EVOLUTIONARY MODELS AND AGE DETERMINATIONS OF GALACTIC CLUSTERS

OSCAR STRANIERO[1], ALESSANDRO CHIEFFI[2], MARCO LIMONGI[3]

[1] *Osservatorio Astronomico di Collurania, Teramo, Italy*
[2] *Istituto di Astrofisica Spaziale CNR, Frascati, Italy*
[3] *Osservatorio Astronomico di Roma, Monteporzio, Italy*

ABSTRACT. The stellar clock, coupled with photometric and spectroscopic observations of galactic clusters, is widely used in order to understand the history as well as the present structure of our galaxy. The reliablitity of the basic ingredient, namely the stellar models, is a necessary requirement for this task. However, since the laboratory conditions are usually far from those of a typical stellar environment, the physics of the stellar interiors is largely investigated by means of pure theory, with few experimental probes. The current status of stellar evolution theory is reviewed in conjunction with the problems of dating the various stellar populations of our galaxy.

1. Introduction

Reliable stellar models are the fundamental tool needed to measure the lifetime of various stellar systems, from the simplest star clusters to the more complex galaxies. Our understanding of the chronology of the formation and evolution of our galaxy, from the halo to the disk, is then practically based on the comparison of the theoretical isochrones to the observed color magnitude diagram of globular and open clusters. A qualitative idea of the ranking in age of the different components of the Milky Way may be obtained by noting that the absolute turnoff luminosities of these clusters roughly range between 4 and -6 mag (Sandage, 1957), which correspond to stellar masses from 0.8 up to more then 20 $M_{\odot}$. Then it was easily recognized that the ages of these stellar systems roughly range from more than 10 Gyr up to few Myr. However, a more quantitative scenario of the galaxy formation still remains uncertain. Some longstanding problems are still open: the age of the oldest globular cluster, the age spread among the globular clusters, the age of the oldest open cluster, the age of the RGB phase transition, just to recall some of them. The development of new technology in astronomy make now available high quality photometric and spectroscopic data of galactic clusters. Thus, a critical analisys of the accuracy of the current theoretical scenario can't be further delayed. In these years the continuous improvement of the input physics (eos, opacity, reaction rates and the like) induced a costant revision of the stellar models. In the following we revise the present status of this research.

2. Low mass stars: the solar interior

Helioseismology as well as solar neutrinos detection provide us a unique opportunity of *observing* a stellar interior. It is therefore clear that the Sun plays a really pivoting role in order to test the stellar evolutionary models. On the other hand, the structure of the Sun is very similar to those of the main sequence stars of a galactic Globular Cluster near the turnoff. In fact, like in the Sun, in these stars i) a radiative core is surrounded by a convective envelope including a few percent of the total mass and ii) the main source of nuclear energy is provided by the pp chain. Moreover, in GC MS stars, the runs of temperature and density are remarkably similar to those existing in the solar interior, so that the relevant input physics (equation of state, opacity and the like) must be the same.

Classical stellar models are obtained by solving the equations of a spherical, non rotating, self gravitating mass of gas in thermal and hydrostatic equilibrium. In some cases the overall validity of these hypothesis can be trivially proved. For example, it can be easily shown that only a very high level of hydrostatic equilibrium may keep almost constant both the radius and the luminosity of the Sun for some Gyr. In some other, like for the absence of a sizable internal angular momentum, only weak evidences can be reported. In such a case, looking forward to an extension of the seismology to other stellar object, the possibility offered by helioseismology to look at the solar interior is really unique. In fact, helioseismology provides us accurate values of the depth of the convective external layers and the surface amount of He in the Sun (see e.g. Dziembowsky et al. 1995). In addition it can be used to bound the internal temperature, the density and the molecular weight (Antia & Chitre, 1995). Recently, thanks to the large network projects, new data concerning the deep rotation are becoming available (see Chaplin et al., 1996, and references therein).

