A&A 429, L17–L20 (2005)
DOI: 10.1051/0004-6361:200400106

Astronomy & Astrophysics

Asteroseismology of Procyon A with SARG at TNG*

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Received 1 October 2004 / Accepted 17 November 2004

Abstract. We present high precision radial velocity measurements on the F5 IV star α CMi obtained by the SARG spectrograph at TNG (Telescopio Nazionale Galileo) exploiting the iodine cell technique. The time series of about 950 spectra of Procyon A taken during 6 observation nights are affected by an individual error of $1.3\,\mathrm{m\,s^{-1}}$. Thanks to the iodine cell technique, the spectrograph contribution to the Doppler shift measurement error is quite negligible and our error is dominated by the photon statistics (Brown et al. 1994). An excess of power between 0.5 and 1.5 mHz, detected also by Martic et al. (2004) has been found. We determined a large separation frequency $\Delta\nu_0 = 56 \pm 2\,\mu$Hz, consistent with both theoretical estimates (Chaboyer et al. 1999) and previous observations (Martic et al. 2004).

Key words. asteroseismology – solar-like oscillations – Procyon A – techniques: radial velocities

1. Introduction

Procyon A (α CMi, HR 2943, HD61421) for its proximity and brightness has already attracted attention of stellar seismologists (Guenther & Demarque 1993; Barban et al. 1999; Chaboyer et al. 1999; Martic et al. 1999). It is a F5 IV star (with $V = 0.363$) at a distance of 3.53 pc in a 40-year period visual binary system; the companion is a white dwarf more than 10 mag fainter than the primary. Adopting the very precisely measured parallax by *Hipparcos*, $\Pi = 285.93 \pm 0.88$ mas, Prieto et al. (2002) derived a mass of $1.42 \pm 0.06\,M_\odot$, a radius of $R/R_\odot = 2.071 \pm 0.02$ and a gravity of $\log g = 3.96 \pm 0.02$.

These parameters cannot unambigously determine the evolutionary status of the star, which could be either in the core hydrogen-burning phase or in the more advanced hydrogen shell-burning phase. Although in principle seismology would help to establish the evolutionary status of Procyon A (Di Mauro 2004), the nature of its pulsational spectrum is a subject of intense debate.

In fact, the excess of power around 1 mHz found by Martic et al. (2004) seems to have a stellar origin and is consistent with a p-mode comb-like pattern with a large frequency separation of about 54 μHz. However, data from the recently launched Canadian *MOST* satellite (Matthews et al. 2004) show no significant power excess in the same spectral region. While Matthews et al. (2004) suggested that the ground-based detection of p-modes may be an artefact caused by a combination of stellar noise, and data sampling and analysis, Christensen-Dalsgaard & Kjeldsen (2004) suggest that the most likely explanation for the null detection seems to be a dominating non-stellar noise source in the *MOST* data.

The aim of this letter is to discuss the observations of Procyon A carried out using the high-resolution spectrograph SARG mounted at TNG (Telescopio Nazionale Galileo), aimed at detecting stellar oscillations by means of high-precision radial velocity measurements. Our findings confirm the presence of an excess of power around the 1 mHz region, where we detect several frequencies whose distribution is consistent with a p-mode spectral pattern. In addition, our results show the high efficiency of the SARG spectrograph in detecting solar-like oscillations in stars, being an ideal instrument for multisite ground-based observing campaigns.

2. Observations

SARG is a high resolution cross dispersed echelle spectrograph (Gratton et al. 2001) which offers both single object and long

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* Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

