Asteroseismic modelling of the metal-poor star \(\tau\) Ceti

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ABSTRACT

Context. Asteroseismology is an efficient tool not only for testing stellar structure and evolutionary theory but also constraining the parameters of stars for which solar-like oscillations are presently detected. As an important southern asteroseismic target \(\tau\) Ceti, is a metal-poor star. The main features of the oscillations and some frequencies of \(\tau\) Ceti have been identified. Many scientists propose to comprehensively observe this star as part of the Stellar Observations Network Group.

Aims. Our goal is to obtain the optimal model and reliable fundamental parameters for the metal-poor star \(\tau\) Ceti by combining all non-asteroseismic observations with these seismological data.

Methods. Using the Yale stellar evolution code (YREC), a grid of stellar model candidates that fall within all the error boxes in the HR diagram have been constructed, and both the model frequencies and large- and small- frequency separations are calculated using the Guenther’s stellar pulsation code. The \(\chi^2\) minimization is performed to identify the optimal modelling parameters that reproduce the observational constraints within their errors. The frequency corrections of near-surface effects to the calculated frequencies using the empirical law, as proposed by Kjeldsen and coworkers, are applied to the models.

Results. We derive optimal models, corresponding to masses of about 0.775–0.785 \(M_\odot\) and ages of about 8–10 Gyr. Furthermore, we find that the quantities derived from the non-asteroseismic observations (effective temperature and luminosity) acquired spectroscopically are more accurate than those inferred from interferometry for \(\tau\) Ceti, because our optimal models are in the error boxes B and C, which are derived from spectroscopy results.

Key words. asteroseismology – stars: individual: \(\tau\) Ceti – stars: oscillations – stars: low-mass

1. Introduction

The solar five-minute oscillations have led to a wealth of information about the internal structure of the Sun. These results have stimulated various attempts to detect solar-like oscillations for a handful of solar-type stars. Solar-like oscillations have been confirmed for several main-sequence, subgiant and red giant stars by a handful of solar-type stars. Solar-like oscillations have been con-stimulated various attempts to detect solar-like oscillations for a number of stars, and the results have been published in various papers. The observational constraints available to \(\tau\) Ceti are summarized in Sect. 2, while the details of the evolutionary models are presented in Sect. 3. The seismic analyses are carried out in Sect. 4. Finally, the discussion and conclusions are given in Sect. 5.

\(\tau\) Ceti (HR 509, HD 10700) is a G8 V metal-poor star, belonging to population II. Extensive analyses of this star have been performed by many scientists who have provided different non-seismic observational results (such as effective temperature \(T_{\text{eff}}\) and luminosity \(L\)), depending on the different methods used, i.e. interferometry and spectroscopy. Teixeira et al. (2009) detected solar-like oscillations on \(\tau\) Ceti, identified some possible existing frequencies, and obtained the large separation around \(\Delta v = 169\ \mu\text{Hz}\) with HARPS. These seismological data will provide a constraint on the fundamental parameters of \(\tau\) Ceti. Moreover, \(\tau\) Ceti will be one of the most promising southern asteroseismic targets of the seismology programme of Stellar Observations Network Group (Metcalfe et al. 2010).

In this work, using a mixture of conventional and asteroseis-mic observed constraints, we try to determine modelling parameters of \(\tau\) Ceti with YREC. The observational constraints available to \(\tau\) Ceti are summarized in Sect. 2, while the details of the evolutionary models are presented in Sect. 3. The seismic analyses are carried out in Sect. 4. Finally, the discussion and conclusions are given in Sect. 5.
Table 1. Non-asteroseismic observational data of τ Ceti.

| Observable | Value | Source |
|------------|-------|--------|
| Effective temperature $T_{\text{eff}}$(K) | 5264 ± 100 | (1) |
| Luminosity $L/L_\odot$ | 5525 ± 12 | (3) |
| Metallicity [Fe/H] | 0.52 ± 0.03 | (4) |
| Surface heavy-element abundance $[Z/X]_S$ | 0.0073 ± 0.0005 | (5) |
| Radius $R/R_\odot$ | 0.773 ± 0.024 | (5) |

References. (1) Soubiran et al. (1998); (2) Teixeira et al. (2009); (3) Pijpers et al. (2003); (4) Pijpers (2003); (5) this paper.

