Asteroseismic observations and modelling of 70 Ophiuchi AB

P Eggenberger¹, A Miglio¹, F Carrier², J Fernandes³ and N C Santos⁴

¹ Institut d’Astrophysique et de Géophysique de l’Université de Liège, 17 Allée du 6 Août, B-4000 Liège, Belgium
² Institute of Astronomy, University of Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
³ Observatório Astronómico da Universidade de Coimbra e Departamento de Matemática, FCTUC, Portugal
⁴ Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, P-4150-762 Porto, Portugal

E-mail: eggenberger@astro.ulg.ac.be

Abstract. The analysis of solar-like oscillations for stars belonging to a binary system provides an opportunity to probe the internal stellar structure and to test our knowledge of stellar physics. We present asteroseismic observations of 70 Oph A performed with the HARPS spectrograph together with a comprehensive theoretical calibration of the 70 Ophiuchi system.

1. Introduction
The solar five-minute oscillations have provided a wealth of information on the internal structure of the Sun. These results stimulated various attempts to detect a similar signal on other solar-type stars by photometric or equivalent width measurements. In past years, the stabilized spectrographs developed for extra-solar planet search have finally achieved the accuracy needed to make these detections [see e.g. 1–3]. A major difficulty is the confrontation between these observations and theoretical models. The classical observational measurements available for an isolated star (effective temperature, metallicity, luminosity) combined with the oscillation frequencies provide indeed strong constraints to the global parameters of the star but are often not sufficient to unambiguously determine a unique model and to really test the input physics included in the computation of the stellar models [see for example the case of the isolated star β Virginis, 4]. In this regard, binary stars constitute ideal asteroseismic targets in order to test our knowledge of stellar physics. The additional constraints imposed by the binary nature of the system, namely the same age and initial chemical composition, are indeed extremely valuable to accurately determine the global properties of the stars. Moreover, in the case of a visual binary system, the masses of both components can be accurately known by combining visual and spectroscopic orbits.

For binary stars, individual frequencies of solar-like oscillations have only been identified for stars belonging to two different systems: α Cen A [5–7], α Cen B [8; 9] and Procyon A [10; 11]. Very recently, Carrier & Eggenberger [12] reported the detection of solar-like oscillations on the bright K0 dwarf star 70 Ophiuchi A (HD 165341A) belonging to the nearby visual binary system 70 Ophiuchi which is among the first discovered binary systems. We present a calibration of the
Table 1. Non-asteroseismic observational constraints for 70 Oph A and B.

|                  | 70 Oph A         | 70 Oph B         |
|------------------|------------------|------------------|
| \( \pi \) (mas) | 194.2 ± 1.2      |                  |
| \( M/M_\odot \) | 0.89 ± 0.02      | 0.73 ± 0.01      |
| \( V \) (mag)   | 4.191 ± 0.014    | 6.061 ± 0.021    |
| \( L/L_\odot \) | 0.53 ± 0.02      | 0.15 ± 0.02      |
| \( T_{\text{eff}} \) (K) | 5300 ± 50       | 4390 ± 200       |
| \([\text{Fe/H}]\) | 0.04 ± 0.05      |                  |

70 Ophiuchi system which includes the new seismological data available for the A component. In addition to determining the global parameters of 70 Ophiuchi AB, we will also test and compare the theoretical tools used for the modelling of stars for which p-modes frequencies are detected by performing this analysis with three different stellar evolution codes and two different calibration methods. This work therefore takes place in the continuity of the work undertaken by the Evolution and Seismic Tools Activity (ESTA) group within the CoRoT mission [13].

The observations obtained for the 70 Ophiuchi system are summarized in Sect. 2. The results of the calibration are presented in Sect. 3, while the conclusion is given in Sect. 4.

2. Observations

2.1. Non-asteroseismic observational constraints

The non-asteroseismic observational constraints adopted for the present calibration of the 70 Ophiuchi system are listed in Table 1.

2.2. Asteroseismic measurements

Solar-like oscillations in 70 Ophiuchi A have been recently observed by Carrier & Eggenberger [12] with the HARPS echelle spectrograph. Fourteen oscillation frequencies have been detected in the power spectrum between 3 and 6 mHz with amplitudes in the range of 11 to 14 cm s\(^{-1}\). A mean value of 161.8 ± 0.8 \( \mu \text{Hz} \) is found for the large separation.

