Astron. Astrophys. 340, 457–462 (1998)

ASTRONOMY
AND
ASTROPHYSICS

New limit on the p-mode oscillations of Procyon obtained by Fourier transform seismometry

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Received 26 June 1998 / Accepted 29 September 1998

Abstract. The Fourier transform spectrometer based at the CFH telescope was used as a stellar accelerometer in a new seismometric mode. One fringe at a selected path difference of the interferogram produced by the flux of a star through a bandpass chosen in the near infrared is continuously scanned. Its phase is measured and translated directly into velocity with an absolute calibration, providing a sensitive measurement of the Doppler signal.

This paper reports the 4.5 nights observation of Procyon in February 1998 with this instrumentation. The final 1-σ noise of the spectrum beyond 0.8 mHz is as low as 0.12 $\mathrm{m\,s^{-1}}.\mu\mathrm{Hz}^{-1/2}$. Even with this noise level, in a single site observation we cannot report a firm detection of *p*-modes. We do not detect any significant excess in the power spectrum near 1 mHz. A limit on the amplitude of the modes can be deduced, which cannot exceed 1 $\mathrm{m\,s^{-1}}$. However, the "comb response" exhibits the signature of a possible regular pattern with a large splitting ν_0 of 53 μHz, which would indicate that a signal of stellar origin has been detected. Both values agree with theoretical predictions, but are in contradiction with claimed detection of *p*-modes previously reported.

Key words: techniques: interferometric – techniques: radial velocities – stars: individual: α CMi = Procyon – stars: oscillations

1. Introduction

Procyon (α CMi), a F5 IV-V star, is the brightest solar-like star of the northern hemisphere and therefore the primary target of the search for solar-like oscillations. Several groups have already conducted thorough attempts to detect a Doppler signature of the pressure mode oscillation spectrum, with a resonance cell spectrometer (Gelly et al. 1986), a Fabry-Perot interferometer (Ando et al. 1988), a magneto-optical filter (Innis et al. 1991, Bedford et al. 1995), or a fiber-fed échelle spectrograph (Brown et al. 1991, Barban et al. 1998). Theoretical predictions have been proposed by Guenther & Demarque (1993), Houdek et al. (1995) and Kjeldsen & Bedding (1995). Claims of a positive detection of possible *p*-mode oscillations on Procyon were reported by Gelly et al. (1986), Brown et al. (1991) and Innis et al. (1991).

We contribute to this quest for solar-like oscillations by a new observational method, based on the search for a Doppler signal in the interferogram given by a Fourier transform spectrometer and tested on Procyon in February 1998. The principle of the method is described in Sect. 2. Data acquisition and data analysis are given in Sect. 3. Sect. 4 is devoted to the discussion of the intrinsic and experimental properties of Fourier Transform seismometry. Possible improvements of the method are described. Finally, in Sect. 5, we compare our results with the ones previously obtained and with theoretical predictions.

2. Principle of the observation

2.1. Search for the Doppler signature in the interferogram

The principle of Fourier Transform seismometry, proposed first by Forrest & Ring (1978) and developed in detail in Mosser et al. (1993) and generalized in Maillard (1996) (hereafter Mo93 and Ma96), consists of searching for the Doppler signal not directly in the spectrum of an object but in its interferogram. The achievement of the method rests on the stability of a metrologic laser, that allows to control the path difference between the two arms of the interferometer with a precision better than a few nanometers. In the region of a local interferometric maximum I_f, the signal can be represented as:

$$I(\delta) \;\propto\; I_\mathrm{f}\;\cos 2\pi\sigma\delta \;=\; I_\mathrm{f}\;\cos 2\pi\sigma_0\delta\;\left[1+\frac{v}{c}\right] \qquad (1)$$

where σ_0 is the mean wavenumber selected by a narrow-band filter limiting the incoming flux, and v the contribution of all the velocity components: the diurnal rotation, the relative motion between the source and the observer, the spurious velocity components induced by instrument drifts, and the seismic signal.

