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Asteroseismology and calibration of α Cen binary system

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Abstract. Using the oscillation frequencies of α Cen A recently discovered by Bouchy & Carrier (2001, 2002), the available astrometric, photometric and spectroscopic data, we tried to improve the calibration of the visual binary system α Cen. With the revisited masses of Pourbaix et al. (2002) we did not succeed in obtaining a solution satisfying all the seismic observational constraints. Relaxing the constraints on the masses, we have found an age $t_{\alpha\,\rm Cen} = 4\,850 \pm 500$ Myr, an initial helium mass fraction $Y_{\rm i} = 0.300 \pm 0.008$, and an initial metallicity $(Z/X)_{\rm i} = 0.0459 \pm 0.0019$, with $M_{\rm A} = 1.100 \pm 0.006\,M_\odot$ and $M_{\rm B} = 0.907 \pm 0.006\,M_\odot$ for α Cen A & B.

Key words. Stars: binaries: visual - Stars: evolution - Stars: oscillation - Stars: fundamental parameters - Stars: individual: α Cen

1. Introduction

Over the last decade, many efforts to derive accurate fundamental parameters of the double star α Cen A & B (HD128620/1) and to predict asteroseismic frequencies have been carried on (e.g. Guenther & Demarque 2000; Morel et al. 2000 and references therein). For α Cen A, the first frequency measurements done by Bouchy & Carrier (2001) exhibit discrepancies with the past predicted frequencies of the calibrated system. The comparison of published theoretical frequencies (Morel et al. 2000) with those deduced from the observations suggests that the discrepancies come from the adopted value for the mass of α Cen A. Recently, taking into account the gravitational red-shift and the convective blue-shift, Pourbaix et al. (2002) have revisited their previous analysis of astrometric and spectroscopic data. As a result, the masses of stars α Cen A & B deviate significantly from their previous determination by more than 2σ; new mass values: $M_{\rm A} = 1.105 \pm 0.007\,M_\odot$ and $M_{\rm B} = 0.934 \pm 0.006\,M_\odot$ are lower than their old ones. In this letter we present attempts to calibrate the binary system taking into account all these new observational constraints.

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2. New constraints on the α Cen binary

2.1. Luminosities.

For both components we consider the effective temperatures $T_{\rm eff}$ and metallicities derived in our previous work (Morel et al. 2000). We derive the luminosities from the accurate Geneva photometry (Burki et al. 2002). The magnitudes $V_{\rm A} = -0.003 \pm 0.004$ and $V_{\rm B} = 1.332 \pm 0.005$ are combined with the new value of the parallax $\varpi = 747.1 \pm 1.2$ mas (Pourbaix et al. 2002) to derive the luminosities $L_{\rm A}$ and $L_{\rm B}$. The bolometric corrections used are from Flower's (1996). Lejeune et al. (1998) and Bessell et al. (1998) bolometric corrections have been tried in order to estimate the uncertainty on the derived luminosities. Both range the luminosity values derived from Flower's calibration leading us to adopt these last ones with an uncertainty of 0.018 and 0.016 (solar unit) respectively for $L_{\rm A}$ and $L_{\rm B}$ as reported in Table 1.

2.2. P-modes oscillations discovered.

Recently, solar-like p-mode oscillations in α Cen A have been detected by Bouchy & Carrier (2001) with CORALIE fiber-fed spectrograph. With a longer time series of observations Bouchy & Carrier (2002) have identified 28 oscillation frequencies $\nu_{n,\ell}$ in the velocity power spectrum, with degrees $\ell = 0, 1, 2$ and radial orders n from 15 to 25. The values of the frequencies depend strongly on the surface properties of the star poorly described by the models. In seismological analysis one rather characterizes the set of oscillation frequency: three frequency spac-

