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Stellar and tidal evolution of TZ Fornacis: a case of asynchronism

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Abstract. In this paper, we intend to explain the behaviour of the evolved double-lined eclipsing binary TZ Fornacis on the basis of tidal evolution derived from standard theories and the use of modern internal structure stellar models. TZ For is a binary system with a period of 75.7 days and a circular orbit, in which the less massive component (1.95 $M_\odot$) is rotating conspicuously faster than synchronism while its more massive mate (2.05 $M_\odot$) shows synchronized rotation with orbital motion. We discuss the use of the corresponding differential equations of tidal evolution, for the orbital eccentricity and the rotational velocities, instead of the generally assumed expressions for time scales. Results show that the integration of the differential equations provides a satisfactory explanation for the tidal and evolutionary status of TZ For. Using a normalized initial rotational velocity at the ZAMS for the components and assuming a rigid body rotation, we have found that at its present status, for an age of 1.3 Gyears, the system should show a ratio between the individual rotational velocities of the two components, v_2/v_1, of around 11 in good agreement with the observed value.

Key words: stars: TZ For – binaries: genreal – binaries: eclipsing – stars: evolution – stars: rotation

1. Introduction

TZ For is one of the very few double-lined eclipsing binary with evolved components and accurate determination of absolute dimensions. The masses of the two components are very similar, 1.95±0.03 and 2.05±0.06 $M_\odot$, but while the most massive member of the system has a radius of 8.32±0.12 $R_\odot$, the radius of the secondary is only 3.96±0.09 $R_\odot$. A detailed study of the system was published by Andersen et al. (1991) who found that the primary, more massive, star is rotating synchronously with the orbital period while the secondary is rotating about 16 times faster than expected under the assumption of synchronization. The observed values of vsin i are 42 ±2 and 4±1 km/s, i.e., the secondary component rotates about 10 times faster than the primary. These values should be compared with those corresponding to synchronization of 2.6±0.1 and 5.5±0.1 for the secondary and the primary, respectively.

In the following section, we analyze TZ For from the point of view of stellar models and tidal interactions taking into account the existing controversy about the actual position of the component stars in the HR diagram which is due to the uncertainties in the input physics of the adopted theoretical models, namely, the actual amount of convective core overshooting and new radiative opacities.

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2. Numerical methods and stellar models

We have adopted the formalism proposed by Tassoul (1987) to investigate the tidal interactions of TZ For, and the derived equations are given here. The effective time of circularization takes into account the influence of both stars simultaneously and can be written as

$$\frac{1}{\tau_{cir}} = \frac{1}{\tau_{cir,1}} + \frac{1}{\tau_{cir,2}} \quad (1)$$

where the subindices 1 and 2 refer to the primary and the secondary component, respectively.

For synchronization effects, the time scale is given by

$$\tau_{syn} = 5.35 \times 10^{2+\gamma-N/4}\frac{(1+q)}{q}L^{-1/4}M^{5/4}R^{-3}P^{11/4} \quad (2)$$

while, for circularization, we have

$$\tau_{cir} = 9.4 \times 10^{3+\gamma-N/4}(1+q)^{2/3}\beta^{-2}L^{-0.25}M^{23/12}R^{-5}P^{49/12} \quad (3)$$

where masses, radii and luminosities are expressed in solar units, q is the mass ratio, the period P is given in days, and β is the fractional gyration radius. N is given by the eddy viscosity in the outermost surface layers, in such way that $\mu_v=10^N\mu_r$ where μ_r is the radiative viscosity (see Tassoul 1987).

