

# Consequences of Hipparcos parallaxes for stellar evolutionary models<sup>\*</sup>

## Three Hyades binaries: V 818 Tauri, 51 Tauri, and $\theta^2$ Tauri

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**Abstract.** Three binary systems in the Hyades open cluster (51 Tau, V818 Tau, and  $\theta^2$  Tau), with known metallicity and good Johnson photometric data are used to test the validity of three independent sets of stellar evolutionary tracks. A statistical method is described and applied to the colour-magnitude diagram of the six selected components, giving rise to  $\chi^2$ -contours in the metallicity–age plane. The effects of the Hipparcos parallaxes on these confidence regions are studied in detail for these binaries through a comparison with very accurate but older orbital parallaxes. There are no significant differences in 51 Tau and  $\theta^2$  Tau, and hence the test validates the sets of theoretical tracks used. However the orbital parallax of V 818 Tau leads to metallicities too large in comparison with the observed range, while the Hipparcos parallax give consistent results, at the  $1\sigma$  level. Comparisons between the predicted and measured masses are also made and show a good agreement. However, even if the Padova tracks predict correct masses for each component of V 818 Tau, there is no Padova track that fits both components simultaneously in the mass-radius diagram. Finally, since the individual masses of these binaries are accurately known, some issues about the influence of the Hipparcos parallaxes on their location in the mass-luminosity diagram are also discussed.

**Key words:** stars: binaries: general – stars: fundamental parameters – stars: individual: 51 Tau;  $\theta^2$  Tau; V 818 Tau – Galaxy: open clusters and associations: individual: Hyades

### 1. Introduction

Since the members of an open cluster are assumed to be of same age and chemical composition, these stars are currently used to test the validity of stellar evolution theories<sup>1</sup>, mainly

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<sup>\*</sup> Based on data from the ESA Hipparcos satellite

<sup>1</sup> Some of the most recent detailed works on such critical tests of stellar evolution in open clusters are due to Nordström et al. (1997) and Pols et al. (1998).

because main sequence stars define a tight sequence in a colour-magnitude diagram (CMD). Unfortunately, this tightness is sometimes misleading because of the contamination by field stars, the presence of unresolved binaries and also the influence of stellar rotation on the location of massive stars in CMDs.

Alternatively, well-detached binaries are powerful tests when fundamental parameters are accurately known (see the comprehensive review by Andersen 1991 on double-lined eclipsing binaries). Unfortunately, the determination of the chemical composition often remains a difficult and unresolved issue. It appears therefore that a better test could be performed by combining both advantages, that is, testing the tracks with well-detached double-lined binaries which are members of open clusters.

The work developed in this paper is the application of this idea to three well-detached binaries members of the Hyades: 51 Tau, V 818 Tau, and  $\theta^2$  Tau. Torres et al., 1997 ([TSL97a], [TSL97b] and [TSL97c]) obtained the first complete visual-spectroscopic solutions for these systems, from which they carefully derived very accurate parallaxes and individual masses. They also gathered some individual photometric data in the Johnson system. Furthermore, we found useful trigonometric parallaxes information in the Hipparcos catalogue (ESA, 1997). By combining the two sources of data, we investigate the influence of the Hipparcos parallaxes on our method which was developed to test stellar evolutionary models in HR diagrams.

According to Leitherer et al. (1996), the most widely used stellar theoretical tracks in the literature are those computed by the Geneva group (Schaller et al. 1992, Schaerer et al. 1993a, 1993b, and Charbonnel et al. 1993) and the Padova group (Bresnan et al. 1993, Fagotto et al. 1994a,b<sup>2</sup>). We also used the stellar tracks from Claret & Giménez (1992) (CG92 thereafter). The tests presented in the next section are done with these 3 series

<sup>2</sup> High metallicity tracks ( $Z = 0.10$ ) are also available for the Padova group (Fagotto et al. 1994c), and the Geneva group (Mowlavi et al. 1998), but they are not relevant for the expected Hyades metallicity.

of stellar tracks to assess the possible systematics introduced by the use of a single set.

The test we want to perform has two aims. Firstly it has to check whether the two components of the systems are on the same isochrone, i.e. on a line defined by the same age and the same chemical composition for the two single stars. Secondly, as all the selected stars are members of the Hyades whose metallicity has been well measured, we can also check that the predicted metallicity from theoretical models are correct. Therefore, if one of these two criteria is not clearly fulfilled by a given set of tracks, then these models have obvious problems since they do not account for several observational constraints (namely the metallicity and/or the photometric data).

We would like to emphasize that we do not claim that the 6 selected Hyades stars allow us to test without ambiguity any set of theoretical stellar tracks. Since the data are presented in colour-magnitude diagrams, we are in fact testing not only the validity of the tracks (computed in terms of effective temperature and bolometric luminosity in the HR diagram) but also the validity of the photometric calibrations, and disentangling the relative influence of both is a tricky task. However, since we use the Basel Stellar Library (BaSeL) photometric calibrations, extensively tested and regularly updated for a larger set of parameters (see Lejeune et al. 1997, Lejeune et al. 1998, Lastennet et al. 1999 and Lejeune et al. 1999), we assume that the calibrations are reliable for our purposes. Moreover, it is worth noticing that in the range of interest of the  $(B-V)$  colour in the present work ( $[0.15, 1.25]$  mag.), the agreement between the various extant calibrations, i.e., the transformations between theoretical  $T_{\text{eff}}$  and observational  $(B-V)$  colour, is quite good around metallicities close to solar (see, for example, Alonso et al. 1996 and Fig. 8 of Flower 1996 for some comparisons). Significant differences do occur at cooler temperatures, but they are not relevant for the present study. For these reasons, we will assume that the calibrations from the BaSeL models are reliable enough for this work.

Another crucial point is the question of reddening. The Hyades open cluster does not show any evidence for reddening ( $E(B-V)=0.003\pm 0.002$ , Taylor 1980), consequently  $E(B-V)$  is assumed to be consistent with 0 in this paper.

The paper is organised as follows: Sect. 2 is a brief description of the method used to produce confidence level contours, Sect. 3 is devoted to the study of each binary, completed by comments on the influence of the Hipparcos parallaxes on the location of the 6 stars in a mass-luminosity diagram. Finally, Sect. 4 draws our general conclusions.

## 2. Statistical method description

It is not an easy task to disentangle metallicity and age effects in a colour-magnitude diagram with only two stars, particularly if they both lie close to the main sequence. This difficulty is due to the degeneracy between these two quantities in this area of the CMD. For this reason, any analysis of binary star data should be presented in the (metallicity, age) plane. In order to derive

simultaneously the metallicity ( $Z$ ) and the age ( $t$ ) of the system, we minimize the  $\chi^2$ -functional defined as:

$$\chi^2(t, Z) = \sum_{i=A}^B \left[ \left( \frac{M_V(i)_{\text{mod}} - M_V(i)}{\sigma(M_V(i))} \right)^2 + \left( \frac{(B-V)(i)_{\text{mod}} - (B-V)(i)}{\sigma((B-V)(i))} \right)^2 \right] \quad (1)$$

where  $A$  is the primary and  $B$  the secondary component.  $M_V$  and  $(B-V)$  are the observed values (more details will be given later on  $M_V$ ), and  $M_{V_{\text{mod}}}$  and  $(B-V)_{\text{mod}}$  are obtained from the synthetic computations of the BaSeL models using a given set of stellar tracks.