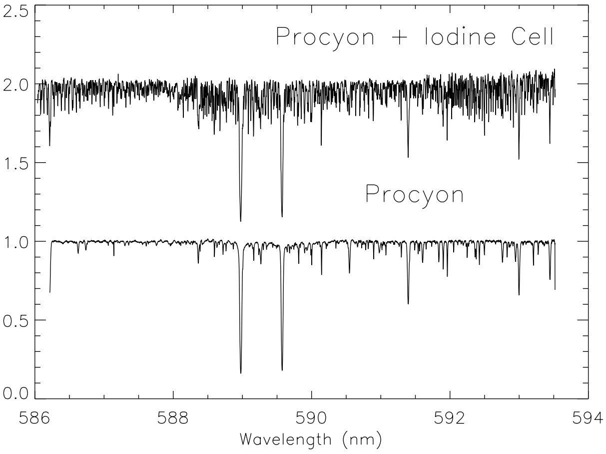

Fig. 1. A segment of the echelle spectrum of Procyon obtained by SARG. *Top panel*: iodine absorption lines are superimposed to the Procyon lines. *Bottom panel*: the Procyon spectrum without iodine absorption features. This spectrum has been used as the template spectrum in the determination of radial velocity from star plus iodine spectra.

Table 1. Observing log: date, number of spectra, signal-to-noise ratio and seeing.

Date	Sp. number	*SNR*	Seeing (as)
2001/01/02	160	325 ± 4	1.04 ± 0.02
2001/01/03	149	248 ± 4	0.81 ± 0.01
2001/01/04	181	292 ± 3	0.82 ± 0.01
2001/01/06	181	295 ± 5	0.93 ± 0.01
2001/01/08	125	291 ± 5	0.89 ± 0.02
2001/01/09	153	328 ± 4	0.87 ± 0.01

slit (up to 26 arcsec) observing modes covering a spectral range from $\lambda = 370$ nm up to about 1000 nm, with a resolution ranging from $R = 29\,000$ up to $R = 164\,000$.

Our spectra were obtained at $R = 144\,000$ in the wavelength range between 462 and 792 nm. The iodine cell covers only the blue part (see Fig. 1) of the spectrum (from 462 up to 620 nm) which has been used for measuring stellar Doppler shifts. The red part of the echelle spectrum of Procyon A has been used for measuring equivalent width of absorption lines sensitive to temperature. Here we present the results concerning the blue part of the spectrum while the analysis of the red one will be the topic of a future work. During the observations (the first SARG scientific run after commissioning and testing phases) we collected about 950 spectra with high signal-to-noise ratio and a mean exposure time of about 10 s. Due to weather and technical conditions (see Table 1 for more details) a few gaps are present in the time series.

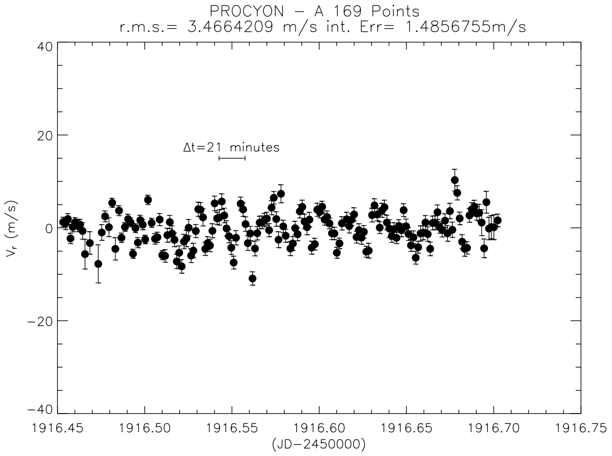

Fig. 2. Radial velocities of Procyon obtained on 2001/01/06. The data are affected by an internal error of 1.48 $\mathrm{m\,s^{-1}}$ and an rms of 3.5 $\mathrm{m\,s^{-1}}$. The 21-min pulsation is also reported.

