OBSERVING SOLAR-LIKE OSCILLATIONS : α CMI, η CAS A AND ζ HER A

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ABSTRACT

We have used ELODIE fiber-fed cross-dispersed echelle spectrograph and the 1.93m-telescope of Observatoire de Haute Provence to obtain precise Doppler measurements of a sample of bright stars that are likely to undergo solar-like oscillations. Here we report the results for Procyon from three observing runs carried out in December 1997, November 1998, and January 1999. We show also some preliminary results for two other solar-like stars (η Cas A and ζ Her A).

Key words: oscillations, solar-like stars, radial velocity.

1. INTRODUCTION

The application of seismology analysis techniques to solar-like stars is difficult because of extremely small variations in velocity and intensity associated with the pulsation modes: 0.1 - 1. m/s in disc integrated Doppler shift and $3 - 5\,10^{-6}$ in integrated relative intensity. To detect such small amplitudes, the photometric methods are confronted with scintillation noise (unless conducted from space, e.g. the future COROT mission), while the spectroscopic methods require high S/N (and small $v \sin i$) which is attainable for the bright solar-like stars. Recent advances in echelle spectroscopy have led to important improvements in the precision of radial velocity measurements. In Martic et al. (1999), we showed that ELODIE/OHP spectrograph is capable of making Doppler measurements that are nearly photon noise-limited, with good stability on asteroseismic time scales. For three bright target stars (Procyon, η Cas and ζ Her) the frequencies of expected p-modes are anticipated to lie within of a few of the solar oscillation frequencies. The oscillation characteristics in the power spectrum are expected to scale (Kjeldsen & Bedding, 1995) as a function of the stellar luminosity (radius), mass and temperature according to :

$$\Delta\nu_0 = (M/\,\mathrm{M}_\odot)^{1/2}(R/\,\mathrm{R}_\odot)^{-3/2}\,134.9\mu\mathrm{Hz} \qquad (1)$$

$$\nu_{\max} = \frac{M/\,\mathrm{M}_\odot}{(R/\,\mathrm{R}_\odot)^2\sqrt{T_{eff}/5777\,K}}\,3.05\mathrm{mHz} \qquad (2)$$

For the three target stars we listed below the main parameters used to compute the expected primary frequency splitting ($\Delta\nu_0$) and fundamental maximum frequency ($\nu_{\max}$) for oscillations.

	α CMi	ζ Her A	η Cas A
HR	2943	6212	219
Spectral type	F5IV-V	G0IV	G0V
Π(mas)	283.2	93.7	167.99
V	0.34	2.81	3.45
T_{eff}(K)	6530	5825	6087
$L/L_\odot$	7.10	6.52	1.14
$M/M_\odot$	1.5	1.3-1.5	0.95-1.0
$\Delta\nu_0(\mu\mathrm{Hz})$	54.0	39.3-42.2	139.3-142.9
$\nu_{\max}(\mu\mathrm{Hz})$	968.1	640.1-738.6	3048-3208

Stellar fundamental parameters, most notably mass, are usually well specified in binary pairs. ζ Her binary system is an exception, it offers a challenging task to asteroseismology to discriminate between possible mass estimations from stellar models and astrometric measurements.

2. OBSERVATIONS

All the observations were made using the ELODIE echelle spectrograph on the 1.93m telescope at Observatoire de Haute Provence. We built an asteroseismic mode see (Martic et al., 1999) to acquire automatically long uninterrupted sequences of simultaneous stellar and reference (Fabry-Perot) exposures with high temporal resolution. The advantage of using the closely-spaced channelled spectrum from a fixed (ZERODUR) Fabry-Perot interferometer is that it gives the best possible reference even for very short exposure times and allows to monitor with a high precision the spectrograph instabilities. In our configuration, the reduction process produces for each CCD (Tk 1024) frame a set of stellar and Fabry-Perot spectra, at a resolution of $R \sim 42000$, interleaved into 67 echelle orders, each covering 5.25 nm or in total a wavelength domain from 390.6 to 681.1 nm. The standard radial velocity computation algorithm was replaced by our own one based on a method explained in detail in Connes (1985).

