Abstract

Which sample of objects can give strong constraints on single-star evolution theory? Whilst star cluster members share the same age and the same metallicity, many questions (e.g. field stars contamination, stellar rotation, presence of unresolved binaries) are difficult to clarify properly when using their colour-magnitude diagram to compare with theoretical isochrones. Alternatively, binary stars can be used to put constraints on theoretical predictions. However, while the stellar mass is accurately known for some sample of well-detached binary stars, their metallicities are often poorly known. Then it appears that a better test could be obtained by combining both advantages (well-detached binaries members of a star cluster). This idea is applied in this work to binaries in the Hyades and one binary in the Cepheus OB3 association to test the validity of three independent sets of theoretical tracks. A detailed comparison of theoretical vs. observational masses (and radii when possible) are presented.

1. Introduction

Binary systems are the main source of fundamental data on stellar masses and radii. These data give stringent constraints that should be fitted by any set of theoretical stellar models. This work is exclusively focused on the mass estimate (and radius when available) of well-detached binary systems which can be presumed typical of single stars properties. Moreover three of them should share same age, chemical composition and distance due to their membership to the same open cluster. The 5 selected Hyades stars have individual stellar masses known with an accuracy of about 10% for 51 Tauri and \( \theta^2 \) Tauri and better than 1% for V818 Tauri. The mass accuracy is better than 3% for the CW Cephei eclipsing binary (Table 1). Moreover, these stars cover a wide mass range which is useful to obtain some interesting tests between \( \sim 0.77 \) and \( 13.5M_\odot \).

Comparisons between measured masses and predictions of three widely used models from the Geneva group (Mowlavi et al. 1998 and references therein), the Padova group (Fagotto et al. 1994 and references therein) and from Claret & Giménez (1992) (CG92 thereafter) are presented in the next sections. The theoretical quantities are derived from the isochrone technique in the colour magnitude diagram as described in Lastennet et al. (1999).

2. HIP 20087 = 51 Tauri

The 51 Tauri system is a spectroscopic binary and also a visual binary resolved by speckle interferometry. Since the masses of the two components of 51 Tauri are known to a good accuracy (respectively 7% and 12%), it is essential to check that the predicted masses are in agreement with the measured masses. The best Geneva fit slightly underestimates the masses of 51 Tauri (by \( 0.5\sigma \) for the primary and \( 1\sigma \) for the secondary component) as do the Padova 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). This means that these models are able to reproduce to a satisfying level the stellar masses in the mass range of 51 Tauri (see Table 2 for details).

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

| Stars | HIP Mass \((M_\odot)\) | Ref. |
|-------|-------------------|-----|
| 51 Tau A | 1.80 ± 0.13 | [TSL97a] |
| 51 Tau B | 1.46 ± 0.18 | [TSL97a] |
| V818 Tau A | 1.072 ± 0.010 | [PS88] |
| V818 Tau B | 0.769 ± 0.005 | [PS88] |
| \( \theta^2 \) Tau A | 2.42 ± 0.30 | [TSL97b] \(^{(1)}\) |
| \( \theta^2 \) Tau B | 2.11 ± 0.17 | [TSL97b] \(^{(2)}\) |
| CW Cep A | 13.52 ± 0.39 | [A91] |
| CW Cep B | 12.08 ± 0.29 | [A91] |

\(^{(1)}\) The value originally quoted by [TSL97a], 2.10±0.60 \( M_\odot \), is the determination of Tomkin et al. (1995) adjusting the error upward by a factor of two.

\(^{(2)}\) The value quoted by [TSL97a], 1.60±0.40 \( M_\odot \), is also from Tomkin et al. (1995) adjusting the error upward by a factor of two.
of each component adopting a 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 (ESA, 1997), one derives (from Eq. 2 in [TSL97b]) the new masses $M_A \approx 1.66M_\odot$ and $M_B \approx 1.40M_\odot$, values that are even better matched by the three sets of theoretical models.

3. HIP 20019 = V818 Tauri

The V818 Tau system 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 relative errors on the masses are less than 1% (Peterson & Solensky, 1988, [PS88]), 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 for a comprehensive review of accurate data in double-lined eclipsing binaries). 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 $M_\odot$.

Since the masses of the two components of V818 Tau are known with an excellent accuracy, checking that the stellar masses predicted by models are in agreement with the true masses is a critical test. A comparison is given in Table 3. The result is that the best Padova fit underestimates the masses of V818 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 0.05$M_\odot$ for V818 Tau A and 0.025$M_\odot$ for V818 Tau B.