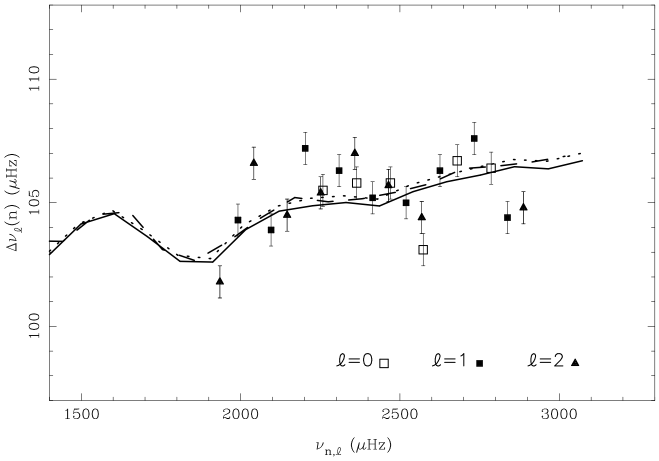

Fig. 1. Large frequency spacing as a function of the frequency. Symbols indicate the Bouchy & Carrier (2002) observed values with their error bars. Continuous lines correspond to the model with $M_{\rm A} = 1.100\, M_\odot$. Full, dashed and dotted lines correspond to modes ℓ=0, 1, respectively. and 2.

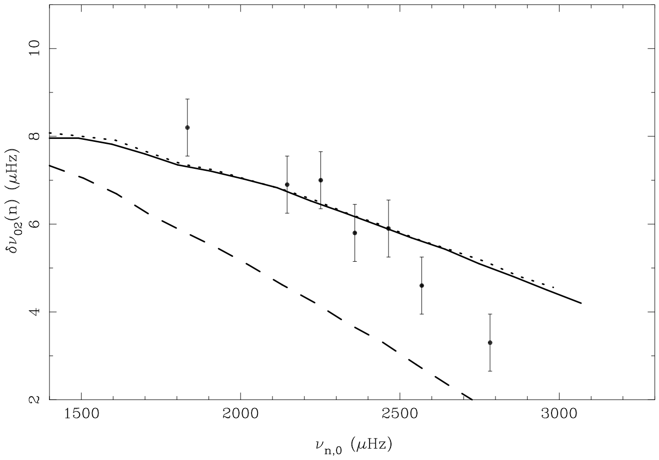

Fig. 2. Small frequency spacing $\delta\nu_{0,2}$ as a function of the frequency. Symbols indicate the observed values with their error bars. Full, dashed and dotted lines correspond respectively to models with $M_{\rm A} = 1.100\, M_\odot$, $M_{\rm A} = 1.105\, M_\odot$ (mass of Pourbaix et al. 2002) and $M_{\rm A} = 1.114\, M_\odot$ (without convective core).

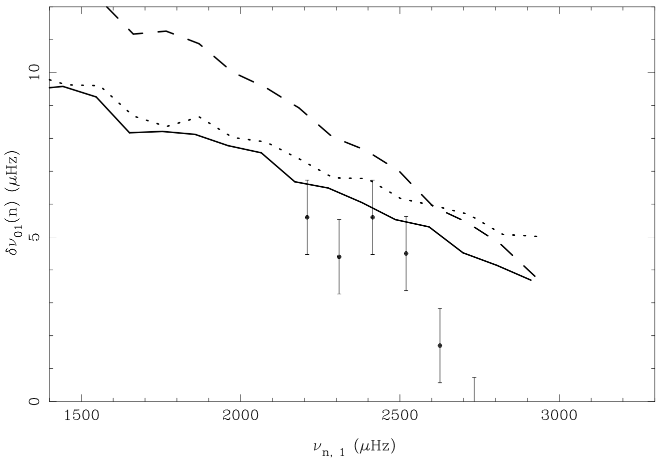

Fig. 3. Same as Fig. 2 for small frequency spacing $\delta\nu_{0,1}$.

