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An evidence for global pressure oscillations on Procyon

M. Martic[1], **J. Schmitt**[1], **J.-C. Lebrun**[1], **C. Barban**[2], **et al.**

[1] Service d'Aéronomie du CNRS, BP No 3, 91371 Verrières le Buisson, France
[2] Observatoire de Paris, DASGAL, URA CNRS 335,92195 Meudon, France

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Abstract. Precise Doppler measurements of the star Procyon (α CMi, HR 2943) have been obtained with the ELODIE fiber-fed cross-dispersed echelle spectrograph on the 1.93m-telescope at Observatoire de Haute Provence. Here we present the analysis of data from 10 days observing run carried in November 1998. We detect significant excess in the power between 0.5–1.5 mHz in the periodograms of the time series of mean Doppler shifts. Observations of η Cas made with the same instrument during the same time interval and in almost identical night conditions show a flat spectrum in this frequency range, indicated that the excess of Doppler signal seen on Procyon is of stellar origin. When data from the whole run are jointly analysed, a period analysis places an upper limit of 0.47 m/s for the amplitude of oscillations, while the frequency cutoff is around 1.5 mHz. The power evidently drops near 0.55 and 1.5 mHz on the average of unfiltered power spectra of individual nights, which is consistent with the expected p-mode oscillation properties for Procyon. Several equispaced peaks in frequency are recurrent in the power spectra of two independent segments of 4 and 3 contiguous nights; the most probable frequency spacing seems to be 55 μHz. More detailed cleaning of the power spectrum of the entire run (2022 spectra) interrupted by two large gaps of 42 hours, is needed to identify with higher precision the oscillation mode frequencies on Procyon. In conclusion, we consider that we now have a system which is sufficiently stable and rapid to be used for a multi-site campaign involving the instruments having a comparable velocity precision, to detect the oscillation modes of sun-like stars.

Key words: stars: oscillations – stars: individual: Procyon – techniques: spectroscopic

1. Introduction

The Procyon binary system consists of an F5 IV-V primary and a white dwarf secondary in about 40 year orbit. Procyon A is an apparently ordinary object but of great interest to Doppler seismology of solar-like stars. It is the brightest northern hemisphere near-solar type star with now, well-determined characteristics, which simplifies the interpretation of asteroseismological results. Effectively, the long standing discrepancy between astrometric mass determination of Procyon (1.75 $M_\odot$) by Irwin et al. (1992) and astrophysical mass (1.5 $M_\odot$) required by theory (e.g. Guenther and Demarque, 1993) to reproduce Procyon's observed luminosity and temperature, have shown the importance, in this particular case, of an unambiguous detection of the oscillations in order to constrain the stellar-interior model. The problem of Procyon's mass has posed a challenging task to asteroseismology to discriminate between these two values for the mass but, on the other hand it did not help to confirm different new instrumental and reduction methods and especially mode identification.

For example, Gelly et al. (1986) using a resonance cell spectrometer, reported the detection of solar like modes on Procyon with a mean first-order half spacing of $0.5\,\Delta\nu = 39.7\,\mu$Hz, while Brown et al. (1991) found 35.5 μHz when observing with the FOE spectrograph. The other attempts were with a Fabry-Perot interferometer (Ando et al., 1988), and magneto-optical filter (Innis et al. 1991, Bedford et al. 1995).

Recently, astrometric measurements based on Wide Field Planetary Camera Images (WFPC2) by Girard et al. (1996) produced a mass for Procyon A as $1.47 \pm 0.045 M_\odot$, which agrees well with the theoretically predicted model. Chaboyer et al. (1988) calculated a new grid of stellar evolution models for Procyon A, based on the revised astrometric mass, and predict the large separation between 52.91 μHz and 55.47 μHz. They claimed that even a difference in spacing greater than 1 μHz can be used to determine the evolutionary state of Procyon, e.g. main sequence or shell hydrogen burning state, which has a large effect on the predicted p-mode frequencies. However, such high frequency resolution can be obtained only from the observing campaigns in sites distributed in longitude and involving the instruments having comparable photometric or spectroscopic precision. The best time-series coverage

Send offprint requests to: M. Martic
Correspondence to: milena@aerov.jussieu.fr

(156 hours) was obtained thus far by Gilliland et al. (1993) using a global network of several 4-m telescopes to search for oscillations in solar-type stars in M67. This tentatively approached the limit of differential CCD photometry. The other attempts to detect small amplitude p-mode oscillations on very few possible bright solar or near-solar type star candidates (Gelly et al. 1986, Brown & Gilliland 1990, Pottasch et al. 1992, Edmonds & Cram 1995, Kjeldsen et al. 1995 etc.) were not conclusive or were not confirmed by an independent team of observers.

Recent advances in echelle spectroscopy have led to important improvements in the precision of radial velocity measurements (Brown, 1998). Mayor & Queloz (1995) succeeded to detect the first exo-planet around the nearby star 51Peg using a new ELODIE fiber-fed echelle spectrograph at Observatoire de Haute Provence (OHP). Our first observing runs (Connes et al. 1996) were dedicated to evaluate the suitability of the (ELODIE) spectrograph for asteroseismology. ELODIE was designed for precise Doppler measurements, but the whole system (e.g., guiding camera, shutter, data reduction etc.) was not tested for the use in a rapid cadence necessary for the detection of oscillations on stars similar to the Sun. Over the past three years, the instrument and observing runs were optimised to measure the fluctuations in radial velocities for a sample of bright stars that are likely to undergo solar-like oscillations. A more extensive discussion of the actual instrument performances tested on these stars, mainly those which have the narrowest spectra and excellent photon rates, will be presented in subsequent paper. Here, we report the observations of Procyon and η *Cas* (HR219). The primary target, Procyon, has a higher expected amplitude of oscillations in the low frequency domain, compared to the fainter star η *Cas*. However, G-type solar-twin star, η *Cas* has expected oscillations in a higher frequency band than Procyon, at a place where instrumental noise is low.

