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Solar-like oscillations in the G5 subgiant μ Her: preliminary results from SARG

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Abstract. We present the results of seven nights of observation on μ Her with the SARG echelle spectrograph. A clear excess of power centered at 1.2 mHz, with peak amplitudes of about 0.9 m s^{-1} in the amplitude spectrum is present. Fitting the asymptotic relation to the power spectrum, the most likely value for the large separation turns out to be 56.5 μHz, consistent with theoretical expectations.

Key words. stars: individual (μ Her) — stars: oscillations— techniques: radial velocities

1. Introduction

Asteroseismology is one of the most important and rapidly growing fields of modern astrophysics. In particular, the search for solar-like oscillations in stars has experienced a tremendous growth in recent years (See Bedding & Kjeldsen 2006, for a summary). Most of the results came from high-precision Doppler measurements using spectrograph such as CORALIE, HARPS, UCLES, UVES. In particular, recent measurements obtained with the SARG spectrograph have led to the determination of frequencies, mode amplitudes, lifetime and granulation noise on Procyon A (Claudi et al. 2005; Leccia et al. 2007), a star for which the nature of oscillation spectrum is still debated (Christensen-Dalsgaard & Kjeldsen 2004; Matthews et al. 2004).

We report the detection of excess of power, providing evidence for oscillations, in the G5 subgiant μ Her (HR 6623, $V = 3.417 \pm 0.014$, G5 IV), a slightly evolved solar-type star with mass 1.1 $M_{\odot}$, effective temperature $T_{\rm eff} = 5596 \pm 80$ K, and log g = 3.93 ± 0.10 (Fuhrmann 1998).

2. Observations and data reduction

The observations were carried out over seven nights (2006 June 13–19) with the high resolution cross dispersed echelle spectrograph SARG (Gratton et al. 2001) mounted on the Italian 3.6m telescope TNG at La Palma ob-

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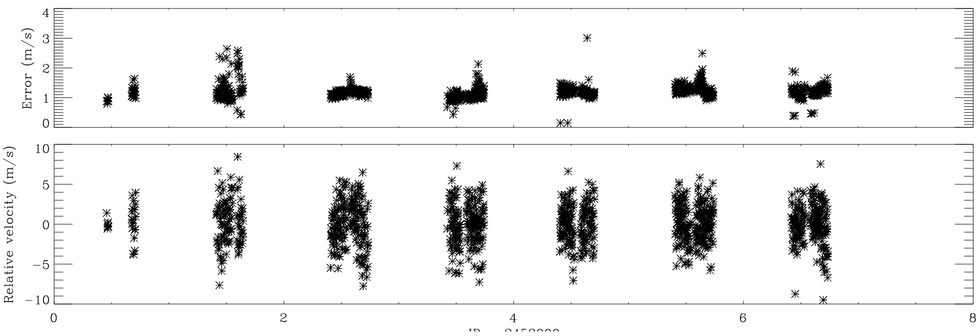

Fig. 1. Velocity measurements of μ Her obtained with SARG (lower panel) and the corresponding uncertainties (upper panel).

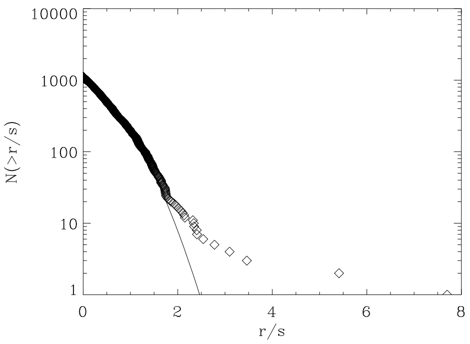

Fig. 2. Cumulative histograms of $|r/s|$ for SARG data, being r the residuals obtained after elimination of all the signal below 2 mHz, and s are the corresponding error. The diamonds show the observed data, and the solid curve shows the result expected for a Gaussian-distributed noise.

serving station. Our spectra were obtained at $R = 144,000$ in the wavelength range between 462 and 792 nm, where the calibration iodine absorbing cell covers only the blue part of the spectrum (from 462 up to 620 nm). Exposure times were typically 60 s, with a dead-time of 55 s between exposures due to the readout time. The signal-to-noise ratio for most spectra was in the range from 200 to 400, depending on the seeing and extinction. In total, 1106 spectra were collected, with the following distribution over the seven nights: 27, 106, 183, 186, 180, 226, 198. The first two nights were affected by poor weather and technical problems.