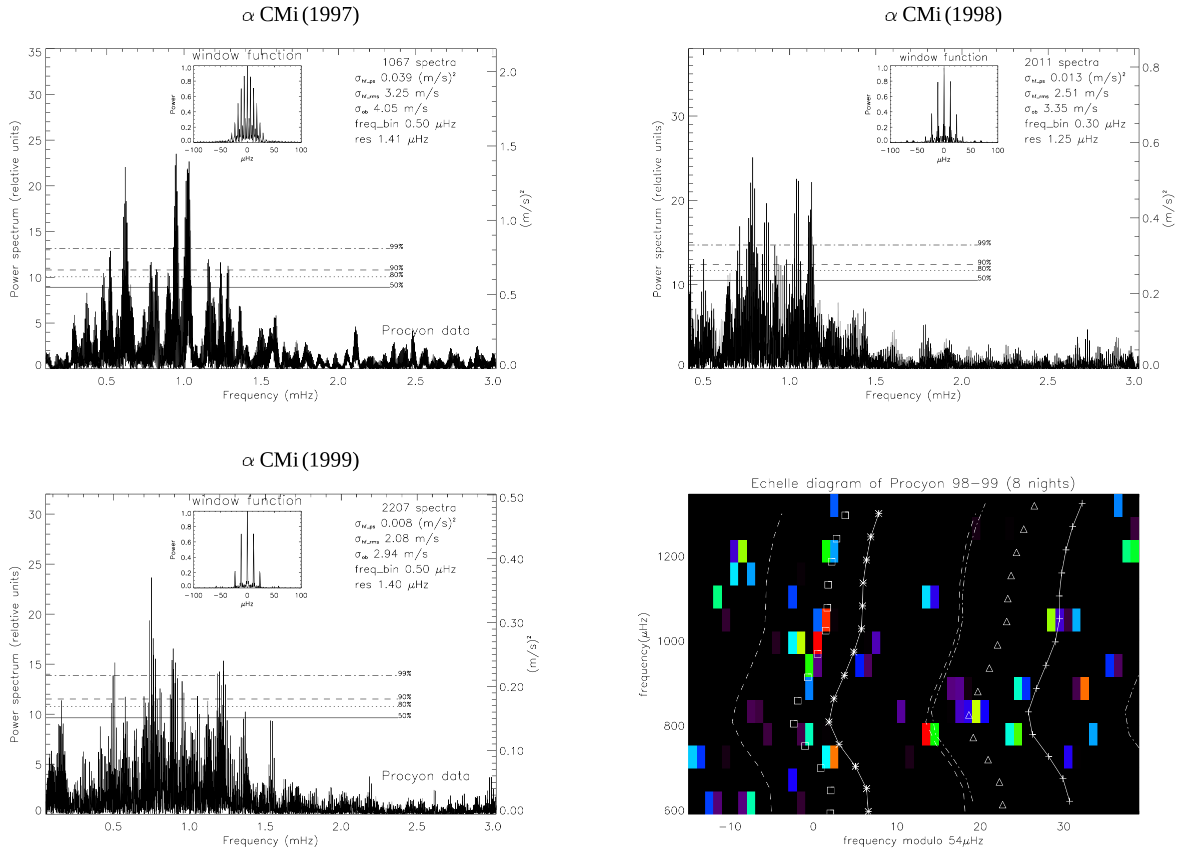

Figure 1. Power analysis of Doppler shift measurements for Procyon (see text).

3. PROCYON (1997-1998-1999)

A total of 35 nights of OHP-1.93m time telescope was allocated for Procyon in three separate observing runs. In 1997 we observed only, due to weather conditions, for four non consequtive nights; in 1998 we obtained a sequence of 8 nights interrupted by two large gaps of 42 hours and finally in 1999, we got the longest run of 12 nights but with variable seeing conditions. From the three independent observing sessions we selected respectively, 1047, 2011 and 2207 exposures with high S/N. Doppler shifts for the echelle orders were averaged by weighting each order with the inverse square of its time series rms. For further power spectral analysis, the time sequences were constructed only from nights with rms between 2 and 4 m/s.

