A&A 406, L23–L26 (2003)
DOI: 10.1051/0004-6361:20030856

Astronomy & Astrophysics

Solar-like oscillations in the K1 dwarf star α Cen B*

F. Carrier and G. Bourban

Observatoire de Genève, 51 chemin de Maillettes, 1290 Sauverny, Switzerland

Received 12 May 2003 / Accepted 9 June 2003

Abstract. The K1 dwarf α Cen B was observed with the CORALIE spectrograph on the 1.2-m Swiss telescope at La Silla in April 2003. Thirteen nights of observations have made it possible to collect 3626 radial velocity measurements with a standard deviation of 1.4 m s^{-1} exhibiting a mean noise level in the amplitude spectrum of only 3.75 cm s^{-1}. Twelve oscillation modes have been identified in the power spectrum between 3 and 4.6 mHz with amplitudes in the range 8.7 to 13.7 cm s^{-1} and showing a regularity with a large separation of 161.1 μHz. A preliminary discussion on the physical parameters of the α Cen binary system is presented.

Key words. stars: individual: α Cen B – stars: oscillations

1. Introduction

The measurements of the frequencies of p-mode oscillations provide an insight into the internal structure of stars and are nowadays the most powerful constraint to the theory of stellar evolution. The five-minute oscillations in the Sun have led to a wealth of information about the solar interior. These results stimulated various attempts to detect a similar signal on other solar-like stars by photometric or equivalent width measurements, with little success due to the extreme weakness of the expected amplitude. These past years, the stabilized spectrographs developed for extra-solar planet detection achieved accuracies needed for solar-like oscillation detection by means of radial velocity measurements (Bedding & Kjeldsen 2003).

Recently, and for the first time, p-modes have been unambiguously detected and identified, on the near twin star of the Sun, α Cen A (Bouchy & Carrier 2002). The seismological data obtained on this star have been compared with detailed theoretical models (Thévenin et al. 2002; Thoul et al. 2003). However, this confrontation can present some problems. In the case of α Cen A, up to now the best studied star in asteroseismology, two different theoretical groups led to different properties: Thévenin et al. describe the star with an age of 4.85 Gyr and a convective core, whereas Thoul et al. propose an older model (6.41 Gyr) without convective core.

In order to resolve this ambiguity, the companion α Cen B (HD 128621, HR 5460, $m_V = 1.33$) was monitored from La Silla. This K-dwarf star has tiny oscillation amplitudes, at a level never measured before. Scaling from the solar case, the frequency of its greatest mode is expected to be $\nu_{\rm max} =$ 3.9 mHz, the large frequency spacing $\Delta\nu_0 = 162\ \mu$Hz, and the oscillation amplitude $A_{\rm osc} = 13$ cm s^{-1} (Kjeldsen & Bedding 1995). In this Letter, we provide clear evidence of the presence of solar-type oscillations in this star. The first results of our study are presented; detailed modelling will be postponed to a subsequent paper.

2. Observations and data reduction

α Cen B was observed over a campaign of thirteen nights (2003 April 12–25) with CORALIE (Queloz et al. 2001), the high-resolution (50 000) echelle spectrograph mounted on the 1.2-m Swiss telescope at La Silla (ESO, Chile). During the stellar exposures, the spectrum of a thorium lamp carried by a second fiber is simultaneously recorded in order to monitor the spectrograph's stability and thus to obtain high-precision velocity measurements. The wavelength coverage of the spectra is 3875–6820 Å, recorded on 68 orders. The dead-time between two exposures was improved from the usual 125 s to 80 s, removing all unnecessary procedures such as hardware tests, statistics calculations, object pointing and external parameter determinations. Moreover, the image was archived during the following exposure. Exposure times of 20 s, thus cycles of 100 s, allowed us to obtain 3626 spectra, with a typical signal-to-noise ratio (S/N) in the range of 80–150 at 550 nm.

