A&A 500, 457–458 (2009)
DOI: 10.1051/0004-6361/200912194

Astronomy & Astrophysics
Special issue

COMMENTARY ON: BERTELLI G., BRESSAN A., CHIOSI C., ET AL., 1994, A&AS, 106, 275;
GIRARDI L., BRESSAN A., BERTELLI G., CHIOSI C., 2000, A&A, 141, 371

The stellar clocks of galaxies

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The paper by Bertelli et al. presents isochrones for a wide range of ages and metallicities and is part of the series of very fine papers published by the Padova group in stellar physics. The high number of citations that the present paper obtained (and still continues to accumulate today) reflects the continuous effort by this very successful group for many years. In that respect it is interesting to mention that a second paper of the same group (Girardi 2000) is also among the 40 most cited papers published by A&A (see the editorial by Claude Bertout in the present special issue).

A part of the success of this paper relies on isochrones being one of the few tools available for estimating ages in the Universe, used by a broad community of researchers addressing questions going from measuring the lifetimes of HII regions, to studying star formation history in galaxies, passing through estimating the ages of stars hosting planets.

Let us recall that there are essentially three methods of estimating ages in the Universe, those based on 1) radioactivity; 2) on stellar evolutionary timescales; 3) on the global evolution of our expanding universe. They each have their own domains of application: radioactivity can only be applied to systems for which it is possible to measure isotopic ratios involving unstable[1] and stable nuclei . This method gives the best estimate of the solar age, which is $4.57 \pm 0.02 \times 10^9$ yr (see e.g. Bahcall 1995). Observational cosmology provides a value for the time that has elapsed since the Big Bang through observations of the rate of expansion of the Universe and estimates of the cosmic density of mass and energy. According to the WMAP results, the age of the Universe is $13.69 \pm 0.13 \times 10^9$ yr (Hinshaw 2008). Stellar lifetimes allow the age of stellar systems to be measured, such as associations, open and globular clusters, and starbursts, and they span a very wide range of timescales going from a few million years to more than ten billion years. They are actually the main tool for exploring the evolution of galaxies, since stars drive their photometric and chemical evolution and have a strong impact on the dynamical properties of their interstellar medium, hence on the star formation processes. A lot of the physics of galaxies reside in their stars!

The understanding of how stars form and evolve relies on a very rich set of physical processes involving the four fundamental interactions of physics. Much of the progress in this field was made in the 20th century, and more important steps await us. Some of them will be provided by new techniques in observing stars, asteroseismology and interferometry, and by detections of neutrinos and gravitational waves. Others will come from improvements in the numerical models and the modeling of physical processes. The Padova group has contributed a lot toward enriching and developing the research in stellar evolution. The papers by Bertelli et al. and the one by Girardi (2000) are wonderful examples of results obtained following long and continuous efforts to update the physical ingredients of the stellar models and to make them more reliable and efficient in reproducing real stars. The effort of the Padova group is still pursued today (see their web page http://pleiadi.pd.astro.it/ and references therein).

The physical ingredients of stellar models can be classified into four categories. There are first the ingredients such as the nuclear reaction rates, the neutrino emission rates, the opacities, the equation of state, obtained through laboratory experiment and theoretical considerations. The builders of stellar models have no real choice here but to use the best ingredients available at the time of the computations. It may happen that different estimates for the same quantity are available and that no strong argument exists that can be used to retain the correct one. For instance, the rate of $^{12}C(\alpha,\gamma)^{16}O$ was ambiguous at the time the isochrones were computed by Bertelli et al. (and still is today!). Typically these authors used the rate of Caughlan (1988), which is lower than the rate of Caughlan (1985) adopted for instance in the models of Schaller (1992)[2]. Today another uncertainty arises from the solar abundances (see e.g. Asplund 2004)[3].

The second category of stellar ingredients are those that are deduced from "observations" of stars, so-called because in astrophysics they nearly always involve theoretical models. This is the case for instance for the estimates of the mass loss rates by stellar winds. These rates are deduced from the shape of

[1] Or stable nuclei resulting from radioactive decays.

[2] The rate of this reaction has important consequences for the way the advanced evolutionary phases occur, for the nature of the stellar remnant, and for nucleosynthesis.

[3] Let us note that solar abundances are important for computing not only solar models, but also stellar models of other masses and other compositions, since some factors as the mixing length or the solar helium abundance are calibrated on solar models.

spectroscopic lines, so their measures imply a model for the stellar wind and atmosphere.

The third category of input ingredients are those determined from observed features of the Sun or of stars. In that respect they present little difference with the ingredients of the second category except that they may be determined by the builders of the stellar models themselves. In this category quantities enter such as the mixing length scale, the solar helium abundance, the degree of overshooting, or the efficiency of rotational mixing. These quantities can all be calibrated on well-observed features.

Finally the fourth category consists in the choice of the physical processes included in the models. Indeed, grids of models may differ not only by differences in the physical ingredients as described above, but also by the inclusion (or not) of various physical processes like semiconvection or mass loss and the effects of rotation or of magnetic fields.