We used the well-known Lomb-Scargle algorithm (Lomb , 1976; Scargle, 1982), to compute the periodograms (cf. Fig. 1). The mean white noise level ($\sigma_{\rm hf\_ps}$), the rms scatter ($\sigma_{\rm ob}$) and a few levels of power associated with the false alarm probability (Horne & Baliunas, 1986) are indicated for each data set. The window functions for different time sequences are shown in the insets of the Fig. 1. Clearly one can see that the central response peak from 97 window data set is surrounded by sidelobes of much higher amplitude than in two other sequences. However, an excess power was observed around 1 mHz in all sequences and several peaks have an amplitude equal or higher than the level of probability of 80 %. The irregular shape of the excess power can be explained by the interaction of modes with different phases through observational window and interference with randomly distributed noise peaks (Martic et al., 1999; Barban et al., 1999). We performed several simulations with noise consistent with our data and with an artificial oscillating signal containing 3 sets of frequencies equally spaced within a broad solar-like envelope centred at 1 mHz. The power spectrum of the simulated time series with the rms almost equal to that in observed data sets shows that it is still possible to detect the hump of excess power with the injected signal with a maximum amplitude of 50 cms^{-1}. The amplitudes of the significant peaks in the range of the excess power are lower than estimated mode amplitudes (1.-2. m/s) from theoretical predictions (Houdek et al., 1999).

In conclusion, the power analysis of the time series of Doppler shifts obtained from three independent observing runs (1997-1998-1999) confirmed the presence of a strong concentration of power between 0.5 mHz and 1.5 mHz, which is likely to be due to solar-like p-modes on Procyon.

In order to reduce the effects of the window functions from our single-site measurements we processed the times series with the CLEAN procedure (Roberts et al., 1987). In Martic et al. (2000), we showed the results of the cleaning from different time series of Procyon data. On the right bottom panel of the Fig. 1, we display the first echelle diagram of Procyon oscillations from the 98 and 99 observing runs. It was constructed from the