2. Observations

The observations were carried out using the ELODIE echelle spectrograph which was newly installed on the 1.93 m OHP Telescope. A full operating principle of the spectrograph is explained in (Baranne et al. 1996, hereafter Paper 1). The ELODIE spectrograph is fed from the Cassegrain focus using 100μ optical fibers. The fibers avoid light losses, and improve the uniformity of illumination in the spectrograph (e.g. Connes 1978). Our first results (Connes et al. 1996) on a bright star ψ UMa HR4335 (V=3.0, K1III) showed the fast fluctuations coming from imperfect stellar-beam scrambling by the present fibers. Last year, a significant improvement was obtained by introducing an image scrambler (built by D. Kohler at OHP) on the stellar fiber path, which reduces the spurious line shifts due to changes in spectrograph illumination. In order to monitor the spectrograph calibration variations, the reference fiber is illuminated, during stellar exposures in

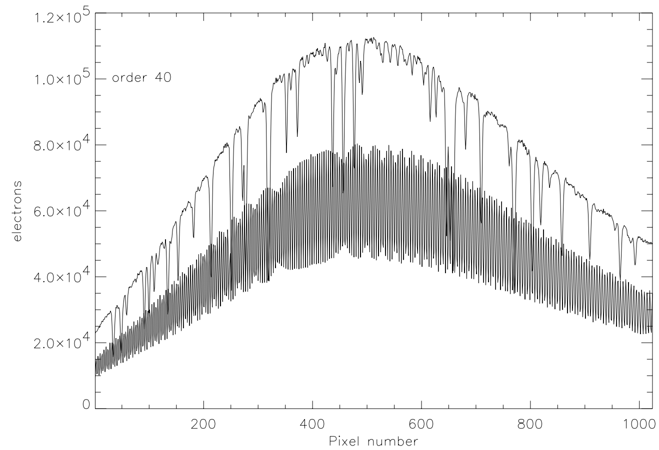

Fig. 1. Examples of stellar and Fabry-Perot spectra from a single order. The wavelength range is 519-524 nm.

regular ELODIE operation, by a Thorium-Argon lamp. In our configuration we introduced in the sky-hole, the channeled spectrum obtained with white light through a fixed (zero-dur) Fabry-Perot (FP) interferometer, which insures, by using the second optical fiber, the condition of almost identical optical path crossed by the stellar beam and FP beam. The comb of fringes from the Fabry-Perot etalon is exposed on the detector simultaneously with the stellar spectrum. The FP etalon thickness is 6 mm and fringe spacing of $72\,\mu$Hz and is itself temperature controlled to a precision of 0.001 K. To check various sources of errors in spectrograph operation like the variations due to the thermal relaxation, air pressure variations, CCD cooling, we made simultaneous recordings of FP/FP spectra on both fibers. We will show in the following sections that we are able to achieve a similar or better accuracy to that of the absorption cell instruments. Actually, the Absolute Acceloremetry technique proposed by Connes (1985) and observations described here do not suffer from the limitation of introducing gas cell in the beam which increases photon-noise radial velocity limit.

The optical layout, as explained in Paper 1 allows to record in one single exposure a wavelength domain from 390.6 to 681.1 nm at a resolution of $R \sim$ 42000. The 67 orders are recorded, each covering about 52.5 nm and with an overlap of about 10 nm between adjacent orders, on Tk 1024 CCD with $24\,\mu$ pixels. A rapid cadence for our observations is achieved by a parallel readout (7.5 microsec/pixel) of the two halves of the CCD with a read-out noise of 4.2 e^- which is insignificant for the high levels of the illumination we used. The CCD detector is currently maintained at 183 K operating temperature during observing runs. It needs twice-daily filling of a liquid-nitrogen dewar which introduces an important thermal shocks but of short duration at the beginning and at the end of long observing runs.

Table 1. Observational log(UT time)

Procyon					η Cas				
Date	Start	End	Nb spectra	$\sigma(ms^{-1})$	Date	Start	End	Nb spectra	$\sigma(\mathrm{ms}^{-1})$
98/11/07	00.00	06:11	307	4.17	98/11/07	18:05	23:32	193	1.99
98/11/08	23:48	06:17	322	4.55	98/11/08	18:03	23:19	187	2.46
98/11/10	00:33	04:11	151	4.01	98/11/09	17:31	23:19	203	2.99
98/11/10	23:45	06:15	230	5.01	98/11/10	17:45	22:58	185	3.95
98/11/11	23:37	01:41	91	—	98/11/11	17:53	23:14	190	
98/11/12	23:29	05:16	248	3.89	98/11/12				
98/11/14	23:29	06:07	291	3.31	98/11/14				
98/11/15	23:38	06:21	294	3.37	98/11/15	17:49	23:06	187	
98/11/16	23:24	07:06	338	2.69*	98/11/16	17:56	22:43	170	

* A few bad spectra eliminated

A total of 10 nights of OHP 1.93 m telescope time were allocated in November 1998 for the observations reported here. In addition to our primary target, Procyon, we also observed the η *Cas* for four hours at the beginning of each night. A journal of the observations is given in Table 1. We took sequences of about 40 s exposures, which with detector readout time and transfer of images yielded an almost regular interval between exposures averaging 90 s. In our run we did not use atmospheric differential correctors since placing and checking the corrector position is rather time consuming. The Doppler rms shown in the last column of the Table 1 applies to the time series of the data after all reduction described below have been carried out.