A similar method has already been developed and used by Lastennet et al. (1996) and by Lastennet & Valls-Gabaud (1999) for HR diagrams. Eq. 1 simply means that the best  $\chi^2$  is obtained when an isochrone is close to both stars  $A$  and  $B$  in the CMD. With  $n = 4$  observational data ( $M_V$  and  $B-V$  for each star) and  $p = 2$  free parameters (age  $t$  and metallicity  $Z$ ), we expect to find a  $\chi^2$ -distribution with  $q = n - p = 2$  degrees of freedom. Finding the central minimum value  $\chi^2_{\text{min}}$ , we form the  $\chi^2$ -grid in the (metallicity, age)-plane and compute the boundaries corresponding to  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  confidence levels. We do not use any additional information in the  $\chi^2$  functional such as radii or masses since (1) these are not always available at the same time, and (2) they should be predicted by the tracks (Lastennet & Valls-Gabaud 1999).

## 3. Tests with well-detached binaries

In this section tests of the widely used theoretical stellar tracks are presented. They are based on a few number of binary systems belonging to the Hyades open cluster, for which Johnson BV photometric magnitudes and accurate mass estimates are available: 51 Tau, V 818 Tau, and  $\theta^2$  Tau. V 818 Tau is the only eclipsing binary among these three systems. Contrary to Lastennet & Valls-Gabaud (1999) where tests are presented in the theoretical HR diagram, our tests are performed in the CMD.

The main advantage to study such binaries, members of an open cluster, is that the heavy element abundance of the Hyades has been extensively studied and estimated by different authors. As a matter of fact, the metallicity of the binaries studied in Lastennet & Valls-Gabaud (1999), mainly from the field, was seldom known. The more recent determinations of the Hyades metallicity have been reviewed by Perryman et al. (1998):  $[\text{Fe}/\text{H}] = 0.14 \pm 0.05$ , i.e.  $Z = 0.024^{+0.0025}_{-0.003}$  assuming a subsolar helium abundance ( $Y = 0.26$ ), which is the value found by Lebreton et al. (1997) in order to reproduce the Hyades main sequence, with an uncertainty of about 0.02 resulting both from the error bars of the Hyades members in the HR diagrams and from the observational uncertainty on  $[\text{Fe}/\text{H}]$ . A second advantage is that very accurate parallaxes are now available from Hipparcos for these three systems (the last estimation of the Hyades distance from Perryman et al. (1998) is:  $d = 46.34 \pm 0.27$  pc). Moreover, we pay attention to the quality of the Hipparcos results using the indicators F1 (percentage of rejected

**Table 1.** Cross identification and basic data for the 3 selected binary systems in the Hyades. Distances are derived quantities from either orbital parallaxes (Torres et al. 1997 [TSL97a]) or Hipparcos trigonometric parallaxes. Masses and Johnson photometry are from Torres et al. (1997) [TSL97a].

Stars	HD	HIP	vB <sup>†</sup>	Mass ( $M_{\odot}$ )	V	B–V	Distance (pc)	
							Torres et al. (1997)	Hipparcos
51 Tau A	27176	20087	24	$1.80 \pm 0.13$	$5.87 \pm 0.03$	$0.24 \pm 0.05$	$55.8 \pm 1.8$	$54.8 \pm 2.5$
51 Tau B	...	...	...	$1.46 \pm 0.18$	$7.48 \pm 0.10$	$0.47 \pm 0.19$	...	...
V818 Tau A	27130	20019	22	$1.072 \pm 0.010^a$	$8.44 \pm 0.01$	$0.713 \pm 0.017$	$50.4 \pm 1.9$	$46.7 \pm 2.7$
V818 Tau B	...	...	...	$0.769 \pm 0.005^a$	$10.74 \pm 0.05$	$1.190 \pm 0.08$	...	...
$\theta^2$ Tau A	28319	20894	72	$2.42 \pm 0.30^{b1}$	$3.74 \pm 0.02$	$0.18 \pm 0.02$	$47.1 \pm 1.7^c$	$45.7 \pm 1.8$
$\theta^2$ Tau B	...	...	...	$2.11 \pm 0.17^{b2}$	$4.84 \pm 0.03$	$0.18 \pm 0.02$	...	...

<sup>†</sup> The acronym vB stands for van Bueren.

<sup>a</sup> from Peterson & Solensky (1988).

<sup>b1</sup> from [TSL97c]. The value originally quoted by [TSL97a],  $2.10 \pm 0.60 M_{\odot}$ , is the determination of Tomkin et al. (1995) adjusting the error upward by a factor of two.

<sup>b2</sup> from [TSL97c]. As <sup>b1</sup>, the value quoted by [TSL97a],  $1.60 \pm 0.40 M_{\odot}$ , is also from Tomkin et al. (1995) adjusting the error upward by a factor of two.

<sup>c</sup> from [TSL97c]. Other values:  $44.1 \pm 1.7$  pc in [TSL97a],  $44.1 \pm 2.2$  in Tomkin et al. (1995) and  $42.4 \pm 1.5$  pc in Peterson et al. (1993).

observations<sup>3</sup>) and F2 (goodness-of-fit statistic) in order to ensure that the parallaxes are reliable. The data used in the present work are gathered in Table 1.

Absolute magnitudes of each binary component are directly inferred from Hipparcos parallaxes  $\pi$  and visual magnitudes V:

$$M_V = V + 5 + 5 \times \log(\pi) \quad (2)$$

$$\Delta M_V = \Delta V + \frac{5}{\ln(10)} \times \frac{\Delta(\pi)}{\pi} \quad (3)$$

We do not take into account the Lutz–Kelker correction because relative errors on parallaxes,  $\sigma_{\pi}/\pi$ , are always smaller than 10%: respectively 4.5%, 5.8% and 3.8% for 51 Tau, V 818 Tau and  $\theta^2$  Tau. Therefore the correction can be neglected as noted by Brown et al. (1997). In Table 1, the systematically larger distance found by Torres et al. is, at least in part, caused by the fact that the PPM proper motions that they used (see Schwan 1991 and references therein) are almost all smaller than those of Hipparcos (see Perryman et al. 1998 for details).

### 3.1. Results for 51 Tau

The 51 Tau system is a spectroscopic binary and also a visual binary resolved by speckle interferometry.