In the last five years a growing amount of papers have demonstrated that solar models without microscopic diffusion cannot account for some feature of the seismic Sun (Bahcall & Pinsonneault, 1992 and 1995; Guzik & Cox 1992 and 1993; Lydon, Fox & Sofia 1993; Guenther 1994; Proffitt 1994; Demarque, Guenther and Pinsonneault 1995; Richard et al. 1996; Babu et al. 1996; Guenther, Kim & Demarque 1996; Straniero, Chieffi & Limongi 1997). Diffusion is usually neglected in the computation of the stellar models due to the very large time scale of this phenomenon. Nevertheless it could play a non negligible role in evaluating the age of the oldest clusters of our galaxy (i.e. the Globular Clusters and perhaps the oldest Open Clusters). Thus the efficiency of microscopic diffusion in low mass stars, as well as the accuracy of the other input physics, may be checked by comparing the solar models with the helioseismic data (Straniero, Chieffi & Limongi 1997).

In figure 1 we illustrate the internal distribution of H, He, C, N, O and Fe in our best solar models with and without diffusion. Let us summarize the main results of this investigation of the solar interior. By comparing standard solar models with helioseismic data, we found that it is now possible to obtain a reasonable reproduction of the internal structure of the present Sun if:

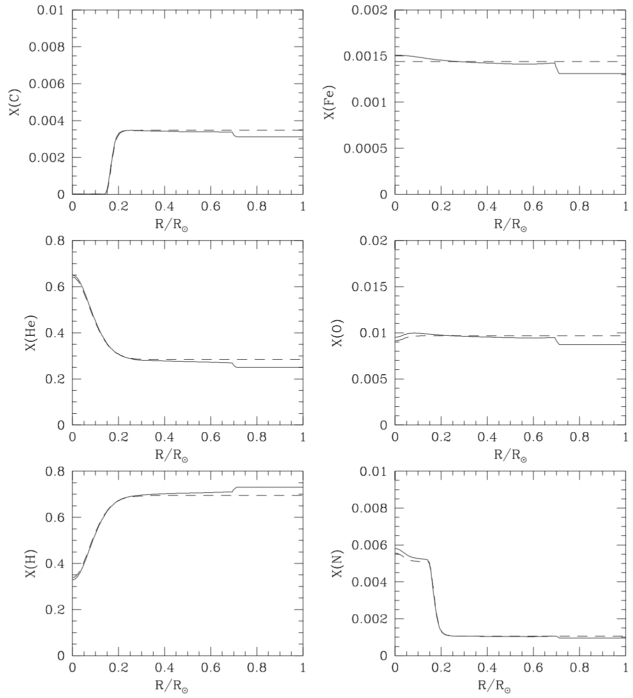

Fig. 1. Radial distributions of H, He, C, N, O and Fe in our best Standard Solar Models with diffusion (solid lines) and without diffusion (dashed lines).

a) Coulomb corrections are applied to the EOS
b) Microscopic diffusion is taken into account.
c) Internal rotation is neglected.

By applying this physics to the low mass stellar models we got younger Globular Cluster ages. As an example in figure 2 we report our latest theoretical calibration of the fundamental age indicator for the Globular Clusters, namely the turnoff luminosity. Solid lines refer to models which include Coulomb correction but without diffusion, whereas dotted lines include diffusion.

Then by means of this age indicator, we found that the Globular Cluster Ages must be systematically reduced of about 10 % with respect to the previous study. As an example, in figure 3 we show the best fit of M68, one of the most metal poor cluster in the galaxy, with isochrones computed with microscopic diffusion. With this new models we obtain an age of 13 Gyr, whereas in the past we got 14 Gyr (Salaris, Chieffi & Straniero 1993).

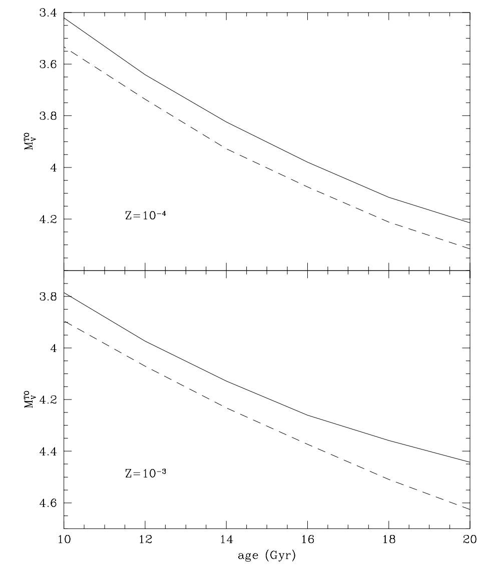

Fig. 2. The turnoff luminosity-age relations: the solid line represents the standard relation (i.e. without diffusion), while the dashed line is the diffusion relation.

