Stellar models and Hyades: the Hipparcos test

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\textbf{ABSTRACT}

We compare theoretical stellar models for Main Sequence (MS) stars with the Hipparcos database for the Hyades cluster to give a warning against the uncritical use of available theoretical scenarios and to show how formal MS fittings can be fortuitous if not fictitious. Moreover, we find that none of the current theoretical scenarios appears able to account for an observed mismatch between theoretical predictions and observations of the coolest Hyades MS stars. Finally, we show that current theoretical models probably give too faint He burning luminosities unlike the case of less massive He burning models, with degenerate progenitors, which have been suggested to suffer the opposite discrepancy.

\textbf{Key words:} open clusters and associations:individual:Hyades, stars: evolution, stars:horizontal branch

\section{INTRODUCTION}

The prediction of cluster isochrones is one of the most popular results of stellar evolutionary theories and in the current literature the comparison of theoretical isochrones with observed CM diagrams of stellar clusters is widely adopted to investigate the evolutionary status of cluster stars, yielding information on cluster distances and ages. However, the success achieved by theory in reproducing all the main evolutionary features observed in actual clusters has perhaps produced too much confidence in the quantitative theoretical predictions, which are often taken at their face values without accounting for the uncertainties still existing in the theoretical scenario. One should indeed bear in mind that theoretical predictions are still affected by uncertainties due either to the physics input (equation of state, EOS, opacity, etc.) or to assumptions about the efficiency of some macroscopic mechanisms like core overshooting, diffusion, supradiabatic convection and so on.

Moreover, the fitting of theoretical isochrones to cluster stars does depend on the adopted transformations from the theoretical to the observational plane, often with the additional degrees of freedom introduced by current uncertainties in the cluster distance and reddening. The different varied results in the recent literature concerning theoretical predictions and, in turn, the evaluation of evolutionary parameters for a given cluster can be taken as a clear indication of the uncertainty in this kind of procedure. On this basis evolutionary theory is just indicative whereas experiments (i.e. observations) must provide the right answer.

In this context the results of the Hipparcos satellite have opened a new era in stellar astrophysics, fixing the distance...
and thus the absolute magnitude of stars in several nearby open clusters, removing a noisy degree of freedom affecting previous evaluations. Among these clusters we will focus our attention on the Hyades cluster, which has already been the object of several careful investigations and, in particular, for which one has reliable evaluations of the cluster metallicity together with indications for a rather negligible reddening (see e.g. Perryman et al. 1998). In this paper we will take advantage of the beautiful CM diagram for cluster members presented by Dravins et al. (1997) and Madsen, Dravins, & Lindegren (2000), reported here in Fig.1. MS stars hotter than B-V $\sim$0.9 have already been compared with suitable theoretical models by Perryman et al. (1998). However, the well defined sequence of MS stars gives the opportunity for testing much cooler stellar models than the above quoted limit.

Moreover, one finds that the diagram provides evidence for two red giants, easily interpreted as He burning structures, worthy of comparison with the predictions of current evolutionary scenarios. This paper deals with these questions. For this purpose, the next section will first discuss the level of confidence for theoretical predictions. On this basis, we will use Hyades stars as a test of several current evolutionary scenarios.

2 THE HYADES MS

Present stellar models were computed by adopting our version of the FRANEC evolutionary code (Chieffi & Straniero 1989; Ciacio, Degl’Innocenti, Ricci 1997), which relies on the most recent input physics (Cassisi et al. 1998). In particular, to start our investigation we adopted the OPAL equation of state (Rogers et al. 1996) using model atmospheres by Kurucz (1993) to transform theoretical results into the observational plane (V, B-V).

On these grounds, we computed suitable canonical (without core overshooting) isochrones, assuming for the Hyades stars $Z$=0.024 (see e.g. Perryman et al. 1998) together with $Y$=0.278, as given by extrapolation of the linear relation between $Y$ and $Z$, connecting metal poor Pop.II stars ($Z = 10^{-4} \ Y = 0.23$) to the results of standard solar models ($Z = 0.02 \ Y = 0.27$) (see e.g. Pagel & Portinari 1998, Castellani, Degl’Innocenti, Marconi 1999).