3. Theoretical interpretation

Using the observational constraints listed in Sect. 2, a first calibration is performed by computing a dense grid of stellar models with the Geneva stellar evolution code [15]. In this way, we find the following solution: \( t = 6.2 \pm 1.0 \text{ Gyr} \), \( M_A = 0.91 \pm 0.02 \text{ M}_\odot \), \( M_B = 0.72 \pm 0.01 \text{ M}_\odot \), \( Y_i = 0.266 \pm 0.015 \) and \( (Z/X)_i = 0.0300 \pm 0.0025 \). The characteristics of this model (denoted model M1a in the following) are reported in Table 2. The confidence limits of each modelling parameter given in Table 2 are estimated as the maximum/minimum values which fit the observational constraints when the other calibration parameters are fixed to their medium value.

In order to compare results obtained by using a different stellar evolution code, the same calibration is done by using the CLES code [16] and the Levenberg-Marquardt method. This calibration (called model M1b) leads to the following solution: \( t = 6.5 \pm 1.0 \text{ Gyr} \), \( M_A = 0.90 \pm 0.02 \text{ M}_\odot \), \( M_B = 0.73 \pm 0.01 \text{ M}_\odot \), \( Y_i = 0.266 \pm 0.018 \) and \( (Z/X)_i = 0.0300 \pm 0.0025 \). The characteristics of this solution are given in Table 2. A third comparison is finally performed by using the CESAM evolution code [17]. The following solution (denoted model M1c) is then found: \( t = 6.2 \pm 1.0 \text{ Gyr} \), \( M_A = 0.91 \pm 0.02 \text{ M}_\odot \), \( M_B = 0.72 \pm 0.01 \text{ M}_\odot \), \( Y_i = 0.271 \pm 0.015 \) and \( (Z/X)_i = 0.0300 \pm 0.0025 \). The global parameters of 70 Oph AB determined with this solution are also given in the bottom part of Table 2.
Table 2. Models for 70 Oph A and B obtained with three different stellar evolution codes. The M1 models are computed with the solar mixture of Grevesse & Noels [14] and include atomic diffusion of helium and heavy elements. The upper part of the table gives the modelling parameters with their confidence limits, while the bottom part presents the global parameters of both stars.

|                  | Model M1a Geneva code | Model M1b CLES code | Model M1c CESAM code |
|------------------|-----------------------|---------------------|----------------------|
|                  | 70 Oph A   | 70 Oph B   | 70 Oph A   | 70 Oph B   | 70 Oph A   | 70 Oph B   |
| $M/M_\odot$     | 0.91 ± 0.02 | 0.72 ± 0.01 | 0.90 ± 0.02 | 0.72 ± 0.01 | 0.91 ± 0.02 | 0.72 ± 0.01 |
| $t$ (Gyr)       | 6.2 ± 1.0   | 6.5 ± 1.0   | 6.5 ± 1.0   | 6.2 ± 1.0   | 6.2 ± 1.0   | 6.2 ± 1.0   |
| $Y_i$           | 0.266 ± 0.015 | 0.266 ± 0.018 | 0.266 ± 0.018 | 0.272 ± 0.015 | 0.272 ± 0.015 | 0.272 ± 0.015 |
| $(Z/X)_i$       | 0.0300 ± 0.0025 | 0.0300 ± 0.0025 | 0.0300 ± 0.0025 | 0.0300 ± 0.0025 | 0.0300 ± 0.0025 | 0.0300 ± 0.0025 |
| $L/L_\odot$     | 0.527 ± 0.152 | 0.521 ± 0.163 | 0.521 ± 0.163 | 0.535 ± 0.152 | 0.535 ± 0.152 | 0.535 ± 0.152 |
| $T_{\text{eff}}$ (K) | 5293 ± 4438 | 5283 ± 4434 | 5283 ± 4434 | 5290 ± 4395 | 5290 ± 4395 | 5290 ± 4395 |
| $R/R_\odot$     | 0.865 ± 0.661 | 0.863 ± 0.685 | 0.863 ± 0.685 | 0.872 ± 0.674 | 0.872 ± 0.674 | 0.872 ± 0.674 |
| $Y_s$           | 0.238 ± 0.248 | 0.238 ± 0.247 | 0.238 ± 0.247 | 0.244 ± 0.253 | 0.244 ± 0.253 | 0.244 ± 0.253 |
| $(Z/X)_s$       | 0.0269 ± 0.0280 | 0.0267 ± 0.0279 | 0.0267 ± 0.0279 | 0.0266 ± 0.0277 | 0.0266 ± 0.0277 | 0.0266 ± 0.0277 |
| $[\text{Fe}/\text{H}]_s$ | 0.04 ± 0.06 | 0.04 ± 0.06 | 0.04 ± 0.06 | 0.04 ± 0.05 | 0.04 ± 0.05 | 0.04 ± 0.05 |