Radial velocities[1] are computed for each night relative to the highest S/N spectrum obtained in the middle of the night by the use of the optimum-weight procedure

Send offprint requests to: F. Carrier,
e-mail: fabien.carrier@obs.unige.ch

* Based on observations collected at the Swiss 120 cm telescope at the European Southern Observatory (La Silla, Chile).

[1] The radial velocity data are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/406/L23

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20030856

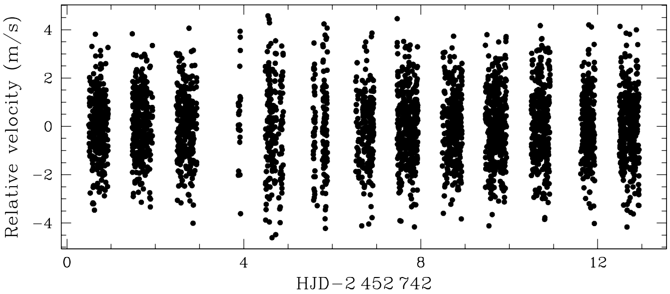

Fig. 1. Radial-velocity measurements of α Cen B. The dispersion reaches 1.43 m s^{-1}.

Table 1. Distribution and dispersion of Doppler measurements.

Date	No. spectra	No. hours	σ (m s^{-1})
2003/04/12	326	10.45	1.26
2003/04/13	324	10.94	1.28
2003/04/14	320	11.10	1.31
2003/04/15	24	1.79	1.18
2003/04/16	191	9.72	1.86
2003/04/17	139	7.66	1.80
2003/04/18	209	9.76	1.40
2003/04/19	392	11.28	1.42
2003/04/20	323	10.69	1.35
2003/04/21	385	11.43	1.47
2003/04/22	360	10.22	1.49
2003/04/23	254	7.60	1.38
2003/04/24	379	10.59	1.40

(Bouchy et al. 2001). This method requires a Doppler shift that remains small compared to the line-width (smaller than 100 m s^{-1}). Since the Earth's motion can introduce a Doppler shift larger than 700 m s^{-1} during a whole night, each spectrum is first corrected for the Earth's motion before deriving the radial velocities. Subsequently, the mean for each night is subtracted. The rms scatter of the time series is 1.43 m s^{-1} (see Fig. 1 and Table 1), which can be directly compared with the fundamental uncertainty due to photon noise. The uncertainties coming from the thorium spectrum used in the instrumental tracking are quite stable with a value about 0.62 m s^{-1}. The quadratic sum of the stellar spectrum photon noise and this instrumental photon noise varies between 0.9 and 2 m s^{-1}.

3. Power spectrum analysis

In order to compute the power spectrum of the velocity time series, we use the Lomb-Scargle modified algorithm (Lomb 1976; Scargle 1982) with a weight being assigned to each point according its uncertainty estimate. The time scale gives a formal resolution of 0.93 μHz. The resulting periodogram, shown in Fig. 2, exhibits a series of peaks near 4 mHz, exactly where the expected solar-like oscillations for this star are situated. Toward the lowest frequencies, the power scales inversely with frequency squared, as expected for instrumental instabilities. The mean white noise level $\sigma_{\rm ps}$, computed in the range 1−2 mHz, reaches 1.79×10^{-3} m^2 s^{-2}, namely 3.75 cm s^{-1} in amplitude, supposing this noise is Gaussian. Since this latter

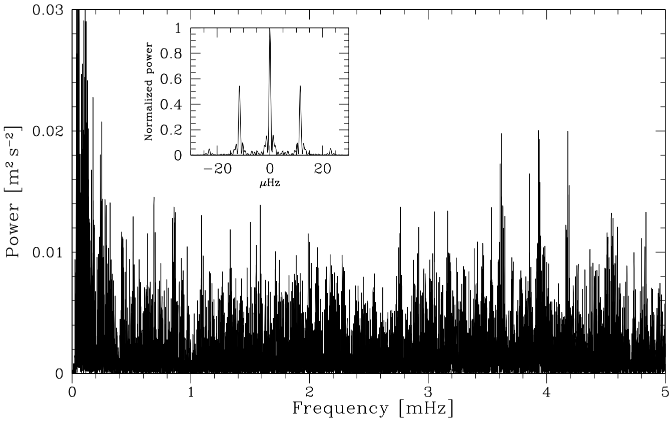

Fig. 2. Power spectrum of the radial velocity measurements of α Cen B. The window function is shown in the inset.

