THE AGE AND HELIUM CONTENT OF THE HYADES REVISITED

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ABSTRACT

The observational main sequence of the Hyades cluster resulting from the careful analysis of the Hipparcos data by Brown et al. (1997) is analysed by means of modern theoretical stellar evolution models with the objectives of determining the helium content and the age of the cluster.

In a first step we have calculated zero age main-sequence models in a mass range from 0.8 to 1.6 $M_{\odot}$ for various chemical compositions. The input physics includes the most recent opacity data and an appropriate equation of state. We have adopted the solar value of the mixing-length (l = 1.64 pressure scale-heights) derived from solar calibration with the same input physics.

Interpolation in chemical composition of the theoretical zero-age main sequence lines is performed in order to reproduce the observed lowest part of the HR diagram, composed of the less massive stars which do not significantly depart from the ZAMS line. This provides the helium content Y, in mass fraction, of the cluster (Y=0.26 $\pm$ 0.02), the metallicity of which (Z=0.024 $\pm$ 0.004) being determined independently by detailed spectroscopic analysis. This part is discussed with more details by Cayrel de Strobel et al. (1997).

In a second step we have calculated evolved stellar models with the same input physics, with and without overshooting, adopting Y=0.26 and Z=0.024. We compare the associated isochrones to the whole observational main sequence of the cluster in the ($M_{\rm V}$, $B-V$) diagram. Our results suggest a cluster age of 625 Myr with observational indications for the presence of overshooting. We estimate that the uncertainty on age is at least 50 Myr.

Key words: Hyades; HR diagram; chemical composition; age.

1. INTRODUCTION

The Hyades cluster is the nearest moderately rich cluster. It is therefore of great importance for astrophysics and has already been thoroughly studied. In particular the knowledge of the properties of the Hyades cluster intervenes in studies of galactic structure, chemical evolution of the Galaxy and extragalactic distance determinations.

With Hipparcos, the individual distances of the Hyades stars are now measured with a mean accuracy of about 5 per cent which considerably improves the precision on the absolute magnitude (0.1 mag on average). New information has also been provided on the cluster membership (Perryman et al. 1997, Brown et al. 1997). On the other hand many physical parameters of this cluster were already known, due to the large progress of observational and theoretical means. In particular detailed spectroscopic analysis on large telescopes interpreted by means of sophisticated theoretical stellar atmospheres models has provided the effective temperature and metallicity of about 40 Hyades dwarfs (Cayrel de Strobel et al. 1997).

As a result we now have access to a new improved observational Hertzsprung-Russell diagram of the Hyades. On the other hand great progress on the comprehension of the microscopic physics which determines stellar interior structure (opacities, equation of state, nuclear reaction rates) has also been made during the ten last years. The purpose of this work is to re-interpret the Hyades main sequence by means of appropriate theoretical models of stellar evolution and their associated isochrones. In Section 2 we describe the theoretical stellar models and their input physics. In Section 3 we compare the lower part of the main sequence of the Hyades observed by Hipparcos with theoretical zero-age main sequence lines with the objective of estimating the Hyades helium content. The question of the possible correlation of the helium abundance with metallicity being of great interest for the understanding of the chemical evolution of the Galaxy (Pagel 1995, Fernandes et al. 1996, Lebreton et al. 1997). In Section 4 we compare the whole Hyades main sequence with theoretical isochrones calculated with and without overshooting, for the Hyades chemical composition determined in Section 3. We obtain the age of the cluster and we estimate the uncertainties on its determination.