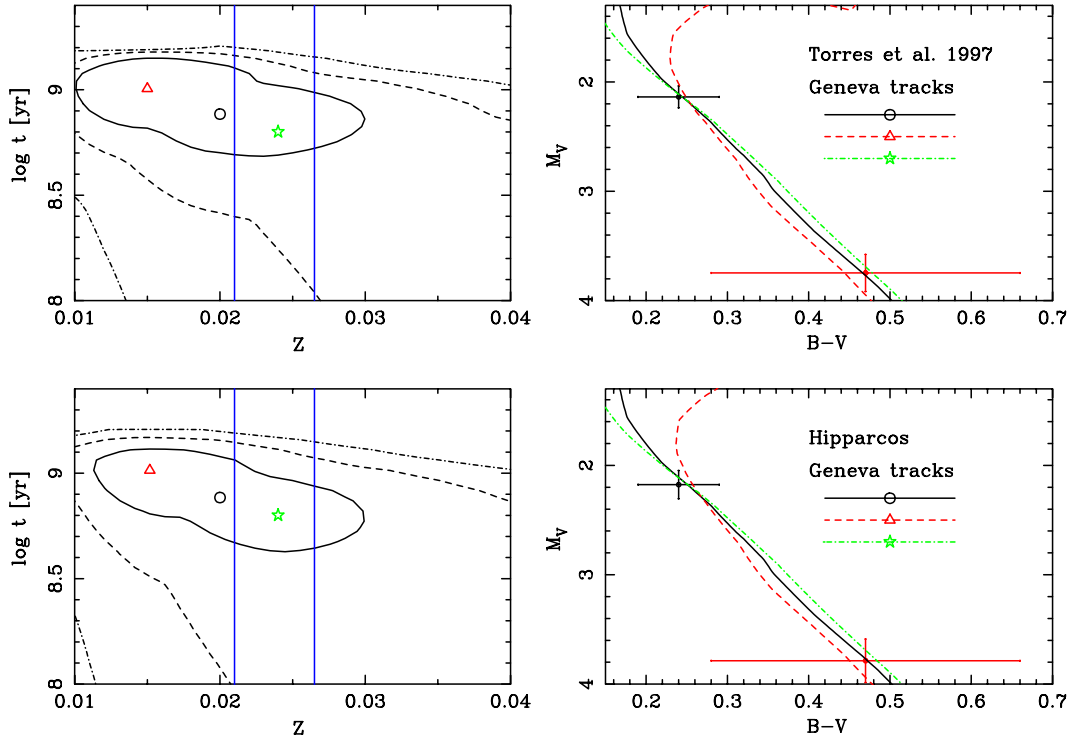
In order to address the question of the effect of the Hipparcos parallaxes on our results, we first need to present what the results are without using these new parallaxes. Fig. 1 shows both the isocontours and CMD without using Hipparcos (*upper panels*) and with Hipparcos parallaxes (*lower panels*). The effect of using the Hipparcos parallaxes is hardly visible on the results, in particular the shapes of the isocontours are not modified a great deal. Actually, the difference between the distance from Torres et al. 1997 ( $d = 55.8 \pm 1.8$  pc from the orbital parallax) and the distance derived from Hipparcos ( $d = 54.8_{-2.4}^{+2.6}$  pc) is

<sup>3</sup> This field gives the percentage of data that had to be rejected in order to obtain an acceptable astrometric solution.

rather small. Since the errors on distance are slightly larger with Hipparcos data, the error bars estimates are slightly larger on the  $M_V$  axis.

As mentioned previously, the more recent determinations of the Hyades metallicity have been reviewed by Perryman et al. (1998):  $[\text{Fe}/\text{H}] = 0.14 \pm 0.05$  (i.e.  $Z = 0.024_{-0.003}^{+0.0025}$ ). These constraints are shown in the (Z, age)-plane as vertical lines. Torres et al. (TSL97a) adopt  $[\text{Fe}/\text{H}]_{\text{Hyades}} = 0.13$  (following Cayrel et al. 1985, Boesgaard 1989 and Boesgaard & Friel 1990) and hence  $Z = 0.027$ , which is about the upper limit quoted by Perryman et al. (1998). From the  $\chi^2$ -contours in Fig. 1 and Fig. 2, one can see that the stellar evolutionary tracks from Geneva, Padova and CG92 yield acceptable and essentially equivalent fits of isochrones in agreement with the Hyades metallicity. However, the preferred solution (i.e. with the minimum  $\chi^2$ -value) in the sets of tracks points systematically to a smaller metallicity than expected (cf. in each Z–age diagram the location of the *open circle*, best fit, in comparison with the metallicity constraints shown with vertical lines).

Since the masses of the two components of 51 Tau are known to a good accuracy (respectively 7% and 12%), to check that the predicted masses are in agreement with the measured masses is one more stringent test. The best Geneva fit slightly underestimates the masses of 51 Tau (by  $0.5\sigma$  for the primary and  $1\sigma$  for the secondary component) as well as the Padova best fit (respectively  $1\sigma$  for the primary and  $\sim 1.2\sigma$  for the secondary) and CG92 (respectively  $0.5\sigma$  for the primary and  $1\sigma$  for the secondary) which means that these models are able to reproduce to a satisfying level the stellar masses in the mass range of 51 Tau (see Table 2 for details). The agreement is even better if we take into account the following point. When spectroscopic and astrometric orbital elements are known, one can derive the mass of each component, according to an hypothesis on the distance (i.e. the parallax). Hence, if we keep all the orbital parameters (period, eccentricity, velocity amplitude,...) as given in [TSL97a] and take the Hipparcos parallax value of 51 Tau, one



**Fig. 1.** 51 Tau system: influence of the Hipparcos parallax on the contour levels derived from the Geneva tracks. The photometric locations of each single star in the CMD are from Torres et al. [TSL97a], except the absolute magnitudes  $M_V$  in the *bottom panel* which are derived from the Hipparcos parallax. The correspondence between isochrones and symbols are directly given on the plots. For instance, the best fit isochrone (*solid line* in the CMD) is defined by  $Z = 0.020$ ,  $\log t = 8.88$ . In isocontours plots, the parameter values corresponding to the best fits ( $\chi^2_{\text{minimum}}$ ) are marked by *open circles*. The metallicity–age pair ( $Z = 0.024$ ,  $\log t = 8.80$ ) from Perryman et al. (1998) for the Hyades is shown for comparison (*star symbol*). It is important to notice that all the isochrones inside the  $1\sigma$  confidence levels are also good fits: an older isochrone is also a possible fit (e.g. the isochrone corresponding to the *triangle* defined by  $Z = 0.015$  and  $\log t = 9$ ). A comparison between *upper and bottom panels* shows that the  $1$ ,  $2$ , and  $3\sigma$  contour levels (respectively *solid*, *dashed* and *dot-dashed lines*) are not significantly modified. Vertical lines in contour levels diagrams show the observational limits for the metallicity of the Hyades.

**Table 2.** Comparison of theoretical mass estimates from isochrone age fitting of the system 51 Tau with the values of Torres et al. [TSL97a].

	[TSL97a]	Geneva <sup>a</sup>	Padova <sup>a</sup>	CG92 <sup>a</sup>
A	$1.80 \pm 0.13$	$1.74 \pm 0.06$	$1.67 \pm 0.04$	$1.72 \pm 0.05$
B	$1.46 \pm 0.18$	$1.27 \pm 0.05$	$1.24 \pm 0.04$	$1.28 \pm 0.05$

<sup>a</sup>  $1\sigma$  interval (this work).

**Table 3.** Comparison of theoretical age estimates from isochrone age fitting of 51 Tau with Perryman et al.’s determination.

Stellar models	$\log(\text{age})$ [yrs]
Geneva <sup>a</sup>	[8.60, 9.00]
Padova <sup>a</sup>	[8.50, 9.05]
CG92 <sup>a</sup>	[8.75, 9.05]
CESAM <sup>b</sup>	[8.76, 8.82]

<sup>a</sup>  $1\sigma$  interval (this work), assuming  $0.021 < Z_{\text{Hyades}} < 0.026$ .

<sup>b</sup> Perryman et al. (1998).