The first observations made with the FTS at CFHT were conducted at a fixed path difference. The targets were Jupiter (Mo93), Saturn and Procyon (Ma96). In this case, the intensity changes ΔI at a zero-crossing of the interferogram, in the linear

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part of a fringe, are proportional to the velocity variation Δv, according to:

$$\Delta I = I_{\mathrm{f}}\ 2\pi\sigma_0\delta\ \frac{\Delta v}{c} \tag{2}$$

In fact, this method appeared to be critically sensitive to the drifts of the working point, which are added to the seismic signal. The linear part of a fringe of period $1/\sigma_0$ has an extent of $\pm 1/8\sigma_0$. For a total drift larger than this value, the response decreases to become null for $1/4\sigma_0$.

2.2. Scanning of the fringes

In order to eliminate this major limitation on the detection of a Doppler signal, the principle of the data recording was changed into a phase measurement. In practice, a small portion of the interferogram, roughly equal to one fringe, is repeatedly scanned step-by-step, in order to obtain a time series of the phase (Fig. 1). According to Eq. 1, the phase of a given fringe of the interferogram relative to a fixed sinusoidal reference is defined by:

$$\frac{\varphi}{2\pi}\ =\ \sigma_0\delta\ \frac{v}{c} \tag{3}$$

This relation between the phase φ and the velocity v summarizes the advantages of this method:

- The determination of the phase is independent of the amplitude of the fringe. This means that the phase measurement is not affected by photometric changes of the source intensity to a large extent, except for those varying more rapidly than the registration time of one fringe.
- The phase can be always determined, and therefore the detection sensitivity is constant and no longer affected by low frequency drifts of the working point.
- The method provides an absolute calibration of the velocity signal. The interferometric gain being $\sigma_0\delta$, the calibration factor between phase and velocity is simply $c/2\pi\sigma_0\delta$. All the terms are perfectly determined.
- The precision in velocity which results from the stability of the path difference itself is better than 1 $\mathrm{cm\,s^{-1}}$. The detection can be purely photon noise limited.

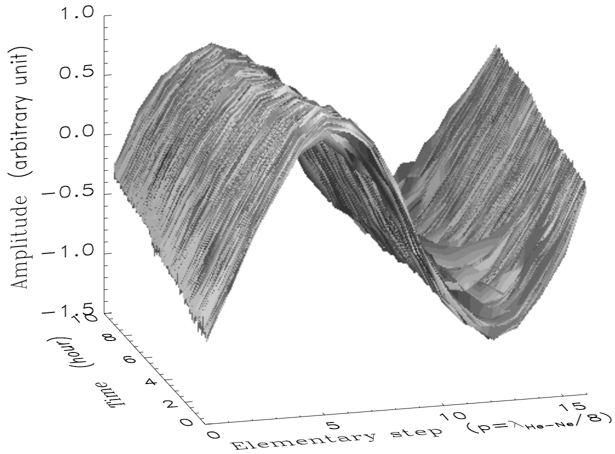

Fig. 1. Display of the fringe signal of a full night. The same fringe, corresponding to the optimized seismometric signal, is continuously scanned forward and backward along the entire night.