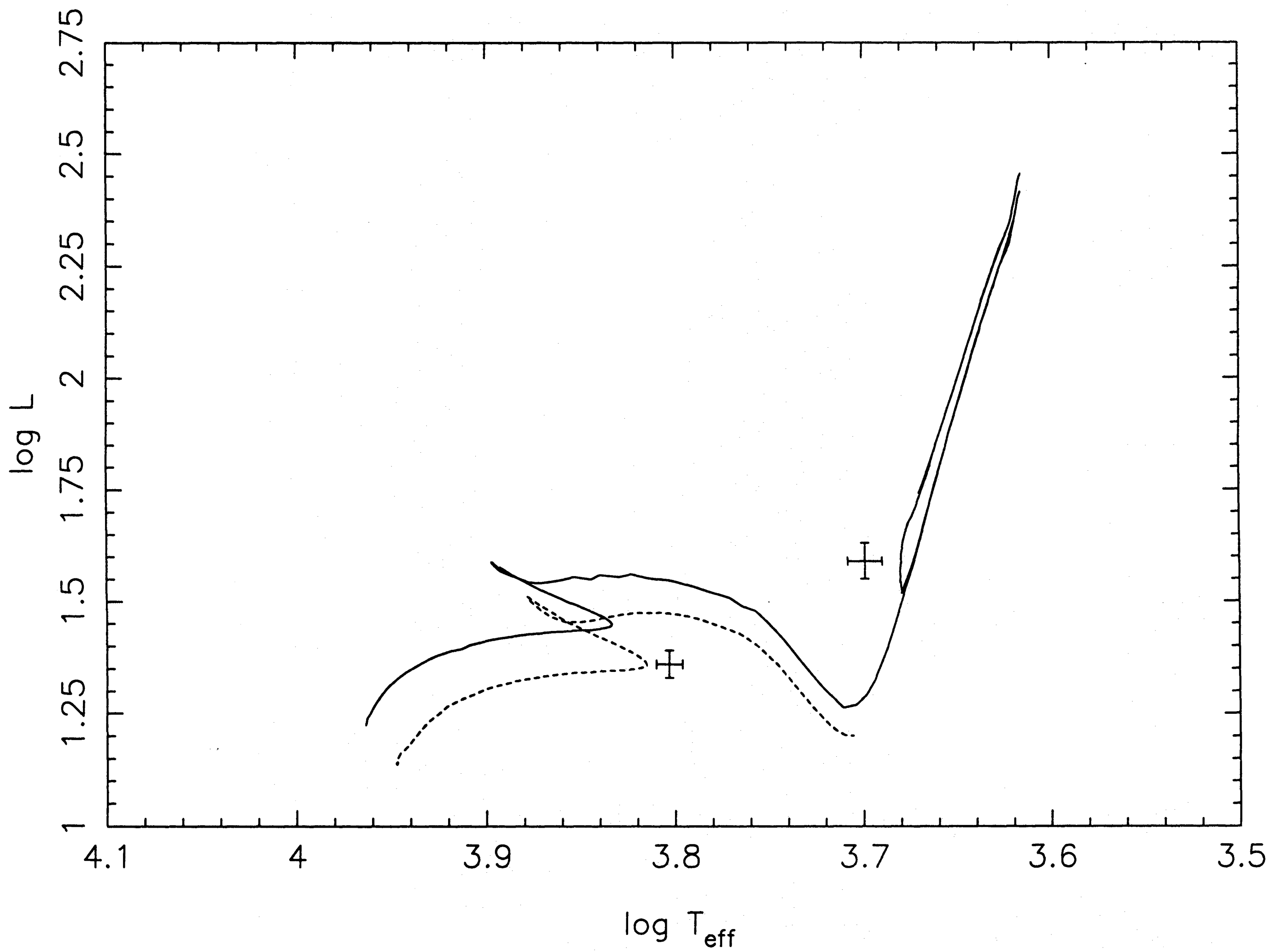

Fig. 1. HR diagram for TZ Fornacis. Theoretical models were computed for the accurately measured masses. The full line denotes the evolutionary track for 2.05 $M_\odot$ and the dashed line the 1.95 $M_\odot$ model. For the sake of clarity, we have drawn only part of the evolutionary track for the secondary component. Core overshooting was considered with α_{ov}=0.20, and the adopted chemical composition was X=0.70, Z=0.02, while the mixing length parameter was taken to be α=1.5

We assumed in our study that the period remains constant during the evolutionary life of the binary system and the corresponding differential equations, for the above given time scales, are

$$\frac{d\ln(\Omega_i - \Omega_o)}{dt} = -\frac{1}{\tau_{syn}} \tag{4}$$

$$\frac{d\ln e}{dt} = -\frac{1}{\tau_{cir}} \tag{5}$$

It should be noted that we do not assume the synchronization time scale to be given by $10\tau_{sd}$, with N=0, as adopted by Tassoul (1987). We have used a different approach as a consequence, among other effects, of eq. 1., which leads to an expression for the synchronization time scale as $10^{\gamma}\tau_{sd}$, where γ should not be far from 1. A detailed analysis of around 40 double-lined eclipsing binary systems with good determinations of their absolute dimensions (Andersen 1991), through the comparison with stellar models and the study of tidal interactions (Claret et al. 1994), has allowed us to estimate γ to be of the order of 1.6, i.e, τ_{syn}=$40\tau_{sd}$.

