Solar-like oscillations in Procyon A[★]

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Abstract. The F5 subgiant Procyon A (α CMi, HR 2943) was observed with the CORALIE fiber-fed echelle spectrograph on the 1.2-m Swiss telescope at La Silla in February 1999. The resulting 908 high-accuracy radial velocities exhibit a mean noise level in the amplitude spectrum of 0.11 m s^{-1} at high frequency. These measurements show significant excess in the power spectrum between 0.6–1.6 mHz with 0.60 m s^{-1} peak amplitude. An average large spacing of $55.5 \mu\text{Hz}$ has been determined and twenty-three individual frequencies have been identified.

Key words. stars: oscillations – stars: individual: α Canis Minoris – techniques: radial velocities

1. Introduction

The success of helioseismology encourages corresponding investigations on other stars. The measurement of frequencies and amplitudes of p-mode oscillations for solar-like stars provides an insight into the internal structure and is currently the most powerful constraint on the theory of stellar evolution (see Guenther & Demarque 1993).

Solar-like oscillation modes generate periodic motions of the stellar surface with periods in the range of 3–30 min but with extremely small amplitudes. Essentially, two methods exist to detect such a motion: photometry and Doppler spectroscopy. In photometry, the oscillation amplitudes of solar-like stars are within 2–30 ppm, while they are in the range of $10\text{--}150 \text{ cm s}^{-1}$ in radial velocity measurements. Photometric measurements made from the ground are strongly limited by scintillation noise. To reach the needed accuracy requires observations made from space. In contrast, Doppler ground-based measurements have recently shown their ability to detect oscillation modes in solar-like stars. Since 1999, solar-like oscillations have been detected in a growing list of main sequence and subgiant stars (see the review by Bouchy & Carrier 2003).

Procyon is the first northern hemisphere candidate for the search for p-mode oscillations. Several groups have made thorough attempts to detect the signature of oscillation modes on this bright F5 subgiant star. The first convincing result was obtained by Martić et al. (1999) with observations conducted with the ELODIE spectrograph. These Doppler observations led to the detection of p-modes in the 0.6–1.6 mHz frequency range with amplitudes 2 times solar and a most likely frequency

spacing equal to $55 \mu\text{Hz}$, but no individual frequency was identified. On the theoretical side, several stellar evolution models of Procyon have been computed predicting a large spacing between 50 and $60 \mu\text{Hz}$ (Barban et al. 1999; Chaboyer et al. 1999; Di Mauro & Christensen-Dalsgaard 2001; Provost et al. 2002; Kervella et al. 2004).

In this paper, we report Doppler observations of Procyon A made with the CORALIE spectrograph, well known for the characterization of p-modes on α Cen A (Bouchy & Carrier 2001, 2002). These new measurements, made independently with a different calibration method than the one used by Martić et al. (1999) on ELODIE (simultaneous thorium method instead of a tunable Fabry-Perot illuminated by a white source), confirm the detection of p-modes and enable the identification of twenty-three individual mode frequencies.

The data reduction and the acoustic spectrum analysis of Procyon A are presented in Sects. 2 and 3, respectively. The conclusion is given in Sect. 4.

2. Observations and data reduction

Procyon was observed over a campaign of eleven nights (8–18 February 1999) with CORALIE, the high-resolution fiber-fed echelle spectrograph mounted on the 1.2-m Swiss telescope at La Silla (ESO, Chile).

A description of the spectrograph and the data reduction process is presented in Bouchy & Carrier (2001) and Bouchy et al. (2001). The exposure times were 60 s with 110 s dead-times in between. In total, 908 optical spectra were obtained with a signal-to-noise (S/N) ratio in the range of 200 to 300 at 550 nm. For each night, radial velocities were computed relative to the highest signal-to-noise ratio optical spectrum obtained in the middle of the night (when the target had the highest elevation). The radial velocity measurements are shown in

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[★] Based on observations collected with the CORALIE echelle spectrograph on the 1.2-m Euler Swiss telescope at La Silla Observatory, ESO Chile.

Fig. 1. Radial velocities of Procyon relative to a reference spectrum taken during each night (the best spectrum of the night). The dispersion (which includes the noise and the oscillations) reaches 3.1 m s^{-1} .

Table 1. Distribution and dispersion of Doppler measurements.

Date	Nb spectra	Nb hours	$\sigma[\text{m s}^{-1}]$
1999/02/08	76	6.22	2.83
1999/02/09	89	5.43	2.92
1999/02/10	98	6.36	2.97
1999/02/11	93	6.30	2.95
1999/02/12	97	4.00	3.45
1999/02/13	95	6.04	3.03
1999/02/14	79	5.78	2.59
1999/02/15	68	5.72	3.17
1999/02/16	68	5.84	2.56
1999/02/17	75	5.65	3.32
1999/02/18	70	5.19	2.61

Fig. 1 and their distribution and dispersion are listed in Table 1. The dispersion of these measurements reaches 3.1 m s^{-1} .