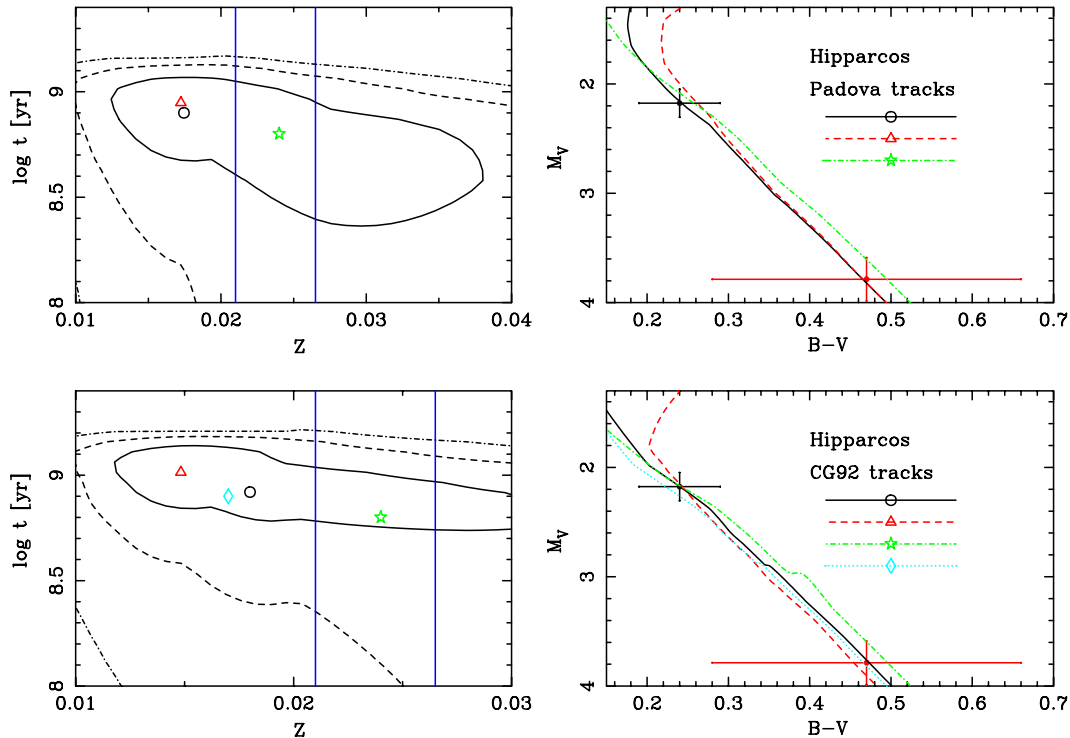
derives (from Eq. 2 in [TSL97c]) the new masses  $M_A \simeq 1.66 M_\odot$  and  $M_B \simeq 1.40 M_\odot$ , values that are even better matched by the three sets of theoretical models. Assuming the most conservative metallicity values of the Hyades, a close inspection of the

isocontours derived from the Geneva models reveals that the contours provide an age estimate – at the  $1\sigma$  level – between  $\log t = 8.6$  and  $9.0$  years (i.e. between  $0.4 \times 10^9$  and  $10^9$  years). A similar work with the Padova tracks give an age between  $\log t = 8.5$  and  $9.05$ , and with CG92 between  $\log t = 8.75$  and  $9.05$  years. As summarized in Table 3, these values are in good agreement with the age estimation of Perryman et al. (1998):  $\log t = 8.80^{+0.02}_{-0.04}$ , inferred from the isochrone fitting technique with the CESAM stellar evolutionary code (Morel 1997).

Finally, we would like to point out the need of new photometric data: the uncertainty on the Johnson (B–V) colour of the faintest star is larger by a factor of 4 than the primary. So, even if it appears clearly that the three sets of tracks do not fail the test, accurate (B–V) data for the less massive component at the same level as the primary should reduce the extent of the contours, allowing to perform more stringent tests.

### 3.2. Results for V 818 Tau

The V 818 Tau system (vB22) is a double-lined eclipsing binary (Mc Clure, 1982) with very well estimated masses (actually the most accurate masses known for Hyades members). Indeed, the



**Fig. 2.** 51 Tau system: Padova (*upper panels*) and CG92 tracks (*lower panels*) both taking into account the Hipparcos parallaxes. The photometric locations of each star in the CMD are from Torres et al. [TSL97a], but the absolute magnitude  $M_V$  is derived from the Hipparcos parallax. As in Fig. 1, vertical lines in contour levels diagrams show the observational limits of the metallicity of the Hyades, and the correspondence between isochrones and symbols are directly given on the plots. The best fits ( $\chi^2_{\text{minimum}}$ ) are marked by *open circles* (Padova:  $Z = 0.017$ ,  $\log t = 8.90$ , CG92:  $Z = 0.018$ ,  $\log t = 8.92$ ), but good fits can also be obtained with other isochrones: for example, the isochrones corresponding to the *star* ( $\log t = 8.80$  and  $Z = 0.024$ , from Perryman et al., 1998) and to the *triangle* (Padova:  $Z = 0.017$ ,  $\log t = 8.95$ , CG92:  $Z = 0.015$ ,  $\log t = 9.01$ ), slightly older and more metal poor than the best solution. In the CG92 diagrams (*lower panels*), the *dotted line* isochrone ( $Z = 0.017$ ,  $\log t = 8.90$ ) corresponds to the *diamond symbol* which is very close to the best solution (*open circle*). However, the two isochrones are quite different. In the CG92 CMD (*right bottom panel*), the small kink around  $B-V=0.4$  is not due to the colour transformation but to the CG92 model at  $1.41 M_{\odot}$ .

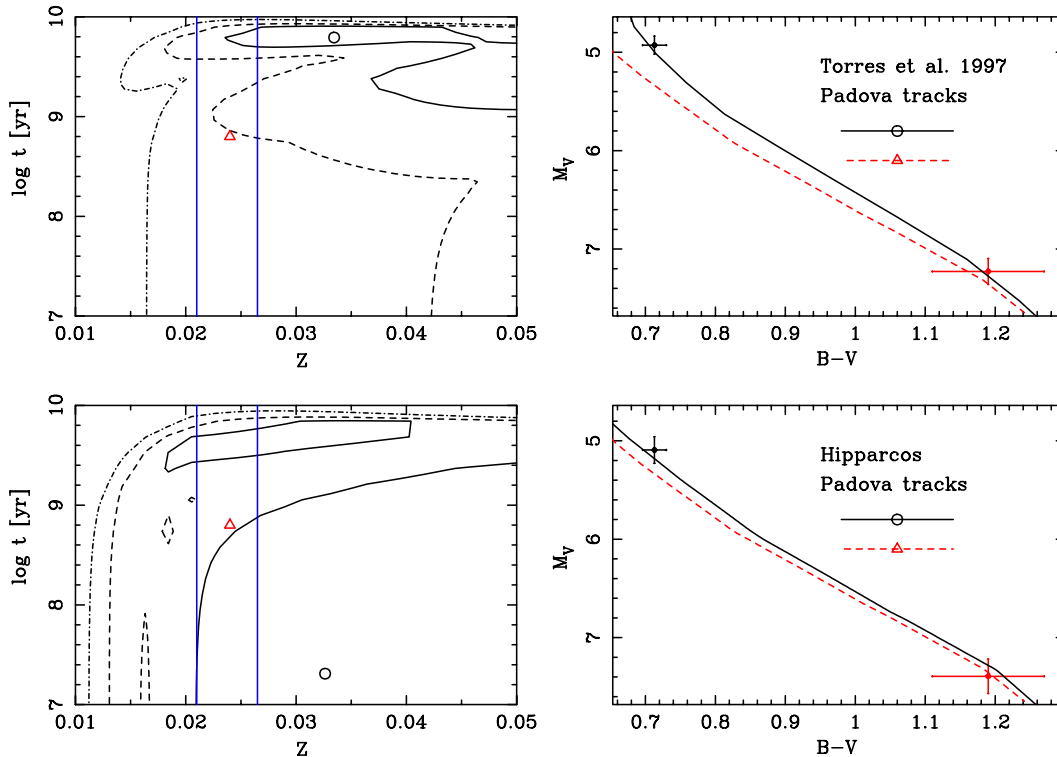
relative errors on the masses are less than 1%, and the secondary component is particularly interesting because it is one of the rare stars which is less massive than the Sun and whose mass is known with such high accuracy (cf. Andersen 1991). Unfortunately, this low mass star (about  $0.77 M_{\odot}$ ) does not allow us to test either the CG92 models – the lower available mass of these models being  $1 M_{\odot}$  – or the Geneva models whose lower mass limit is  $0.8 M_{\odot}$ . Nevertheless, we have tested Geneva tracks (for the primary component) coupled<sup>4</sup> with the Baraffe et al. (1995) models (for the low-mass secondary star), as well as the Padova group models whose lower mass limit is small enough for our purpose ( $0.6 M_{\odot}$ ).