On the other hand, the comparison with stellar models by Claret & Giménez (1992) indicated that the existence of some amount of core overshooting is needed to explain the position of the secondary which appears to be near the "red hook" of the HR diagram. These theoretical models take into account the latest opacity tables by Rogers & Iglesias (1991). The primary component should moreover be in the core helium burning phase. By assuming this, we can derive a common age of 1.3 Gyears (log age=9.11) for both stars of TZ For. The theoretical HR diagram for this system is shown in Fig. 1. The models were

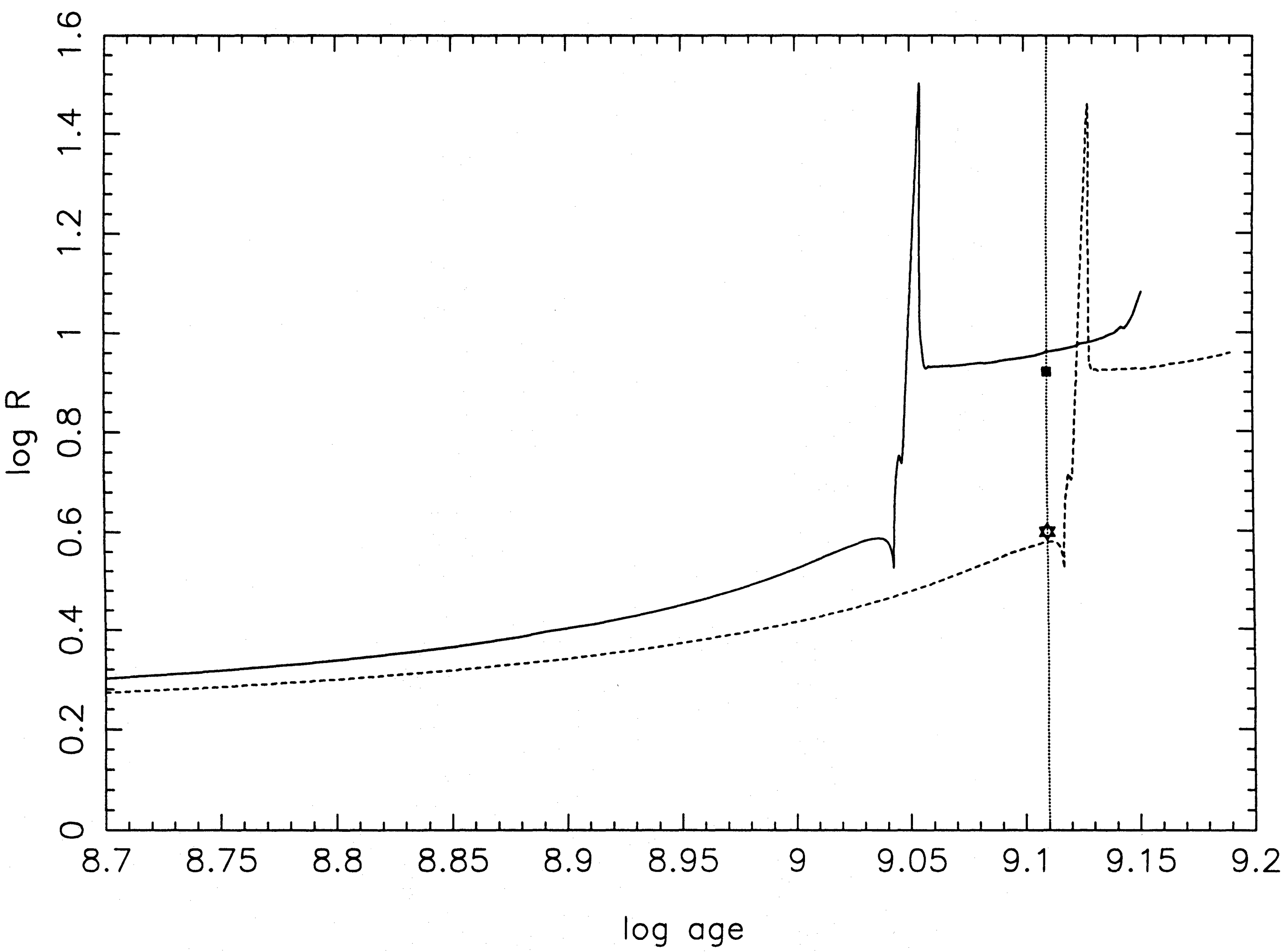

Fig. 2. Log age versus log R (R in solar units) for the same models of Fig. 1. Note that the best isochrone is represented by a dotted vertical line which connects the full square (denoting the primary component) and the asterisk (for the secondary)

computed with X=0.70, Z=0.02, α=1.5 and an amount of core overshooting corresponding to d/H$_p$=0.20.

A more detailed inspection of the models in the log R-log age plane (Fig. 2) indicates indeed that a reasonable good fitting is achieved for a common age of 1.3×10^9 years. The advantage of this procedure is that we do not use observational data about the effective temperatures which may present calibration problems.

Assuming that the primary is in the core helium burning phase and the secondary is near the "red hook" we are, moreover, able to analyse the tidal evolution of the system. The differential Eqs. 4 and 5 can be integrated, assuming that the period is constant along the evolutionary life of both stars, and the results