Multi-periodic oscillations of $\alpha$ Hya *

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Abstract. We report the detection of multi-periodic oscillations of the cool evolved star $\alpha$ Hya (HD 81797, K3II-III). Two-hundred and forty-three high-resolution spectra ($R = 48,000$) of this star have been obtained in March and April 2005 with FEROS at the 2.2 m-MPG/ESO telescope in La Silla Observatory, Chile. We observed oscillations in the stellar radial velocity and the asymmetry of the spectral line profile. We detected oscillation frequencies of the stellar radial velocity in two frequency regions, $\nu = 2 - 30 \mu$Hz and $\nu = 50 - 120 \mu$Hz. The corresponding periods are $P = 0.6 - 5.6$ days and $P = 2.3 - 5.5$ hours, respectively. In addition to these oscillations we also observed a trend in the radial velocity which shows evidence for a long-term variability. Furthermore, our measurements show a correlation between the variation in the radial velocity and the asymmetry of the spectral line profile, as measured in the bisector velocity spans. The line bisectors also show oscillations in the same frequency regions as those of the radial velocity. We identified 13 oscillation frequencies in the bisector variation with equidistant separations of $8.09 \pm 0.32 \mu$Hz in the lower frequency region and $7.44 \pm 0.47 \mu$Hz in the higher frequency region. The source of the short-term oscillations of $\alpha$ Hya is obviously due to non-radial stellar pulsations. These oscillations may have a similar origin like oscillations in solar-like stars. The detection of the multi-periodic oscillations in $\alpha$-Hya makes this star to be an amenable target for asteroseismology, in particular, as it is a star in the red giant branch.

Key words. stars: individual $\alpha$ Hya – stars: oscillations – stars: late-type – technique: radial velocities

1. Introduction

Since the last two decades the precise radial velocity (RV) technique has been very successful in the detection of planets around stars other than the Sun. In fact, this technique gives also a possibility to study the stellar interiors by using seismology methods similar to helioseismology, which has been applied to probe the interior of the Sun by measuring low-amplitude solar oscillations.

Stars with outer convection zones are in principle subject to “solar-like” oscillations because the turbulent motions in the outer convection zones could drive solar-like oscillations. The amplitudes of those oscillations are smaller compared to the pulsations of the Mira variable stars and are a challenge to detect. With the precise RV techniques several reports on the detection of solar-like oscillations have been made from ground (Bedding & Kjeldsen 2003 and references herein).

In the 1980s red giant stars have been found to be variable stars by measuring the radial velocity (Walker et al. 1989; Smith et al. 1987). The amplitude of the variation in RV is between 30 – 300 m s$^{-1}$. Further RV surveys showed that G and K giants exhibit RV variations on time scales from several hours up to hundreds of days. Multi-periodicities in the RV variations have also been reported (Hatzes & Cochran 1994a,b).

The observed RV variability in red giant stars can either caused by the presence of stellar or sub-stellar companions, surface inhomogeneities, e.g., starspots, or stellar pulsations.

Evidences for sub-stellar companions have been reported by several authors (see e.g., Hatzes et al. 2005 and references herein). These detections are complimentary to the detection of planetary companions around solar-like stars.

Concerning the rotational modulation in red giants, some methods have been used to measure stellar activity, e.g. by using chromospheric activity indicators such as Ca II H and K emission lines or the variation in spectral line bisector. Choi et al. (1995) reported rotational modulation in a sample of K giants by analysing Ca II H and K emission lines. Setiawan et al. (2004) detected rotational...
modulation in the giant HD 78647 by examining the spectral line bisector.

Evidences for non-radial stellar oscillations in G and K giants have been detected, e.g., in Arcturus (Smith et al. 1987; Hatzes & Cochran 1994b), β Oph (Hatzes & Cochran 1994a), α UMa (Buzasi et al. 2000) and ξ Hya (Frandsen et al. 2002).

Dziembowski et al. (2001) presented a theoretical analysis of oscillations observed in red giants. According to stellar model calculations red giant stars can be subject to gravity and acoustic modes (g and p modes), however these models are not in perfect agreement with the observations. Especially, the driving mechanisms are still unclear. Besides the convective driving, Mira-like mechanisms are also possible with a decrease in oscillation amplitude with increasing frequency. Further observations of stellar oscillations would be a valuable source for such asteroseismic investigations of stellar properties.

In this paper we report the detection of multi-periodic oscillations in α Hya. We observed short-term oscillations with periods of several days up to hours (Sect. 4). We also confirmed the presence of a long-period RV variation reported already earlier. However, based on our data we are still not able to give the best interpretation of this long-term variability. In Sect. 5 we present our analysis of the spectral line profile asymmetry (bisector). We found a correlation between the variation in the bisectors and the RVs. This finding leads to the source of the observed short-period RV oscillations (Sects. 5, 6).