Torres et al. [TSL97a] derived for this binary the distance  $d = 50.4 \pm 1.9$  pc indicating that V 818 Tau is slightly more distant than the cluster center. By using the Hipparcos parallax, we obtain  $d = 46.7^{+2.9}_{-2.6}$  pc, which seems to be in a better

<sup>4</sup> This simply means that the Geneva tracks were extrapolated with the Baraffe et al. models in the low mass region (below  $0.8 M_{\odot}$ ) for each metallicity. Of course, this point is a very rough approximation because the physics of these models are different, but it will not change our final conclusions.

agreement with the distance of the Hyades center. The confidence levels that we obtain by combining pre-Hipparcos data (see *upper panels* in Fig. 3) and the isochrone fitting technique with the Padova tracks in order to match simultaneously the locations of the two stars in the CMD, are in a clear disagreement with the observational constraints of the Hyades metallicity. As a matter of fact, the Padova as well as the Geneva tracks predict metallicities much larger than expected from observational determinations: 1.5 to 2 times solar metallicities ( $Z \in [0.03, 0.04]$ ) provide the best fits as shown in the *upper panels* of Fig. 3. The Padova isochrone corresponding to the metallicity–age Hyades solution of the detailed work of Perryman et al. (1998) is also shown (*dashed line* in the upper CMD of Fig. 3). This solution should be consistent with the observational metallicity of the Hyades, however, the fit is clearly bad in the CMD.

Now, if we consider the Hipparcos parallax of this binary system, the absolute magnitude (see in particular the primary component, which puts the more stringent constraints) is shifted towards fainter magnitudes, giving rise to significantly different  $\chi^2$ -contours (see confidence contours in the *lower panel* of Fig. 3). Hipparcos parallaxes have a strong influence on the shape of the isocontours that we obtain: for instance,  $1\sigma$  confi-



**Fig. 3.** V 818 Tau system: influence of the Hipparcos parallaxes on the contour levels derived from the Padova tracks. The photometric locations of each star in the CMD are from Torres et al. [TSL97a], except the absolute magnitude  $M_V$  in the *bottom panel* which is derived from the Hipparcos parallax. The best fit isochrones (*solid lines*) are defined by  $Z = 0.033$ ,  $\log t = 9.79$  (with Torres et al. parallaxes, *upper CMD*) and  $Z = 0.033$ ,  $\log t = 7.30$  (Hipparcos, *bottom CMD*). It is crucial to notice that all the isochrones inside the  $1\sigma$  confidence levels are also good fits. Vertical lines in contour levels diagrams show the observational limits for the metallicity of the Hyades. The metallicity–age couple ( $Z = 0.024$ ,  $\log t = 8.80$ ) from Perryman et al. (1998) for the Hyades is also shown for comparison (*triangle*). The corresponding isochrone (*dashed line*) clearly does not fit the system.

dence levels occupy a larger region with Hipparcos and are in a better agreement with the observational constraints (*vertical lines* in the  $Z$ - $t$  diagram). We wish to emphasise that even if the best displayed  $Z$ -value inferred from Hipparcos (*open circle* in the *bottom panel* of Fig. 3) is actually the same as with Torres et al. (1997) ( $Z \simeq 0.033$ ), it is worth noticing that the Hipparcos parallaxes give also possible solutions at  $1\sigma$  level with metallicities and ages lower than in the pre-Hipparcos  $Z$ - $t$  diagram (*left upper panel*) where solutions are confined in a region roughly defined by  $Z \geq 0.024$  if  $\log t \geq 9.7$ , and  $Z \geq 0.037$  if  $\log t \geq 9$ . Therefore, if one considers the confidence levels, the disagreement found using orbital parallaxes disappears, and the models do not fail anymore. We would like to mention the fact that this result is rather puzzling because the orbital parallaxes are a little more accurate than the Hipparcos parallaxes, that is why such variation was not expected. The change of shape is due to the fact that the distance derived from Hipparcos for V 818 Tau is about 8% smaller than from its orbital parallax. The better consistency between the contours diagram of the Hipparcos solution and the metallicity of the Hyades, which is the only reliable constraint, gives more weight to the Hipparcos distance than to the orbital parallax. This example highlights the importance of having very accurate but also reliable fundamental data,

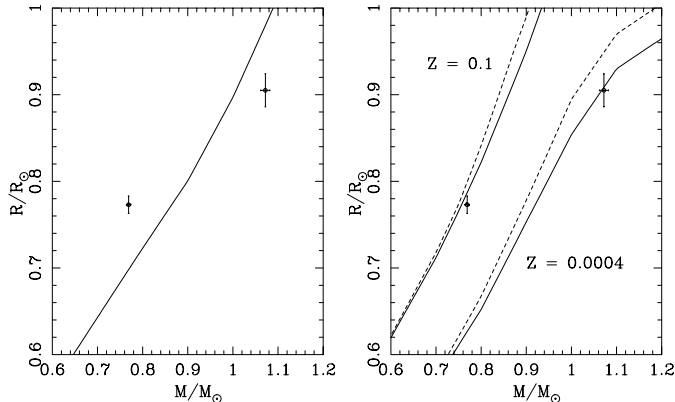
**Table 4.** Comparison of theoretical mass estimates from Padova isochrone age fitting of the system V 818 Tau with the values of [SM87] (Schiller & Milone, 1987) and [PS88] (Peterson & Solensky, 1988).

	[SM87]	[PS88]	Padova <sup>a</sup>
A	$1.080 \pm 0.017$	$1.072 \pm 0.010$	$1.020 \pm 0.04$
B	$0.771 \pm 0.011$	$0.769 \pm 0.005$	$0.744 \pm 0.02$

<sup>a</sup>  $1\sigma$  interval (this work).

because small errors on the data can lead to reject – by mistake – the validity of a stellar model.