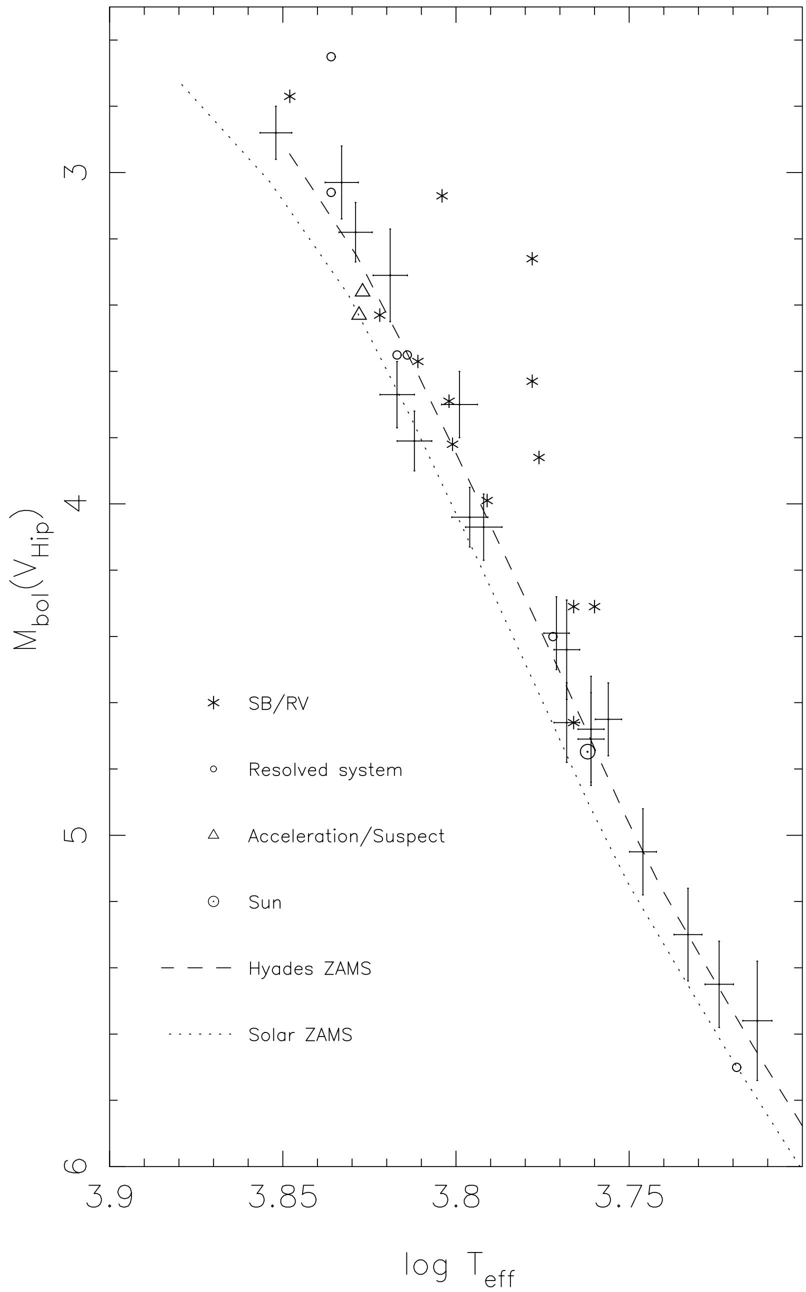

Figure 1. HR diagram for the 40 selected stars. Stars with given error bars are the 19 stars which are not suspected to be variable or double. Theoretical ZAMS loci are given for the Hyades (dashed line) and solar (dotted line) chemical compositions.

2. THEORETICAL MODELS

The stellar evolution calculations have been computed with the CESAM code (Morel 1997) in which we have included recent and appropriate input physics. To interpret the observational HR diagram of the Hyades we calculated theoretical stellar models in the mass range from 0.8 to 4.0 $M_\odot$ from the zero-age main sequence (ZAMS) to the base of the red giant branch.

In the range of mass considered the CEFF equation of state (Eggleton et al. 1973, Christensen-Dalsgaard 1991), which includes the Coulomb corrections to the pressure, is appropriate. We used the most recent OPAL opacities (Iglesias & Rogers 1996) complemented at low temperatures ($T \leq 10\,000$ K) by atomic and molecular opacities from Alexander & Fergusson (1994). Both sets of opacities were provided for a mixture of heavy elements corresponding to the solar mixture of Grevesse & Noels (1993). We also adopted the Grevesse & Noels (1993) mixture in internal structure calculations. Nuclear reaction rates were taken from Caughlan & Fowler (1988). We used the Eddington's $T(\tau)$ law to describe the atmosphere and the mixing-length theory of Böhm-Vitense (1958) to describe convection. In order to examine the effect of the overshooting of the convective core of stars of mass higher than about 1.25 $M_\odot$, we extended the mixing of the convective core by 0.2 pressure scale-heights according to the prescription of Schaller et al. (1992). We did not take into account in the models the possible mixing of chemical elements by microscopic diffusion processes such as gravitational settling. Although these processes can be non-negligible in determining the present structure of stars like the Sun or the age of globular clusters, they are not expected to have influenced significantly the structure of relatively young stars such as the Hyades, the age of which being lower than 1 Gyr, according to theoretical models (see Section 4).