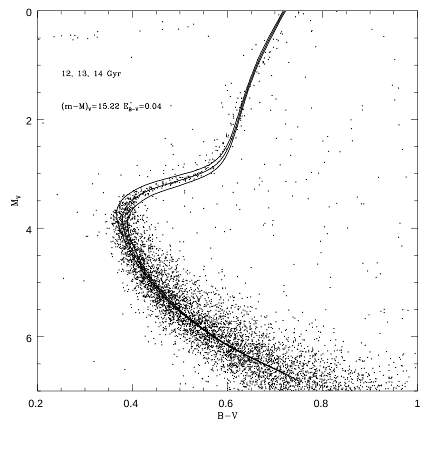

Fig. 3. Comparison of the diffusion isochrones to the observed color magnitude diagram of M68.

3. Intermediate mass stars and convection in stellar interior.

The most uncertain ingredient in stellar models with mass larger then 1.5 $M_{\odot}$ which affects their evolutionary time $M_{\odot}$ concerns the treatment of convection. It as been early recognized that the mixing of material induced by convection significantly alters the stellar lifetime and in turn it could modify the age estimations.

Instabilities against turbulent convection are usually handled by means of a thermodynamical criterion (namely the Schwartzchild criterion for a chemically homogeneous fluid). It is based on the evaluation of the expected gradient of temperature induced by the radiative transport of energy: when the required gradient is too high, the radiative flux cannot account for the whole energy transport and convection is settled on.

A first problem consists in the accuracy of the thermodynamical theory used to compute the temperature gradient. In fact, any improvement of the micro-physics (eos, opacity, cross section and the like) might imply a variation of the estimated temperature gradient and in turn it could modify the location of the borders of the convective regions with sizable consequences on the resulting stellar lifetime.

A second question concerns the possibility that the convective motion is not drastically inhibited in a stable region located just outside the convective core. In fact, although out of the Schwartzchild border a moving elements of matter is subject to a strong deceleration, it might be possible that a non zero velocity is maintained for a certain path before it will be stopped. In such a case this "mechanical overshoot" might induce a mixing of material in a radiatively stable region and might also contribute to the energy transport. Unfortunately the available convection theory is still inadequate for a reliable description of this phenomenon (see Renzini 1988 for a critical discussion on this argument), so that the evaluation of the degree of both matter and energy transport out of the unstable regions must be obtained by comparing the result of parameterized models with the measurements of some observable key quantities. Let us emphasize that, since in order to solve the stellar structure equations we must know at least the chemical modifications induced by the overshooting and the resulting temperature gradient, it seem improbable that just one free parameter (as for example the size of the overshooting zone) is sufficient to describe such a complex phenomenology. In any case, the calibration of this (these) free parameter(s) is necessarily model dependent. In fact, since the assumed micro-physics affects the size of the unstable regions, the calibration of the overshooting depends on these assumptions. This implies that when new opacity or new equation of state are adopted one might get different evaluations of the amount of overshooting. For example the larger is the opacity the larger is the convective region and in turn the lower is the required amount of overshooting. As it is well known the opacity are likely underestimated, rather then overestimated. For this reason, if at the beginning of the eighty Becker & Methews (1983) claimed a relatively strong overshoot to describe the stellar population of young Globular Clusters in the Magellanic Clouds, the latest attempts to derive the size of the convective core overshoot in an H-burning stars indicates that, if it's present, it should be "mild" (see e.g. Sthothers & Chin ,1992; Castellani, Chieffi & Straniero 1992; Demarque et al. 1994, Mermilliod et al. 1994; Schröder et al. 1997). In particular these studies generally found that the best reproduction of the various indicators of the convective core size is

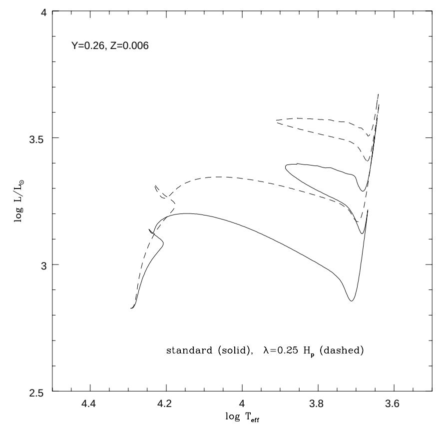

Fig. 4. Evolutionary traks of a 5 $M_\odot$: the solid line represents canonical models, whereas the dashed line was obtained by assuming an overshoot of 0.25 H_p.

obtained with models including an overshoot roughly confined in between 0 and 0.3 (in units of pressure scale height).