2. Observational constraints

2.1. Non-asteroseismic observational constraints

The metallicity derived from observations is [Fe/H] = −0.5 ± 0.03 (Soubiran et al. 1998). The mass fraction of heavy-elements, Z, was derived assuming log[$Z$/X] = [Fe/H] + log[$Z$/X]$_\odot$, and [Z/X]$_\odot$ = 0.0230 (Grevesse & Sauval 1998), for the solar mixture. We can therefore deduce that [Z/X]$_\odot$ = 0.0068−0.0078. The radius, as an important parameter for constraining stellar models, was first measured by Pijpers et al. (2003) using interferometry. They determined the radius of τ Ceti corresponding to 0.773 ± 0.004(int)± 0.02/ext $R_\odot$. The measurement of the radius was then improved by Di Folco et al. (2004) and Di Folco et al. (2007). Finally, Di Folco et al. (2007) determined the radius $R$ = 0.790 ± 0.005$R_\odot$. In our work, we use a large value of radius $R$ = 0.773 ± 0.024$R_\odot$ which includes all the surrounding observational radius.

The effective temperature and luminosity of τ Ceti are both derived from spectroscopy (5264±100 K and 5.2±0.03 $L_\odot$), and by ensuring that we reproduce the measured radius (5525±12 K, 0.500±0.006 $L_\odot$), using interferometry (Soubiran et al. 1998; Pijpers et al. 2003). In addition the luminosity of a star can be obtained by combining our knowledge of the magnitude and distance. For τ Ceti, the apparent magnitude $V$ = 3.50 ± 0.01, with the revised parallax, gives an absolute magnitude $M_V$ = 5.69 ± 0.01. Teixeira et al. (2009) derived a luminosity for τ Ceti of $L/L_\odot$ = 0.488 ± 0.010, using bolometric correction for τ Ceti B.C. = −0.17 ± 0.02 (Casagrande et al. 2006) and adopting an absolute bolometric magnitude for the Sun of $M_{\odot}$ = 4.74 (Bessell et al. 1998).

Using above different effective temperatures and luminosities, we can obtain three error boxes, which error box A (5255±12 K, 0.50 ± 0.06 $L_\odot$) are denoted by crosses, error box B (5264 ± 100 K, 0.52 ± 0.03 $L_\odot$) denoted by triangles, and error box C (5264 ± 100 K, 0.488 ± 0.010 $L_\odot$) denoted by diamonds, shown in Fig. 1d, respectively. Meanwhile, we decided to increase all errors by a factor of 1.5, so that our calibration of the star is only weakly constrained by these values.

All non-asteroseismic observational constraints are listed in Table 1.

2.2. Asteroseismic constraints

Solar-like oscillations of the G8V star τ Ceti were detected by Teixeira et al. (2009) with the HARPS spectrograph. Thirty-one individual modes are identified (see Table 1 in Teixeira et al. 2009). The large frequency separation is about $\Delta \nu$ = 169 $\mu$Hz.

| Variable | Minimum value | Maximum value | $\delta$ |
|----------|---------------|---------------|---------|
| Mass $M/M_\odot$ | 0.770 | 0.795 | 0.005 |
| Mixing length $\alpha$ | 0.8 | 1.8 | 0.2 |
| Initial heavy element abundance $Z$ | 0.001 | 0.008 | 0.0005 |
| Initial hydrogen abundance $X$ | 0.70 | 0.75 | 0.01 |

Notes. The value $\delta$ defines the increment between minimum and maximum parameter values used to create the model array.