As is well known, an exhaustive theory of convection in the turbulent external regions of stars is not yet available; thus the Mixing Length Theory (MLT) is generally adopted, where the free parameter $\alpha$ is varied to tune the efficiency of superadiabatic convection until the agreement with the observations is reached. As a consequence, stellar evolution cannot give firm predictions about the effective temperature and the radius of cool stars with convective envelopes, which depend on the assumptions regarding the value of $\alpha$. To have a look into such an occurrence, Fig.2 shows again the CM diagram of the Hyades stars but comparing them with MS loci computed under the different labelled assumptions about the value of the free parameter $\alpha$. One easily
recognizes that, within a given theoretical scenario, theory can give firm predictions only for stars hotter than \( B-V \sim 0.4 \) (where convection vanishes) or cooler than \( B-V \sim 1.2 \) (where convection becomes adiabatic).

In this context, one finds that at the hotter end of the “uncertainty region” \( (0.4 < B-V < 1.2) \) theoretical predictions appear to be in reasonable agreement with observation. Luckily enough, below \( B-V \approx 0.4 \) the observational sequence is well within the uncertainty region, and the figure discloses that the assumption \( \alpha = 1.9 \) fits the observations best, at least down to \( B-V \sim 0.8 \). For \( B-V > 0.8 \) models with \( \alpha = 1.9 \) become bluer than observations but up to \( B-V \approx 1.1 \) this problem can be overcome by decreasing the mixing length parameter. However, at the cooler end, theoretical predictions give models that are too blue, independently of the assumption on the mixing length, revealing that something is wrong, either in the models or in the adopted colour transformations.

However, it is not difficult to recognize that even the above quoted agreement is far from being firmly established.

Fig. 2. CM diagram of Hyades as in Fig. 1 compared with a 0.5 Gyr theoretical isochrone for the Hyades composition \( (Z=0.024, Y=0.278) \) and \( \alpha = 1.9 \), and with Zero Age Main Sequences (ZAMSs) for the same chemical composition and two extreme values of the mixing length: \( \alpha = 1 \) and \( \alpha = 2.2 \). Equation of state is from Livermore (Rogers et al. 1996). Colour transformations and bolometric corrections are from Kurucz (1993).

Fig. 3. Upper panel: 0.55 Gyr theoretical isochrone \( (Z=0.024, Y=0.278, \alpha = 1.9) \) transposed in the observational plane by using the labelled colour transformations. Lower panel: ZAMS location in the HR diagram from the labelled papers. ZAMS from the present work with two different adopted Equations of State (EOS) are drawn with a solid line (see text). Mass values at given positions on a selected ZAMS are also shown. The luminosity is expressed in solar units.
One finds that improved semiempirical colours by Alonso et al. (1996, 1999) would make our theoretical MS bluer, whereas the recent empirical colours by Di Benedetto (1998) will make it even bluer. In other words the stellar models become, for each given MS colour, underluminous. By adopting, as many people do, Alonso et al. colours the agreement between theory and observation, inside the “uncertainty region” of Fig.2, could still be reached by tuning the mixing length parameter while a variation of $\alpha$ cannot solve the increasing disagreement below $B-V \approx 1.1$. With the choice of Di Benedetto colours there are no reasonable assumptions for the efficiency of the external convection which could reconcile theory and observation for stars both hotter than $B-V \approx 0.5$ or cooler than $B-V \approx 1.0$. We conclude that, for any choice of mixing length and colour transformations, stellar models are certainly underluminous for colours redder than $B-V \approx 1.1$.

Luckily enough brighter models are within the range of current theories. As shown in the same figure (lower panel) one finds in the literature that MS in all cases computed with “reasonable” input physics cover a non negligible range of luminosity, all being brighter than the MS computed with “the most updated” physics. Among the brightest, one finds the MS by Straniero, Chieffi, Limongi (1997), which differs mainly from our computations by adopting the Equation of State by Straniero 1998 (see also Straniero 1988). As a matter of fact, and as shown in the same figure, our models computed, however, with the above quoted equations of state closely follow the results of Straniero et al. (1997).