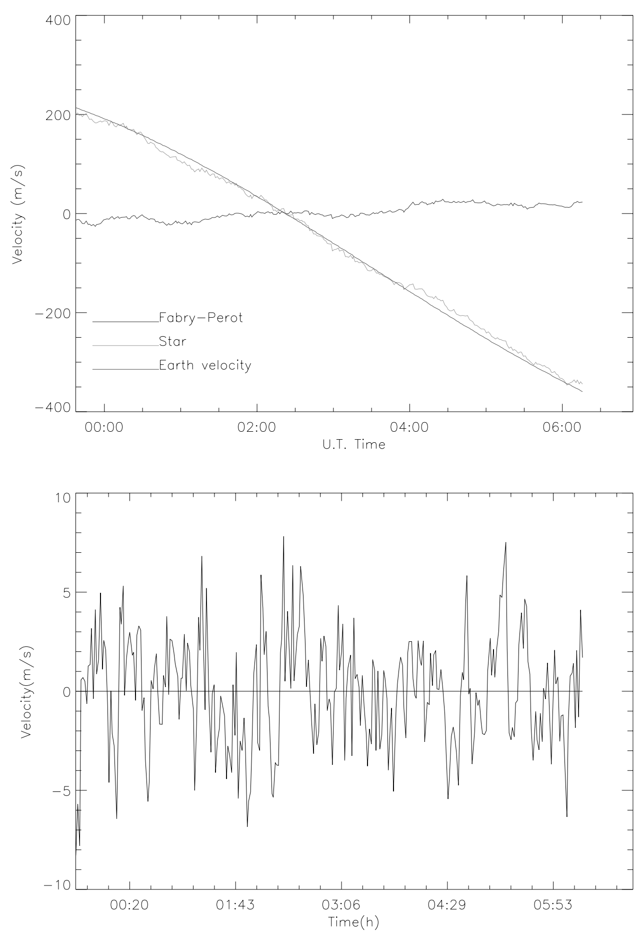

Fig. 2. Time series of the mean Doppler shifts. Top panel : Doppler shift of Procyon superposed to the radial earth velocity and instrumental shift as measured by the Fabry-Perot (FP) spectrum. Bottom panel : Residual averaged Doppler shift after the correction for Earth's motion and substraction of the FP shift.

3. Data Reduction

The reduction was carried out using a modified standard ELODIE data analysis package to extract the echelle spectra from row CCD (1024x1024) frames which where previously corrected pixel by pixel by subtracting the bias. The position of the orders on the detector is obtained by illuminating the fibers by a tungsten lamp. The geometrical definition and extraction of the orders based on Horn's (1986) algorithm are explained in detail in Paper 1. In our configuration, the result of this process produces for each CCD exposure a set of stellar and Fabry-Perot spectra interleaved into 67 echelle orders falling on the frame. Fig. 1 shows some typical extracted Procyon and Fabry-Perot spectra. We used neutral density filters to maintain consistent exposure levels from the FP beam for the different exposure times depending on weather conditions and star signal. The advantage of using the high quality channelled spectrum from a fixed FP is that it gives the best possible reference even for very short exposure times of bright stars.

The main modification of regular ELODIE software consisted in the adaptation of the observing run in order to obtain long uninterrupted sequences with high tempo-

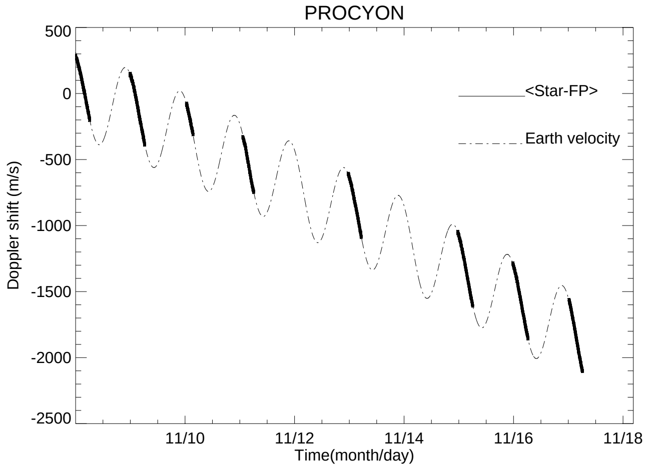

Fig. 3. Residual mean Doppler shift of Procyon superposed to the diurnal and orbital components of the relative earth velocity for the whole observing run.

ral resolution. Actually, not just during the development phase of this programme but also during the observations we found extremely useful to have real time reduction and display of the Doppler shifts and power spectra at the end of each exposure. Since the observing period allocated was short, this allowed us to correct for, when possible, problems, concerning CCD output, guiding errors, etc. The extraction of the 67 spectra for both star and FP and a computation of velocity shifts with our Sun Sparcstation (with two fast processors) last less than 40 s which is of the order of the CCD readout time. The standard radial velocity computation by a cross-correlation algorithm was replaced by our own algorithm based on a method explained in detail in Connes (1985).