indicate, within the uncertainties of the theory of tidal evolution, that the time of synchronization for the components stars and the circularization time of the orbit are of the same order of the evolutionary age, i.e., log t_{syn1}=9.00, log t_{syn2}=9.03, log t_{cir}=9.05. It should be noted here that we refer to synchronization and circularization times, and not to time scales, as the times derived from theoretical models to be needed to achieve the equilibrium status. The use of estimations based only on time scales is particularly dangerous in some evolutionary phases, like that of TZ For, and may lead to wrong interpretations.

Figure 3 shows the dependence of the critical values of surface gravity with the orbital period for both stars (see Fig. 1 by Claret & Giménez 1991).

The position of the secondary component is "out of the critical curve", but closer to it than the primary. In fact, the ratio r_1/r_2 is around 2 while the masses are very similar, and the differential evolution has a relevant role here. It should be remembered that log g in Fig. 3 represents the values for which the equilibrium is achieved and therefore they have intrinsic errors much larger than the evolutionary values.

It is very difficult to establish boundary conditions for the rotation of ZAMS stars and we shall avoid this additional complication. At the same time we would like to get some information about the evolution of the rotational velocities. We have adopted a simple model assuming that the stars rotate as rigid bodies. In such a way, we are able to predict, with respect to ZAMS velocities, what will be the rotation at a given time.

