relations as a consequence of a more accurate treatment of the opacitive properties in model atmospheres of cool and dense stellar objects. In this context to have the

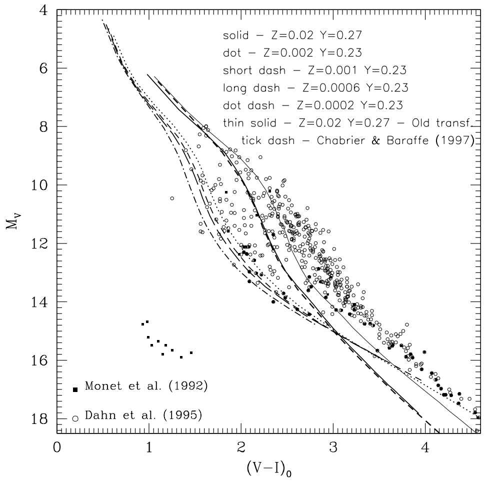

Fig. 5. Comparison between VLM models (Cassisi et al. 2000) and the observed distribution of field dwarfs with known parallaxes. Solar composition models by Chabrier & Baraffe (1997) are also shown. Thin solid line refers to solar metallicity VLM models transferred in the observational plane by using an old set of colour - T_{eff} transformations (see Cassisi et al. 2000 for more details).

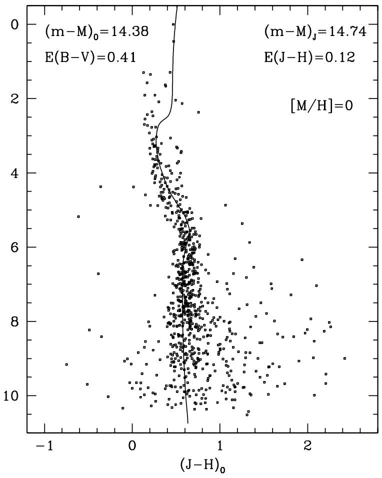

Fig. 6. The fit of the MS stars population in a window of the bulge (Zoccali et al. 2000). The VLM models are the solar metallicity ones adopted also in Fig. 5.

possibility to use independent sets of model atmosphere would be very helpful.

4.2. Stellar systems

Since long time, the comparison between suitable model predictions such as isochrones and luminosity functions, and observed CMDs, has been the best tool for deriving the main properties of any given, resolved stellar systems.

When applied to galactic stellar clusters as both open and GGCs, this approach allows to derive their age and distance as well as - on a more general ground - to investigate the mechanism(s) of formation of the Galaxy. In the same time, the comparison of empirical data with various stellar models computed by adopting different physical assumptions, allows to discriminate among the various physical scenarios.

In Fig. 7, we show the comparison between recent data for the open cluster M67 (Yadav et al. 2008) and various sets of isochrones. In the case of M67, the mass evolving at the Turn Off is equal to $\sim 1.2 M_{\odot}$; i.e., it is in the mass interval where the amount of convective core overshooting during the central H-burning stage, is expected to decrease with mass. Therefore, the cluster M67 is crucial for determining the efficiency of overshooting in stars whose mass is large enough to have a convective core but not so large to allow the presence of a quite extended convective core. From this kind of comparison between theory and observations is possible to investigate this still unsettled issue.

In this context, double-lined, detached eclipsing binary systems represent also a formidable tool to provide fundamental stellar parameters, first of all masses and radii. Such basic observables, when known at the 1-2% level of accuracy and accompanied by accurate determination of effective temperatures and metallicities, represent a formidable test for current stellar models. In order to put firmer constraints on the theoretical background is really important to perform the comparison between empirical data and observations by using

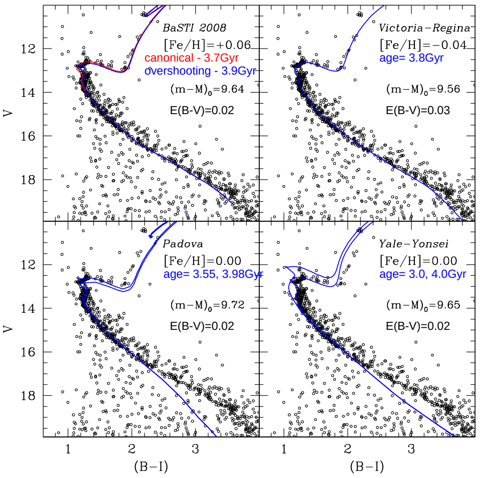

Fig. 7. Comparison of empirical data for the open cluster M67 with theoretical isochrones from independent libraries of stellar models (see the text for more details). The fit between theory and observations has been performed by adopting the labeled values for the true distance modulus and reddening.