### 2. The star α Hya

α Hya (HD 81797) is a cool evolved star. In the Hertzsprung-Russell diagram this star is located in the upper part of the red giant branch (RGB). The basic information and stellar parameters are listed in Table 1.

The spectral type, parallax, visual magnitude $m_v$ and color index $B - V$ were taken from the HIPPARCOS and Tycho Catalogues, ESA (1997). By using the HIPPARCOS photometry data and the calibration for effective temperatures $T_{\text{eff}}$ and bolometric corrections $BC$ by Flower (1996), we computed a stellar radius of $R \approx 61 \ R_\odot$ (0.29 AU). We determined an angular diameter of $\Theta = 10.5$ mas, which is in good agreement with the values given in the CHARM and CHARM2 catalogues (Richichi & Percheron 2002; Richichi et al. 2005). The projected rotational velocity $v \sin i$ was computed with the cross-correlation technique (see Setiawan et al. 2004 for details).

We adopted the metallicity [Fe/H] and the surface gravity log $g$ from Cayrel de Strobel (2001). The accurate mass determination of red giants is more difficult than that of main-sequence stars. Based on the evolutionary track by Girardi et al. (2000) we estimated a stellar mass of $2.5 \pm 3 \ M_\odot$.

The RV variation of α Hya has been reported by Walker et al. (1989), Murdoch & Harrnshaw (1993), Skuljan et al. (2000) and Setiawan et al. (2004). They found long-period RV variation with a period of several hundreds of days. However, there is still no clear explanation about the nature of this long-term variability. It can be the result of rotational modulation due to surface inhomogeneities (starspots) or the presence of stellar/substellar companion(s). The previous RV surveys of α Hya did not report evidence for short-period RV oscillations. This may be caused by the poor sampling of the data and/or the instrumental limitation in the velocity accuracy.

### 3. Observations and data reduction

We observed α Hya with FEROS at the 2.2 m MPG/ESO telescope in La Silla observatory, Chile. The spectrograph resolution of FEROS is $R = 48,000$. It has a wavelength coverage from 3500 – 9200 Å (Kaufer & Pasquini 1998). FEROS is equipped with two fibres. In the science exposure, the first fibre is used to take the spectrum of the object (star), whereas the second fibre can be used either to take the sky background, or the calibration spectrum (ThAr+Ne) in the “simultaneous calibration” mode. The short-term (few weeks) velocity precision of FEROS is 5 m s$^{-1}$.

During eight consecutive nights from 17 – 24 March 2005 (data set I) and other four consecutive nights from 30 March 2005 – 2 April 2005 (data set II) we acquired 243 high-resolution spectra of α Hya with the simultaneous calibration mode. Since α Hya is a bright star ($m_V \approx 2.0$), under good observing condition, an exposure time of 20 – 30 s was optimal to obtain a stellar spectrum with a signal-to-noise ratio of $\sim 500 – 600$ in the wavelength region $\lambda = 5000 – 5500$ Å.

In order to resolve the oscillations with time scale of minutes and hours, we recorded several time series of exposures. The time needed for a series of 10 spectra including the CCD-readout time was 10 – 12 minutes ($\approx 50$ minutes for a series of 40 spectra). The time interval between the series was 1 – 6 hours.

The data reduction has been carried out by using the FEROS-DRS pipeline, which produced 39 one-dimensional wavelength calibrated spectra for each fibre.

| Identifier | α Hya, HD 81797 | SIMBAD |
|-------------|-----------------|--------|
| Spectral type | K3II-III | HIPPARCOS |
| Parallax | 18.4 ± 0.78 mas | |
| $m_v$ | 1.99 mag | |
| $B - V$ | 1.44 | |
| $BC$ | -1.002 | |
| $T_{\text{eff}}$ | 4086 K | |
| Angular diameter | 10.5 ± 0.5 mas | |
| Radius | 61.2 ± 0.4 $R_\odot$ | |
| $v \sin i$ | <1.4 km/s | |
| [Fe/H] | -0.12 .. -0.19 dex | |
| log $g$ | 1.77 .. 1.86 cm/s$^2$ | |
| Stellar mass | 2.5 – 3 $M_\odot$ | |
4. Radial velocity variation

We measured the RVs by using the cross-correlation technique. The stellar spectra were cross-correlated with a numerical template (Baranne et al. 1996). The cross-correlation function was then fitted with a Gaussian. The RV was obtained from the position of the dip of the cross-correlation function. The detailed procedures of the computation were described in Setiawan et al. (2003).