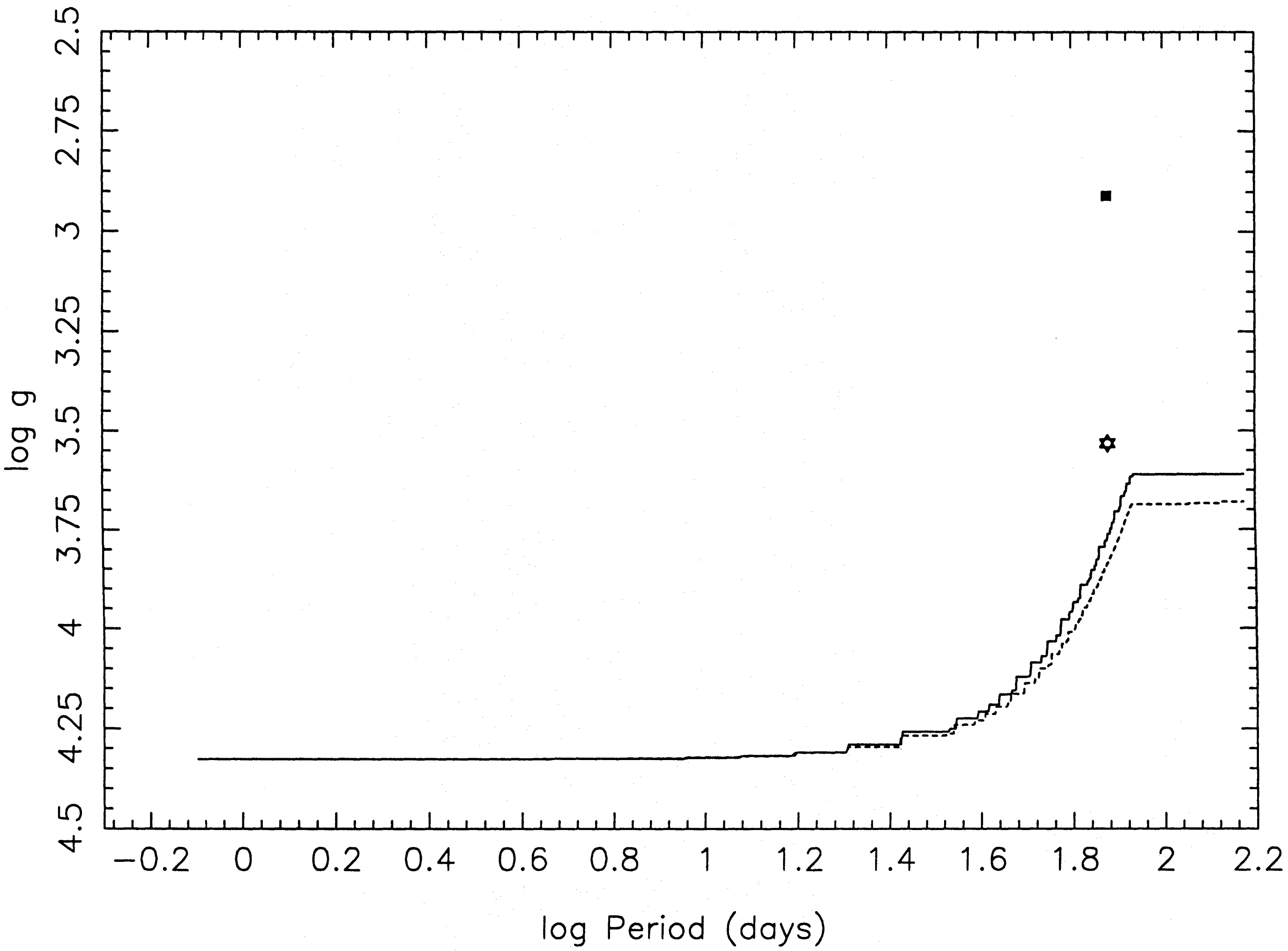

Fig. 3. Critical values for log g for synchronization computed for a binary system with 1.95 and 2.05 $M_\odot$ components as a funtion of the orbital period. Symbols as in Fig. 2

The most important data will come as the theoretical ratio v_2/v_1. The results can be seen in Fig. 4 were we drawn only part of the main sequence since the values in that phase are nearly equal. A gratifying result can be extracted from this figure: the theoretical ratio for the normalized velocities is about 11 for a log age=9.11, as indicated by the full square (secondary) and for the asterisk (primary). As commented before, the observed value is around 10.

3. Final remarks

Of course, one could use other γ values and "decrease" in this way the corresponding circularization and synchronization times, so that they become a little smaller than the derived age and can achieve a more confortable explanation in terms of inequalities. We think that such a procedure would have two inconvenients: firstly, it does not have observational (in terms of statistics) support and secondly, given the theoretical errors involved in the computation of stellar models and in the theory of tidal interactions, the present results are very satisfactory. On the other hand, it is important to point out that in this scenario, we did not have to assume an initial nearly-circular orbit.

We would like to emphasize the importance of the integration of the differential equations governing orbital parameters, namely, orbital frequency and eccentricity, as well as the careful comparison with stellar models in tidal interactions investigations. Indeed, to consider only the scale time is a risky approach for the more evolved systems.

Considering Figs. 2 and 4, we see that TZ For A is in a relative slow evolutionary phase and its radius remains almost constant up to log age $\approx$ 9.14. However, for TZ For B the situation is the opposite since in the same time interval its radius will increase twice the present value. In such a situation the secondary would also be synchronized as we can inspect directly from Fig. 4.