The upper part of Fig. 2 shows the simultaneous time series of the FP and stellar mean Doppler shifts and telescope motion relative to the solar system barycenter for one night. The orders were averaged by weighting each order with the inverse square of its time-series rms. Orders 1 to 9 were not taken in the resulting mean shift. The lower part of the Fig. 2 shows the stellar shift for the same night after subtracting the instrumental drift (FP time sequence) and correction for earth's motion. The rms residuals is $\sim$3 m/s as compared roughly to 1m/s expected from photon noise alone. Note that after wavelength calibration, the velocity of 100 m/s corresponds to a 0.0316 pixel displacement. The accurate wavelength scale is obtained using a Thorium-Argon lamp; but this calibration is not necessary if we remind a useful property of echelle spectra, that in the spectrograph image plane the ratio $\Delta\lambda/\lambda\ 1/dx$ is very nearly a constant, independent of the order or of the position within orders. As a result Brown (1995) argues that the Doppler shifts appear as translations of the entire spectrum in the direction parallel to the dispersion with no stretching or deformation of the spectra. In our case, we computed the velocity shift taking into account the Doppler stretch but, we found very small differences compared to the constant case.

Fig. 3 illustrates the result of overall reduction on Procyon data from the whole 10 nights run. Individual bad points (clouds, non-corrected cosmic rays) were replaced with linearly predicted points or simply eliminated by comparing a difference of two successive spectra, when the shift is calculated. Subtraction of the scattered straylight, since the orders are very close, was achieved by using respectively, star only or FP only exposures for reference. We verified that the scaling law "average intensity of one fiber/average scattered light on the other fiber" is roughly preserved. The effect of the approximate correction of the straylight contamination in the average is small since the first low S/N orders were not used in averaging. The same is true for higher orders affected by the telluric lines. They were not systematically included in the computation of the mean shift. Nevertheless, we obtained a telluric water vapour template by observing the nearly featureless spectrum of the rapidly rotating B star, as suggested by Young & Rottler (1992). For the orders contaminated by the telluric lines, a mask was constructed and residual lines were used to calculate the shift. We made this effort in order to use, as much as possible, the broad wavelength coverage provided by ELODIE echelle spectrograph. It is worth noting that the photon-noise limited Doppler sensitivity can be approached only using a very large number of narrow lines from a stellar spectra. For η *Cas*, whose spectra have a high quality Q factors similar to the Sun (Q $\sim$ proportional to the number, depth and finesse of the spectral lines, see Connes 1985) we obtained for one order Qmax=12137. This is to be compared with the Qmax=14179 for a spectrum of the Sun obtained during the daytime runs in scattered light. The Qmax for the Fabry-Perot spectra is 40000 and the photon noise limit obtained from the whole spectral range in 40 s integration, is of the order of 0.2 m/s. For Procyon (Qmax=8672), we calculated, for an average S/N in a single exposure of 40 s a photon noise equal to 0.8 m/s. For one hour of our best run, the measured radial velocity deviation is approximately twice the photon noise limit.

4. Analysis

We used the Lomb-Scargle (LS) modified algorithm (Lomb 1976, Scargle 1982) for unevenly spaced data to compute the power spectra of the Doppler shift time series described in Table 1. The sampling rate in the individual nights was almost constant (90 s) but the window function of the entire run was complicated by two missing nights (or large gaps of 42 hours) due to the weather conditions. Therefore, we first separated Procyon data into two independent set of Doppler shift time series : the first one results from the concatenation of the four adjacent nights of observation, the second one from the three last nights.

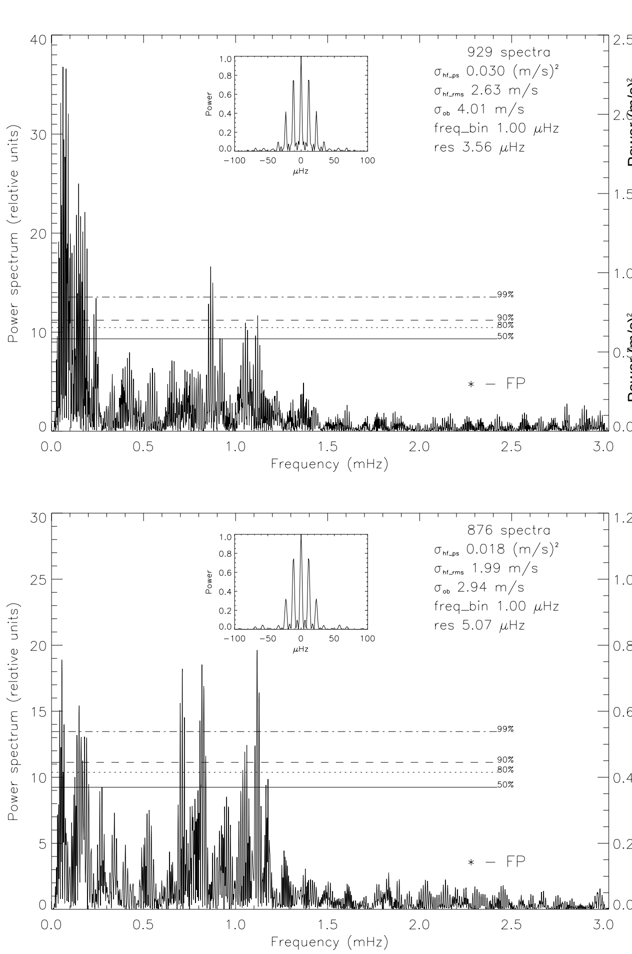

Fig. 4. Power spectra of the Doppler shift for Procyon, computed with 1μHz resolution. Top panel : Power spectrum of the four first nights (Nov 7-10, 1998). Bottom panel : Power spectrum of the three last nights (Nov 14-16, 1998). The horizontal dashed lines indicates the amplitude of several peaks having a "true alarm probability" of $\geq$50%. The inset shows the power spectrum of the window function for a signal amplitude of 1 m/s and the same sampling rate as the observations.