3. Stellar models

We calculated many evolutionary tracks using Yale stellar evolution code (YREC; Demarque et al. 2008) by inputting different parameters shown in Table 2.

The mass range are $M = 0.770$–0.795 $M_\odot$ with the increment value 0.005 $M_\odot$. Initial heavy element abundance range are $Z_\odot$ (0.001–0.008) with the increment value 0.0005 and initial hydrogen abundance $X_\odot$ (0.70–0.75) with the increment value 0.01. Energy transfer by convection is treated according to the standard mixing-length theory, and the boundaries of the convection zones are determined by the Schwarzschild criterion (see Demarque et al. 2008, for details of the YREC). We set the mixing length parameter $\alpha = 0.8−1.8$ with the increment value 0.2. Using these parameter space, we created the model array. The initial zero-age main sequence (ZAMS) model used for τ Ceti is created from pre-main-sequence evolution calculations. These models are calculated using the updated OPAL equation-of-state tables EOS2005 (Rogers & Nayfonov 2002). We used OPAL high temperature opacities (Iglesias & Rogers 1996)
supplemented with low temperature opacities from Ferguson et al. (2005). The NACRE nuclear reaction rates (Angulo et al. 2005) supplemented with low temperature opacities from Ferguson 1999) were used. The Krishna-Swamy Atmosphere T- relation (refer to the values from Teixeira et al. 2009) as constraint, we using the temperature, luminosity, radius, and larger separation (Kjeldsen & Bedding 1995; Miglio et al. 2009a, b). Furthermore, the temperature, luminosity, radius, and larger separation, which are also given in Table 1. We also decided to adopt a large error (all errors are increased by a factor of 1.5), so that our calibration of the star is only weakly constrained by these values, which is not precisely determined. Figure 2a presents the values χ^2 versus age t of selected models that are shown in Fig. 1d. We find that we cannot select an optimal model from Fig. 2a. From Fig. 2a, we find that it is difficult to select an optimal model depending mainly on the non-seismic constraints and Δν, which was estimated by simply scaling from solar value using Eq. (1). Hence, a detailed pulsation analysis are needed in the next step.

\[
\Delta \nu = \sqrt{\frac{M/M_\odot}{(R/R_\odot)}^2} \times 134.9 \mu Hz.
\]  

(1)

We now consider a function that describes the agreement between the observations and the theoretical results

\[
\chi_1^2 = \sum_{i=1}^{5} \frac{(\delta \nu_i - \Delta \nu_i)^2}{\sigma_C^{obs}_i}.
\]

(2)

Table 3. The observational frequencies and the theoretical frequencies for model M1 & M2 before and after correction for near-surface offset, respectively.

| n   | l = 0 | l = 1 | l = 2 | l = 3 | l = 0 | l = 1 | l = 2 | l = 3 | l = 0 | l = 1 | l = 2 | l = 3 |
|-----|------|------|------|------|------|------|------|------|------|------|------|------|
| 18  | 3293.4 | ...  | ...  | 3296.149 | 3377.700 | 3455.831 | 3529.092 | 3296.276 | 3377.775 | 3455.826 | 3529.043 |
| 19  | 3461.7 | ...  | ...  | 3692.9 | 3465.623 | 3547.268 | 3625.910 | 3699.994 | 3645.717 | 3547.304 | 3625.854 | 3699.900 |
| 20  | 3634.5 | ...  | ...  | 3863.7 | 3635.309 | 3717.485 | 3796.205 | 3870.802 | 3635.352 | 3717.479 | 3691.199 | 3870.664 |
| 21  | 3799.3 | 3885.3 | ...  | 4030.3 | 3805.155 | 3878.715 | 3967.102 | 4042.136 | 3805.169 | 3966.871 | 4041.987 | 3804.971 |
| 22  | 3976.1 | 4046.8 | 4126.1 | 4202.5 | 3975.769 | 4058.363 | 4138.126 | 4213.984 | 3975.764 | 4058.279 | 4137.957 | 4213.769 |
| 23  | 4139.9 | 4222.7 | 4298.2 | ...  | 4146.398 | 4229.669 | 4305.760 | 4385.981 | 4146.331 | 4229.539 | 4305.577 | 4385.721 |
| 24  | ...  | 4388.3 | 4469.5 | 4545.1 | ...  | 4317.694 | 4401.101 | 4481.820 | ...  | 4317.566 | 4400.922 | 4481.566 |
| 25  | ...  | 4481.8 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 26  | ...  | 4548.1 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 27  | ...  | 4652.3 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 28  | ...  | 4816.1 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 29  | ...  | 5072.3 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 30  | ...  | 5240.0 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 31  | ...  | 5497.9 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |

\[
\Delta \nu = \sqrt{\frac{M/M_\odot}{(R/R_\odot)}^2} \times 134.9 \mu Hz.
\]

(1)

We now consider a function that describes the agreement between the observations and the theoretical results

\[
\chi_1^2 = \sum_{i=1}^{5} \left( \frac{\delta \nu_i - \Delta \nu_i}{\sigma_C^{obs}_i} \right)^2.
\]

(2)

4. Asteroseismic constraints of fundamental parameters

Using Guenther’s pulsation code (Guenther 1994), we calculate the adiabatic low-\( l \)-mode frequencies, the large- and small- frequency separations (\( \Delta \nu_{l,l} \equiv \nu_{l,l} - \nu_{l-1,l} \) and \( \Delta \nu_{l,l,l} \equiv \nu_{l,l,l} - \nu_{l-1,l,l} \), defined by Tassoul 1980) of all the selected models. We compare
Fig. 2. a) $\chi^2_1$ values derived from Eq. (2), plotted as a function of age; b) $\chi^2_\nu$ values derived from Eq. (3), plotted as a function of age; c) $\chi^2_{\nu,c}$ values derived from Eq. (6), plotted as a function of age; d) $|r_0 - 1|$ values plotted as a function of age.

the theoretical frequencies with the corresponding observational frequencies using the function $\chi^2_1$

$$\chi^2_1 = \frac{1}{N} \sum_{n,l} \left( \frac{\nu_{\text{theo}}(n) - \nu_{\text{obs}}(n)}{\sigma} \right)^2,$$

(3)

where, $N = 31$ is the total number of modes, and $\nu_{\text{theo}}(n)$ and $\nu_{\text{obs}}(n)$ are the theoretical and observed frequencies respectively, for each spherical degree $l$ and the radial order $n$, where $\sigma = 2 \, \mu Hz$ (Teixeira et al. 2009) represents the uncertainty in the observed frequencies and $\chi^2_1$ values, plotted as function of age, are shown in Fig. 2b.

Since existing stellar models fail to accurately represent the near-surface layers of the solar-like stars, where the turbulent convection take place, the systematic offset between the observed and model frequencies appears. Furthermore, this offset between observed and best model frequencies turns out to be closely fitted by a power law (Christensen-Dalsgaard & Gough 1980; Kjeldsen et al. 2008; Metcalfe et al. 2009; Doğan et al. 2009, 2010; Bedding et al. 2010; Christensen-Dalsgaard et al. 2010). In other words, this offset increases with increasing frequency shown in Fig. 3. This power law can be expressed using the equation

$$\nu_{\text{obs}}(n) - r_l \nu_{\text{theo}}(n) = a_l [\nu_{\text{obs}}(n)/\nu_{\text{max}}]^b,$$

(4)

where $\nu_{\text{obs}}$ are the observed frequencies of radial and non-radial order, $\nu_{\text{best}} = r_l \nu_{\text{theo}}(n)$ are the corresponding calculated frequencies of the best-fit model, and $\nu_{\text{max}}$ is a constant frequency corresponding to the peak power in the spectrum, which is taken as $4490 \, \mu Hz$ for $\tau$ Ceti and $r_l$, $a_l$, and $b$ are parameters described in detail by Kjeldsen et al. (2008), (for a different spherical degree $l$, the values of $r$ and $a$ are denoted by $r_l$ and $a_l$, respectively). For the Sun and a solar-like star, the exponent $b = 4.90$ is appropriate, as has been proven by many scientists. We use
the Kjeldsen et al. (2008) prescription to correct the theoretical frequencies from near surface effects.