ings, one "large" and two "small", that are less surface dependent. The large frequency spacing are differences between frequencies of modes with consecutive radial order n: $\Delta\nu_\ell(n) \equiv \nu_{n,\ell} - \nu_{n-1,\ell}$. In the high frequency range, i.e. large radial orders, $\Delta\nu_\ell$ is almost constant with a mean value Δ_0, strongly related to the mean density of the star. The small separation, difference between frequencies of modes with degree of same parity and with consecutive radial order: $\delta\nu_{0,2}(n) \equiv \nu_{n,0} - \nu_{n-1,2}$ is very sensitive to the core of the star, i.e. to its age. Another small spacing sensitive to the core is obtained by combining modes of degrees ℓ=0 and 1: $\delta\nu_{0,1}(n) \equiv \nu_{n+1,0} + \nu_{n,0} - 2\nu_{n,1}$. Figure 1 shows the observed large spacing of α Cen A as a function of the frequency. Error bars of $\pm 0.65\,\mu$Hz have been determined considering the frequency resolution of the time series. The dispersion of the observed points according to the mode degree is larger than the error bars. As discussed in Bouchy & Carrier (2002), it may be due partly to a possible systematic error of $\pm$ 1.3 μHz introduced at some identified mode frequencies, especially above 2.5 mHz, by aliases and/or rotational splitting. Figures 2 & 3 show the small spacings $\delta\nu_{0,2}$ and $\delta\nu_{0,1}$ as a function of the frequency.

3. New evolutionary models

This work is an extension of Morel et al. (2000), taking into account the additional seismic constraints. It consists in computing evolved models of α Cen A & B until they reach together at the same age, the measured luminosity, effective temperature and metallicity. The free parameters are the age $t_{\alpha\,\rm Cen}$, the initial helium content $Y_{\rm i}$ and metallicity $(Z/X)_{\rm i}$ and the mixing-length parameters $\lambda_{\rm A}$, $\lambda_{\rm B}$. We assume that $\lambda_{\rm A} \equiv \lambda_{\rm B} \equiv \lambda$ because both stars have similar masses and chemical abundances. The relaxation of this constraint gives similar results as emphasized in the discussion of Morel et al. (2000). All models have been computed with the CESAM code (Morel 1997) – see Morel et al. (2000) for details. Models are initialized at the homogeneous ZAMS, using the Canuto & Mazitelli (1991, 1992) convection theory.

In a first step the new Pourbaix et al. (2002) masses are used as observable constraints and without the seismic constraints. The solution obtained by a χ^2 fitting gives $t_{\alpha\,\rm Cen} = 8\,600\,$Myr, $Y_{\rm i} = 0.256$, $(Z/X)_{\rm i} = 0.0459$ and $\lambda = 1.3$. This solution does not fulfill all available seismic constraints for α Cen A. The large spacing is well fitted by this solution leading to estimates of the mean density and, at fixed mass, to a radius $R_{\rm A} \approx 1.23\, R_\odot$. On the contrary, the small frequency spacings (Fig. 2 & 3) of this model deviate significantly from the observations, leading us to reject this solution; $\delta\nu_{0,2}$ is too small, therefore the age is too large (Morel et al. 2000). Moreover, an age of $t_{\alpha\,\rm Cen} = 8\,600\,$Myr is difficult to accept for a star having a metallicity larger than the solar one. Note also that the derived mixing length parameter, $\lambda = 1.3$, is rather large for the convection theory of Canuto & Mazitelli (1991, 1992) predicting values closer to unity.

Table 1. Characteristics of α Cen A & B models. The first four rows recall the observed and used effective temperatures in K, metallicities, luminosities and mean large spacing Δ_0 (in μ Hz). Symbols are defined in text. The five next rows present the deduced calibration parameters and the next ones show some characteristics of the model. At center, T_c, ρ_c, X_c, Y_c are the temperature (in MK), the density (in g cm^{-3}), the hydrogen and the helium mass fractions, respectively. Indexes s, c, i, cz and co correspond to observed surface values, center values, initial values and convective envelope and core, respectively. R, T and ρ are the radius, the temperature and the density, respectively.

	α Cen A	α Cen B
$T_{\rm eff}$	5790 ± 30 K	5260 ± 50 K
[Fe/H]	0.20 ± 0.02	0.23 ± 0.03
$L/L_\odot$	1.519 ± 0.018	0.5002 ± 0.016
Δ_0	105.5 ± 0.5	
$t_{\alpha\,\rm Cen}$ (Myr)	$4\,850 \pm 500$	
$Y_{\rm i}$	0.300 ± 0.008	
$(Z/X)_{\rm i}$	0.0459 ± 0.0019	
λ	0.98 ± 0.04	
$M/M_\odot$	1.100 ± 0.006	0.907 ± 0.006
$R/R_\odot$	1.230	0.857
X_s	0.715	0.694
Y_s	0.258	0.277
$(Z/X)_s$	0.0384	0.0417
[Fe/H]$_s$	0.195	0.231
$R_{\rm cz}/R_\star$	0.725	0.679
$T_{\rm cz}$	1.893	2.802
$R_{\rm co}/R_\star$	0.052	
T_c	19.00	13.89
ρ_c	177.1	117.1
X_c	0.182	0.428
Y_c	0.785	0.539