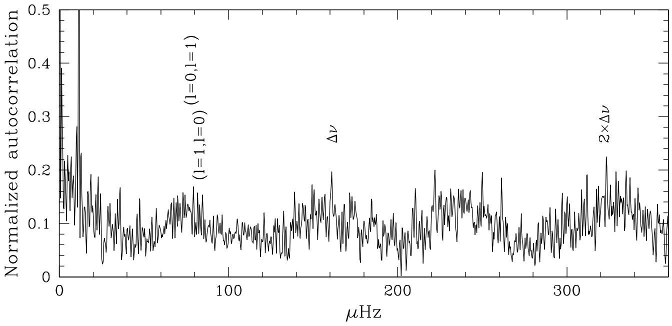

Fig. 3. Autocorrelation of the power spectrum using all peaks greater than 0.004 m^2 s^{-2} in the frequency range 1−5 mHz, the rest of the power spectrum was set to zero.

is based on 3626 measurements, we can derive that the velocity precision on the corresponding timescales is 1.28 m s^{-1}. The amplitude of the strongest modes, corresponding to the power excess near 4 mHz, is estimated to be 13.5 cm s^{-1}, namely 3.5 σ above the noise level (see Sect. 3.3).

3.1. Search for a comb-like pattern

In solar-like stars, p-mode oscillations are expected to produce a characteristic comb-like structure in the power spectrum with mode frequencies $\nu_{n,l}$ reasonably well approximated by the asymptotic relation (Tassoul 1980):

$$\nu_{n,l} \approx \Delta\nu\left(n + \frac{l}{2} + \epsilon\right) - l(l+1)D_0. \quad (1)$$

Here D_0, which is equal to $\frac{1}{6}\delta\nu_{02}$ if the asymptotic relation holds exactly, and ϵ are sensitive to the sound speed near the core and to the surface layers respectively. The quantum numbers n and l correspond to the radial order and the angular degree of the modes, and $\Delta\nu$ and $\delta\nu_{02}$ to the large and small spacings. To fit to this relation, an autocorrelation of the power spectrum is calculated and presented in Fig. 3. The strongest peak at 11.57 μHz corresponds to the daily alias. Excesses appear centered near 80, 160, 240 and 320 μHz, showing that a comb-like structure is present among the data. According to stellar evolution models of α Cen B (Edmonds et al. 1992;

Table 2. Mode frequencies (in μHz). Signal-to-noise ratio is indicated between brackets. Modes with amplitude lower than $3\,\sigma$ have to be considered with caution ($\sigma = 3.75\,\mathrm{cm\,s^{-1}}$). The frequency resolution of the time series is $0.93\,\mu$Hz.

	$\ell = 0$	$\ell = 1$	$\ell = 2$
$n = 17$		3052.0 ($3\,\sigma$)	
$n = 18$			
$n = 19$			
$n = 20$		3532.9 ($3\,\sigma$)	3607.2 ($3.5\,\sigma$)
$n = 21$	3617.2 ($3.5\,\sigma$)		
$n = 22$		3855.0 ($3\,\sigma$)	3930.6 ($3.5\,\sigma$)
$n = 23$	3937.6 ($3.5\,\sigma$)	4016.3 ($2.5\,\sigma$)	
$n = 24$		4177.4 ($3.5\,\sigma$)	4253.8 ($2.5\,\sigma$)
$n = 25$			
$n = 26$	4423.1 ($2.5\,\sigma$)		
$n = 27$	4585.0 ($2.5\,\sigma$)		

Kim 1999; Guenther & Demarque 2000; Thévenin et al. 2002; Thoul et al. 2003), the large spacing $\Delta\nu$ is expected to lie between 140 and 180 μHz. The peak at 161 μHz in the autocorrelation is therefore identified with the large spacing, the peak at 322 μHz corresponds to twice this spacing, and the peaks near 78−82 μHz are associated with correlations between modes of degree $\ell = 0$ and $\ell = 1$.