Fig. 1 shows the RV measurements of \(\alpha\) Hya. As seen in the Fig. 1a there is an observational gap between the two data sets. The RVs show variations with time scale of days. By treating the data set I (Fig. 1b) and II (Fig. 1c) separately, a linear trend can be recognized by visual inspection in each data set.

We also observed a long-term RV variation. Our measurements did not cover the full period of this long-term variability. Therefore, we are not able to find the best model which may fit the whole long-period RV oscillation. Such a fit-function, when subtracted from the RVs, would allow to compute the residual velocities. Nevertheless, it is possible to treat the data sets I and II separately and subtract the respective linear trends from the two sets of RV measurements. The then calculated residual velocities of each data set are displayed in Fig. 2a,b. The figures show oscillations of the residual with a maximal velocity amplitude of \(\sim 20 \, \text{m s}^{-1}\).

We computed a Lomb-Scargle (LS) periodogram (Lomb 1976; Scargle 1982) of each data set to find the oscillation frequencies. Fig. 3a and 3b show the respective LS periodograms of the residual RV measurements. We identified significant oscillation frequencies in two regions, i.e., \(\nu = 2 - 30 \, \mu\text{Hz}\) and \(\nu = 50 - 120 \, \mu\text{Hz}\) in both data sets I and also in the data set II.

In Table 2 we list the frequencies and the corresponding periods obtained from the periodogram of the residual velocities. The LS periodogram of data set I shows the highest power at \(\nu = 2.513 \, \mu\text{Hz}\) (\(P = 4.61\) days). Due to the observational time coverage of data set II the peak at this low frequency however, could not be observed, but it is merged in the peak at \(\nu = 7.530 \, \mu\text{Hz}\). In both data sets we found periods around 1.5 days, 4.4 hours and 3.0 hours. These periods are also found in the line bisector variation (see Sect. 5). The oscillation frequencies in the region \(\nu = 50 - 120 \, \mu\text{Hz}\) are not equidistant. A possible explanation is, that the “missing” oscillation frequencies still have not been detected yet. This could have been occurred if the RV variation amplitudes of these modes were too small, i.e., beyond the accuracy of the spectrograph. Longer observations will be necessary to identify these oscillations, too.

5. Spectral line profile asymmetry

Surface inhomogeneities such as starspots or/and granulation will leave imprints in the spectral lines. They introduce an asymmetry in the spectral line profile (Gray 1982). This feature can be measured from the shape of the line bisector. An equivalent method to measure the variation in the line profile’s asymmetry is to measure the bisector velocity span (Hatzes 1996). Non-radial oscillations are expected to be also mapped into the bisector velocity span (BVS). If oscillations like \(p\)- and \(g\)-modes are
Fig. 2. Residual RV of α Hya for the data sets I (upper panel) and II (lower panel).

present, then they would result in a temporal variation of the BVS.

The measurement of the BVS can be done as well with the cross-correlation method, as demonstrated by Queloz et al. (2001). We computed the bisector velocity spans of the cross-correlation profile. We observed a time variation of the BVS. When plotted the BVS against the RV, we found a correlation between them (Fig. 4).

This correlation indicates that the observed RV variation is most likely due to intrinsic processes in the star, i.e., (non-radial) stellar pulsations.

Other possibilities, like companions and rotational modulation due to starspots can be excluded. Because, a companion with an orbital period of a time scale of few days would have an orbit which is smaller than the stellar radius of α Hya. A rotational modulation of the period of several days would imply, that the star should rotate very fast ($v \sin i > 100 \text{ km s}^{-1}$). Such a fast rotating K giant would have a strong X-ray emission and thus, it should have been detected by the ROSAT survey.

The detection of oscillations in the time series of the BVS (Fig. 5a) is an observational approval of the method proposed by Hatzes (1996). There, it was demonstrated, that pulsations affect the shape of the spectral line profile and can be measured as variation in the bisector.