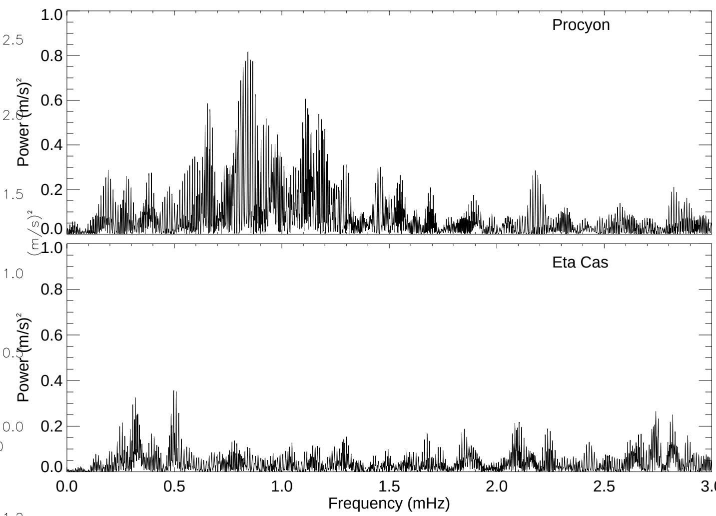

Fig. 5. Power spectra of the Doppler shift for Procyon and η Cas computed from the first four nights of the observations. The data of Procyon were cut in order to have the same number of spectra by night for the comparision. The low frequency contribution has been slightly filtered out.

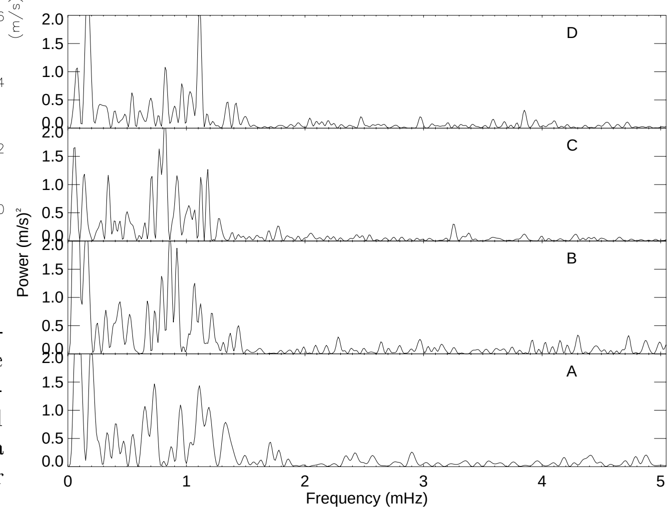

Fig. 6. Power spectra of the Doppler shift for Procyon computed for four individual nights of observations in 1998. The spectra are shown at a frequency resolution of 10 μHz.
A Power spectrum, 7-8 Nov. **B** Power spectrum, 8-9 Nov. **C** Power spectrum, 14-15 Nov. **D** Power spectrum, 15-16 Nov.

Fig. 4 show the LS periodograms at a frequency resolution of $1\,\mu$Hz, of the first sequence and the second one separated about 78 hours from the first. The window function plotted in the inset shows sidelobes whose frequency separation is about 1/day=11.57 μHz. The two power spectra show an excess power around 1 mHz with a few common peaks in the 0.6–1.5 mHz band where p-mode oscillations are expected to occur (Guenther & Demarque (1993). A sharp cutoff below 50 μHz is due to the linear detrending, but no other high-pass filtering operation was used. The power at frequencies up to 0.3 mHz is rather low which indicates the excellent elimination of the instrument instabilities by simultaneous FP recordings. The rms scatter $\sigma_{\rm rms}$ ($\sigma_{\rm ob}$ in Fig. 4) is greater 4.01 $\rm ms^{-1}$ for the first sequence of four nights than 2.94 $\rm ms^{-1}$ for the second sequnce of three nights. The mean white noise level in the power spectrum $\sigma_{\rm hf\_ps}$ within the frequency interval 2-5 mHz is respectively $0.03\,({\rm ms}^{-1})^2$ and $0.018\,({\rm ms}^{-1})^2$ for the first and second data set (see Fig. 4).