Thus, in a second step, we take into account the additional constraints given by observed small frequency spacings and we consider the masses of the two stars as free parameters and no longer as observational constraints. Our best solution comes up with $t_{\alpha\,\rm Cen} = 4\,850$ Myr, $M_{\rm A} = 1.100\,M_\odot$, $M_{\rm B} = 0.907\,M_\odot$, $Y_{\rm i} = 0.300$, $(Z/X)_{\rm i} = 0.0459$ and $\lambda = 0.98$. The sum of masses and the fractional mass we derive are compatible with the astrometrical values of Heintz (1958, 1982), Kamper & Wesselink (1978) and with the values adopted in the calibration of Guenther & Demarque (2000). Figure 1, 2 and 3, respectively, show the large and small frequency spacings. We are aware that the two observed small spacings above 2.5 mHz are considered as less reliable as previously discussed discussed. Table 1 gives characteristics of the corresponding models of α Cen A & B. The confidence limits of each calibration parameter, the other being fixed, correspond to the maximum and minimum values that can be reach, so that the generated models fit the observable targets within their error bars. Figure 4 presents evolutionary tracks of two stars in the HR diagram. Table 2 presents their p-mode frequencies to predict large and small spacings for future observations.

At the age $t_{\alpha\,\rm Cen} = 4\,850$ Myr the model of α Cen A presents a convective core with still burning hydrogen. As emphasized by Guenther & Demarque (2000) two kinds of a model, with and without convective core, can satisfy the HR diagram constraints. Indeed, we have also found models of α Cen A without a convective core satisfying the seismic constraints for $\Delta\nu_\ell$ and $\delta\nu_{0,2}$ but, they are ruled out by the $\delta\nu_{0,1}$ constraint. As an example we have plotted in Fig. 2 & 3 the small spacings for models $M_{\rm A} = 1.114\,M_\odot$, $M_{\rm B} = 0.923\,M_\odot$, corresponding to $t_{\alpha\,\rm Cen} = 5\,170$ Myr and $Y_{\rm i}$=0.285. According to Guenther & Demarque (2000) models with and without a convective core can be discriminated by the so-called mode-bumped spacing; our work shows that the small spacing $\delta\nu_{0,1}$ can be also successfully used for this purpose.

4. Discussion and conclusion

Within the validity of the physics we use, our classical calibration of the binary system α Cen A & B with astrometric, photometric spectroscopic constraints and the dynamical masses of Pourbaix et al. (2002) does not fully satisfy the seismic constraints derived from the observations of Bouchy & Carrier (2002). Relaxing the constraint on the masses we obtain a solution that agrees with the seismic observations. The derived masses are close to those retained by Guenther & Demarque (2000). For α Cen B the difference, with respect to Pourbaix et al. (2002) dynamical mass determination, could indicate the presence of an unseen companion, a Jupiter like planet or a brown dwarf, although its mass will be larger than the upper limit given by Endl et al. (2001). However, it must be kept in mind that the masses we obtained are stellar model dependent contrary to the astrometric masses which are mainly based on the assumption of a purely Keplerian two-body problem. Thus, the detection of oscillations of α Cen B is needed to better constrain its mass. For this purpose Table 2 gives a set of expected frequencies of this star corresponding to a mean large spacing around $\Delta_0 = 162\,\mu$Hz. In addition, more accurate seismic observations of α Cen A are requested to decrease the dispersion of the large spacing values and improve the small spacings.

Hopefully, ground based experiments with CORALIE and HARPS fiber-fed spectrograph (Bouchy & Carrier 2002) and the antarctic project CONCORDIASTRO (Fossat et al. 2000), and future space missions like EDDINGTON (Roxburgh 2002) will provide accurate frequencies for both components of our neighbour binary system.