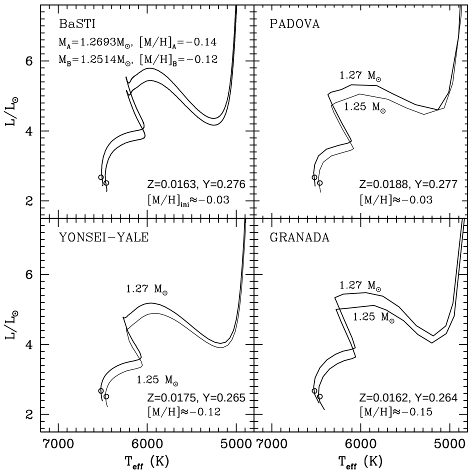

Fig. 8. Comparison of evolutionary tracks accounting for convective core overshooting, as provided by various libraries (see the text for more details), with the observed parameters of the binary V505 Per (open circles) (from Tomasella et al. 2008). For the evolutionary tracks, the adopted values of the metallicity, Helium content and total mass are labeled.

as many as possible independent sets of models. In Fig. 8, we show this kind of comparison for the binary system V505 Per.

5. Why stellar evolution ‘in’ the Virtual Observatory?

One of the main aim of the Virtual Observatory Project is to allow an easy access to various databases of observational data. On the basis of the previous discussion, it appears clear that the possibility to have an easy access to various theoretical models would be extremely useful for both people working with observations and those researchers involved in the model computations. This notwithstanding, this possibility has been, so far, limited to the free initiative of few researchers which have been the effort of making their own models publicly available, and in any case this effort does not satisfy all the required needs (as completeness, accuracy, clear description of the stored data models, etc.). Therefore, the Virtual Observatory appears as the perfect ‘environment’ for making available to the whole scientific community the results of stellar model computations.

In fact, the Virtual Observatory would be of great help in supporting interoperability between various theory resources, such as stellar models, EOS, opacity, model atmospheres computations. In the meantime, it would make easier the exchange of data between observers and theorists.

Although, the need to achieve this result is clear, very few initiatives have been done so far. In addition, the implementation of stellar model predictions in the framework of the Virtual Observatory has to address a number of still unsettled issues such as:

- Standardization of the outputs and data description;
- Clear ‘rules’/procedures for defining the ownership/credits;
- To make quite easy the updating of the model data sets;
- How to identify univocally the models;
- Quality control on the data models included in the Virtual Observatory.

A big advantage that should be provided by the inclusion of data models in the Virtual Observatory framework, is the possibility to develop - or use already existing - interfaces with tools allowing a quick look and/or the analysis of the retrieved data, and to check the accuracy of the models on template objects (stellar clusters, binary systems, etc.).

5.1. Our experience: the BaSTI project

This project corresponds to the second step inside of Italian Theoretical Virtual Observatory (ITVO) project (Pasian et al. 2006), whose first step consisted of archiving and publishing the data of many cosmological simulations (Manzato et al. 2007), to offer the scientific community the possibility of reusing a large archive of stellar model computations. As very long central processing unit (CPU) time was required to obtain these stellar simulations, it was decided to insert other simulation data, like theoretical stellar data, in the Virtual Observatory (Hanisch & Quinn 2003) standards as part of VO-Data Centre Alliance (DCA) WP4[1] and WP5[2] European asset and the ITVO Italian project.

In consideration of the covered wide range of stellar masses and chemical compositions, as well as of choices about important parameters such as mass loss and core convective overshooting efficiency, the Bag of Stellar Tracks and Isochrones (BaSTI) database (DB) (see Pietrinferni et al. 2004, 2006; Cordier et al. 2007, Percival et al. 2008) represents a fundamental tool to investigate the properties of stellar populations in both galactic and extragalactic systems.

The DB is structured to archive all the parameters regarding a stellar model simulation, starting from the initial chemical composition to their proprieties such as type of model, photometric system, heavy element distribution, mass loss, and even type of scenario[3], 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 many sets 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 the Frascati RAphson Newton Evolutionary Code (FRANEC) evolutionary code (see Pietrinferni et al. 2004 and references therein). So the new web portal provides users with the opportunity of downloading a single tar file within stellar tracks and/or isochrones of interest. We assigned a plus value to these data, thus developing a structure: archive + DB + Web portal (for a detailed discussion on this issue we refer to Manzato et al. 2008).

All files are stored in two different formats: ASCII and VOTable format. So any user can open them with, for instance, the TOPCAT VO tool to easily create a plot of the selected physical quantities.

6. Conclusions

Stellar evolutionary models represent fundamental ingredients for tackling with many important astrophysical problems. Therefore, it is extremely important to allow an easy and direct access to the already existing model predictions archives.

This requirement could be easily achieved by including these theoretical data inside the Virtual Observatory. Some efforts in this direction have been done but a lot of work has still to be performed. In any case, the whole international scientific community would recognize the importance and benefits that would result by the extension of the Virtual Observatory - initially devised for managing with observational data only - to theory resources.

The experience we made, in making our archive of stellar models (BaSTI) VO compliant, demonstrates that this result can be achieved but, in the same time, that is fun-

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[1] http://cds.u-strasbg.fr/twikiDCA/bin/view/EuroVODCA/WP4Theory

[2] http://cds.u-strasbg.fr/twikiDCA/bin/view/EuroVODCA/WP5Grid

[3] In this context, with 'scenario' we refer to the fact that the stellar models are computed under various assumptions about the efficiency of non-canonical physical processes such as core convective overshooting, atomic diffusion, and rotation.

damental to realize a concerted effort among the researchers computing theoretical models and those which have the necessary expertise and capabilities for managing with huge model archives and developing the requested tools and interfaces.

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