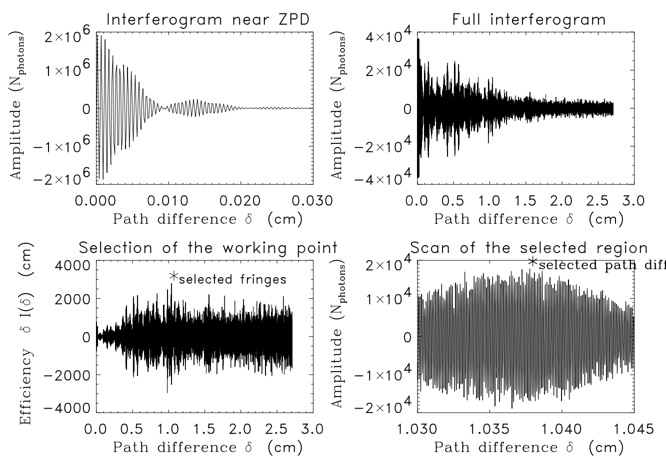

Fig. 2. a Interferogram near zero path difference. Intensity is scaled to the total number of photons collected within the filter; path difference δ is in cm. **b** Full interferogram; beyond $\delta \simeq 2$ cm, the interferogram is dominated by photon noise. **c** Efficiency function $\delta \times I(\delta)$; the highest peak corresponds to the best working point. **d** Fine scanning of the fringe peak, and determination of the working path difference.

2.3. Choice of the working point

In order to optimize the sensitivity of the method, two conditions must be fulfilled which, of course, are contradictory. It is necessary to look for a fringe with a high contrast in order to maximize the signal-to-noise ratio, which means to work at a path difference not too high. In order to increase the interferometric gain $\sigma_0\delta$, that is preferable to work at the highest possible path difference. Then, an optimum path difference must be found, as detailed in Mo93 and Ma96.

The method used in practice to find the working path difference is as follows (Fig. 2). The interferogram $I(\delta)$ is scanned from zero path difference (ZPD) (Fig. 2a) up to a few centimeters (Fig. 2b). This first step makes it possible to determine the envelope of the fringe maxima (Fig. 2b). From this record, the efficiency function $\delta \times I(\delta)$ can be computed. The working point corresponds to the largest peak out of the noise (Fig. 2c). A fine scanning of the fringes of this selected peak leads to the determination of the best working path difference δ_{opt} (Fig. 2d). The calibration factor between the signal level delivered by the FTS and the photon equivalent number is derived from the comparison of the signal at ZPD and at high path difference. The signal at ZPD is directly proportional to the total number of photons N_0 received within the filter bandpass. At large path difference, where the interferometric contribution has decreased, the signal corresponds only to photon noise. The rms value of this noise is proportional to $\sqrt{N_0}$.

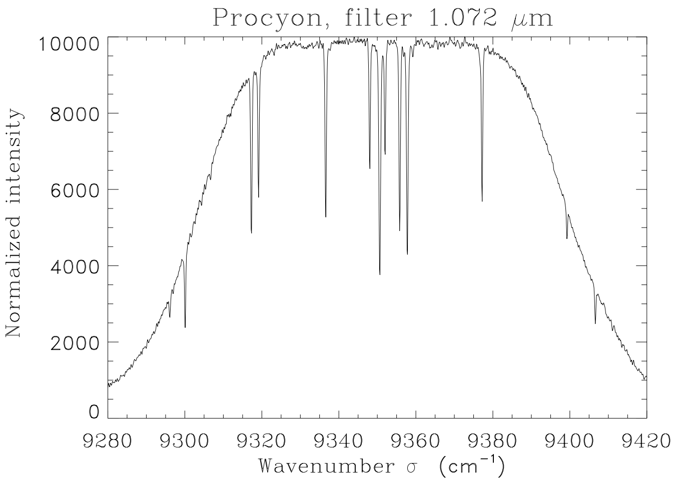

Fig. 3. Bandpass of the filter, selecting a dozen lines (mostly SiI lines) without any telluric contribution.

2.4. Phase measurement

The amplitude and the phase of the fringes are determined by using a least square fit method. This method proved to be the most efficient among the ones we tested. However, from simulation on synthetic signals, the phase determination is affected by a small error due to the fact that the fringe is sampled over a path difference range which is not an exact multiple of its period λ_0. However, this error does not affect the result, since it is practically equivalent to a constant small shift of the phase determination.

3. Data acquisition and data analysis

3.1. Detector, filter

The telescope time was scheduled from 3 to 10 February 1998, about 3 weeks after the opposition of the star. We obtained finally 4.5 consecutive nights of observation. On the last three nights, it was possible to guide on the star continuously during almost 9 hours, so that a total of 38 hours of observations was reached out of a time span of about 100 hours. The final window function is given as an inset in Fig. 5.