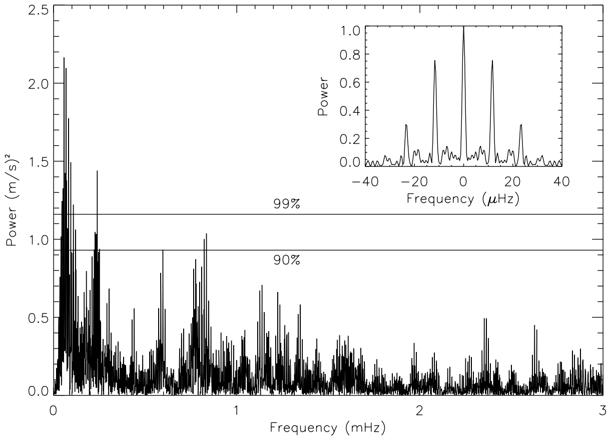

Fig. 3. The Scargle-Lomb periodogram of the data. An excess of power around 1 mHz is evident. The horizontal solid lines show the confidence levels corresponding to the probability of detecting a peak due to a genuine signal equal to 90% and 99%. The inset shows the power spectrum of the window function for a sine wave signal of amplitude 1 $\mathrm{m\,s^{-1}}$, sampled as the observations. The power unit are the same as the main figure.

3. Data analysis

Radial velocities have been obtained using the AUSTRAL code (Endl et al. 2000) which models instrumental profile, star and iodine cell spectra in order to measure Doppler shifts. Since the instrument profile changes along a spectral order, the spectrum was divided in segments (chunks) approximately 100 pixels long (~2 Å), each one modeled independently. About 400 segments were used in the final analysis. The internal velocity error of a spectrum is calculated as the error of the mean velocity of all segments used for the analysis. The parameters for the instrument profile modelling were determined by using fast rotating featureless stars, the standard radial velocity star τ Cet and the planet-bearing 51 Peg and ρ CrB stars. Detailed description of the technique is given in Desidera et al. (2003). Figure 2 shows, as an example, the radial velocity time series obtained on 2001/01/06. In this case, the radial velocity internal error and the r.m.s. of the data set are 1.48 $\mathrm{m\,s^{-1}}$ and 3.5 $\mathrm{m\,s^{-1}}$, respectively. A 21-min pulsation pattern is clearly visible.

We have used the modified Scargle-Lomb periodogram (Scargle 1982) in order to perform the spectral analysis. The result obtained by combining all the six observing nights is shown in Fig. 3, where an excess of power around 1 mHz

Table 2. Prominent peaks present in the periodogram of Procyon A detected by SARG with a confidence level larger than 90%: bold characters indicate the frequencies consistent, within our spectral resolution of 1.62 μHz, with those found by Martic et al. (2004) with a spectral resolution of 1.79 μHz.

Frequencies (μHz)						
230.2	233.7	238.4	245.4	**596.5**	**776.7**	**822.8**

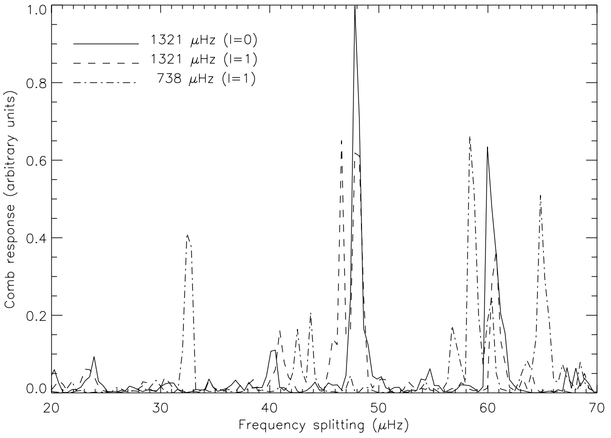

Fig. 4. Comparison between modified comb responses for the two central frequencies 738 μHz and 1321 μHz of the power spectrum of Procyon A data. The responses are scaled to the maximum peak obtained for the frequency $\nu_0 = 1321\,\mu$Hz at $\Delta\nu_0 = 47.8\,\mu$Hz.