In order to estimate the statistical significance of the peaks in 0.6–1.5 mHz frequency range, we used the statistical properties of the LS periodogram. According to the method of Horne - Baliunas (1986), we calculated a few levels of power corresponding to a few values of the quantity 1-F where F is the "false alarm probability". Four peaks have an amplitude equal or higher than the level

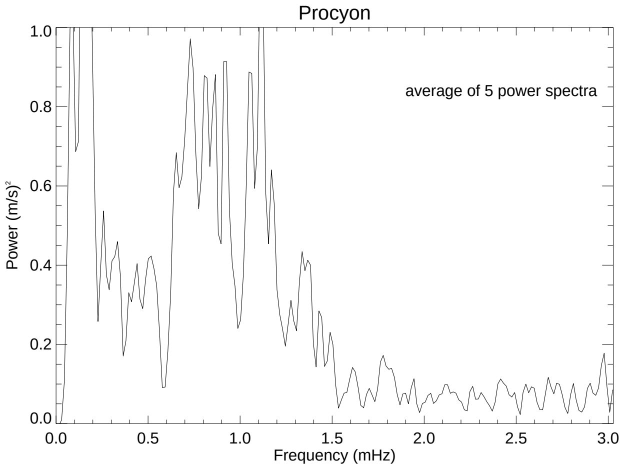

Fig. 7. Average of power spectra of the Doppler shift measurements for Procyon over 5 best nights of observations in 1998.

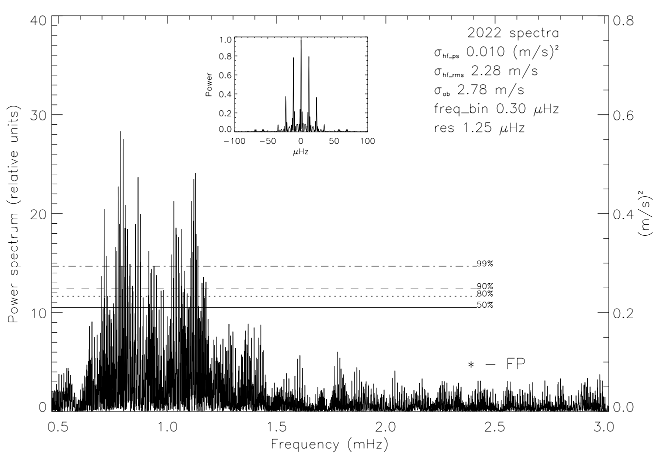

Fig. 8. Power spectrum of the eight-night time-series of the Doppler shift measurements for Procyon. The inset shows the power spectrum of the window function of the observations, for a signal amplitude of 1 m/s.

probability of 80% (see Fig. 4) and may result from a genuine signal particularly for the last sequence which has the best signal to noise ratio. A positive result is also obtained when we calculate according to Hoyng (1976) the relative error of individual peaks. This relative error expressed by :

$$\sigma(\nu)/P(\nu) \approx (2x - x^2)^{1/2} \text{ where } x = \sigma_{\mathrm{hf\_ps}}/P(\nu)$$

gives the probability that data are pure noise. For two common peaks at ∼1.120 mHz in both sequences, we estimated respectively a relative error of 26 % and 21 %.

In order to calculate the amplitude of the signals suspected to be the oscillation modes of Procyon, we used the following formulae (Kjeldsen & Bedding 1995) :

$$(A_{\mathrm{osc}})^2 = (A_1)^2 - (8.7 \pm 2.3)\sigma_{\mathrm{amp}}^2$$

where A_1 is the amplitude of the strongest peak, σ_{amp} is the mean noise level in the amplitude spectrum and A_{osc} is the searched "true" amplitude. If we assume only a gaussian noise around 1 mHz, we have $\sigma_{\mathrm{amp}}^2 = \pi\sigma_{\mathrm{hf\_ps}}/4$. Using the statistical values written on the graphes, we estimate the amplitude of the peak at frequency $\nu_{\mathrm{max}} = 1.12$ mHz to about $0.75\,\mathrm{ms}^{-1}$ for the two sequences.

The difference of power in other large peaks of two data sets can be explained by constuctive interferences with a noise. We did not apply the high-pass filter on the individual time sequences in order to not artificially create or modify the shape of the hump of power. strenghthened for the first sequence which σ_{rms} is larger.

The individual peaks can also be examined by simple visual inspection of the oscillation frequencies on the single-night spectra. Several nights of data on Procyon show the repeatability of the structure (see Fig. 6) in the power spectrum. The excess of power and few common peaks present in adjacent nights indicates the possible detection of coherent oscillations. It is however not evident to determine the lifetime of the signal since the peaks could be increased by noise which is not the same from one night to another.

An another test for the existence of periodic signal in the power spectrum is to compute the average power spectrum. The hump of excess power between 0.5 and 1.5 mHz is always present when we calculate a trivial average by adding several power spectra of the Doppler shift of individual nights of observations (see Fig. 7). An obvious low-frequency cutoff, already visible in the best individual nights, appears about 0.55 mHz.

In addition, the power spectra of Procyon and *η Cas* (see Fig. 5) issued from the same number of spectra observed during the same 4 nights show clearly the existence of an excess of power on Procyon within the frequency range 0.55–1.5 mHz comparing to *η Cas*. The mean noise high frequency level in the power spectrum, equal for the two series of data, is about 0.035 $(\mathrm{ms}^{-1})^2$. Since *η Cas* was observed only for about four hours at the beginning of each night, the length of the sequence was too short to allow to search for the p-modes on this solar twin star. Note however, that with this noise level in 5-min frequency range and longer run, we can expect to detect in future the oscillations on *η Cas*.