Preparatory work prior to the run led us to choose a filter selecting a dozen stellar lines (mostly SiI lines), around 1.072 μm (Fig. 3), from a synthetic spectrum of Procyon kindly provided by Kurucz (1995). The bandpass of this filter was chosen also to avoid any telluric contribution. InGaAs diodes were used, as they offer the best quantum efficiency in the very near infrared. The tank housing the FTS was put under vacuum, in order to cancel any turbulence on the interferometric light path (Mo93, Ma96).

3.2. Data acquisition

The data acquisition consists of scanning step-by-step one fringe at the selected path difference and recording repeatedly a set of N points along it. (Fig. 1). The recording parameters are summarized in Table 1. The integration time τ was chosen to be 1 s, with a sampling of $N = 16$ points along the fringe, alternatively forward and backward. This tight sampling is obtained by using the elementary step of the FTS, namely $p = \lambda_{\rm He-Ne}/8$, with $\lambda_{\rm He-Ne}$ the red wavelength in vacuum of the helium-neon metrologic laser.

Table 1. Interferometric data

Mean wavenumber	σ_0	9350	cm^{-1}
Mean wavelength	$\lambda_0 = 1/\sigma_0$	1072	nm
Elementary step	$\lambda_{\rm He-Ne}/8$	79.1	nm
Integration time per step	τ	1	s
Number of steps along a fringe	N	16	
Working path difference	$\delta_{\rm opt}$	1.037	cm
Calibration factor	$c/2\pi\sigma_0\delta_{\rm opt}$	4924	$\mathrm{m\,s}^{-1}$

The total path $N \times p$ scanned along the interferogram covers a little more than a fringe period, representing in fact 1.16 $\times\lambda_0$ (with $\lambda_0 = 1/\sigma_0$). The total duration for the acquisition of one fringe and the measurement of one phase is $(N + 1)\ \tau$, i.e. 17.4 s. This duration leads to a strong oversampling of the time series, as the maximum frequency of the *p*-mode spectrum of Procyon is given by the Lamb cutoff frequency and should occur around 1.5 mHz according to the stellar mass and radius values reported in Guenther & Demarque (1993). The choice of this short recording time comes from observational considerations. Providing a high enough signal-to-noise ratio, any photometric variations evolving more slowly than 60 mHz are cancelled. Therefore, a filtering of this source of noise is obtained in the seismic signal domain. However, the photometric variations include the stellar scintillation which has faster components. Local corrections of few points had to be made, representing a total of about 5% of the sample.

3.3. Analysis of the signal: low frequency drifts

Each night we observed a reproducible low frequency drift of the phase φ, with a slope of about 4.10^{-5} rad.s^{-1}, corresponding to an acceleration of 0.2 $\mathrm{m\,s}^{-2}$. The acceleration is one order of magnitude greater than the term produced by the diurnal rotation. This high value being incompatible with a drift of the metrologic laser, the only possible origin of this signal is a drift of the mean path difference. Knowing the fact that the FTS is installed at the IR Cassegrain focus of the CFH telescope (Maillard & Michel 1982) and is working over a very large hour angle range for this type of observation ($\simeq \pm 5$ h), the interferometer undergoes necessarily some mechanical flexures which cannot be fully compensated by the servo-system. The full phase shift over a night corresponds to a path difference variation of 0.22 μm. As the reference laser and the scientific beams are parallel and separated by about 1 cm, a deviation between the two directions of about 4” over a night is enough to produce this difference between the servo-controlled path and the IR path, which is plausible. This differential path difference translates into a total velocity drift of about 5 $\mathrm{km\,s}^{-1}$ for a full night. This drift is mainly composed of a low frequency contribution with a quasi-constant acceleration and can be cancelled in the data processing. However, small discontinuities are randomly superimposed, and must be corrected before any Fourier treatment of the time series. The cause of these discontinuities was identified as due to sudden corrections of the tracking rate generated by the automatic guiding system of the telescope, when the seeing conditions on the star were poor, particularly at large hour angles.