According to Eq. (4), we can use the following equation to obtain the corrected frequencies of models:

\[ \nu_{\text{correct}}(n) = r_l \nu_{\text{theo}}(n) + d_l \nu_{\text{obs}}(n)/\nu_{\text{max}}. \]

We define the function \( \chi^2_{\text{fc}} \) in a similar way to Eq. (3) as

\[ \chi^2_{\text{fc}} = \frac{1}{N} \sum_{n,l} \left( \frac{\nu_{\text{correct}}(n) - \nu_{\text{obs}}(n)}{\sigma(\nu_{\text{obs}}(n))} \right)^2. \]

The values of \( \chi^2_{\text{fc}} \), plotted as a function of age are shown in Fig. 2c. From Fig. 2c, we can see that the values of \( \chi^2_{\text{fc}} \) are lower than \( \chi^2_{\text{f}} \) and their lowest values correspond to model ages from 8 to 10 Gyr. We conclude that the optimal model corresponds to the lower values of \( \chi^2_{\text{fc}} \) and \( r_\ell = 1 \). From Figs. 2c and 2d, we infer that only two models M1 and M2 can be accurately described by the observational constraints. The difference between the observed and uncorrected model frequencies of M1 and M2 are shown in Fig. 3. The uncorrected and corrected frequencies of the optimal models M1 and M2 and the observational frequencies are shown in Table 3.

To clearly compare all of the theoretical frequencies of the models with observational frequencies, we provide echelle diagrams of models M1 and M2 in Fig. 4. An Echelle diagram is a useful tool for comparing stellar models with observations. This diagram presents the mode frequencies along the ordinate axis, and the same frequencies modulo the large separations in abscissae. From Figs. 4a and 4d, it can be seen that the uncorrected theoretical frequencies are not closely in agreement with the observed frequencies. The corrected theoretical frequencies indicated by Eq. (5) fit perfectly the observation shown in Figs. 4b and 4e. Because the observed frequencies of orders \( n \) are not consecutive and the values of \( \nu_{\text{obs}}(n) \) are very close to those of \( \nu_{\text{theo}}(n) \), we substitute the \( \nu_{\text{theo}}(n)/\nu_{\text{max}} \) for \( \nu_{\text{obs}}(n)/\nu_{\text{max}} \). Hence Eq. (5) becomes

\[ \nu_{\text{correct}}(n) = r_l \nu_{\text{theo}}(n) + d_l \nu_{\text{theo}}(n)/\nu_{\text{max}}. \]

From Figs. 4b, 4c, 4e, and 4f, it can be seen that corrected frequencies given by Eqs. (5) and (7) respectively are uniform and reproduce the observed frequencies perfectly. Furthermore, we can use the function \( \chi^2_{\text{fc}} \) to select the fitting model parameters. As we all know, the suitable model parameters correspond to the lowest values of \( \chi^2_{\text{fc}} \), which can be clearly seen in Fig. 5. From Fig. 5, we can conclude that the mass is in the range 0.775–0.785 \( M_\odot \), \( \delta \nu \) is in the range 1.6–1.8, and \( X_i \) is 0.0065–0.0075, and \( X_i \) is 0.73–0.75. Hence, the model parameters of \( \tau \) Ceti can be constrained to within these narrow ranges. Finally, we list the model parameters and characteristics of models M1 and M2 in Table 4.