In figure 4 we show a comparison between an evolutionary track of 5 $M_\odot$ computed without any extra-mixing (solid line), and a similar one obtained by assuming an overshoot of 0.25 H_p. When convective core overshoot is taken into account, a larger amount of fuel is available in the burning region of the star. However, since the larger is the mixed region the brighter is the star, the additional fuel is more rapidly burned, so that the effect of the core overshoot on the H-burning lifetime is partially counterbalanced. This expectation is confirmed by figure 5 where we compare our canonical H-burning lifetime with the one derived by Bressan et al. (1993). We recall that the latter models were computed by assuming a mild overshoot.

For this reason, although the evolutionary track for a given stellar mass appears highly modified even by a moderate core overshoot, the effect of this assumption on the isochrones is definitely lower. This is illustrated in figure 6 where we compare our canonical isochrones with the moderate overshoot ishocrones of Bertelli et al. 1994.

The effect of the overshoot on the He-burning models is furthermore lowered by the occurrence of semiconvection. In fact, in the case of canonical models, when He is burned in C and O in the convective core, the opacity increases and a semiconvective layer develop just outside the full convective region. Thus, as a consequence of this mixing of fresh He toward the center and C/O toward the surface, the duration of the He burning increases. If a mechanical overshoot is taken into account, the semiconvective layer is hidden by the extra-mixing. Thus, in this case the amount of fuel (He) available for the central nuclear burning is similar to the one found in models without overshoot (but including semiconvection), so that the resulting lifetimes are very similar.

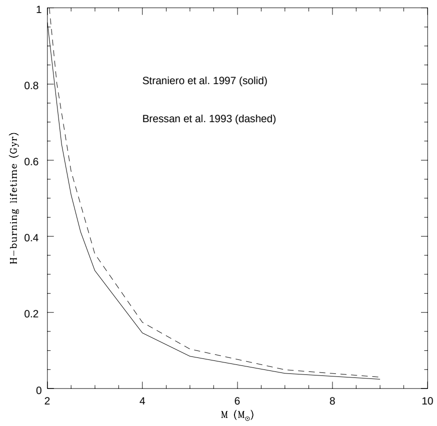

Fig. 5. H-burning lifetime versus the stellar mass.

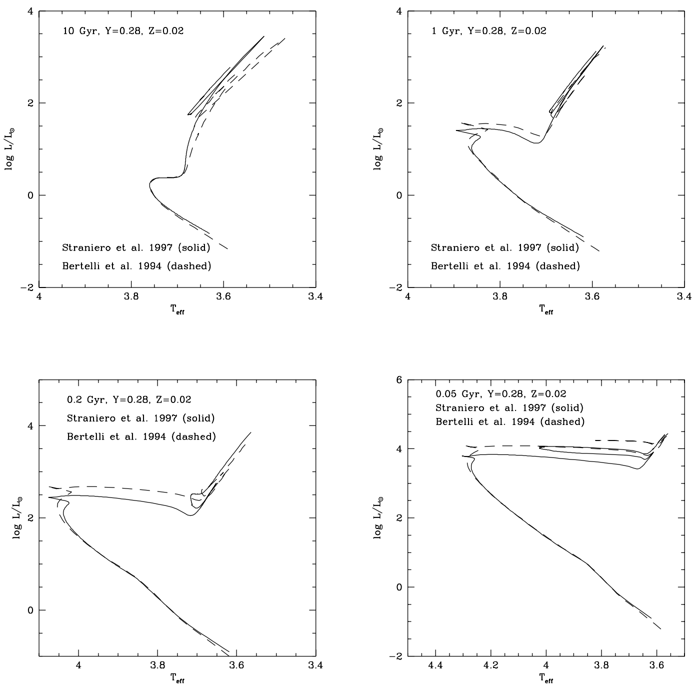

Fig. 6. Comparison of our latest isochrones (no overshoot) of solar chemical composition to those of Bertelli et al. 1994 based on models including a moderate amount of convective core overshoot.