4. Results

4.1. Raw data

Fig. 4 presents the Fourier spectrum without any filtering, except that each time series corresponding to a given night was apodized with a Hanning function, and that we took care to avoid steps in the global time series at the beginning and the end of each night. The Fourier spectrum (Fig. 4) is composed of 2 parts. The low frequency domain, up to 0.7 mHz, is dominated by a noise component varying as $1/\nu^{2.9}$. The high frequency part corresponds to a white noise with an equivalent velocity of 12 $\mathrm{cm\,s^{-1}.\mu Hz^{-1/2}}$. The highest peaks reach the 0.4 $\mathrm{m\,s^{-1}}$ level. There is no clear evidence for any excess power in the frequency range around 1 mHz, where *p*-modes are expected (Kjeldsen & Bedding 1995, and reference therein) and where their detection was claimed (Brown et al. 1991).

4.2. Filtered data

We considered it necessary to filter out the low frequency part of the spectrum, since this part is contaminated by the drift reported in the previous section, which cannot be otherwise consistently corrected. The high-pass filter (an "à trous" algorithm) does not affect the frequency range above 0.9 mHz. As a direct consequence of the filtering process we observe an artificial bump in the Fourier spectrum in the 1-mHz region (Fig. 5). Hence, the filtering operation prevents us from claiming a positive detection of the pressure mode oscillation of Procyon based on the presence of some excess power.

Usual tests were made on the Fourier spectrum in order to detect a possible regular spacing. The autocorrelation of the spectrum, the spectrum of the Fourier spectrum did not provide any positive results. We also made use of the "comb response", a method proposed by Kjeldsen et al. (1995) in order to search for regularity in the power spectrum, namely to search for a comb-like pattern around the greatest peaks $S(\nu_{\rm M})$ identified in the power spectrum S. The comb response of a regular pattern based on the equidistance $\Delta\nu$ around the peak $S(\nu_{\rm M})$ expresses as:

$$\mathcal{C}(\nu_{\rm M}, \Delta\nu) \;=\; \sum_{i>0} \left[S\left(\nu_{\rm M} + i\frac{\Delta\nu}{2}\right) S\left(\nu_{\rm M} - i\frac{\Delta\nu}{2}\right)\right]^{\alpha_i} \quad (4)$$

where α_i represents the weight of the components $\pm i$ of the comb structure. As in Kjeldsen et al. (1995), we limit the structure to $\pm 2\,\Delta\nu$ (i.e. $\alpha_i = 0$ for $i > 4$), and give a stronger weight

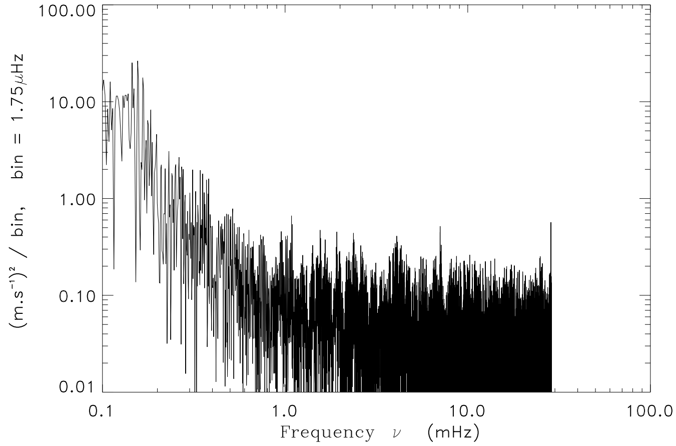

Fig. 4. Fourier spectrum in logarithmic scales. The integration time for one fringe is 17.4 s