From these results, we first conclude that a consistent model of the 70 Ophiuchi system that correctly reproduces all observational constraints now available for 70 Oph A and B can be determined. Indeed, Table 2 show that the three solutions are in very good agreement with all classical observables included in the calibration. Moreover, the M1 models correctly reproduce the observed value of the mean large separation of 70 Oph A. Note that the global asteroseismic features of the three M1 models of 70 Oph A are very similar; they all exhibit a mean large separation of about 161 ± 3 µHz with a mean small separation between $\ell = 2$ and $\ell = 0$ of about 9.5 ± 0.5 µHz. From Table 2 we also conclude that the three different stellar evolution codes give very similar results. We only note a slightly higher value of the initial helium mass fraction determined with the CESAM evolution code which is directly related to the larger value of this parameter found for the solar calibration. These results are comforting since the input physics included in these three codes is similar (although not strictly identical) and must therefore lead to a coherent determination of the modelling parameters of the 70 Ophiuchi system. It is also worthwhile to recall here that, in addition to the stellar evolution codes, the calibration methods have been compared. Indeed, the M1a model has been obtained by computing a dense grid of stellar models, while the solution M1b has been determined by using an optimization algorithm. We thus find that these methods lead to the same determination of the global parameters of 70 Oph AB. These results are in good agreement with previous computations done for the calibration of the $\alpha$ Centauri system by using the Geneva and the CLES evolution code [see 18; 19].

Thus an age of 6.3 ± 1.2 Gyr is determined for the 70 Ophiuchi system independently of the evolution code used for the computation. Concerning the initial chemical composition, we find an initial ratio between the mass fraction of heavy elements and hydrogen $(Z/X)_i = 0.0300 ± 0.0025$ which is slightly larger than for a solar model. This value is directly constrained by the observed surface metallicity $[\text{Fe}/\text{H}]_s = 0.04 ± 0.05$. Contrary to the initial ratio between the mass fraction of heavy elements and hydrogen, a slightly smaller value of the initial helium abundance is found for 70 Oph AB than for a solar model. We however note that the error on this parameter is large. Moreover, we recall here that all these results have been obtained by fixing the mixing-length
Table 3. Models for 70 Oph A and B. Model M2 is computed with the new solar mixture of Asplund et al. [20] complemented with the neon abundance of Cunha et al. [21] and includes atomic diffusion of helium and heavy elements. Model M3 is computed with the solar mixture of Grevesse & Noels [14] but without atomic diffusion. The upper part of the table gives the modelling parameters with their confidence limits, while the bottom part presents the global parameters of both components.

|                  | Model M2                        | Model M3                        |
|------------------|---------------------------------|---------------------------------|
|                  | Solar mixture: Asp+Cunha         | No atomic diffusion             |
|                  | 70 Oph A                        | 70 Oph B                        |
|                  |                                  | 70 Oph A                        |
|                  |                                  | 70 Oph B                        |
| $M/M_\odot$      | $0.90 \pm 0.02$                 | $0.90 \pm 0.02$                 |
|                  | $0.73 \pm 0.01$                 | $0.73 \pm 0.01$                 |
| $t$ (Gyr)        | $6.3 \pm 1.0$                   | $7.2 \pm 1.2$                   |
| $Y_0$            | $0.255 \pm 0.018$               | $0.254 \pm 0.018$               |
| $(Z/X)_i$        | $0.0220 \pm 0.0023$             | $0.0266 \pm 0.0025$             |
| $L/L_\odot$      | $0.522$                         | $0.522$                         |
|                  | $0.164$                         | $0.163$                         |
| $T_{\text{eff}}$ (K) | $5284$                         | $5286$                         |
|                  | $4445$                         | $4437$                         |
| $R/R_\odot$      | $0.864$                         | $0.863$                         |
|                  | $0.684$                         | $0.684$                         |
| $Y_s$            | $0.228$                         | $0.254$                         |
|                  | $0.237$                         | $0.254$                         |
| $(Z/X)_s$        | $0.0192$                         | $0.0266$                         |
|                  | $0.0201$                         | $0.0266$                         |
| $[\text{Fe/H}]_s$ | $0.04$                         | $0.04$                         |
|                  | $0.06$                         | $0.04$                         |