Looking at the above list of ingredients, one realizes that obtaining reliable isochrones is hardly an easy process. At the time of the publication of the paper by Bertelli et al., the main processes being discussed were the degree of overshooting and the effects of mass loss for the most massive stars. Also, two years before the publication of this paper, an important change occurred in the field of the opacity determinations. Rogers & Iglesias (1992a,b) had found that the opacity should be enhanced by a factor between 2–3 in stellar envelope conditions. The new enhanced opacities led to understanding the cause for the variability of the β Cephei stars, a κ-mechanism by ion absorption peaked at a temperature around 2×10^5 K.

Interestingly we see that stars are at the frontier of multi-scale processes: large-scale forces like gravity, as well as short range ones, such as nuclear interactions, are key features governing their evolution. The same is true along the time dimension. Stellar evolution involves processes with typical timescales less than a second, like the core collapse at the end of the evolution of massive stars and durations longer than the age of the Universe, like the H-burning lifetimes of very low mass stars! This makes this domain one of the richest because of the variety of the physical processes involved.

Another important aspect participating in the success of the paper by Bertelli et al. is the very broad ranges of ages and metallicities that these computations cover. The published data provide a set of homogeneously computed evolutionary tracks and isochrones spanning the whole of cosmic history. The homogeneity of the physics involved in computing the stellar models is a key factor in studying the relative effects of metallicity on stellar evolution and on the expected stellar populations in different environments and for providing reliable relative ages. Homogeneous stellar model databases are also necessary input ingredients for population synthesis models and for setting the timescales of photometric and chemical evolution models of galaxies. Another important factor that contributes to making this paper very useful is that it provides not only the shapes of the isochrones in the theoretical plane $\lg L/L_\odot$ versus $\lg T_{\rm eff}$ but also in observed color-magnitude diagrams. This last aspect underlines the importance of the calibration relations used for translating effective temperatures into colors, among other features. They are the keys that allow theory to be compared with observations and result from the complex physics of the interactions between matter and electromagnetic waves. The paper also gives the luminosity function and integrated colors of single-star population models.

As a conclusion to this commentary we can try to answer that question. Do we still need to compute extended grids of stellar models or can we now rely on past results to provide accurate descriptions of how stars evolve? Of course, we might say that the improvements in stellar models are nearly a never-ending process. Indeed, refinements in the opacities, nuclear reactions rates, equation of states, neutrinos emissions, descriptions of such hydrodynamic processes as convection, stellar winds, instabilities induced by rotation, effects of magnetic fields, mass transfer/loss in closed binary systems, and so on, will continue for a very long time. But such an answer is not very satisfactory because it is too general an assessment. Instead we may wonder whether we can still expect some significant changes in our view of how stars evolve or whether we may only expect some modest corrections, interesting per se, but not implying really new views. We have probably acquired a good knowledge of the overall picture of the evolution of stars. However, big challenges still need to be overcome; for instance, how did the first stellar generations evolve and affect the early phases of the evolution of galaxies? How do massive stars form? How do massive stars explode? What are the progenitors of the gamma ray bursts (GRB)? What are the progenitors of the type Ia supernovae? What are the effects of stellar winds and supernova explosions on the gas in a galaxy? Which are the progenitors of the black holes? Do stars participate in the formation/evolution of intermediate and supermassive black holes? Finally, let us mention that still more precise models will allow the stars to be used as laboratories of physics. Subjects can be addressed, such as turbulence and equation of states in extreme conditions, or more exotic topics treated, such as the possible effects of WIMPS annihilations in stars or the effects of variations during the cosmic history of the fundamental constants. But of course for reaching the stage where stars may be used to reveal new physics (as done by solar physics for the neutrinos), much more precise models have to be obtained. The Padova group plays a very important role in that context, and their most cited papers (Bertelli et al. 1994; Girardi 2000) are important stages in the long road towards those fascinating aims.

References

Asplund, M., Grevesse, N., Sauval, A. J., Allende Prieto, C., & Kiselman, D. 2004, A&A, 417, 751

Bahcall, J. N., Pinsonneault, M. H., & Wasserburg, G. J. 1995, Rev. Mod. Phys., 67, 781

Bertelli, G., Bressan, A., Chiosi, C., et al. 1994, A&AS, 106, 275

Caughlan, G. R., & Fowler, W. A. 1988, At. Data Nucl. Data Tables, 40, 283

Caughlan, G. R., Fowler, W. A., Harris, M. J., & Zimmermann, B. A. 1985, At. Data Nucl. Data Tables, 32, 197

Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371

Hinshaw, G., Weiland, J. L., Hill, R. S., et al. 2008, ApJS, 180, 225

Rogers, F. J., & Iglesias, C. A. 1992a, ApJS, 79, 507

Rogers, F. J., & Iglesias, C. A. 1992b, ApJ, 401, 361

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Simon, N. R. 1982, ApJ, 260, L87