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A golden age for stellar evolution and evolutionary grids[⋆]

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Model grids represent the basis for an enormous number of astrophysical studies and are a valuable help in many fields. The paper "New grids of stellar models from 0.8 to 120 $M_\odot$ at $Z = 0.020$ and $Z = 0.001$", by Schaller, Schaerer, Meynet, & Maeder, has had a strong impact reaching by today (April 14 2009) a total of 1900 citations in the (incomplete) ADS Citation database. What are the reasons for such an impact? I comment first on the reasons why these particular grids of stellar models were computed and made available to the community, and then briefly discuss some problems with the physical inputs of these models and annotate some of their applications in the course of years.

Extended grids of stellar models that follow the evolution of the main phases for stars with different masses, possibly until their final stage as either a supernova or white dwarf for different initial chemical compositions, are one of the most useful tools in modern astrophysics, together with their most common derivation, the isochrone tables. They are used in the field of stellar astrophysics as a term of reference either in the study of individual binaries or in the study of the stellar populations of individual clusters. In addition, they are the most useful in studies of galactic and extra-galactic astrophysics to achieve models of population synthesis and to assign ages to stellar systems in the Universe. The nucleosynthesis resulting from stellar evolution and the yields of the matter expelled by stars of different mass at different times, either in winds or in supernova explosions, are the basic ingredients for studying the chemical evolution of galaxies. Computation of a grid is a necessary step in linking stellar physics to the study of the structure and evolution of galaxies.

By commenting on the work by Schaller et al., we touch on some of the problems of stellar models concerning their "micro-physics" inputs, that is, the opacities, equation of state, nuclear reaction rates, neutrino losses, and whatever else constitutes a physical input in the models that can be (at least formally) derived on the basis of first principles and that is generally made available to the stellar community by researchers dedicated to their specific computation. Models of stellar structure, however, need a proper understanding of other inputs, which we can call "macro-physics" that are not known from first principles (e.g. mass loss, rotation, convection). The best known of these problems – especially for model grids, which require a feasible and flexible model – is how we deal with super-adiabatic convection and what the "extra-mixing" is beyond the formal borders of convective regions, generally called overshooting. In the following we show that the Schaller et al. work had a huge impact for two reasons: first of all, it was the first release of tracks into which a very important "micro–physics" update was introduced. In addition, the "macro-physics" inputs were carefully dealt with and calibrated on the available observational data sets, in order to provide a coherent framework for interpretation.

This paper and all the works preceding and following it by the Geneva group, as well as by other groups in the same years, are the products of the significant knowledge acquired by researchers who, step by step starting with the study of the input physics, built up their own models in the course of years of work and efforts toward deep understanding. Nowadays, stellar evolution and the computation of stellar models are not only a research field in their own right, but they have also found wide application fields in fields such as population synthesis and galactic evolution. In some cases, stellar evolutionary codes are therefore used by non-specialists, who may not necessarily have full understanding of all the model's intricacies as gained from years of studying stellar evolution. There is therefore a risk that some model properties may be overinterpreted, leading to the possibility of inaccurate interpretation of the observational data. For this reason, but also – and mainly – because many of the main physical ingredients of stellar structure remain to be explored in detail, studying the evolution of stars for its own sake remains an essential task today.

In the year in which these models appeared, 1992, most of the basic problems of stellar evolution (nuclear fusion phases of low- and high-mass stars, treatment of convection) had already been fully debated. Even for the massive stars, for which the treatment of core overshooting and mass loss pose formidable problems – not yet fully solved today – a review by Chiosi & Maeder (1986) had already been published in the Annual Review of Astronomy and Astrophysics. In the preceding years, however, a very important improvement in the basic microphysics of stellar models had occurred. In fact, for more than 25 years, the opacity tables used in the stellar models had been those computed at Los Alamos National laboratories in the 1960s and 1970s (e.g. Cox & Tabor 1976, online). These opacities were successful in explaining the main properties of stellar evolution, but were unable to explain some stellar variability properties, summarized in the abstract of a famous paper by Simon (1982): "it is shown that increasing the opacity due to heavy elements by a factor of 2–3 leads to classical Cepheid models which reproduce observed period ratios at evolutionary masses and luminosities. Thus the mass anomalies are removed in both the double-mode and bump Cepheid regimes. The proposed increases may also serve to energize β Cephei variables, thus solv-

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ing yet another important problem in the theory of pulsating stars. It is argued that opacity changes of this order are not implausible, and further work in this important area is urged".