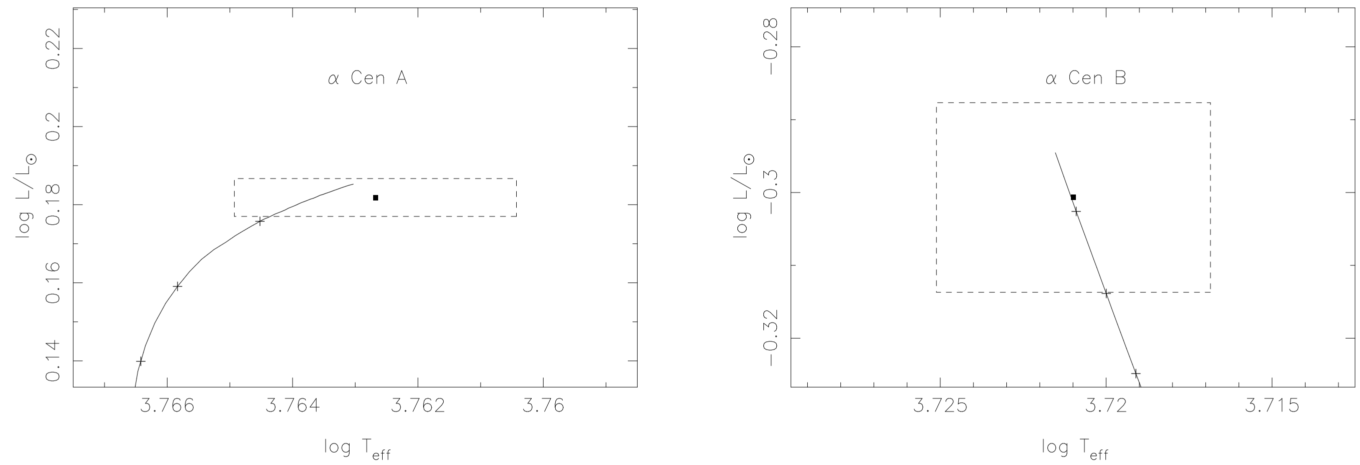

Fig. 4. Evolutionary tracks in the H-R diagram of models α Cen A & B. Dashed rectangles delimit the uncertainty domains. The "+" denote a path of 500 Myr age.

Table 2. Low degree p-mode frequencies (in μ Hz) for our calibrated models of α Cen A & B.

	α Cen A			α Cen B		
n	$\ell = 0$	$\ell = 1$	$\ell = 2$	$\ell = 0$	$\ell = 1$	$\ell = 2$
7	860.3	910.9	962.5	1340.7	1421.6	1497.7
8	971.1	1020.9	1072.1	1514.7	1595.5	1671.5
9	1080.5	1129.6	1179.5	1688.2	1767.1	1841.8
10	1187.6	1235.2	1284.0	1858.1	1936.2	2008.9
11	1292.0	1338.7	1386.9	2024.4	2101.1	2173.6
12	1394.8	1442.1	1491.0	2188.6	2264.7	2337.0
13	1499.0	1546.6	1595.7	2351.7	2428.7	2501.2
14	1603.5	1651.3	1699.6	2515.4	2592.3	2665.1
15	1707.2	1754.4	1802.4	2678.8	2755.1	2827.2
16	1809.8	1857.0	1905.2	2840.3	2916.6	2988.4
17	1912.4	1960.5	2009.3	3001.0	3076.9	3149.3
18	2016.3	2064.9	2114.1	3161.6	3237.9	3310.6
19	2121.0	2170.1	2219.3	3322.5	3399.6	3472.8
20	2225.9	2275.1	2324.6	3484.4	3561.4	3635.1
21	2330.9	2380.3	2429.8	3646.4	3723.6	3797.4
22	2435.7	2485.7	2535.5	3808.2	3885.8	3960.0
23	2541.2	2591.5	2641.6	3970.6	4048.3	4124.0
24	2647.0	2697.8	2748.1	4133.2	4211.4	4286.4
25	2753.2	2804.3	2854.8	4296.4	4374.9	4450.4
26	2859.6	2911.0	2961.5	4460.1	4538.7	4614.5
27	2966.0	3017.9	3068.5	4624.0	4703.0	4779.0
28	3072.7	3124.7	3175.6	4788.2	4867.4	4943.9

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