3. Stellar power spectra analysis

In order to compute the power spectrum of the velocity time series, we use the Lomb-Scargle modified algorithm (Lomb 1976; Scargle 1982) giving directly a power in $\text{m}^2 \text{s}^{-2}$ without the need for correction by other normalization factors. The time scale gives a resolution of $1.13 \mu\text{Hz}$. Figure 2 shows this periodogram. Typically for such a power spectrum, the noise has two components:

- At high frequencies it is flat, indicative of the Poisson statistics of photon noise. The mean white noise level σ_{pow} calculated between 2 and 2.5 mHz is $0.015 \text{ m}^2 \text{s}^{-2}$, namely 0.11 m s^{-1} in amplitude. With 908 measurements, this high frequency noise corresponds to $\sigma_{RV} = \sqrt{N}\sigma_{\text{pow}}/4 = 1.85 \text{ m s}^{-1}$.
- Towards the lowest frequencies, the power should scale inversely with frequency squared as expected for instrumental instabilities. However, the computation of the radial

Fig. 2. Power spectrum of the radial velocity measurements of Procyon with the observational window response. The white line indicates the noise in the power spectrum.

velocities introduces a high pass filter. Indeed, the radial velocities were computed relative to one reference for each night and the average radial velocities of the night fixed to zero (see Sect. 2). This results in an attenuation of the very low frequencies which can be seen in Fig. 2.

The power spectrum presents an excess in the range 0.6–1.6 mHz. The combined noise has a value decreasing from 0.027 to $0.016 \text{ m}^2 \text{s}^{-2}$ in the above-mentioned interval (see Fig. 2). The noise has been determined by fitting a function of the type $1/\text{frequency}^2$ without considering the attenuated values at very low frequencies. Note that the filtering induced by the radial velocities computation does not influence the frequency of the peaks in the range 0.6–1.6 mHz, but could slightly change their amplitudes. The amplitude of the strongest peaks reaches 0.60 m s^{-1} , corresponding to a signal to noise of 5 (in the amplitude spectrum). This amplitude is estimated as the height of the peaks in the power spectrum with a quadratic subtraction of the mean noise level. To investigate if the peaks are due to noise or are p-modes, we have conducted simulations in which we analyzed noise spectra containing no signal. For this purpose, a velocity time series is build, using the observational time sampling and radial velocities randomly drawn by assuming a Gaussian noise (Monte-Carlo simulations). The simulated noise does not need to include a spectral dependence, since the threshold determination is made relative to σ (see below). Indeed, the spectral dependence is already included in the observed σ (noise), which varies with frequency in the power spectrum (see Fig. 2). The amplitude spectrum of this series is then calculated and peaks with amplitude greater than $3, 4$ and 5σ are counted; note that a peak and its aliases are only counted once. The whole procedure is repeated 1000 times to ensure the stability of the results. In this way, we find that the number of peaks due to noise with an amplitude larger than 3σ varies between 0 and 12 in the range 0.6–1.6 mHz, with a mean value of 2.6 and a standard deviation of 3.4. For 4σ , the number of peaks due to noise varies between 0 and 2 in the range

0.6–1.6 mHz, with a mean value of 0.0 and a standard deviation of 0.3. No peaks due to noise are expected with an amplitude larger than 5σ . These very convincing results show that the power excess is due to p-modes.

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 $\nu_{n,\ell}$ reasonably well approximated by the simplified asymptotic relation (Tassoul 1980):

$$\nu_{n,\ell} \approx \Delta\nu \left(n + \frac{\ell}{2} + \epsilon \right) - \ell(\ell+1)\delta\nu_{02}/6 \quad (1)$$

with $\Delta\nu = \langle \nu_{n,\ell} - \nu_{n-1,\ell} \rangle$ and $\delta\nu_{02} = \langle \nu_{n,0} - \nu_{n-1,2} \rangle$.

The two quantum numbers n and ℓ correspond to the radial order and the angular degree of the modes, respectively. $\Delta\nu$ and $\delta\nu_{02}$ are the large and small spacing. For stars whose disk is not resolved, only the lowest-degree modes ($\ell \leq 3$) can be detected. In the case of stellar rotation, the degeneracy of the modes is lifted and p-modes need to be characterized by a third quantum number m called the azimuthal order:

$$\nu_{n,\ell,m} \approx \nu_{n,\ell,0} + m\tilde{\Omega}_{n\ell m}/2\pi, \quad (2)$$

with $-\ell \leq m \leq \ell$ and $\tilde{\Omega}_{n\ell m}$ the averaged angular velocity over the whole volume of the star.