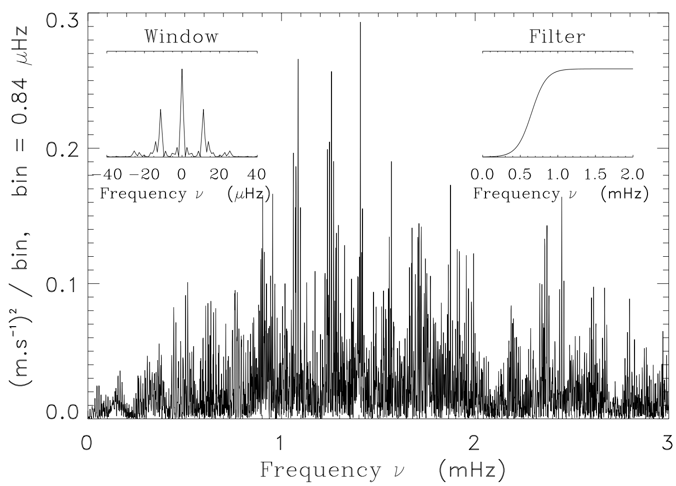

Fig. 5. Fourier spectrum in linear scales. The low frequency contribution has been filtered out. The time step is rebinned to about 140 s.

to the closest neighbours ($\alpha_{1,2} = 1$, whereas $\alpha_{3,4} = 1/2$). This method gives a recurrent signature around 53 μHz in the frequency range [0.8, 1.2 mHz] (Fig. 6). This signature seems to be statistically significant: among the 8 largest peaks in this frequency range, only one doest not exhibit a comb structure at 53 μHz. On the other hand, there is no other recurrent candidate, except for multiples of the diurnal splitting, which have been discarded. Furthermore, the signature at 53 μHz does not appear in other frequency ranges ($\nu < 0.5$ mHz, $\nu > 2$ mHz), where no signal is expected, and disappears when the data set is randomly scrambled.

In order to infer a maximum value for a possible oscillation pattern detected with a low signal-to-noise ratio, we add to the data an artificial signal corresponding to a plausible oscillation spectrum of Procyon based on an asymptotic development, with an amplitude dependence function of the frequency and the degrees ℓ scaled to the solar one: $\nu_{n,\ell} \propto [n + \ell/2]\ \Delta\nu$ + 2nd order term. A level of around 1 $\mathrm{m\,s^{-1}}$, taking into account the window function, is necessary to be compatible with the power detected in the frequency range [0.8, 1.2 mHz]. This detection

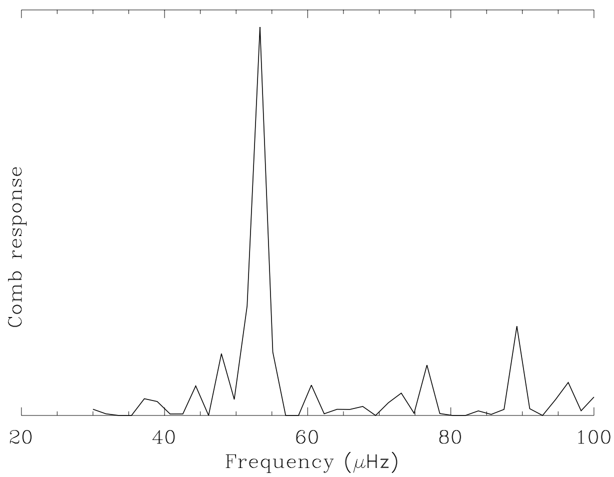

Fig. 6. Coaddition of the comb responses based on the major peaks identified in the power spectrum in the frequency range [0.8, 1.2 mHz]. The 53 μHz value is the only one exhibiting a recurrent signature. The vertical scale is in arbitrary units.

limit does not depend on the exact shape of the spectrum. The change of the asymptotic parameters only slightly modifies the result.

The comb response was also calculated with the synthetic spectrum that mimics the Procyon spectrum, in order to test the relevance of the signature mentioned above. It gave results statistically similar to the one obtained with the observed spectrum.