Figure 4 reveals that the simultaneous inclusion of Straniero’s EOS and Alonso colours again provides a reasonable fitting of the Hipparcos data, also improving the fitting for cooler stars, with only a residual discrepancy at the cooler end of the sequence. However, comparison of Fig.4 with the upper panel of Fig.3, shows that if the Di Benedetto empirical colours will be confirmed, one cannot escape the conclusion that theories should give brighter models than those provided by current evaluations. An increase in the adopted original He content could help in reaching a good fit all along the major portion of the MS, but with the lower end still requiring some modification of the adopted theoretical scenario. However we feel that any attempt to theoretically constrain the Hyades He content cannot give reliable results until firm evaluations of the colour-temperature relations will become available.

3 ADVANCED EVOLUTIONARY PHASES

Even a quick inspection of the data in Fig.1 reveals that when including only highly probable members, with the exclusion of binaries, the luminous termination of the cluster MS appears rather poorly defined, making it difficult a clear identify the Turn-Off (TO) and, thus, a precise evaluation of the cluster age. We will discuss this point by relying on the

![Figure 4. 0.55 Gyr theoretical isochrone for Z=0.024, Y=0.278, $\alpha = 1.9$ with Straniero 1998 EOS and Alonso et al. (1996,1999) colour transformations (completed with Kurucz 1993 colour-temperature relations as shown in Fig.3) compared to the observational data of Fig.1. The dotted region of the theoretical isochrone indicates the fastest part of the central He burning phase which is expected to be populated very little.](image-url)
Figure 5. Theoretical isochrones for the labelled ages (Z=0.024, Y=0.278, α = 1.9) with Straniero 1998 EOS and Alonso et al. (1996,1999) colour transformations compared to the observational data of Fig.1. The younger are the isochrones the brighter is the subgiant phase and the bluer is the central He burning region.

Theoretical scenario adopted in Fig.4, as based on Straniero’s EOS and Alonso et al. colours.

The evaluation of the cluster age depends on the choice made about the actual Turn-Off. Oddly enough, Fig.5 shows - as an extreme case - how four different assumptions about the cluster age are needed to cover all the stars observed at the top of the cluster MS. If, as the most reasonable choice, one fits the five hottest stars, then one derives for the cluster an age of the order of 0.55 Gyr. By the way, any attempt to detect possible signatures of core overshooting mechanisms (see e.g. Maeder 1975, Bressan et al. 1981) appears beyond any actual possibility.

As already mentioned, observations support the evidence for two stars in the He burning phase, at around B-V≈ 1.0. According to the fit with a 0.55 Gyr isochrone one expects at the cluster TO stars as massive as 2.5 M⊙ whereas the He burning clump would be populated by 2.55 M⊙ stars. However, comparison with predictions concerning the major phase of central He burning, as given in Fig.5, suggests that theory is slightly underestimating the actual star luminosities. Even if the statistics is rather poor, this appears to be a relevant outcome since for less massive stars with degenerate progenitors, theoretical models have been already suggested to be, on the contrary, overluminous (see e.g. Pols et al. 1998 and Castellani et al. 2000).

Comparison of Fig.2 with Fig. 4 shows that the problem cannot be overcome by adopting the OPAL EOS. Nor the assumption of an efficient overshooting is of actual help in solving the observed discrepancy. This is shown in Fig.6, where we present the best fit for cluster stars as alternatively obtained from canonical or mild overshooting models.

More in general, it appears that the discussed underluminosity is a problem concerning several recent models. We already found that Pols et al. (1998) give He burning luminosities in good agreement with present computations (see Fig.1 in Degl’Innocenti et al. 2000). Figure 7 discloses that similar luminosities can be also found in other independent investigations.

Thus, at least for this cluster, one finds that theoretical predictions for masses larger than the critical mass for the

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red giant (RG) transition, i.e. stars which during their RG evolution were not affected neither by electron degeneracy nor by relevant neutrino cooling, seems to show the problem opposite to that found for He burning stars with degenerate progenitors.

4 CONCLUSION

In this paper we discussed Hipparcos data for the Hyades cluster, showing that the fitting of theoretical isochrones to open clusters is still affected by non negligible uncertainties in the theoretical predictions which require a much firmer evaluation of colour temperature relations. However, none of the current theoretical scenarios appears able to account for the mismatch between theoretical predictions and observations of the Hyades coolest MS stars. Finally we found that Hyades He burning stars suggest an underluminosity of the current theoretical models, unlike the case of less massive He burning models, with degenerate progenitors, which probably suffer the opposite problem.

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