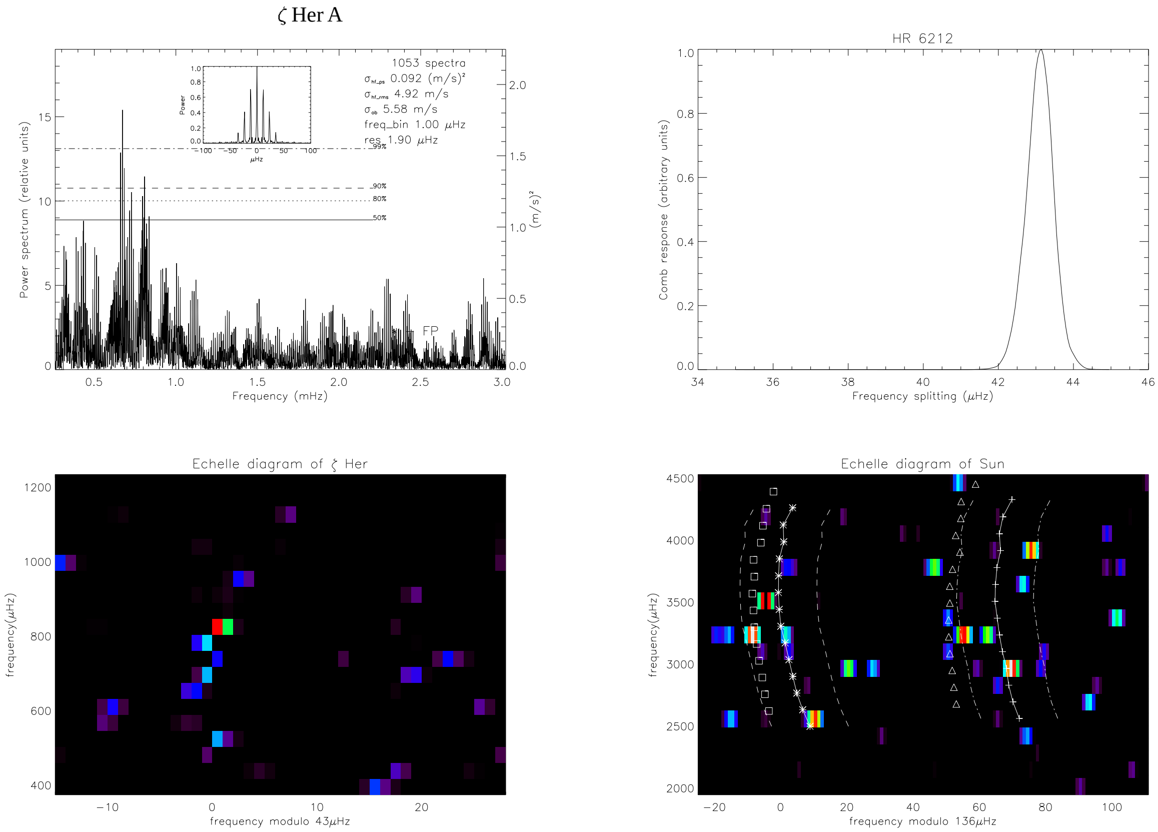

Figure 2. Power analysis of Doppler shift measurements for ζ Her A (see text).

CLEANed spectra by adding the values over threshold for the frequencies modulo $\Delta\nu_0$= 54 μHz, within cells of 1.5 μHz (frequency bin is 0.5 μHz). The threshold is determined by the mean noise level of each time sequence. The echelle diagram from Procyon observations reveals the overall distribution of the predicted p-modes. The frequencies from the standard model (Chaboyer et al., 1999) are indicated by asterisk, plus sign, square and triangle respectively for $l = 0, 1, 2$ and 3, dashed lines are at $l = 0, 1 \pm 11.6\mu$Hz). A statistical analysis and identification of the p-mode frequencies on Procyon is in progress and will be presented in a next paper.

4. ζ Her A (first results)

In May 2000, 15 nights were allocated for the observations of ζ Her A. Unfortunately, due to variable weather conditions, we could not observe for as long as possible each night. We obtained between 150 and 200 frames per night, with exposures of 60 to 100 s. The time sequence of Doppler shift measurements has been constructed from 7 nights. The corresponding periodogram with window function is displayed on the left top panel of the Fig. 2. The power spectrum shows a narrow excess power around maximum peak at 0.675 mHz, and the frequency cut-off about 1.2 mHz. Using the statistical values written within a graph, we can roughly estimate the maximum amplitude of the oscillations to 90 cms^{-1}. From the CLEANed power spectrum of the ζ Her time sequence, we obtained the first estimation of the average splitting. The maximum from Comb response is obtained at 43 μHz (cf. left upper panel of the Fig. 2). In the same manner as for Procyon (cf. § 3) we constructed from the cleaned spectrum of ζ Her an echelle diagram modulo 43 μHz. One can see several frequencies distributed along typical ridge structure (cf. bottom panel of the Fig. 2). For comparison, we show also the echelle diagram for the Sun obtained from our daytime runs in scattered light with a same instrument (solar oscillation frequencies for $l = 0, 1, 2$ and 3 are superposed on the diagram). A detailed analysis of these results will be presented in the next paper. Note, however that with the value of the average large separation $\Delta\nu_0$= 43 μHz deduced from our results and the latest estimation of the parallax from Soderhjelm (1999) we obtain, using scaling laws, a mass of $1.5\,\mathrm{M}_\odot$ for ζ Her A. This asteroseismological estimation should be compared with the results from stellar evolution models from e.g. Chmielewski et al. (1995).

5. η Cas A (first results)

Being a near twin of the Sun, η Cas A is the most promising candidate in the northern hemisphere for the detection of the 5-min oscillations. Because of tiny expected amplitudes of oscillations, the conditions of observation of η Cas A (mv = 3.45) are highly demanding.