4.3. Noise analysis

The noise of the Doppler signal, hence the performance of the detection chain, can be derived by two different manners, from the noise directly measured in the interferogram, or derived by comparison between the fringe signal and a pure sine wave. The comparison of both methods allows us to check the performance at each step of the detection.

The interferogram being calibrated in photon equivalent number, the signal-to-noise ratio of the selected fringe expresses simply as $\mathrm{snr}_{\mathrm{interf}} = N_{\mathrm{opt}}/\sqrt{N_0}$, with N_{opt}/N_0 the fringe contrast at the working point δ_{opt}, and N_0 the intensity at ZPD being made equal to the number of photons within the continuum through the filter. Its value in the scan displayed in Fig. 2 is about 12, for an integration time per step of 30 ms, corresponding to 70 with an integration time of 1 s.

The photometric noise, derived from the difference between the recorded fringes and a pure sinusoide, must be theoretically equal to the noise measured in the interferogram. In practice, it was not. Then a careful examination of each fringe of the time series allowed us to identify systematic errors. In fact, the equidistance of the elementary step ($\lambda_{\mathrm{He-Ne}}/8$) is affected by a regular deviation with period $\lambda_{\mathrm{He-Ne}}$ and peak-to-peak amplitude $\lambda_{\mathrm{He-Ne}}/200$, not prejudicial to the quality of the observations. This systematic effect being taken into account, the photometric signal-to-noise ratio $\mathrm{snr}_{\mathrm{fringe}}$ becomes equal to the interferometric signal-to-noise ratio $\mathrm{snr}_{\mathrm{fringe}}$. The systematic path difference deviation remaining strictly constant during the whole night, we did not correct for it before the phase analysis.

The rms noise in the phase signal σ_φ is theoretically related to the signal-to-noise ratio in the fringe $\mathrm{snr}_{\mathrm{fringe}}$ by

$$\sigma_\varphi = \sqrt{\frac{2}{N}}\,\frac{1}{\mathrm{snr}_{\mathrm{fringe}}} \qquad (5)$$

with N representing the number of points recorded along the fringe, and the $\sqrt{2}$ owing for the fact that the points of the fringe with the largest amplitudes carry very little information on the phase. The rms velocity noise is accordingly $\sigma_{\mathrm{v}} = \sigma_\varphi \times c/2\pi\sigma_0\delta$. We derived it in practice from the standard deviation of the high frequency part of the Doppler signal.

In fact, the theoretical relation expressed in Eq. 5 is not always verified. The agreement between the measured values of the phase and fringe noises occurs only in the middle of the night. The velocity noise reaches its minimum value when the source is between ± 3 h from the meridian, and is otherwise worse than the noise in the fringe. That means that each determination is sensitive to different frequency domains. The fringe noise we measure is only sensitive to instantaneous fluctuations of the signal, varying more rapidly than the recording time τ of one fringe, whereas the velocity noise is only sensitive to lower frequency terms, varying more slowly than τ.

5. Discussion

Actually, the maximum amplitude level we obtain corresponds to the upper limit of the theoretically inferred amplitudes (1.11 ± 0.17 m s^{-1} according to Kjeldsen & Bedding 1995). Therefore, this new limit does not put any constraint on the excitation model, but can be considered as reliable from the accurate velocity calibration of the method. This amplitude can be compared to previous published results. Levels as low as 0.5 m s^{-1} have already been proposed by Brown et al. (1991), based on fiber-fed échelle spectrograph measurements, with a rms value in 1 second as low as 27 m s^{-1}, so better than ours despite a smaller telescope size. Barban et al. (1998) reached a similar level (33 m s^{-1} in 1 s) with an instrumentation of the same type and a 2-m class telescope. On the contrary, the noise level obtained by Bedford et al. (1995) with a magneto-optical filter, hence a single line, is worse.