As mentioned in the beginning of this section, the masses of the two components of V 818 Tau are known with an excellent accuracy (better than 1%, following the study of Peterson & Solensky, 1988, [PS88]). Therefore, to check that the stellar masses predicted by the models are in agreement with the true masses is probably the most critical test. A comparison is given in Table 4. The result is that the best Padova fit underestimates the masses of V 818 Tau by about  $5\sigma$  for both stars. This is not so bad because of the high level of accuracy of the masses:  $5\sigma$  only means  $0.05M_{\odot}$  for V 818 Tau A and  $0.025M_{\odot}$  for V 818 Tau B.



**Fig. 4.** V 818 Tau system in a Mass-Radius diagram where all the isochrones are derived from the Padova tracks. The mass of each star is from Peterson & Solensky (1988), as quoted by Torres et al. [TSL97a], and the radius is from Schiller & Milone (1987). In the *left panel*, the *solid line* isochrone ( $\log t \simeq 7.30$ ,  $Z \simeq 0.033$ ) is the best fit isochrone shown in the CMD of Fig. 3. Even if this isochrone allows to predict the correct mass for each component, it clearly does not fit V 818 Tau in the mass-radius diagram. In the *right panel*, four different isochrones are shown for comparison: with a high metallicity ( $Z = 0.1$ ) for two ages,  $t = 0$  (*solid line*) and  $t = 10^9$  yrs (*dashed line*) and with a very low metallicity ( $Z = 0.0004$ ) for the ages  $t = 0$  (*solid line*) and  $t = 10^9$  yrs (*dashed line*). There is no Padova isochrone which is able to fit simultaneously both components of V 818 Tau in the mass-radius diagram.

Moreover, since V 818 Tau is a double-lined eclipsing binary, the radius of each component is also known with an excellent accuracy (better than 2%). The stellar radius can also be computed from the effective temperature and the luminosity given by the Padova models. Therefore, it is possible to compare the stellar radii predicted by the models with the true radii. Unfortunately, even if Padova models predict a correct mass for each component of V 818 Tau, it appears clearly from Fig. 4 that there is no Padova isochrone able to fit both components of V 818 Tau in the mass-radius diagram. Even with the best fit isochrone obtained from the CMD of Fig. 3, the radius of the more massive component is overestimated by more than  $0.3 R_{\odot}$ , and the radius of the less massive component is underestimated by more than  $0.3 R_{\odot}$ . This test shows that masses are much less discriminant, as far as the power of the test is concerned, than radii, hence the importance of double-lined eclipsing binaries to fully constrain stellar tracks.

### 3.3. Results for $\theta^2$ Tau

The primary component of the spectroscopic binary  $\theta^2$  Tau (spectral type A7 III) is one of the brightest stars in the Hyades. Such a system is *a priori* very critical because it is composed by a main-sequence star and an evolved star, which allows us to test widely different evolutionary stages. The tests that we performed with this binary are shown in Fig. 5 where the locations in the CMD are from Torres et al. [TSL97c], except in

**Table 5.** Comparison of theoretical mass estimates from Geneva isochrone age fitting of the system  $\theta^2$  Tau with the values of [TPM95] (Tomkin et al., 1995) and [TSL97c] (Torres et al., 1997).

	[TPM95]	[TSL97c]	Geneva <sup>a</sup>
A	$2.1 \pm 0.3$	$2.42 \pm 0.30$	$2.37 \pm 0.02$
B	$1.6 \pm 0.2$	$2.11 \pm 0.17$	$1.95^{+0.06}_{-0.03}$

<sup>a</sup>  $1\sigma$  interval (this work).

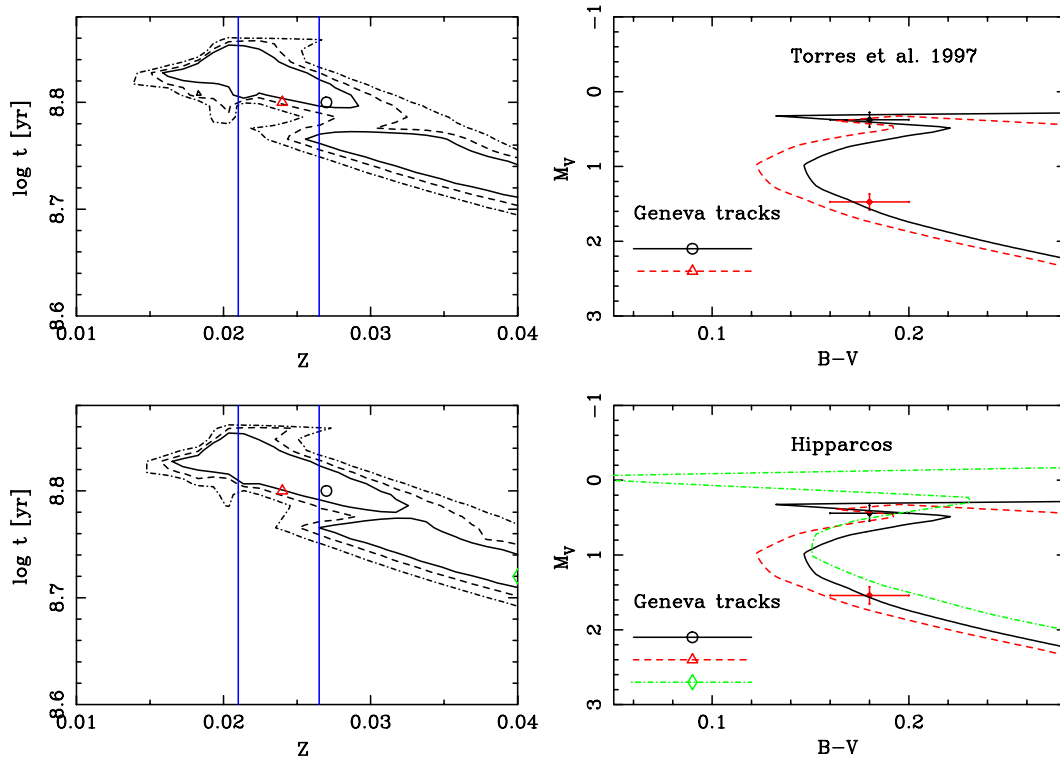
the *bottom panel* where the absolute magnitude  $M_V$  is derived from the Hipparcos parallax.

The first point is that the Hipparcos mission parallax has hardly an influence on the luminosity of the two components. Therefore, the 1, 2 and  $3\sigma$   $\chi^2$ -contour levels show no real significant differences. Moreover, the best fits obtained in Fig. 5 present a very similar age and metallicity, putting the most massive component at the end of the core hydrogen burning phase as pointed out by Torres et al. [TSL97c]. Nevertheless, if one believes a metallicity slightly poorer (for instance the solution shown as a triangle symbol in the *lower panel* of Fig. 5) – more in agreement with the Hyades metallicity and still acceptable inside the  $1\sigma$ -contour levels – then this massive star could already be on the beginning of the hydrogen-shell burning phase.