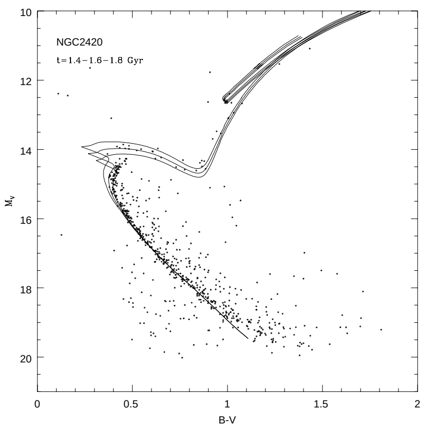

Fig. 7. Isochrones fiiting to NGC 2420.

4. A test of the evolutionary sequences

Although a detailed comparison of our stellar models with the observed properties of different stellar systems is well beyond the purpose of the present paper, let us discuss an interesting test of the evolutionary sequence. An intermediate mass star ($M \sim 5-6M_{\odot}$) end is life as a CO white dwarf (WD). Thus, if this star is a member of an old stellar system (say 1 Gyr or older), it spent most of its life as a WD so that its cooling time might be used as an age indicator for the stellar system. A search for the cutoff of the WD luminosity function has been recently performed by Von Hippel et al. (1995) by means of the HST with the Wide Field Planetary Camera 2. They were able to identify this cutoff in two old open cluster, namely NGC 2420 and NGC 2477. Then, by means of the theoretical cooling sequences computed by Wood (1994), they estimated the ages of these two clusters and concluded that they are in contrast with all the available stellar models. Owing to the existence of an accurate CCD photometry only for one of these two cluster, namely NGC 2420 (Anthony-Twarog et al 1990), we will focus our attention on this one. From the paper of Von Hippel et al. we derive an age based on the WD luminosity function cutoff of 1.5-1.6 Gyr.

In figure 7 we show a comparisons between the isochrones and the Color Magnitude diagram (CMD) of NGC 2420. According to Anthony-Twarog et al. (1990), we have assumed a metallicity of Z=0.008, which correspond to about [M/H]=- 0.4, and an E(B-V)=0.05. Then the distance modulus was derived by reproducing the clump of the He burning stars which is age independent. It results an age of 1.6 ($\pm$ 0.2) Gyr, in very good agreement with the age derived from the WD cooling sequence. A slightly larger value is obtained with isochrones which include a moderate amount of convective core overshoot. For example, Carraro & Chiosi (1994) found 2.1 Gyr while Friel (1995) reported 2.8 Gyr. However, as already noted by Demarque et al. (1994), the canonical isochrones cannot account for the distribution of stars near the turnoff of NGC 2420. In

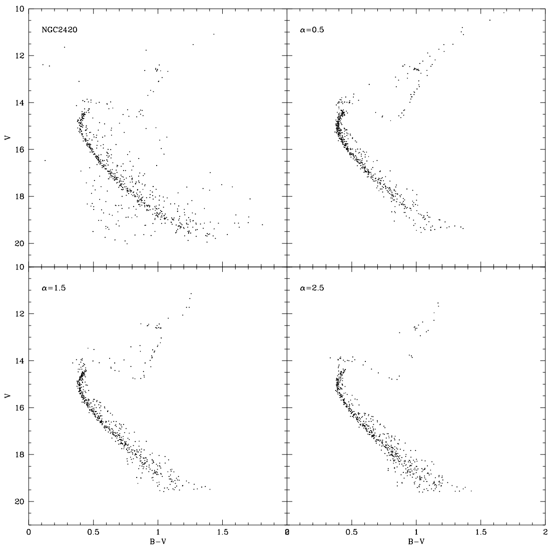

Fig. 8. True and synthetic Color Magnitude Diagrams (CMD). Upper-left panel: Observed CMD of NGC 2420. Other panels: synthetic CMDs computed under different assumptions about the exponet of the mass function.

particular the path of the isochrones just before the overall contraction appears shorter then the observed one. Demarque et al. showed that a moderate amount of convective core overshoot (namely $\lambda = 0.23 H_p$) make longer the isochrones path, but they are forced to use an age of 2.4 Gyr.