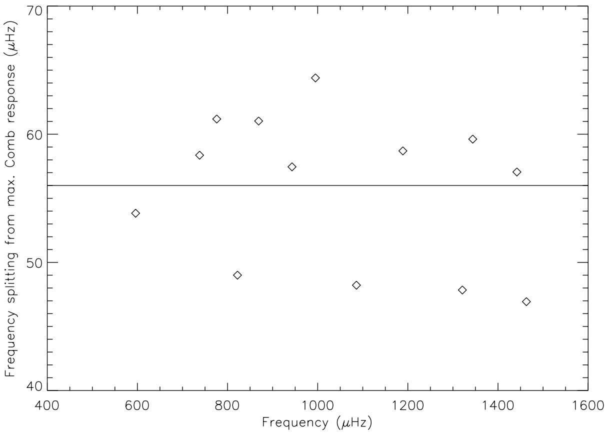

Fig. 5. The first-order spacings over several frequency ranges, as determined from comb analysis. The line shows the mean value of 56 μHz.

is clearly visible. The time scale gives a spectral resolution of 1.62 μHz. The calibration of the Scargle's power in terms of amplitude squared was performed in such a way that a synthetic sine wave of 1 m s^{-1}, sampled as the observations, would yield in the periodogram a cluster of peaks, the largest of which with a power equal to 1 m^2 s^{-2}. We then computed the statistical significance of the detected peaks in terms of the "false alarm probability" F, as defined by Scargle (1982), and adopting the prescription of Horne & Baliunas (1986). F is the probability that a spike (i.e. power in one frequency bin) is due to noise. Consequently the quantity $(1 - F)$ is the probability of detecting a peak due to a genuine signal. The power levels (confidence levels) concorresponding to the value $(1 - F)$ equal to 90% and 99%, equivalent to a false alarm probability of 10% and 1%, respectively, are reported in Fig. 3. In Table 2 we listed all the individual frequencies detected with a confidence level greater than 90%; the frequencies consistent, with those found by Martic et al. (2004) are shown in bold-face. The additional frequencies of 302.0 μHz, 428.0 μHz and 808.8 μHz are also consistent with those of Martic et al. (2004), but have been detected with a confidence level smaller than 90%. By comparing the power spectrum shown in Fig. 3 with the results presented in Martic et al. (1999), it is worth noting that most of the strongest peaks in our periodogram have power of about 0.9 m^2 s^{-2}, a value greater than that found by Martic et al. (1999) in the analysis of the observations carried out on November 1997 using the ELODIE spectrograph, which ranges from 0.8 m^2 s^{-2} in the periodograms obtained for two subsets of data to 0.5 m^2 s^{-2} in the periodogram of the entire data set. On the other hand the high frequency mean white noise level in our periodogram, evaluated in the frequency range 1.8−3 mHz, is 0.049 m^2 s^{-2}, while the values reported by Martic et al. (1999) range from 0.014 to 0.030 m^2 s^{-2}, depending on the different set of data analyzed. The power of most of the strongest peaks reported by Martic et al. (2004) referring to the ELODIE and the combined ELODIE/AFOE data sequences colleced on January–Febraury 1999 is about 0.16−0.20 m^2 s^{-2}, while that reported for the AFOE data is about 0.5−0.6 m^2 s^{-2}; the mean noise levels are quite different in the three sets of data, ranging from 0.0256 to 0.0064 m^2 s^{-2}.

In order to estimate the large frequency separation $\Delta\nu_0$ in the region of the excess of power detected in the periodogram, we CLEAN-ed the spectrum by the window function (for the details of the adopetd procedure see Roberts et al. 1987) and successively we applied to the CLEAN-ed power spectrum the comb-response (CR) method (Kjeldsen et al. 1995) which is a generalization of the power spectrum of a power spectrum and consequently allows us to search for any regularity in a spectral pattern. In the case of solar-like oscillations it allows us to detect their typical comb-like structure. In particular, a peak in the CR at a particular spacing $\Delta\nu_0$ indicates the presence of a regular series of peaks in the power spectrum, centered at the central frequency ν_0 and having a spacing of $\Delta\nu_0/2$. We adopted the modified comb-response function (Martic et al. 2004):

$$C(\nu_0, \Delta\nu_0) = \prod_{i=0}^{4} \left[S\left(\nu_0 + i\frac{\Delta\nu_0}{2} + \delta\right) S\left(\nu_0 - i\frac{\Delta\nu_0}{2} + \delta\right) \right]^{\alpha_i} \quad (1)$$