3.2. Mode identification

The stochastic nature of solar-like oscillations implies that a timestring of radial velocities can not be expected to be a set of coherent oscillations and can therefore not be reproduced perfectly by a sum of sinusoidal terms. In our case, the lifetimes are expected to be of some days (Houdek et al. 1999). Nevertheless, the frequencies were extracted using an iterative algorithm which identifies the highest peak between 2 and 5 mHz and subtracts it from the time series. In the window function (shown in Fig. 2), only aliases at $11.57\,\mu$Hz are clearly present, due to long observation nights. Eleven modes are detected above the $3\,\sigma$ level and confirm the large spacing derived above with the autocorrelation and can be identified unambiguously with the help of the echelle diagram (see Fig. 4). Only the peak at $3618.7\,\mu$Hz needed to be shifted by $11.57\,\mu$Hz. As verified with simulations in which we applied the same extraction algorithm on spectra without signal, three noise peaks are attempted above the $3\,\sigma$ level: peaks at 2765.2, 3164.5 and $4544.3\,\mu$Hz should be due to noise and are rejected. The peak at $4837.4\,\mu$Hz, or rather its daily alias ($4825.8\,\mu$Hz), could be a $\ell = 1$ mode: as it is isolated in high frequencies and as modes can follow an important curvature in the echelle diagram, it was not put in the frequency list. Based on this identification, we completed the frequency list with peaks greater than $2.5\,\sigma$ which fit the asymptotic relation. Peaks having amplitudes below the $2.5\,\sigma$ threshold were not considered, since they were too strongly influenced by noise.

The values of n and ℓ are deduced from the asymptotic relation (see Eq. (1)), assuming that the parameter ϵ is near the solar value. The average large spacing and the parameters D_0 and ϵ are thus deduced from a least-squares fit of this equation with the frequencies of Table 2. The average small spacing is here defined as $D_0 \times 6$ (the perfect asymptotic case, with constant large and small separations):

$$\Delta\nu_0 = 161.1 \pm 0.1\,\mu\mathrm{Hz}, \epsilon = 1.45 \pm 0.01\,,$$
$$D_0 = 1.46 \pm 0.13\,\mu\mathrm{Hz},\ \langle\delta\nu_{02}\rangle = 8.7 \pm 0.8\,\mu\mathrm{Hz}.$$

This average small spacing, taking into account all modes, is very close to the arithmetic mean between the only two small spacings which can be determined from Table 2. All identified modes are shown in Fig. 5.

Saar & Osten (1997) measured a rotational velocity $v \sin i = 1.1 \pm 0.8\,\mathrm{km\,s^{-1}}$ for α Cen B. With an estimated radius of $0.87\,R_\odot$ (Kervella et al. 2003) and supposing that the inclination of the rotational axis is equal to the inclination of the orbital axis of the binary system (79.2°) determined by Pourbaix et al. (2002), the period of rotation is about 39 d. Assuming a uniform rotation, we expect the corresponding splitting of the modes to be $0.3\,\mu$Hz. Our frequency resolution ($0.93\,\mu$Hz) is then too low to attempt a determination of split modes. However, this splitting can slightly increase the uncertainty of the mode frequencies for modes of degrees $\ell = 1$ and 2.