One technique, commonly used to search for periodicity in the power spectrum, is to compute its autocorrelation. To reduce the uncertainties due to the noise, only peaks greater than $0.25 \text{ m}^2 \text{ s}^{-2}$ in the power spectrum (corresponding to a S/N of 4 in the amplitude spectrum at 1.6 mHz) in the frequency range 0.6–1.6 mHz have been used to compute the autocorrelation shown in Fig. 3.

The two strongest peaks at 11.5 and 23 μHz correspond to the daily alias. Two other peaks at 25.5 and 31 μHz and their daily aliases can be identified. According to stellar evolution models of Procyon (Barban et al. 1999; Chaboyer et al. 1999; Di Mauro & Christensen-Dalsgaard 2001; Provost et al. 2002), the large spacing $\Delta\nu$ is expected to lie between 50 and 60 μHz . Figure 3 exhibits no peak having a significant amplitude in this frequency interval. It is not surprising that a clear peak corresponding to the value of the averaged large spacing $\Delta\nu$ cannot be identified with an autocorrelation, since theoretical models predict that $\Delta\nu$ varies sensitively (several μHz) with the frequency between 0.6 and 1.6 mHz. Thus, if only a few consecutive oscillation modes are observed, the different values of the large spacing will not contribute to raising the amplitude of a single peak in the autocorrelation, but will instead give a succession of small peaks around its averaged value.

In the case of Procyon, it is much more interesting to look for characteristic spacings between modes with different angular degrees. Indeed, theoretical models predict that, contrary to the large spacing $\Delta\nu$, these spacings remain approximately constant with the frequency. The peak at 25.5 μHz can be identified as the spacing between the modes $\ell = 1$ and $\ell = 0$ with

Fig. 4. *Top:* Original power spectrum for the eleven nights of observation. *Bottom:* Cleaned power spectrum: all peaks listed in Table 2 have been removed. The continuous, dotted and dashed lines indicate an amplitude of 5σ , 4σ and 3σ , respectively. Numerous peaks are still present below 3σ , since no peaks have been cleaned below this threshold. These peaks can be due to p-mode oscillations and noise or have been artificially added by the extraction algorithm due to the finite lifetimes of the modes.

(see Table 2). Because of the daily alias of $11.57 \mu\text{Hz}$ introduced by the monosite observations (see the observational window response in Fig. 2), we cannot know a priori whether the frequency selected by the algorithm is the right one or an alias. Thus, we considered that the frequencies could be shifted by $\pm 11.57 \mu\text{Hz}$. We then made echelle diagrams for different large spacings between 50 and $60 \mu\text{Hz}$ until each frequency could be identified as an $\ell = 0$, $\ell = 1$, $\ell = 2$ mode or attributed to noise (see Table 2). In this way, we found an averaged large spacing of $55.5 \mu\text{Hz}$.

At 799 and $1136 \mu\text{Hz}$, either the $\ell = 2$ modes are split by the rotation or the second peaks are due to the noise. Allende Prieto et al. (2002) recently estimated $v \sin i = 3.16 \pm 0.50 \text{ km s}^{-1}$ but mentioned that the correct value is probably close to 2.7 km s^{-1} , given that the value of 3.16 km s^{-1} may be slightly overestimated due to the finite numerical resolution of their convection simulation. Using $v \sin i = 2.7 \text{ km s}^{-1}$ and $i = 31.1 \pm 0.6^\circ$ (Girard et al. 2000), the rotational splitting expected for Procyon A is about $0.6 \mu\text{Hz}$. For $\ell = 2$ modes, this splitting can thus result in differences between two modes as high as $2.4 \mu\text{Hz}$, which is the frequency separation between $m = -2$ and $m = +2$ modes. Of course, the quality of our data is not good enough to unambiguously determine this rotational splitting. The possible $\ell = 1$ peak at $1559.5 \mu\text{Hz}$ is rejected, as it is far from the other modes with a doubtful identification. Moreover, the frequency of $1027.1 \mu\text{Hz}$ is difficult to identify; we identify it as a $\ell = 0$ mode, but it could also be a $\ell = 2$ mode.

Table 2. Identification of extracted frequencies. Some frequencies can be either split $\ell = 2$ mode or due to noise. The number of peaks due to noise is in agreement with the simulations described in Sect. 3, which predict 2.6 ± 3.4 noise peaks.