The extraction of radial velocities from the echelle spectra was based on the iodine cell method where the observed spectrum was fitted with a reconstructed one, by using a convolution between the oversampled stellar template, the very high resolution iodine cell spectrum and the measured spectrograph instrumental profile. An key ingredient of this process are the template spectra of μ Her taken with the iodine cell removed from the beam, and of the iodine cell itself superimposed on a rapidly rotating B-type star, which was the same for all the measurements. The power of the lowest frequency region of the power spectrum depends mainly by the instability of the instrument with which the radial velocity measurement are done. In the case of SARG, the RV measurements we made for our search for planetary companion around components of visual binaries and a selected sample of standard stars show that there are no residual instability uncorrected by our analysis procedure at $< 3\ \mathrm{m\,s^{-1}}$ on time scale of 7 years. On timescale of 6 days no detectable effects are expected.

The resulting velocity measurements of μ Her are shown in the lower panel of Fig. 1. They have been corrected to the solar system barycenter and and no other correction, such as decorrelation or high-pass filtering has been applied. The rms scatter of these measurements is $2.53\,\mathrm{m\,s^{-1}}$ and the uncertainties for the velocity measurements were estimated from residuals in the radial velocity extraction

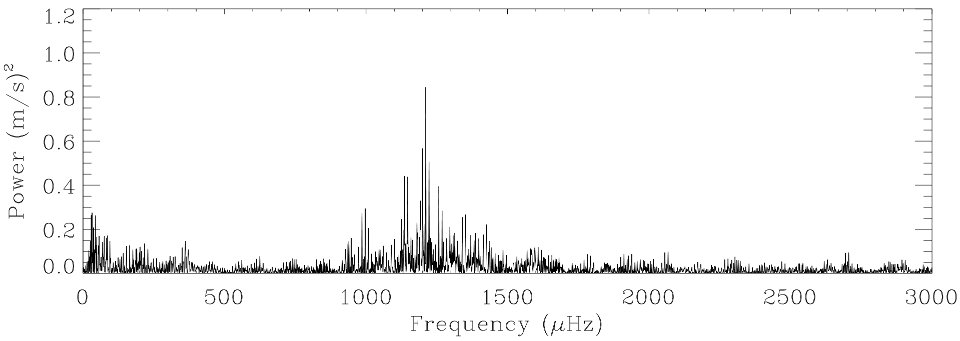

Fig. 3. Power spectrum for the μ Her data

procedure and are shown in the upper panel of Fig. 1 where it can be noticed that most lie in the range 1–2 m s^{-1} , except for the second night where technical problems due to the guiding system occurred.

3. Time series analysis

The amplitude spectrum of the velocity time series was calculated as a weighted least-squares fit of sinusoids (Frandsen et al. 1995; Arentoft et al. 1998; Bedding et al. 2004; Kjeldsen et al. 2005), with a weight being assigned to each point according to its uncertainty estimate obtained from the radial velocity measurement. We have then optimized the weight following the approach discussed in Butler et al. 2004. This consists in (i) cleaning all power at low frequencies (below 250 μHz) from the time series, as well as all power from oscillations (800–1800 μHz); and (ii) searching these residuals for points that deviated from zero by more than it would be expected from their uncertainties. We found that 20 data points needed to be significantly down-weighted as it is shown in Fig. 2

Fig. 3 shows a pronounced excess of power in the power spectrum (PS) around 1.2 mHz. As for this star the excess of power in the PS caused by solar-type oscillation is expected to be

$$\nu = \frac{(M/\mathrm{M}_\odot)\ 3000}{(R/\mathrm{R}_\odot)^2\sqrt{T_{\mathrm{eff}}/5777\mathrm{K}}} \simeq 1250\ \mu\mathrm{Hz} \quad (1)$$

we can deduce that our finding clearly demonstrates the presence of p-mode oscillations. This excess of power is apparent in the power spectra of individual nights, and its frequency and amplitude are in agreement with theoretical expectations, as we shall discuss. Moreover, it is clearly disentangled from the low frequency increase due to slow instrumental drifts ($1/f$ behavior in the amplitude spectrum) and the high frequency white noise. In particular, we find that the mean noise level in the amplitude spectrum in the range 3–5 mHz is $\sigma = 0.1$ m s^{-1} which correspond to a mean noise level in the PS of 0.013 m^2 s^{-2} . Since this is based on 1106 measurements, we can deduce that the velocity accuracy on the corresponding timescales is 1.82 m s^{-1} .