The required enhancement by a factor ∼3 over the Los Alamos opacities was much greater than the estimate of the error in those computations. In the meantime, supercomputers had become available, so a series of physical approximations in the opacity computation were no longer necessary. At Livermore Laboratories, a group of researchers began a new project for opacities of astrophysical plasmas, the OPAL project, that actually resulted in significantly higher opacities than the standard ones for densities and temperatures that are important to Cepheid models. The opacity "bump" mainly stemmed from the M-shell transition in the (very small number of) iron ions, and a large part of the difference came from the improved treatment of the atomic physics (Iglesias et al. 1987). The equation of state (EOS), on which the opacity computation was based, was obtained in fact in the "physical picture", explicitly considering all the long-ranged Coulomb interactions between electrons and ions of the plasma and eliminating the ad hoc cutoff procedures necessary in the free-energy minimization methods to avoid the divergence of the internal partition function (Rogers & Iglesias 1992a,b). In addition, the new opacities produced better agreement of the computed solar oscillations with the frequency spectrum of the Sun and better agreement of the location of main sequence massive models both in the Hertzsprung Russell diagram and in the mass luminosity plane (Stothers & Chin 1991).

Georges Meynet reports that André Maeder learned about these new OPAL opacities at the International Astronomical Union General Assembly held in Buenos Aires, and wrote him immediately about the need to compute a new grid of models using these opacity tables. The project of the Schaller et al. paper was then launched. Schaller did his Ph.D. in the group by André Maeder, but later on he was incorporated into the computer team at Geneva University and left research in astronomy.

These were the first complete model grids computed with the new OPAL opacities, for two different metallicities. A more technical feature made them so popular: there were only 51 points describing each track, and these were chosen so that tracks for masses not on the grid could be easily constructed by interpolation. For instance, point 13 in the tables always corresponds to the end of core hydrogen burning.

Although the model grid extends down to 0.8 $M_{\odot}$, the most important part of it is the one concerning high-mass stars. Several inputs of these stellar models do not (yet) come from first principles so must be parametrized. Indeed, one of the merits of this research has been the careful adjustment of the parameters on the observational constraints. Let us then see how these inputs were dealt with. Convection adopts the mixing-length theory framework. The ratio α between the mixing length and the pressure scale height $H_{\rm p}$ was chosen to be 1.6, by fixing the solar radius and the $T_{\rm eff}$ of red giants. For stars more massive than the Sun with having a convective core, the amount of core "overshooting" needed to achieve the observationally determined main sequence width and plausible fits for the precise data of the eclipsing binaries of intermediate mass is also important. An interesting effect of improving of the micro–physics is the following: the higher opacities reduce the required extension of core overshooting (Stothers & Chin 1991) from ∼0.3 $H_{\rm p}$ in models adopting the previous opacity tables to the 0.2 $H_{\rm p}$ adopted in these grids.

Another very important macro-physics input is the mass-loss rate in the different evolutionary phases. Schaller et al. adopt de Jager et al. (1988) for the whole HR diagram (but they use a different formulation for the Wolf Rayet phase). They also use a mild scaling of the mass loss with metallicity, of the form $\dot{M} \propto Z^{0.5}$. Although based on an observational parametrization, these mass loss rates were too low to explain, for instance, the presence of some Wolf Rayet stars in the range of (low) luminosities $\log L/L_{\odot} \sim 4.5$–5, so Meynet et al. (1994) increased it by a factor two in the final (the fifth) paper of this series of model grids. We notice that these same authors then began the computation of new grids including the effect of rotation, which enhances the mass loss, so that lower mass-loss rates may be needed at zero rotational velocity (for a review of the problems, see Maeder & Meynet 2000, online). This is another point where improvement in a different macro-physics input (rotation) helps to reach better agreement with the observational parametrization of another macro-physics input (mass loss). It must now be seen what varies in the models with the recent updates of the theoretical – empirical mass-loss rates by Vink et al. (2000) for O and B stars, by van Loon et al. (2005) for dust-enshrouded red supergiants and oxygen-rich asymptotic giant branch stars, and by Nugis & Lamers (2000) for Wolf Rayet stars.

Among the numerous applications of the Schaller et al. model grids to population synthesis, I remember their use (along with complementary model grids) as input in the widely used code for synthetic models for galaxies with active star formation (Starburst99 Leitherer et al. 1999, online). Claus Leitherer, however, plans to substitute them with the complete model grids without and with rotation of the Geneva group, when these are fully released. Leitherer also points out that the Geneva models are unique in their treatment of the stellar winds of hot, massive stars. They try to account for the optical depth effects of these winds and to correct the colors and effective temperatures of the most massive stars. This leads to a more appropriate comparison with observations.

For what concerns its use in chemical evolution models, this work has mostly been used to predict the evolutionary times, while the Woosley & Weaver (1995) grids (containing the explosive hydrodynamics and nucleosynthesis of isotopes up to zinc for several metallicities and masses from 11 to 40 $M_{\odot}$) have been the most popular for predicting supernova yields. Several other extended tables of yields for explosive nucleosynthesis are available today (e.g. Limongi & Chieffi 2006, online).

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