Finally, with respect to theoretical velocities ratio, many sources of uncertainty are involved in the process to estimate it, like the angular momentum distribution in the interior. However, despite the numerical good agreement which should be taken with care, the good result of the present investigation is that

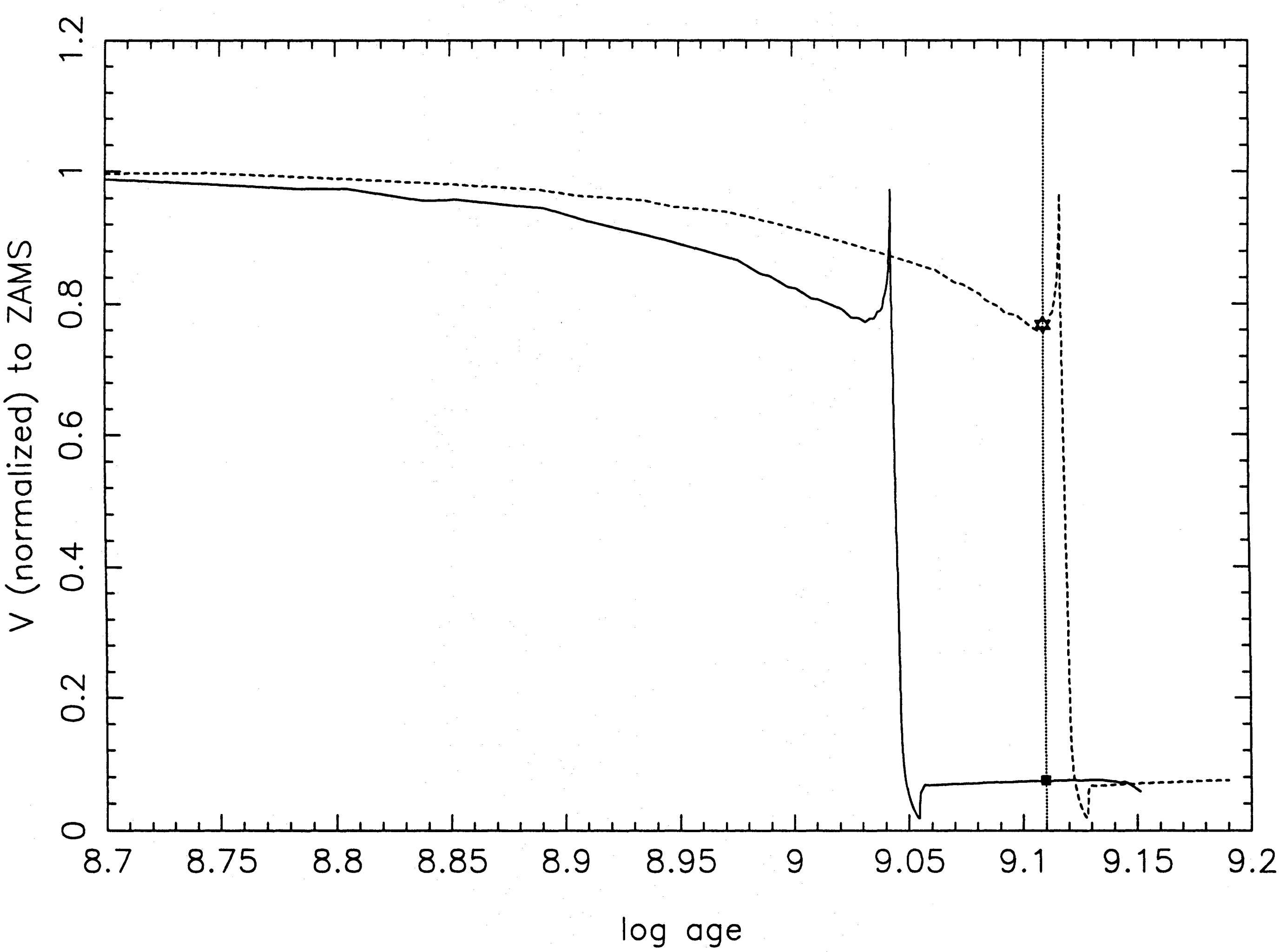

Fig. 4. Normalized rotational velocities as a function of time. The intersection of dotted line with the corresponding evolutionary tracks gives the velocities normalized to ZAMS value

we were able to show, within the theoretical and observational error bars, how TZ For evolved, achieved an equilibrium state for circularization and synchronization for the primary while, simultaneously, the high degree of asynchronism in the secondary could be explained in the same context.

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