Finally, Figure 8 shows the power spectrum of the complete data data set of 8 nights. The data of each night have been high-pass filtered below 0.3 mHz in order to attenuate the power at lowest frequencies, in particular, from the first nights. We checked that the filtering process do not alter the positions of peaks in the interval of excess power. For four significant peaks we calculated the mean "true" power level according to the same method as described above. We found a mean amplitude of about 0.47 ms^{-1} in the 0.6–1.5 mHz frequency range. The power evidently drops near 1.5 mHz which is consistent with expected p-mode properties for Procyon.

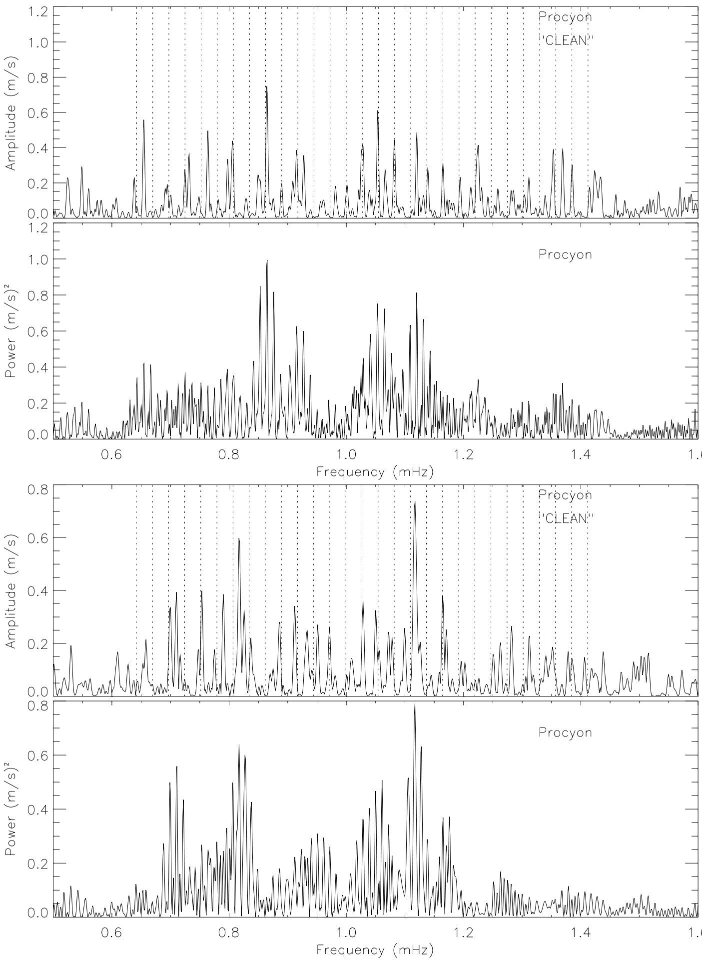

Fig. 9. Top panel : Power and CLEANed spectra of the Doppler shift of the four first nights (Nov 7-10, 1998).
Bottom panel : Power and CLEANed spectra of the Doppler shift of the three last nights (Nov 14-16, 1998). The dashed lines indicate frequencies equal to $\Delta\nu_0(n+l/2)$, $\Delta\nu_0 = 55\,\mu$Hz, $n=[12,24], l=[0,1]$

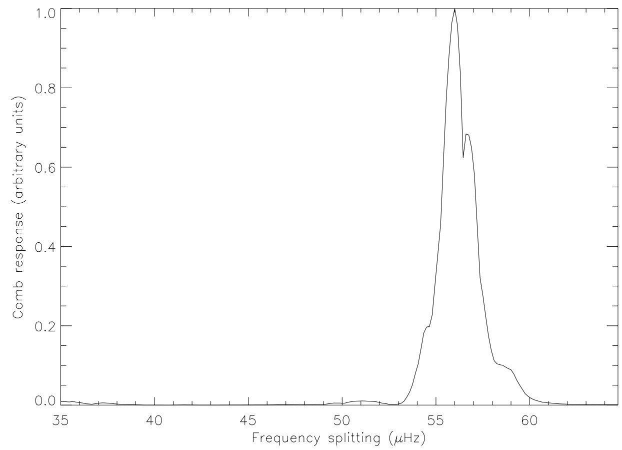

Fig. 10. Example of Comb response of the CLEANed power spectrum of Procyon Doppler shift in one data set.

5. Clean Analysis

The probable detection of solar-like oscillations in Procyon from the time series of Doppler velocity measurements may be established by identifying an equidistant set of peaks within the frequency range of hump of excess power. The asymptotic relation, first developed by Tasoul (1992), for modes with radial order n much greater than l predicts a series of oscillation frequencies with almost uniform separation usually defined as a large frequency splitting ($\Delta\nu_0$). One technique commonly used to determine the first order spacing $\Delta\nu_0$ is to calculate the "comb response" of the power spectrum (Kjeldsen et al. 1995). If the power spectrum includes peaks having regular spacing from the largest peak assumed to be the oscillation mode, then frequency of the maximum peak of the comb function will be the searched value of frequency splitting.

We first applied the comb response to two periodograms of the first four and three last nights of Procyon observations. Because of the sidelobes of substantial amplitude due to daily gaps in the power spectrum, we obtained no clear comb function signature. Consequently, in order to remove the effects of the window function, we processed our two independent time series with the "CLEAN" procedure (Roberts et al. 1987). In the Fig. 9, one may compare the periodogram and the CLEANed spectrum of each time series in the frequency range of excess power. The CLEAN algorithm works well enough, the amplitudes of the sidelobes are clearly reduced and the most of the large peaks stay on the same place as on the periodograms. However in both, periodogram and clean spectrum, the gaps could produce the peaks at frequencies shifted from the real one or reinforce one peak by mixing multiple frequencies. For this reason we computed the comb response for several common peaks but of not equal power in two data sets. Fig. 10 shows one comb response of the sequence of four nights of Procyon calculated at the frequency 1.164 mHz.