We argue that the isochrones give us a rough idea of the distribution of the stars in the CMD. A better analysis can be done by comparing observed and synthetic CMD. When a suitable mass function as well as binary stars are considered, a very good reproduction of the whole observe sequence of NGC 2420 is obtained (see figure 8). In such a case we have used an age of 1.6 Gyr which is in very good agreement with the value implied by WD luminosity function cutoff.

5. Conclusion

If the theoretical investigation of low mass stars appears well anchored to the result of helioseismology concerning the solar interior, this is not the case for intermediate mass stars. The uncertainty in the current theory of turbolent convection still affect our understanding of the disk structure and evolution. Further mesuraments of the ages of young and intermediate age clusters based on independent methods are needed in order to check the reliability of the stellar models.

References

Antia, H.M., Chitre, S.M: 1995, *Astrophys. J.* **442**, 434

Anthony-Twarog, B.J., Kaluzny, J., Shara, M.M., Twarog, B.A.: 1990 *Astron. J.* **99**, 1504

Bressan, A., Fagotto, F., Bertelli, G., Chiosi, C.: 1993, *Astron. Astrophys. Suppl. Ser.* **100**, 647

Becker, S.A., Methews, G.A.: 1983, *Astrophys. J.* **270**,, 155

Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., Nasi, E.: 1994, *Astron. Astrophys. Suppl. Ser.* **106**, 275

Babu, S., Christensen-Dalsgaard, J., Schou, J., Thompson, M.J., Tomczyk, S.: 1996, *Astrophys. J.* **460**, 164

Bahcall, J.N., Pinsonneault, M.H.: 1992, Rev. of Mod. Phys., 64, 885

Bahcall, J.N., Pinsonneault, M.H.: 1995, Rev. of Mod. Phys., 67, 781

Carraro, G., Chiosi,C.: 1994, *Astron. Astrophys.* **288**, 751

Castellani, V., Chieffi, A., Straniero, O.: 1992, *Astrophys. J. Suppl.* **78**, 517

Chaplin, W.J., Elsworth, Y., Isaak, G.R., Mcleod, C.P., Miller, B.A., New, R:. 1996, *Mon. Not. R. Astr. Soc.* **283**, L27

Demarque, P., Sarajedini, A., Guo, X-J.: *Astrophys. J.* **426**,, 125

Dziembowski, W.A., Goode, P.R., Pamyatnykh, A.A., Sienkiewicz, R.: 1995 *Astrophys. J.* **445**, 509

Friel, E.D.: 1995, *Ann. Rev. Astron. Astrophys.* **33**, 381

Guenther, D.B.: 1994, *Astrophys. J.* **422**, 400

Guenther, D.B., Kim, Y.C., Demarque, P.: 1996, *Astrophys. J.* **463**, 382

Guzik, J.A., Cox, A.N.: 1992, *Astrophys. J.* **386**, 729

Guzik, J.A., Cox, A.N.: 1993, *Astrophys. J.* **411**, 394

Lydon, T.J., Fox, P.A., Sofia, S.: 1993, *Astrophys. J.* **413**, 390

Mermilliod,J-C.,Huestamendia, G., del Rio, G.: 1994, *Astron. Astrophys. Suppl. Ser.* **106**, 419

Proffitt, C.R.: 1994, *Astrophys. J.* **425**, 849

Renzini, A.: 1988, *Astron. Astrophys.* **188**, 49

Salaris, M., Chieffi, A., Straniero, O. 1993, *Astrophys. J.* **414**, 580

Schröder, K-P., Pols, O.R., Eggleton, P.P.: 1997, *Mon. Not. R. Astr. Soc.* **285**, 696

Stothers, R.B., Chin, C-W.: 1992 *Astrophys. J.* **390**, 136

Straniero, O., Chieffi, A., Limongi, M.: 1997 *Astrophys. J.* **490**, 0

von Hippel, T., Gilmore, G., Jones, D.H.P.: 1995, *Mon. Not. R. Astr. Soc.* **273**, L39

Wood. M.A.: 1994, in IAU Coll. 147 *The equation of state in astrophysics*, G. Chabrier and E. Schatzman Cambridge Univ. Press, Cambridge, p. 612