Table 3: Comparison of theoretical mass estimates from Padova isochrone fitting of the system V818 Tau with the values of [SM87] (Schiller & Milone, 1987) and [PS88] (Peterson & Solensky, 1988).

|            | SM87       | PS88       | Padova$^a$ |
|------------|------------|------------|------------|
| A          | 1.080±0.017 | 1.072±0.010 | 1.020±0.04 |
| B          | 0.771±0.011 | 0.769±0.005 | 0.744±0.02 |

$^a$ this work.

Moreover, since V818 Tau is a double-lined eclipsing binary, the radius of each component is also known with an excellent accuracy (better than 2%): $R_A = 0.905\pm0.019R_\odot$ and $R_B = 0.773\pm0.010R_\odot$ according to Schiller & Milone (1987). On the other hand, 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 fairly correct mass for each component of V818 Tau, it appears clearly from Fig. 1 that there is no Padova isochrone able to fit both components of V818 Tau in the mass-radius diagram. With the best fit isochrone (which is not a good fit, see Fig. 1), the radius of the more massive component is overestimated by $\sim 4\sigma$, and the radius of the less massive component is underestimated by more than $7\sigma$. This shows that tests using masses without taking radii into account are much less discriminant, hence the importance of double-lined eclipsing binaries to fully constrain stellar tracks.

4. HIP 20894 = $\theta^2$ Tauri

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. 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 a powerful test.
Table 4: Comparison of theoretical mass estimates from Geneva isochrone fitting of the system $\theta^2$ Tau with the values of [TPM95] (Tomkin et al., 1995) and [TSL97b].

|        | TPM95  | TSL97b  | Geneva$^a$ |
|--------|--------|---------|------------|
| A      | 2.1±0.3| 2.42±0.30| 2.37±0.02  |
| B      | 1.6±0.2| 2.11±0.17| 1.95±0.06  |

$^a$ this work.

Torres et al. [TSL97b] updated the previous work on this system (Tomkin et al. 1995), which resulted in an increase of the masses ($M_A = 2.42M_\odot$ instead of $M_A = 2.10M_\odot$ and $M_B = 2.11M_\odot$ instead of $M_B = 1.60M_\odot$). As shown in Table 4, the best Geneva fit gives a quite good agreement which means that these models are able to reproduce to a very satisfying level the stellar masses in the mass range of $\theta^2$ Tau.

5. HIP 113907 = CW Cephei

This massive system is a member of the Cepheus OB3 association (Clausen & Giménez 1991). Table 5 shows a very good agreement between the masses predicted and the true masses (Andersen 1991, [A91]).

Table 5: Comparison of theoretical mass estimates from isochrone fitting of the system CW Cep with the values of Andersen (1991).

|        | A91     | Geneva$^a$ | Padova$^a$ | CG92$^a$ |
|--------|---------|------------|------------|----------|
| A      | 13.52±0.39| 13.48±0.29| 13.52±0.42| 13.44±0.56|
| B      | 12.08±0.29| 12.12±0.51| 12.08±0.50| 12.08±0.55|

$^a$ this work.

While the Padova models fail to fit the radius of the low mass stars of V818 Tau at the level of accuracy required, they do predict correctly the individual radii of V818 Tau and CW Cep, the only double-lined eclipsing binaries of the sample studied in this work. If Padova tracks predict the true stellar masses of V818 Tau (but only at a 5$\sigma$ level), they are not able to reproduce simultaneously its true masses and radii with a great accuracy. Unfortunately, this result cannot be checked with the two other Hyades binaries, hence the importance of double-lined eclipsing binaries to fully constrain stellar tracks.

In this context, accurate data of well-detached double lined eclipsing binaries (e.g. Kurpinska-Winiarska et al. 2000) are highly needed to perform further detailed comparisons. Since 1996, Oblak and collaborators (see Oblak et al. 1999) started an observational campaign of radial velocity curves for a sample of new eclipsing binaries discovered by Hipparcos, and these new data will be of great interest for a better understanding of stellar evolution.

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3/ The result 2/ points out that the Padova models have to be used cautiously for accurate studies in the mass range ~0.7-1.1 $M_\odot$.

4/ It is of interest to keep in mind that mass and radius can be compared with theoretical predictions only for V818 Tau and CW Cep, the only double-lined eclipsing binaries of the sample studied in this work. If Padova tracks predict the true stellar masses of V818 Tau (but only at a 5$\sigma$ level), they are not able to reproduce simultaneously its true masses and radii with a great accuracy. Unfortunately, this result cannot be checked with the two other Hyades binaries, hence the importance of double-lined eclipsing binaries to fully constrain stellar tracks.

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