The solar mixing-length parameter and the initial solar helium content Y in mass fraction are obtained from the calibration of the solar model using the input physics described above and adopting a solar metal abundance Z/X =0.0244 where X is the hydrogen abundance and Z the metal content in mass fraction (Grevesse & Noels 1993). We find that a solar model reaches at solar age ($4.75\ 10^9$ yr) the observed solar luminosity ($L_\odot = 3.846\ 10^{33}$ erg s^{-1}) and radius ($R_\odot = 6.9599\ 10^{10}$ cm) with an initial helium abundance Y=0.2659, a metallicity Z=0.0175 and a mixing-length $l = 1.64$ pressure scale-heights.

We adopted the solar mixing-length value in all our calculations following the results by Fernandes et al. (1997). These authors modeled several visual binary systems with known masses and metallicity with the constraint that each component of the system reaches its observed luminosity and effective temperature for the same common age, helium content and mixing-length parameter. They found similar values of the mixing-length, close to the solar value, for systems spanning a wide range of metallicities and ages.

We calculated several grids of evolutionary models and associated isochrones proceeding in two steps. First, we calculated a network of ZAMS models of various chemical compositions varying the helium and metal contents by small amounts. These models were used to estimate the helium abundance of the cluster, while the metallicity is known from detailed spectroscopic analysis (see Section 3). We then calculated a grid of evolved models with the helium abundance and metallicity previously determined, with and without overshooting. We derived the corresponding isochrones from the Geneva isochrone program in order to estimate the age of the cluster (see Section 4).

3. DETERMINATION OF THE HELIUM ABUNDANCE

The direct measurement of the helium abundance in the photosphere of Hyades low-mass main-sequence stars which constitute the Hyades main sequence is not possible because there are no helium lines in their spectra. On the other hand the position in the HR diagram of the theoretical zero-age main sequence line depends on helium abundance and metallicity, once the mixture of heavy elements and the appropriate physics of the models has been chosen. Therefore it is possible to estimate the helium abundance of a cluster knowing its mean metallicity and the location of the cluster observational ZAMS.

To define the ZAMS of the Hyades cluster we have examined a sample of 40 stars, which have been observed by Hipparcos. The physical parameters (effective temperature and metallicity) of the sample have been derived from high-resolution, high signal to noise spectra (Cayrel de Strobel et al. 1997, Perryman et al. 1997). The metallicity of each star is known with a mean accuracy of 0.05 dex. The mean value of the logarithm of the number abundances of iron to hydrogen relative to the solar value of the 40 stars is [Fe/H] $=0.14 \pm 0.05$. [Fe/H] is related to the metallicity Z, in mass fraction, through $[\mathrm{Fe/H}] = \log(\mathrm{Z/X}) - \log(\mathrm{Z/X})_\odot$, which gives for the Hyades Z/X = 0.034 ± 0.007. The error of 0.007 on (Z/X) includes the error of 11 per cent on the solar (Z/X), according to Anders & Grevesse (1989). The effective temperature is given with an accuracy of 50 K or even better for a few objects. The bolometric magnitudes of the stars have been derived from the V magnitude given in the Hipparcos catalogue, the Hipparcos parallax and applying the appropriate bolometric corrections of Bessel et al. (1997). The uncertainty on bolometric magnitude is dominated by the uncertainty on the parallax (σ_π/π) which is of about 5 per cent on average and never higher than 9 per cent (Perryman et al. 1997).