It is also worth noticing that both components of  $\theta^2$  Tau (also known as 78 Tau) are fast rotators. The primary component has  $v \sin i \simeq 80 \text{ km s}^{-1}$  (Slettebak et al. 1975) and the secondary seems to rotate even faster (estimations range from 90 to 170  $\text{km s}^{-1}$ ). Therefore, the rotational effect on their locations in the CMD should certainly not be neglected. The effect expected is typically a few tenths of magnitude in absolute magnitude and a few hundredths of magnitude in B–V, but these values are highly dependent of spectral type, age, and chemical composition (see for instance Maeder 1971 and Zorec 1992). As a direct consequence, this effect could modify the results presented in Fig. 5 because they are inferred from theoretical tracks which neglect the stellar rotation effect. However, a detailed study of this point is beyond the scope of this paper (and will be developed in a forthcoming paper).

Nevertheless, in the particular case of  $\theta^2$  Tau, the stellar rotation effect should not call into question the validity of the theoretical tracks of Geneva, Padova or CG92, because the contours show a large range of possible metallicity (isocontours derived from Padova models have the same shape/are identical than those of Geneva, as well as the CG92 models whose upper limit is  $Z=0.03$ ). Then, even with slight variations of magnitude and colour in the CMD, a part of these  $\chi^2$ -contours will always be in agreement with the observed metallicity constraints.

Since the masses of the two components of  $\theta^2$  Tau are known to a good accuracy (respectively 12% and 8%), to check that the predicted masses are in agreement with the measured masses is one more stringent test. Torres et al. [TSL97c] updated the previous work on this system (Tomkin et al. 1995), which resulted in an increase of the masses ( $M_A = 2.42 \pm 0.30 M_{\odot}$  instead of  $M_A = 2.10 \pm 0.60 M_{\odot}$  and  $M_B = 2.11 \pm 0.17 M_{\odot}$  instead of  $M_B = 1.60 \pm 0.40 M_{\odot}$ ). As shown in Table 5, the best Geneva



**Fig. 5.**  $\theta^2$  Tau system: influence of the Hipparcos parallaxes on the contour levels derived from the Geneva tracks. The photometric locations of each star in the CMD are from Torres et al. [TSL97a], except the absolute magnitude  $M_V$  in the *bottom panel* which is derived from the Hipparcos parallax. Vertical lines in contour levels diagrams show the observational limits of the metallicity of the Hyades. *Solid lines* isochrones in the CMD correspond to the best  $\chi^2_{min}$  fits (*open circles*,  $Z = 0.027$  and  $\log t = 8.80$ ) and *dashed lines* isochrones correspond to the *triangle* ( $Z = 0.024$  and  $\log t = 8.80$ , values from Perryman et al. 1998 for the Hyades). Another isochrone (*dot-dashed line*) corresponding to the *diamond* symbol ( $Z = 0.04$  and  $\log t = 8.72$ ) in the  $(t, Z)$  diagram is also shown in the Hipparcos CMD. This solution is still an acceptable CMD fit at the  $1\sigma$  confidence level even if the metallicity is twice solar, which is excluded by observational constraints.

fit gives a quite good agreement which means that these models are able to reproduce to a satisfying level the stellar masses in the mass range of  $\theta^2$  Tau.

The general conclusion of the study performed with  $\theta^2$  Tau is that the three theoretical models allow us to fit correctly the system for (metallicity, age)-pairs in agreement with the more recent constraints available about the metallicity of the Hyades cluster.

### 3.4. The influence of the Hipparcos parallaxes on the Hyades mass- $M_V$ relation

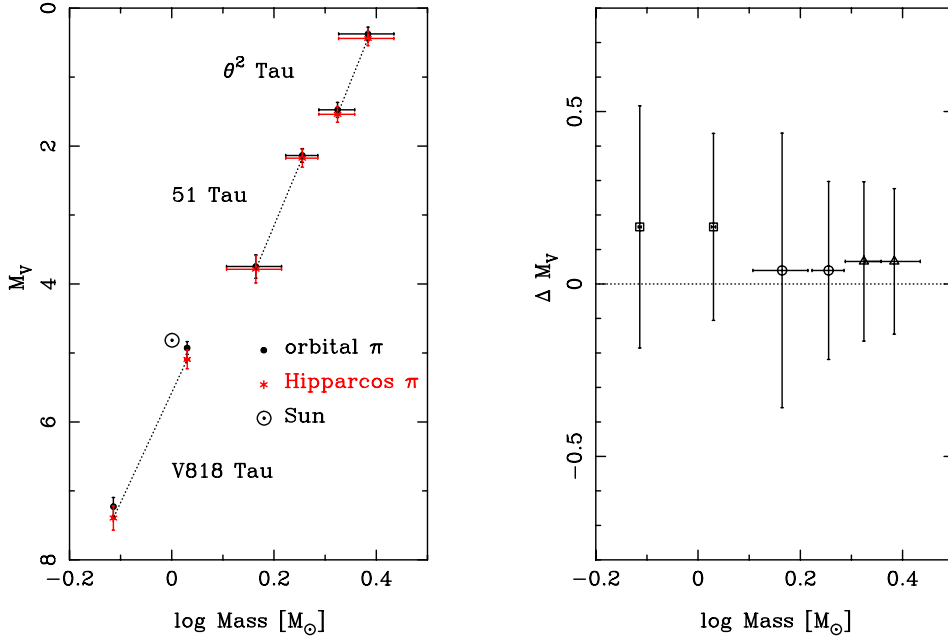
The discussion of the empirical mass-luminosity relation of the Hyades is beyond the scope of this work, because we only studied a tiny sample of member stars (see Torres et al. 1997 [TSL97a,b,c] for a critical and detailed discussion). However, it is interesting to show the influence of the Hipparcos parallaxes on the location of our working sample in a mass-luminosity diagram. As it is only the influence of Hipparcos that is under scrutiny, one can conclude from Fig. 6 (*left panel*) that the global shape of this empirical relation does not change. Actually, such a result was expected because of the excellent accuracy of the orbital parallaxes obtained before Hipparcos, but it was important to check this point. Thus, the difference,  $\Delta M_V$  ( $M_V$  from

Hipparcos parallaxes minus  $M_V$  from orbital parallaxes) is always smaller than 0.2 mag. and the error bars show a very good agreement with  $\Delta M_V = 0$  (Fig. 6, *right panel*).

## 4. Conclusion

The stellar theoretical models and tracks from Geneva, Padova and CG92 have been tested with well-detached binary systems in the Hyades open cluster: 51 Tau, V 818 Tau, and  $\theta^2$  Tau. Firstly, for each of the 3 selected systems, we computed simultaneous metallicity-age solutions to fit the two components in the CMD (a summary of the results is given in Table 6, taking into account the Hipparcos parallax). These results are shown in confidence regions in the  $(Z, t)$ -plane. Under the reasonable assumption that the metallicity must be the same and equal to the Hyades metallicity for the 6 components, we had one more constraint, seldomly available for field binaries. Moreover, the new Hipparcos parallaxes that we found for these systems allowed us to put more weight on the power of the test.

The results of these tests are very satisfying for the 3 sets of tracks, except for the case of V 818 Tau if we used the orbital parallax (unfortunately, the CG92 and Geneva models cannot be tested with the V 818 Tau data because the mass of the secondary is not in the proper range). As shown by the  $1\sigma$  confidence levels,



**Fig. 6.** Influence of the Hipparcos parallaxes on the Hyades mass- $M_V$  relation of the 6 stars studied in the present work. The components of each binary system are connected by *dotted lines* and the Sun is also shown for comparison ( $M_V=4.83$  from Bessell 1991). On the *right panel*, V 818 Tau (*square*), 51 Tau (*circle*) and  $\theta^2$  Tau (*triangle*) are displayed on a mass- $\Delta M_V$  diagram, where  $\Delta M_V$  means  $M_V$  from Hipparcos parallaxes minus  $M_V$  from orbital parallaxes. The  $\Delta M_V=0$  line (*dotted line*) is shown for comparison.