4. Large frequency spacing and oscillation frequencies

The mode frequencies for low-degree, high radial order p-mode oscillations in Sun-like stars are reasonably well approximated by the asymptotic relation (Tassoul 1980):

$$\nu(n, l) = \Delta\nu(n + \tfrac{1}{2}l + \varepsilon) - l(l + 1)\delta\nu_{02}/6 \quad (2)$$

where n and l are integers which define the radial order and angular degree of the mode, respectively; $\Delta\nu$ (the so-called large frequency separation) reflects the average stellar density, $\delta\nu_{02}$ is sensitive to the sound speed gradient near the core, and ε is a quantity of the order

Table 1. Oscillation frequencies in μ Her

(μHz)	S/N	Mode ID
985.5	5.3	$l = 0, n = 16$
1100.4	3.8	$l = 0, n = 18$
1211.2	9.1	$l = 0, n = 20$
1268.7	3.1	$l = 0, n = 21$
1323.2	2.9	$l = 0, n = 22$
1437.6	3.5	$l = 0, n = 24$
1125.1	4.1	$l = 1, n = 18$
1180.0	4.2	$l = 1, n = 19$
1238.9	3.8	$l = 1, n = 20$
1296.4	3.0	$l = 1, n = 21$
1351.9	4.4	$l = 1, n = 22$
1034.0	3.2	$l = 2, n = 16$
947.6	4.0	$l = 3, n = 14$
1061.0	4.0	$l = 3, n = 16$
1173.0	3.2	$l = 3, n = 18$

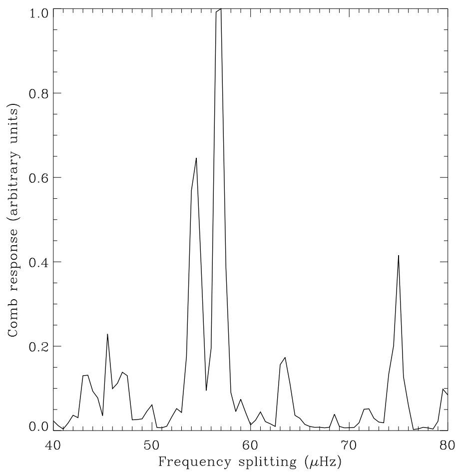

Fig. 4. Comb response function for the PS

unity sensitive to the surface layers. Note that $\delta\nu_{02}$ is the so-called small frequency separation between adjacent modes with $l = 0$ and $l = 2$.

In order to find the peaks in our power spectrum matching the asymptotic relation, we are severely hampered by the single-site window function. As is well known, daily gaps in a time series produce aliases in the power spectrum at spacings $\pm 11.57\,\mu$Hz and multiples, which are difficult to disentangle from the genuine peaks. Various methods for the search of regular series of peaks have been discussed in the literature, such as autocorrelation, comb response and histograms of frequencies. We used the comb response function method where a comb response function $CR(\Delta\nu)$ is calculated for all sensible values of $\Delta\nu$ (See Kjeldsen et al. 1995 for details).

To reduce the uncertainties due to the noise, only frequencies with amplitude greater than $4\,\sigma$ in the amplitude spectrum, in the frequency range $800 - 1800\,\mu$Hz, have been used to compute the CR . We then determined the local maxima of the response function $CR(\Delta\nu)$ in the range $40 \leq \Delta\nu \leq 80$ μHz and the resulting cumulative comb response function, obtained by summing the contributions of all the response functions, had the most prominent peak at about 57μHz as shown in Fig. 4.

The large separation $\Delta\nu$ scales approximately with the square root of the mean density of the star (Cox 1981) and by extrapolating from the solar case ($\Delta\nu = 134.8$ μHz; see Bedding et al. 2007) one obtains where the error derives from the uncertainties on the radius quoted in Fuhrmann (1998). Since we searched over the entire range 40–80 μHz, the agreement between observation and theory is encouraging.

We tried to extract the oscillation frequencies directly from the PS by using the modified extraction method described in Kjeldsen et al. (1995) and recently used in Leccia et al. (2007): for each frequency $\nu_{\max}$ extracted in the step before, a frequency region of $2\,\mu$Hz width centered on $\nu_{\max} \pm n$ $57\,\mu$Hz, with $n = 1, ...$ was selected. When this region contained a peak with an amplitude greater or equal than $3\,\sigma$ in the amplitude spectrum we identified this peak as the second component to be cleaned, and recomputed the PS for each n. The advantage of using this approach is that the extracted frequencies are determined except for the same day-night alias shift for each group of frequencies extracted during the procedure. In order to identify the individual frequencies of the modes we then constructed echelle diagrams corresponding to values of the large separation around $57\,\mu$Hz, so that we could easily identify the ridges of the $\ell = 0$ and then those of $\ell = 1, 2, 3$, for $\Delta\nu = 56.5\,\mu$Hz

The identified frequencies are thus displayed in Table 1.

5. Conclusions

Our observations of μ Her show an evident excess of power in the PS, clearly disentangled from the low frequency increase, and with a position and amplitude that are in agreement with expectations. Although hampered by the single-site window, the comb analysis and the echelle diagram show clear evidence for regularity in the peaks at the spacing expected from asymptotic theory. We hope that in the near future a multi-site observing campaign will allow us to explore further the oscillation spectrum of μ Her.

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