### 5. Discussion and conclusions

Using the asteroseismic analysis and the empirical frequency correction for the near-surface offset presented by Kjeldsen et al. (2008) to correct our theoretical frequencies, we have derived the optimal model of \( \tau \) Ceti and now list our main conclusions:

1. Using the latest asteroseismic observations, we have attempted to construct the optimal model of \( \tau \) Ceti. We have only considered the models M1 and M2, which can closely describe the observations, as the optimal models. Furthermore, the model parameters of \( \tau \) Ceti have been constrained to within narrow intervals by the function \( \chi^2_{\text{fc}} \), where the mass is in the range \( M = 0.775–0.785 \ M_\odot \), the mixing length parameter in the range \( \alpha = 1.6–1.8, \) the initial metallicity in the range \( Z_i = 0.0065–0.0075, \) the initial hydrogen abundance in the range \( X_i = 0.73–0.75, \) and the age in the range \( t = 8–10 \) Gyr.

### Table 4. Final model-fitting results for \( \tau \) Ceti.

| Modelling parameters | Model M1 | Model M2 |
|----------------------|----------|----------|
| Mass \( M/M_\odot \) | 0.775    | 0.785    |
| Mixing length \( \alpha \) | 1.6      | 1.6      |
| \( Z_i \) | 0.007    | 0.007    |
| \( X_i \) | 0.740    | 0.750    |
| \( \Delta \nu \) (\( \mu \)Hz) | 170.8621 | 170.8381 |
| \( \Delta \nu \) (\( \mu \)Hz) | 170.9222 | 170.9106 |
| \( \Delta \nu \) (\( \mu \)Hz) | 171.0332 | 170.9106 |
| \( \Delta \nu \) (\( \mu \)Hz) | 171.5120 | 171.4870 |
| \( \Delta \nu \) (\( \mu \)Hz) | 10.111   | 10.111   |
| \( \Delta \nu \) (\( \mu \)Hz) | 18.136   | 18.136   |

Using the asteroseismic analysis and the empirical frequency correction for the near-surface offset presented by Kjeldsen et al. (2008) to correct our theoretical frequencies, we have derived the optimal model of \( \tau \) Ceti, and now list our main conclusions:

1. Using the latest asteroseismic observations, we have attempted to construct the optimal model of \( \tau \) Ceti. We have only considered the models M1 and M2, which can closely describe the observations, as the optimal models. Furthermore, the model parameters of \( \tau \) Ceti have been constrained to within narrow intervals by the function \( \chi^2_{\text{fc}} \), where the mass is in the range \( M = 0.775–0.785 \ M_\odot \), the mixing length parameter in the range \( \alpha = 1.6–1.8, \) the initial metallicity in the range \( Z_i = 0.0065–0.0075, \) the initial hydrogen abundance in the range \( X_i = 0.73–0.75, \) and the age in the range \( t = 8–10 \) Gyr.
Fig. 4. Echelle diagrams for the optimal models M1 (upper panel) and M2 (lower panel). Left panel shows the case before applying near-surface corrections. Middle panel shows the case after applying near-surface corrections, according to Eq. (5). Right panel shows the case after applying near-surface corrections, according to Eq. (7). Open symbols refer to the theoretical frequencies, and filled symbols refer to the observable frequencies. Squares are used for $l = 0$ modes, diamonds for $l = 1$ modes, triangles for $l = 2$ modes, and circles for $l = 3$. The observable frequencies correspond to the average large separation about 170 $\mu$Hz (see text for details).

Fig. 5. a) $\chi^2_\nu$ values derived from Eq. (6), plotted as function of mass; b) $\chi^2_\nu$ values plotted as function of mixing length $\alpha$; c) $\chi^2_\nu$ values plotted as function of initial heavy element abundance $Z_i$; d) $\chi^2_\nu$ values plotted as function of initial hydrogen abundance $X_i$. 
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