The selected stars have bolometric magnitudes in the range $3 < M_{\rm bol} < 6$ magnitudes. According to theoretical stellar models, stars in that magnitude range and younger than about 1 Gyr (see Section 4) do not depart from the ZAMS line by more than 0.1 magnitude. Among the 40 selected stars, 21 have been eliminated because they are either binaries or variable stars. The 19 others can therefore be considered as non-evolved stars, defining the location of the Hyades ZAMS line. The resulting observational Hertzsprung-Russell diagram is presented in Figure 1.

By interpolation in the theoretical ZAMS grid we found that the observational ZAMS line is well reproduced with models having Y=0.26 and Z=0.024 corresponding to the observed (Z/X) value. The uncertainty on Y resulting both from the error bars in the HR diagram and from the uncertainty on Z is of about 0.02 (Cayrel de Strobel et al. 1997, Perryman et al. 1997). We stress that the Hyades helium value so-obtained is close to the solar helium abundance derived from solar calibration with the same input physics although the metallicity of the Hyades is slightly higher than the solar metallicity.

4. AGE OF THE CLUSTER

Figure 2 shows the global observational HR diagram of the Hyades in the $(M_{\rm V}, B-V)$ plane resulting from the analysis of the Hipparcos data by Perryman et al. (1997) and Brown et al. (1997). It contains 131 reliable cluster members located at less than 10 parsecs from the center of mass of the cluster. The precision on the magnitude is excellent ($\Delta M_{\rm V} \simeq 0.1$ magnitude). The V and $B-V$ values were taken from the Hipparcos catalogue ($\sigma_{B-V} < 0.05$ magnitude).

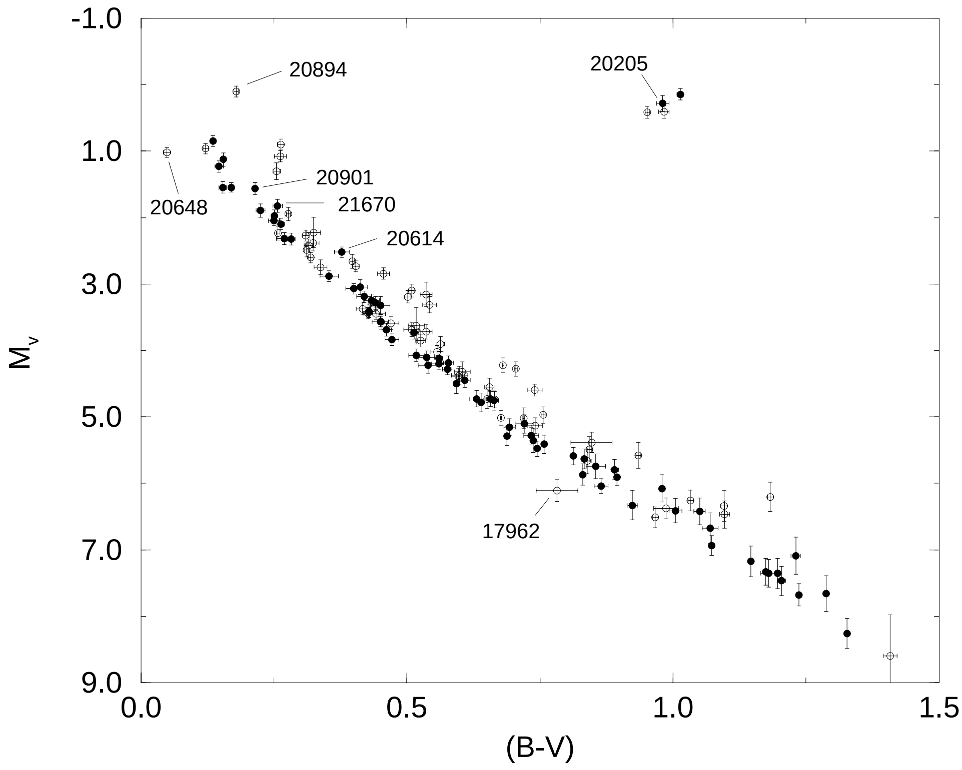

Figure 2. Colour-magnitude diagram for stars considered as reliable cluster members. Filled circles indicate objects which are not classified as double or variable. HIP 17962 is an eclipsing binary, HIP 20648 is a known blue straggler and HIP 20205 is suspected to be double. Other specific objects indicated are discussed in the text.