Frequency [μHz]	Mode ID	S/N
$651.5 - 11.57 = 639.9$	$\ell = 2$	3.2
$630.8 + 11.57 = 642.4$	$\ell = 0$	3.9
662.7	noise	3.2
$683.5 + 11.57 = 695.1$	$\ell = 0$	4.7
720.6	$\ell = 1$	4.5
797.9	$\ell = 2$	4.1
799.7	$\ell = 2$	4.8
$791.8 + 11.57 = 803.4$	$\ell = 0$	3.2
828.5	$\ell = 1$	3.0
835.4	noise	3.6
856.2	$\ell = 2$	4.4
859.8	$\ell = 0$	4.3
911.4	$\ell = 2$	3.2
$929.2 - 11.57 = 917.6$	$\ell = 0$	3.9
$929.2 + 11.57 = 940.8$	$\ell = 1$	3.9
$1009.7 - 11.57 = 998.1$	$\ell = 1$	4.5
1027.1	$\ell = 0$	3.4
$1123.3 + 11.57 = 1134.9$	$\ell = 2$	4.8
1137.0	$\ell = 2$	4.0
$1131.1 + 11.57 = 1142.7$	$\ell = 0$	3.0
1192.4	$\ell = 2$	3.0
$1186.0 + 11.57 = 1197.6$	$\ell = 0$	3.4
$1234.8 + 11.57 = 1246.4$	$\ell = 2$	4.9
1251.8	$\ell = 0$	3.7
$1265.6 + 11.57 = 1277.2$	$\ell = 1$	5.0
1337.2	noise	4.0
1439.0	noise	3.3
1559.5	$\ell = 1?$	3.7

The echelle diagram showing the twenty-three identified modes is shown in Fig. 6. The frequencies of the modes are given in Table 3.

3.3. Amplitudes of the modes

Concerning the amplitudes of the modes, theoretical computations predict oscillation amplitudes for a $1.5 M_\odot$ star like Procyon A between 1 and 2 m s^{-1} , with mode lifetimes of the order of a few days (Houdek et al. 1999). The observed amplitudes of 0.6 m s^{-1} are then lower than expected. This disagreement can be partly explained by the lifetimes of the modes. Indeed, the oscillation modes have finite lifetimes, because they are continuously damped. Thus, if the star is observed for a time longer than the lifetimes of the modes, the signal is weakened due to the damping of the modes and to their re-excitation with a random phase.

Fig. 5. Power spectrum of Procyon with the twenty-eight extracted frequencies indicated by dotted lines. The identification of each extracted frequency is given in Table 2.

Table 3. Mode frequencies (in μHz) of Procyon.

$\ell = 0$	$\ell = 1$	$\ell = 2$
		639.9
642.4		
695.1	720.6	
		797.9 / 799.7
803.4	828.5	856.2
859.8		911.4
917.6	940.8	
	998.1	
1027.1		
		1134.9 / 1137.0
1142.7		1192.4
1197.6		1246.4
1251.8	1277.2	

4. Conclusion

The radial velocity measurements of Procyon A, obtained over 11 nights, show a significant excess in the power spectrum between 0.6–1.6 mHz, centered around 0.8 mHz, with a peak amplitude of 0.60 m s^{-1} , revealing solar-like oscillations with a large spacing of $55.5 \mu\text{Hz}$. Our results confirm the values of the large spacing and of the amplitudes of the modes found by Martić et al. (1999).

Moreover, we presented the identification of twenty-three individual frequencies. Note that this identification is seriously complicated by the presence of daily aliases. Interactions between real peaks and aliases can slightly shift the frequencies of the modes. This is particularly true for the $\ell = 0$ and $\ell = 1$ modes which are separated by $25.5 \mu\text{Hz}$: the interactions between the second alias of the radial modes (separated from the real peak by $23.14 \mu\text{Hz}$) and the $\ell = 1$ modes can slightly shift the observed $\ell = 1$ frequencies, although the different peaks are resolved. Inversely, the second aliases of the $\ell = 1$ modes can influence the observed frequencies of the radial modes. Nevertheless, we think that this identification is

Fig. 6. Echelle diagram for the frequencies listed in Table 3. Dots, triangles and squares correspond respectively to modes identified as $\ell = 0$, $\ell = 1$ and $\ell = 2$. The size of the symbols is proportional to the signal-to-noise ratio of the mode.

reliable, since it is the only one that can explain all the highest peaks in the power spectrum.

To obtain more accurate parameters and to thoroughly test the physics of the models, it is not only important to obtain better data, but also to eliminate the mode identification ambiguity due to the aliases. The space mission MOST (Matthews 2000) launched on 30 June 2003 will observe Procyon A during a whole month and should therefore provide severe constraints on this star.

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