This comparison puts in evidence a constraint of our method. The analysis of the Doppler signal is based on a restricted frequency range, which limits the number of lines carrying a Doppler signal. This range is chosen in order to optimize the ratio between the useful signal and the photon noise coming from the full width of the bandpass. Increasing the bandpass does not necessarily improve the sensitivity (see Ma96 for a full discussion). Currently, it seems that the best intrinsic performances are reached with an échelle spectrograph allowing the analysis of the Doppler shifts of several hundred lines. However, it appears that the stability of the Fourier transform spectrometer compensates partly the deficit of lines. Of course, observing with a 4-m class telescope represents another gain.

The comb response is the only indicator of a possible regular pattern based on the 53 μHz large splitting between 0.8 and 1.2 mHz. The absence of results provided by other tests is not surprising: theoretical simulations clearly show that this test remains less affected by the window effect than other tests, especially in a case such as Procyon, with a low value expected for the large splitting. Keeping in mind that, like all other searches for a regular pattern in a time series interrupted by daytime, the comb response may give false predictions, we may compare the value we derived with the theoretical predictions. The signature at 53 μHz, if real, is quite compatible with the theoretical value (Kjeldsen & Bedding 1995), depending of the stellar mass introduced in the model depending on the average stellar density ($\Delta\nu \propto \sqrt{\mathcal{G}\overline{\rho}} \simeq$ 54 or 59 μHz). In any case, the detection of this signature is the best indicator that a signal of stellar origin has been effectively detected.

On the other hand, our results are in contradiction with the observations reported by Bedford et al. (1995), who report peaks amplitudes higher than 3 $\mathrm{m\,s^{-1}}$, and with the ones of Gelly et al. (1986) and Brown et al. (1991), since we do not see any signature for the large splitting neither at 79 μHz nor at 71 μHz.

6. Conclusion

We report no conclusive detection of *p*-modes on Procyon, with however a possible detection of a regular spacing of 53 μHz in the frequency range [0.8, 1.2 mHz]. The calibration of our data puts an upper limit of 1 $\mathrm{m\,s^{-1}}$ on the oscillation spectrum of Procyon. This value agrees with theoretical predictions, but not with previous reported detections. Does this negative result on Procyon, in fact the second brightest star for the search of solar-like oscillations, proves definitely the uselessness of this new method? A few points should deny this assumption.

- One of the greatest advantage of this seismometric method put in operation with the FTS at CFHT is the absolute calibration, which makes the new upper limit fully reliable.
- Another important property is, on the contrary to Doppler measurements obtained with fiber-fed échelle spectrograph, the absence of errors due to flat-fielding imprecision or to CCD non-linearities (Brown et al. 1994). In fact, the systematic error of about $\lambda_{\mathrm{He-Ne}}/200$ in the determination of the path difference could be considered as the equivalent of flat-fielding errors. It has the advantage to remain strictly constant and measurable.
- Finally, a natural advantage of this type of measurement is the insensitivity to intensity changes, except scintillation.

Significant improvements could come from various actions. The possible correction of the random drifts due to the internal flexures inside the instrument, identified as a major source of noise, must be examined. An increase of the number of lines participating in the fringe signal has to be carefully studied from the examination of the synthetic spectrum of Procyon. The risk of introducing telluric lines by a wider spectral range must be also taken into account. The sensitivity varying directly as the wavenumber σ_0, strong patterns at shorter wavelength exhibiting a large number of cophased lines should be carefully searched for. Already, the present observation has been made in the very near IR, close to the limit currently accessible with the CFH-FTS. An equipment with Si diodes would be necessary to work in the visible, which would produce a gain of about a factor 2. In any case, a factor of 3 is simply lost due to single site observation. Of course, to gain this factor would suppose to set up a network which is not an easy task to realize. Then the actions described above have priority to lead to a final, unquestionable detection of p-modes in a solar-like star.

Acknowledgements. This research was supported by the Groupement de Recherche "Structure interne des étoiles et des planètes géantes" from the Centre National de la Recherche Scientifique (CNRS). BM thanks Annie Baglin, Michel Auvergne and Caroline Barban for useful discussions, and Claude Van't Veer for providing us with a numerical code for modelling the spectrum of Procyon.

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