Among the 131 stars, we eliminated all the stars which were classified as suspected double or variable because such stars have a tendency to lie above the main sequence line and are of no use for age determination through isochrone fitting. Among the 72 remaining stars we eliminated 3 more stars (HIP 20901, 21670 and 20614, see Figure 2) which lie above the main sequence. As discussed with more details by Perryman et al. (1997), HIP 20901 and 21670 are Am type stars amongst which are found a large proportion of spectroscopic binaries and HIP 20614 is a fast rotator and a possible binary, as indicated by its photometry.

The turn-off region which is of great importance for age determination, is quite sparsely populated: here are only 5 stars which are not suspected to be double or variable. In the turn-off region also lies HIP 20894 which is the brighter component of a wide visual pair and well-known spectroscopic binary. The difference in V magnitude and $(B-V)$ index between the two components has been estimated by Peterson et al. (1993). We used these values together with the Hipparcos parallaxes to place the two stars in the HR diagram.

In order to estimate the age of the Hyades cluster we used theoretical isochrones derived from evolutionary models corresponding to the chemical composition of the Hyades obtained in Section 4. We had to transform the isochrones from the theoretical ($M_{\rm bol}$, log $T_{\rm eff}$) plane to the observational $(M_{\rm V}, B-V)$ plane. We used the recent calibration of Alonso et al. (1996) giving the relation between the $B-V$ colour and the effective temperature as a function of metallicity. Since the stellar gravity varies along the position on the isochrone, we had to take into account the influence of gravity on the $B-V$ index using the relationships by Arribas & Martínez Roger (1988). The bolometric corrections from Bessel et al. (1997) were used to estimate $M_{\rm V}$ from $M_{\rm bol}$.

Figure 3 shows the theoretical isochrones corresponding to ages from 550 to 750 Myr calculated with overshooting, superimposed on the observational HR diagram. Figure 4 shows isochrones in an age range 500–700 Myr calculated without overshooting. The visual fitting of the theoretical isochrones to the observations provides an age of 625 Myr using models with overshooting and of about 550 Myr if no overshooting is included. However if we include HIP 20894 as an additional constraint for the fit we have to account for the position of the two components indicated by arrows on Figure 3 and Figure 4. It then seems to be difficult to account for the position of the two components if models without overshooting are used while the fit at 625 Myr with overshooting remains acceptable.

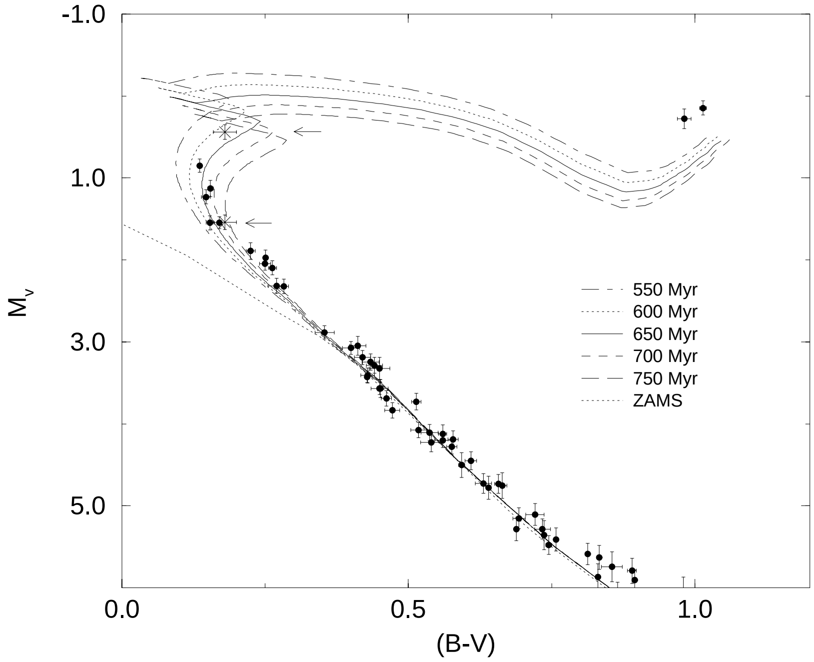

Figure 3. The 69 single stars with the locus of the ZAMS, and with isochrones calculated with overshooting.