where $\delta = \pm(i \bmod 2)D_0$ according to mode degree $l = 0$ or $l = 1$ at the central frequency ν_0 and $\alpha_i = 1$ for $i = 1$ or 2, $\alpha_i = 0.5$ for $i = 3$ or 4. For each central frequency ν_0, alternatively considered as $l = 0$ and $l = 1$, we searched for the maximum CR in the intervals $20 \leq \Delta\nu_0 \leq 80$ μHz and $0.3 \leq D_0 \leq 2$. Figure 4 shows examples of the modified CR computed for the two central frequencies 738 μHz and 1321 μHz. In Fig. 5 we show the variation of $\Delta\nu_0$ in the frequency range $500 \leq \nu_0 \leq 1500\,\mu$Hz, as determined from CR analysis. The arithmetic mean of this spacing is $56 \pm 2\,\mu$Hz, a value of the large separation in good agreement with both theoretical estimates (Chaboyer et al. 1999) and previous observations (Martic et al. 2004). The error on $\Delta\nu_0$ has been estimated as the standard deviation of the $\Delta\nu_0$'s computed from CR analysis.

The determination of $\Delta\nu_0$ is not strongly sensitive to the choice of D_0.

4. Conclusions

The analysis of the periodogram of Procyon A obtained by SARG shows a p-mode spectrum characterized by a large frequency separation $\Delta\nu_0 = 56 \pm 2\,\mu$Hz in agreement with Chaboyer et al. (1999) and Martic et al. (2004). Contrarily to what found by Matthews et al. (2004) our results strongly support the idea that the excess of power detected by Martic et al. (2004) in the range from 0.5 up to 1.5 mHz is caused by p-mode oscillations. In particular we think that the SARG spectrograph can efficiently be used in future multi-site observing campaigns for asteroseismology.

Acknowledgements. We wish to thank H. Kjeldsen and J. Christensen-Dalsgaard for useful comments and suggestions.The authors wish to thank the anonymous referee for useful comments and suggestions which contributed to improve the paper.
This work has partially been supported by MIUR (Italian Ministry of Education, University and Scientific Research) under contract COFIN 2002, No. 2002024732.

References

Barban, C., Michel, E., Martic, M., et al. 1999, A&A, 350, 617
Brown, T. M., Noyes, R. W., Nisenson, P., et al. 1994, PASP, 106, 1285
Chaboyer, B., Demarque, P., & Guenther, D. B. 1999, ApJ, 525, L41
Christensen-Dalsgaard, J., & Kjeldsen, H. 2004, Nature, 430, 29
Desidera, S., Gratton, R. G., Endl, M., et al. 2003, A&A, 405, 207
Di Mauro, M. P. 2004, ESA-SP 559, in press
Endl, M., Kürster, M., & Els, S. 2000, A&A, 353, L33
Gratton, R., Bonanno, G., Bruno, P., et al. 2001, Exp. Astron., 12, 107
Guenther, D. B., & Demarque, P. 1993, ApJ, 405, 298
Horne, J. M., & Baliunas, S. L. 1986, ApJ, 302, 757
Kjeldsen, H., Bedding, T. R., Viskum, M., & Frandsen, S. 1995, AJ, 109, 1313
Martic, M., Schmitt, J., Lebrun, J. C., Barban, C., et al. 1999, A&A, 351, 993
Martic, M., Lebrun, J. C., Appourchaux, T., & Korsennik, S. G. 2004, A&A, 418, 295
Matthews, J. M., Kusching, R., Guenther, D. B., et al. 2004, Nature, 430, 51
Prieto, C. A., Asplund, M., Garcia Lopez, R. J., et al. 2002, ApJ, 567, 544
Roberts, D. H., Lehar, J., & Dreher, J. W. 1987, AJ, 93, 968
Scargle, J. D. 1982, ApJ, 263, 835