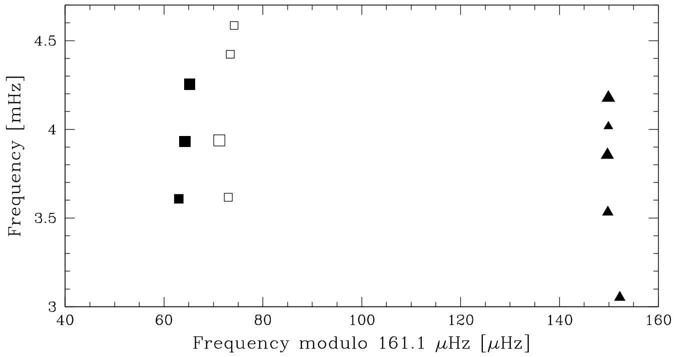

Fig. 4. Echelle diagram of identified modes in the power spectrum. The modes $\ell = 2$ (■), $\ell = 0$ (□), and $\ell = 1$ (▲) are represented with a size proportional to their amplitude.

3.3. Oscillation amplitudes

According to Kjeldsen & Bedding (1995), the expected velocity amplitude for solar-like oscillations scales as L/M. Using the stellar parameters from Kervella et al. (2003), we find $v_{\mathrm{osc}} = 13\,\mathrm{cm\,s^{-1}}$. As the observed amplitudes, determined as the height of the peak in the power spectrum after quadratic subtraction of the mean noise level, are in the range 8.7–13.7 $\mathrm{cm\,s^{-1}}$, they are in perfect agreement with the predictions.

4. Comparison with models

Seismological parameters deduced from our observations are in full agreement with the expected values scaling from the Sun (see Introduction). Our results have been compared with the recent calibration of the α Cen system of Thévenin et al. (2002) based on the acoustic spectrum of the primary. The observed

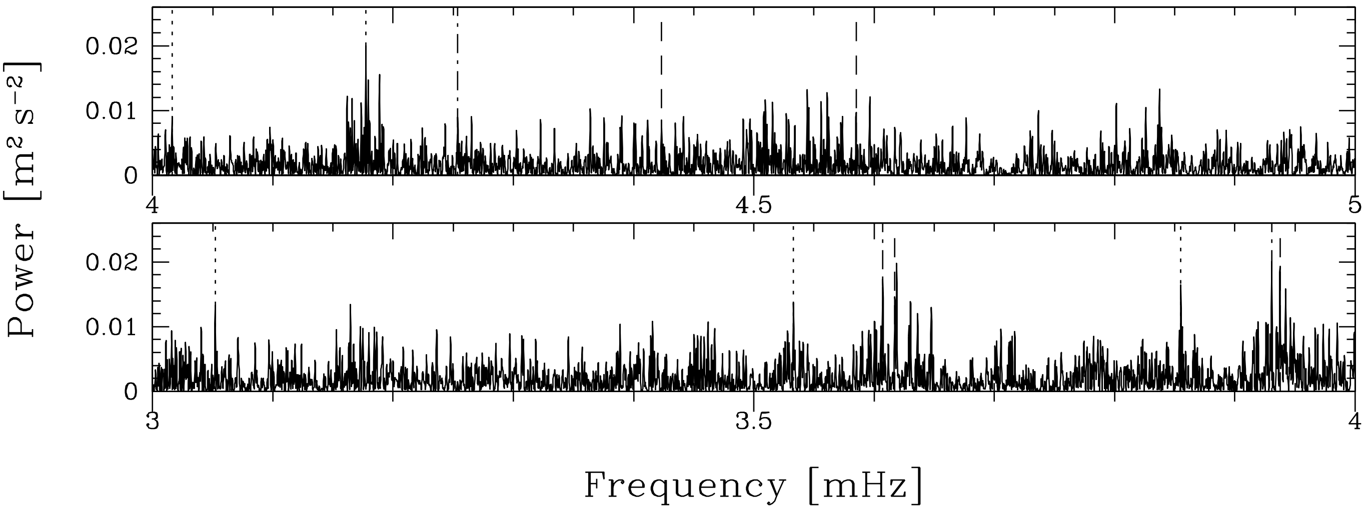

Fig. 5. Identified p-mode oscillations of α Cen B in the power spectrum. Dashed, dotted and dot-dashed lines correspond respectively to modes $\ell = 0$, $\ell = 1$ and $\ell = 2$.