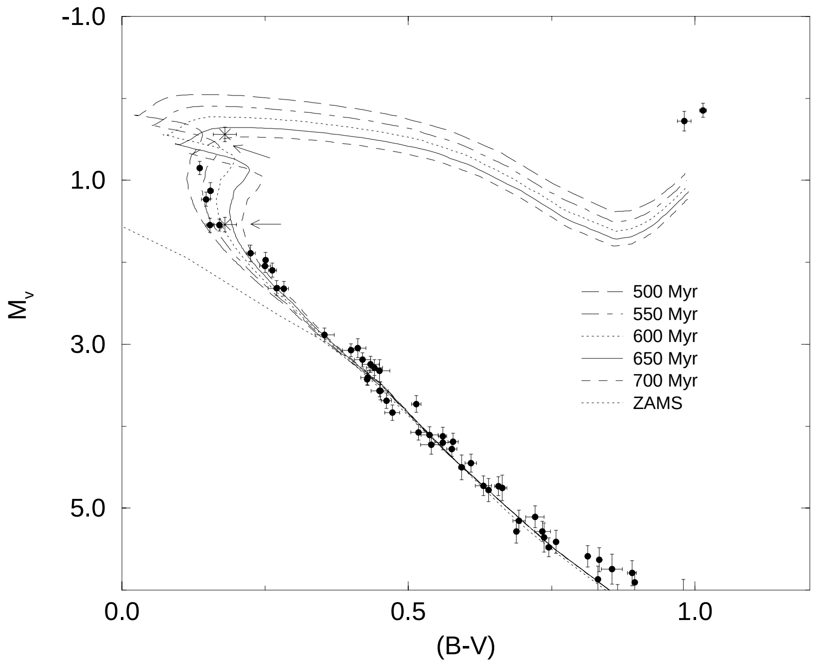

Figure 4. The 69 single stars with the locus of the ZAMS, and with isochrones calculated without overshooting.

Let us now discuss the sources of uncertainty on age determination. For a given set of isochrones (with or without overshooting) we estimate an age uncertainty of about 30 Myr coming from the visual fitting of an isochrone to observations. Moreover the physics used for the calculation of the models brings an additional uncertainty on age, the major uncertainty coming from the uncertainty on the value of the overshooting parameter (Lebreton et al. 1995). We estimate that the resulting uncertainty on age is less than 10 per cent. The transformation of theoretical isochrones from the ($M_{\rm bol}$ to the observational ($M_{\rm V}, B-V$) plane is responsible for age uncertainties which are quite difficult to estimate but which could reach 20 per cent. Stellar rotation also makes the age estimate more difficult since rotating stars appear to be brighter and cooler than the corresponding non-rotating stars. However the Hyades stars located in the turn-off region appear to be slow rotators (Perryman et al. 1997) and the resulting age overestimate is probably lower than 50 Myr (Maeder 1971). An additional uncertainty on age could result from still unrecognised binaries but cannot be quantified. We stress that the minimum uncertainty on age determination is of about 50 Myr. This uncertainty would be obtained if models of stellar internal structure were completely validated using other stellar astrophysical constraints such as those expected from asteroseismology (Lebreton et al. 1995). Actually, the real uncertainty may still be higher and reach 100 Myr.

5. CONCLUSION

We have computed a grid of theoretical models for the Hyades metallicity (Z = 0.024) as determined from high dispersion spectra to determine the helium abundance. These models incorporate the best physics and the latest OPAL opacities. The ZAMS computed with Y = 0.26 and Z = 0.024 give the best fit to the observed unevolved main sequence. Evolved models with this chemical composition have been computed and isochrone derived. The best estimate of the Hyades age is 625 ± 50–100 Myr. The uncertainty is due to the small number of single stars which describe the Hyades turnoff, to remaining uncertainties on mixing processes in stars (overshooting) and to the error on the transformation from theoretical to observed units.

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