For the average spacing $\Delta\nu_0 = 55\,\mu$Hz, we obtained the smallest separation of individual peaks from regular grid indicated by dashed lines in the Fig. 9. This value for the large frequency spacing can be compared to $\Delta\nu_0 = 53\,\mu$Hz found by Mosser et al. (1998). Taking account a frequency resolution of respectively 3.56 mHz and 5.07 mHz for the two time series, the identification of individual modes in clean spectra (oversampled by 4) is subjected to great caution. Here, we note only the frequencies of maximum of peaks (those with power greater than 0.3 $(\mathrm{ms}^{-1})^2$) that are common ($\pm 5\,\mu$Hz) between 0.6 mHz and 1.4 mHz in the two clean spectra. We note also the first-order frequency spacings from the comb response computed at these frequencies :

First data set (4 consecutive nights) :
ν (mHz) : 0.806, 0.914, 1.029, 1.054, 1.082, 1.120, 1.165
$\Delta\nu$ (μHz) 55.6, —, 55.3, 54.9, 56., 55., 55.9
Second data set (3 consecutive nights) :
ν (mHz) : 0.806, 0.911, 1.028, 1.061, 1.081, 1.116, 1.165
$\Delta\nu$ (μHz) 53.1, 56.7, 59., 54.5, 55.4, 54.9, 57.2

Some of the peaks are double or too wide to allow an unambiguous determination of the mode frequencies. For example, the frequency of the largest peak inferred from the power spectra between 1 mHz and 1.2 mHz seems to be in error by +1/day and its amplitude underestimated in the clean spectrum of the first data set.

The CLEANed spectrum of the whole sequences (not presented here) was of limited utility since the sidelobes of the window function were only partially removed. We noted also that the CLEAN algorithm produces spurious peaks shifted from those found in periodograms when the data were more irregularly sampled. For example, if we reject data out of 2 σ (only 5 %) in the individual nights, the periodogram of the global sequence (8 nights) stays unchanged compared to an unrecognizable CLEANed spectrum. In other words, the presence of only a few little gaps in time sequences interleaved with large regular gaps leads to an incorrect deconvolution of the spectral window by CLEAN algorithm. We found nevertheless the same amplitude (∼50 cm/s) for the maximum of the envelope centered at about 1 mHz with both algorithms.

6. Discussion

Rather severe conclusions by Kjeldsen & Bedding (1995) based on their simulations of noise spectra casted serious doubts on all existing claims of p-mode detection on solar-like stars. However the challenge to show the results, even if the doubts persist, is great, since there is always the possibility of the confirmation by future independent observations. In the case of Brown et al. (1991) measurements, Kjeldsen & Bedding arrived to reproduce the overall shape of the observed power spectrum of Procyon only with two noise components model. Our observations confirm the excess of power found by Brown et al. in the 0.5–1.5 mHz range. In our case, one can exclude any influence of high-pass filtering. The estimation of the amplitude of the oscillations is of the order of 50 cm/s or even less which is below predicted amplitudes by Houdek et al. (1994). The most probable frequency spacing is about 55 μHz while the frequency cutoff is around 1.5 mHz. This characteristic frequency spacing of p-modes corresponds to the model b (core hydrogen exhaustion phase) obtained by Guenther & Demarque (1993) for Procyon (M=1.5$M_\odot$, $\log R/R_\odot =$ 0.3270). Here we also presented a preliminary identification of the p-mode frequencies of Procyon. Several modes seemed to be found on both data set constructed from adjacent nights, but more detailed cleaning (e.g. using the CLEANest algorithm, Foster 1995) is needed, especially for a whole run (complicated window function) to unambiguously confirm the mode detection. Although several peaks are recurrent on individual spectra and the average power spectrum shows an excess of power, a typical "picket-fence" effect in solar-oscillations spectrum is not observed. This can be explained by simulations (Barban et al. 1999) or constructive interference with noise. On the other hand one can always suspect some unknown noise effect producing a power excess in the p-mode frequency range of Procyon. We verified that the instrumental noise, given by simultaneous Fabry-Perot recordings, do not present any kind of narrow band feature in the power spectrum. Moreover, the results obtained with the η *Cas* observed in almost identical night conditions and with the same window function like Procyon's first data set (4 consecutive nights) show a flat spectrum in the 0.6–1.5 mHz interval. Note that from this observing run on η *Cas*, we obtained a limit of about 30 cm/s for the detection of 5-min oscillations. As emphasized by Peri (1995), η *Cas* is the most promising candidate in the northern hemisphere for the detection of solar twin type oscillations. It was effectively a difficult choice for us, taking into account a limited number of allocated nights for asteroseismology, to observe Procyon for the rest of the night rather than η *Cas*. Since the primary objective is to have the best temporal coverage as possible in order to identify the p-modes, the seeing conditions favored the brighter star Procyon with higher expected amplitude oscillations. In conclusion, we expect to confirm the results presented in this paper from future multisite observations using the instruments of comparable sensitivity.

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