and theoretical large spacings are nearly the same, and a complete agreement between both values will only require small corrections on the physical parameters. However, their theoretical model predicts a decrease of the small spacing from 12 to 9.5 μHz in the frequency range 3 to 4.6 mHz. The observed small spacing is far smaller (with a mean of 8.7 μHz). This observable, in disagreement with the theoretical one, will need a re-calibration of the whole system. Preliminary models using the stellar evolution code of Geneva show that all constraints ($M = 0.934\,M_\odot$, $R = 0.870\,R_\odot$, physical parameters of the primary and acoustic spectra of both components) can be well adjusted if the system has an age near 6 Gyr. Details of the complete calibration of the α Cen system will be reported in a subsequent paper.

5. Conclusions

Our observations of α Cen B yield a clear detection of p-mode oscillations. Several identifiable modes appear in the power spectrum between 3 and 4.6 μHz with an average large spacing of 161.1 μHz and a maximal amplitude of 13.7 cm s^{-1}. This result, obtained with a small telescope, demonstrates the power of Doppler ground-based asteroseismology. The decrease with the frequency of the small spacing (10 to 7 μHz between 3600 and 3930 μHz) is only constrained by a few modes: additional multi-site data (as the small spacing is expected near the daily alias value) are needed to improve the spectral window and explore further the p-mode spectrum of α Cen B.

The high number of free parameters in theoretical stellar models always enables to find a solution which fits the observations. By the increase of the number of constraints in the α Cen binary system, it will be possible to really test stellar evolution theory. It enables to analyse this system by taking into account the individual masses known from the binary analysis (Pourbaix et al. 2002), the individual radii recently measured by Kervella et al. (2003), and, above all, by confronting the asteroseismological results obtained on both components (see Bouchy & Carrier 2002 for the primary) to theoretical stellar evolution models.

Acknowledgements. L. Weber is acknowledged for his help in the adaptation of the pipeline reduction needed for our observation sequences. The referee T. Bedding is acknowledged for his helpful remarks. Part of this work was supported financially by the Swiss National Science Foundation.

References

Bedding, T. R., & Kjeldsen, H. 2003, PASA, in press [astro-ph/0305425]
Bouchy, F., & Carrier, F. 2002, A&A, 390, 205
Bouchy, F., Pepe, F., & Queloz, D. 2001, A&A, 374, 733
Edmonds, P., Cram, L., Demarque, P., et al. 1992, ApJ, 394, 313
Guenther, D. B., & Demarque, P. 2000, ApJ, 531, 503
Houdek, G., Balmforth, N. J., Christensen-Dalsgaard, J., et al. 1999, A&A, 351, 582
Kim, Y.-C. 1999, JKAS, 32, 119
Kervella, P., Thévenin, F., Ségransan, D., et al. 2003, A&A, 404, 1087
Kjeldsen, H., & Bedding, T. R. 1995, A&A, 293, 87
Lomb, N. R. 1976, Ap&SS, 39, 447
Queloz, D., Mayor, M, Udry, S., et al. 2001, The Messenger, 105, 1
Pourbaix, D., Nidever, D., McCarthy, C., et al. 2002, A&A, 386, 280
Saar, S. H., & Osten, R. A. 1997, MNRAS, 284, 803
Scargle, J. D. 1982, ApJ, 263, 835
Tassoul, M. 1980, ApJS, 43, 469
Thévenin, F., Provost, J., Morel, P., et al. 2002, A&A, 392, L9
Thoul, A., Scuflaire, R., Noels, A., et al. 2003, A&A, 402, 293