**Table 6.** Summary of the theoretical simultaneous metallicity–age estimates obtained from isochrone age fitting ( $1\sigma$  level, this work) taking into account the Hipparcos parallax.

System	Geneva		Padova		CG92	
	Z	log t	Z	log t	Z	log t
51 Tau	$0.020^{+0.010}_{-0.008}$	$8.88^{+0.22}_{-0.23}$	$0.017^{+0.021}_{-0.005}$	$8.90^{+0.15}_{-0.55}$	$0.018^{+0.012}_{-0.006}$	$8.92^{+0.23}_{-0.17}$
V818 Tau <sup>a</sup>			$0.033^{+0.017}_{-0.015}$	$7.30^{+2.50}_{-0.30}$		
$\theta^2$ Tau	$0.027^{+0.013}_{-0.010}$	$8.80^{+0.05}_{-0.09}$	$0.027^{+0.023}_{-0.011}$	$8.80^{+0.03}_{-0.11}$	$0.027^{+0.003}_{-0.005}$	$8.88^{+0.02}_{-0.02}$

<sup>a</sup> As explained in Sect. 3.2, the Geneva and CG92 models cannot be tested with the less massive component of V 818 Tau.

the Padova tracks predict a slightly too rich metallicity for the V 818 Tau members. The Geneva models also predict a larger metallicity but we wish to emphasize the fact that in this particular case the test does not have the same pertinence because we combined the Geneva with the Baraffe et al. (1995) models in order to be able to fit the low mass secondary component of V 818 Tau. Nevertheless, even if the best  $\chi^2$ -fit still gives a too large metallicity (reported as the central value in Table 6:  $Z \approx 0.033$ ) with Hipparcos, the inconsistency with the Hyades metallicity disappears as soon as we use the Hipparcos parallax, because the  $1\sigma$  confidence levels are in agreement with the metallicity constraints.

We also present some comparisons between the masses predicted by the models and the true stellar masses which give more weight to the quality of the models.

Nevertheless, although the Padova models predict a correct mass for each component of V 818 Tau, there is no Padova isochrone able to fit both components of V 818 Tau in the mass-radius diagram.

As explained above, these tests are not completely unambiguous because of the inherent problem of calibration between colour and effective temperature. However we do not expect significant errors due to the photometric transformations because we use the reliable transformations from the BaSeL models in

the well known Johnson photometric system and also because no disagreement exists in the range of (B–V) colour relevant for the present study, for a metallicity close to solar. Finally, for illustration purposes, we also present the influence of the Hipparcos parallaxes on the empirical mass-luminosity relation existing for these 6 stars.

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## References

- Alonso A., Arribas S., Martinez-Roger C., 1996, A&A 313, 873
- Andersen J., 1991, A&AR 3, 91
- Baraffe I., Chabrier G., Allard F., Hauschildt P.H., 1995, ApJ 446, L35
- Bessell M.S., 1991, AJ 101, 662
- Boesgaard A.M., 1989, ApJ 336, 798
- Boesgaard A.M., Friel E., 1990, ApJ 351, 467

- Bressan A., Fagotto F., Bertelli G., Chiosi C., 1993, *A&AS* 100, 647
- Brown A.G.A., Arenou F., van Leeuwen F., Lindegren L., Luri X., 1997, Proceedings of the Hipparcos Venice '97 symposium, ESA SP-402, astro-ph/9707040
- Cayrel R., Cayrel de Strobel G., Campbell B., 1985, *A&A* 146, 249
- Charbonnel C., Meynet G., Maeder A., Schaller G., Schaerer D., 1993, *A&AS* 101, 415
- Claret A., Giménez A., 1992, *A&AS* 96, 255, [CG92]
- ESA, 1997, The Hipparcos and Tycho Catalogues. ESA-SP 1200
- Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994a, *A&AS* 104, 365
- Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994b, *A&AS* 105, 29
- Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994c, *A&AS* 105, 39
- Flower P.J., 1996, *ApJ* 469, 355
- Lastennet E., Lejeune T., Valls-Gabaud D., 1996, ASP Conf. Ser. Vol. 90, 157
- Lastennet E., Lejeune T., Westera P., Buser P., 1999, *A&A* 341, 857 (astro-ph/9811103)
- Lastennet E., Valls-Gabaud D., 1999, *A&A*, to be submitted
- Lebreton Y., Gómez A.E., Mermilliod J.-C., Perryman M.A.C., 1997, Proceedings of the ESA Symposium Hipparcos - Venice '97, ESA-SP-402, p. 231
- Leitherer C., Alloin D., Alvensleben U.F.-v., et al., 1996, *PASP* 108, 996
- Lejeune T., Cuisinier F., Buser R., 1997, *A&AS* 125, 229
- Lejeune T., Cuisinier F., Buser R., 1998, *A&AS* 130, 65
- Lejeune T., Westera P., Buser R., 1999, in preparation
- Lutz T.E., Kelker D.H., 1973, *PASP* 85, 573
- Maeder A., 1971, *A&A* 10, 354
- McClure R.D., 1982, *ApJ* 254, 606
- Morel P., 1997, *A&AS* 124, 597
- Mowlavi N., Schaerer D., Meynet G., et al., 1998, *A&AS* 128, 471
- Nordström B., Andersen J., Andersen M.I., 1997, *A&A* 322, 460
- Perryman M.A.C., Brown A.G.A., Lebreton Y., et al., 1998, *A&A* 331, 81
- Peterson D.M., Solensky R., 1988, *ApJ* 333, 256, [PS88]
- Peterson D.M., Stefanik R.P., Latham, D.W., 1993, *AJ* 105, 2260
- Pols O.R., Schröder K.-P., Hurley J.R., Tout C.A., Eggleton P.P., 1998, *MNRAS* 298, 525
- Schaerer D., Meynet G., Maeder A., Schaller G., 1993a, *A&AS* 98, 523
- Schaerer D., Charbonnel C., Meynet G., Maeder A., Schaller G., 1993b, *A&AS* 102, 339
- Schaller G., Schaerer D., Meynet G., Maeder A., 1992, *A&AS* 96, 269
- Schiller S.J., Milone E.F., 1987, *AJ* 93, 1471, [SM87]
- Schwan H., 1991, *A&A* 243, 386
- Slettebak A., Collins II G.W., Boyce P.B., White N.M., Parkinson T.D., 1975, *ApJS* 29, 137
- Taylor B.J., 1980, *AJ* 85, 242
- Tomkin J., Pan X., McCarthy J.K., 1995, *AJ* 109, 780, [TPM95]
- Torres G., Stefanik R.P., Latham D.W., 1997, *ApJ* 474, 256, [TSL97a]
- Torres G., Stefanik R.P., Latham D.W., 1997, *ApJ* 479, 268, [TSL97b]
- Torres G., Stefanik R.P., Latham D.W., 1997, *ApJ* 485, 167, [TSL97c]
- Zorec J., 1992, In: Benest D., Froeschlé C. (eds.) *Hipparcos*. Goutelas 1992, p. 407