3.1. Models with the new solar mixture

In order to test the sensitivity of the global parameters determined for 70 Oph AB on the adopted solar mixture, we decided to redo the whole calibration using the solar mixture proposed by Asplund et al. [20] complemented with the neon abundance of Cunha et al. [21]. This results in a lower solar value of the ratio between the mass fraction of heavy elements and hydrogen $(Z/X)_\odot = 0.0178$. For these computations, we use OPAL opacity tables calculated with the corresponding solar mixture and the mixing-length parameter is fixed to its solar calibrated value. We then find the following solution $t = 6.3 \pm 1.0$ Gyr, $M_A = 0.90 \pm 0.02 M_\odot$, $M_B = 0.73 \pm 0.01 M_\odot$, $Y_0 = 0.255 \pm 0.018$ and $(Z/X)_i = 0.0220 \pm 0.0023$. We note that this solution calibrated with the new solar abundances presents a different initial chemical composition, but no other significant deviation from the global parameters of the M1 models computed with the solar mixture of Grevesse & Noels [14]. Indeed, the M1 and M2 models share the same age and the same locations in the HR diagram. A lower value of the initial helium abundance is then found for the M2 model in order to compensate for the decrease in the initial ratio between the mass fraction of heavy elements and hydrogen resulting from the lower solar value $(Z/X)_\odot$. As it happens for the Sun and for α Centauri A [see 19], the models of 70 Oph A computed with the solar mixture of Grevesse & Noels [14] exhibit a deeper convective zone compared with the M2 model, but the uncertainty in the observational constraints do not enable to reveal this difference which can be masked by other choice of parameters.

3.2. Models without atomic diffusion

The effects of atomic diffusion on the calibration of the 70 Ophiuchi system are also studied by computing models without diffusion. For these computations, the solar mixture of Grevesse & Noels [14] is used and the mixing-length parameter is fixed to its solar calibrated value. Thus the same calibration is made as for the M1 models except for the inclusion of atomic diffusion.
We then obtain the solution (hereafter referred as M3) \( t = 7.2 \pm 1.2 \) Gyr, \( M_A = 0.90 \pm 0.02 \) M\(_\odot\), \( M_B = 0.73 \pm 0.01 \) M\(_\odot\), \( Y_i = 0.254 \pm 0.018 \) and \( (Z/X)_i = 0.0266 \pm 0.0025 \). The characteristics of this solution are given in Table 3. By comparing model M3 with the M1 models, we see that the initial chemical composition differs. Indeed, the M1 models are characterized by a higher initial ratio between the mass fraction of heavy elements and hydrogen than the M3 solution because of the inclusion of atomic diffusion. Moreover the initial helium abundance of the model without diffusion is lower and this results in an increase of the age of about 1 Gyr.

4. Conclusion
Our calibration of the 70 Ophiuchi AB shows that a solution which correctly reproduces all asteroseismic and non-asteroseismic observational constraints now available for both stars can be determined. An age of \( 6.3 \pm 1.2 \) Gyr is found with an initial helium mass fraction \( Y_i = 0.267 \pm 0.020 \) and an initial metallicity \( (Z/X)_i = 0.0300 \pm 0.0025 \) when atomic diffusion is included and a solar value of the mixing-length parameter is assumed. Note that a study of the results found by relaxing this constraint can be found in [22]. This solution does not depend on the choice of one of the three different stellar evolution codes used for the computation. The effects of atomic diffusion and of the choice of the adopted solar mixture on the results of the calibration have also been studied. We then found that a change of the solar mixture results of course in a different initial chemical composition but does not change significantly the other global parameters. Models computed without atomic diffusion also have a different initial chemical composition than models including diffusion but they also exhibit a slightly larger age (difference of about 1 Gyr).

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