We observed this star in 1998 for 4 nights (4 hours per night) before Procyon runs, in order to compare, in al-

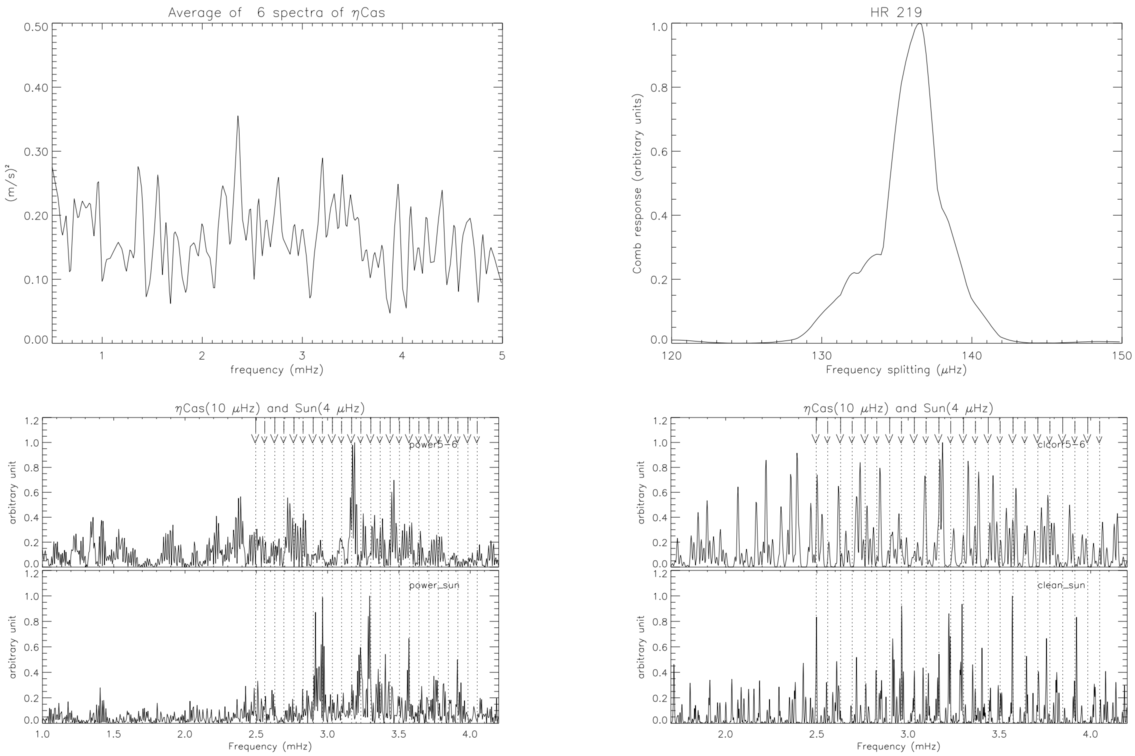

Figure 3. Power spectra analysis for η Cas A and Sun.

most identical night conditions, the Doppler shift measurements for two stars. From relatively flat power spectrum of η Cas (Martic et al., 1999), we estimated the limit of about 30 cm/s for the detection of 5-min oscillations. In October 1999, we observed again η Cas but we only acquired data of varying quality over 6 nights. Note, however that in spite of short 1 min exposure time, we can reach high Doppler sensitivity for this star. Its spectrum has a high quality Q factor (Q $\sim$ proportional to the number, depth and finesse of the spectral lines) similar to the Sun. The average of power spectra of η Cas over 6 nights (rms ~ 2.5 m/s) shows the small excess power between 2. and 4. mHz (cf. left upper panel of Fig. 3). For the illustration, we show on the bottom part of the Fig. 3, the power and corresponding CLEANed spectra of η Cas A with the solar ones from daytime runs in scattered light, both obtained with a similar window function. Typical solar frequencies are marked on the dashed lines. From the CLEANed spectrum, we obtained the Comb response with a maximum value of $\Delta\nu_0 \sim 136.5\,\mu$Hz, close to the value given by the prediction for η Cas from Table in §1. The hump of excess power of η Cas is centred at about $3200\,\mu\mathrm{Hz}$. One can find tentative evidence for p-mode oscillations. These results confirmed the upper limit of about 35 - 40 cm/s for the oscillation amplitudes on η Cas.

6. Conclusions

There is much work still to be done. With future multisite campaigns involving instruments with comparable velocity precisions providing high quality and long time series, we can expect to unambiguously confirm the mode detection on these stars.

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