Table 2. Identification of oscillation frequencies of α Hya from the periodogram of the residual velocities

| Data set I | ν [μHz] | P [day] |
|------------|---------|---------|
| 1          | 2.51    | 4.61    |
| 2          | 8.07    | 1.43    |
| 3          | 14.72   | 0.79    |
| 4          | -       | -       |
| N          | ν [μHz] | P [hours] |
| 5          | 62.62   | 4.44    |
| 6          | 73.46   | 3.78    |
| 7          | 78.89   | 3.52    |
| 8          | 89.73   | 3.10    |
| 9          | 93.80   | 2.96    |
| 10         | 96.96   | 2.87    |
| 11         | -       | -       |
| 12         | 114.14  | 2.43    |

| Data set II | ν [μHz] | P [day] |
|-------------|---------|---------|
| 2          | 7.53    | 1.54    |
| 3          | 29.25   | 0.40    |
| N          | ν [μHz] | P [hours] |
| 5          | 62.45   | 4.45    |
| 6          | -       | -       |
| 7          | -       | -       |
| 8          | 86.71   | 3.20    |
| 9          | 93.09   | 2.98    |
| 10         | -       | -       |
| 11         | 108.41  | 2.56    |
| 12         | -       | -       |
Fig. 4. BVS vs. RV of α Hya. The figure shows a correlation between the BVS and RV.

Depending on the azimuthal order of a mode, the bisector is more or less affected.

Table 3. Identification of oscillation frequencies of α Hya from the periodogram of the BVS

| N | \( \nu \) [\( \mu \)Hz] | \( P \) [days] |
|---|----------------|-------------|
| 1 | 6.550         | 1.77        |
| 2 | 14.639        | 0.79        |
| 3 | 23.177        | 0.50        |

| N | \( \nu \) [\( \mu \)Hz] | \( P \) [hours] |
|---|----------------|-------------|
| 4 | 54.63         | 5.08        |
| 5 | 63.17         | 4.40        |
| 6 | 70.81         | 3.92        |
| 7 | 78.45         | 3.54        |
| 8 | 86.54         | 3.21        |
| 9 | 93.73         | 2.96        |
| 10| 100.92        | 2.75        |
| 11| 108.56        | 2.56        |
| 12| 116.65        | 2.38        |
| 13| 123.84        | 2.24        |

The LS periodogram of the whole determined BVS time series (data set I and data set II) shows peaks in the frequencies between 5 – 30 \( \mu \)Hz and 50 – 120 \( \mu \)Hz (Fig. 5b). As in the case of the RV measurements, the same frequency regions are covered in the BVS periodogram. The highest peaks are at 6.55 \( \mu \)Hz and 78.45 \( \mu \)Hz. The corresponding periods are \( \approx \) 1.8 days and \( \approx \) 3.5 hours, respectively. Moreover, the peaks are equidistant in the smoothed periodogram. The frequency distance of the major peaks in the lower peak region is on average 8.09 ± 0.32 \( \mu \)Hz, whereas in the higher peak region the average peak distance is 7.69 ± 0.47 \( \mu \)Hz. The list of the identified peaks with a false alarm probability of FAP ≤ 10^{-7} is given in Table 3.

The oscillations in the spectral line asymmetry, and in particular the correlation between BVS and RV indicates, that the observed variations are due to non-radial oscillations. The shape of the power distribution in the periodograms of the RV and BVS measurements with high amplitudes at high frequencies indicates that there exists the possibility of convectively driven modes in the frequency range around 78.5 \( \mu \)Hz. These modes therefore are rather solar-like oscillations than Mira-like pulsations (Dziembowski 2001). The modes around 10 \( \mu \)Hz in the RV and the BVS periodograms seem to exhibit a decrease in amplitude with higher frequencies, which would support a Mira-like interpretation for these pulsations. Nevertheless having the solar case in mind, it might also be possible, that these are \( g \)-modes. However, a final statement can only be given on the basis of longer data sets and on stellar models of α Hya.

6. Discussion and conclusion

Only little is understood about the nature of short-period oscillations of evolved stars. Especially, the excitation of the modes itself and the interaction with convection might
be different from what is known of solar oscillations. However, this fact is based on theoretical investigations.

Until now, nonradial pulsations in red giants have been detected only in a few numbers of stars. Therefore, each detection will give a valuable contribution to asteroseismology, which is a powerful tool for performing direct tests of stellar structure and evolution theory. The identification of many pulsation frequencies in a star would provide a wealth of information, which can be obtained by relating the oscillation spectra to stellar physical properties. Moreover, from a lot of oscillation modes the interior of the star could be sounded. Nevertheless, a lot of development is still necessary until it becomes possible to determine stellar parameters as accurately as the solar counterparts. One important step is the surveying of the stars for their pulsations and detecting amenable targets for asteroseismology.

We report of such a possible target, as we detected multi-periodic oscillations in $\alpha$ Hya. The detection of these oscillations is twofold. On the one hand we found them in radial velocity measurements and on the other hand in measurements of the bisector velocity span. Both measurements correlate well. Especially, this correlation hints to the detection of non-radial oscillation modes. Our observations are a direct approvement of the mapping of the oscillation velocities onto the line profile bisector as suggested by Hatzes (1996).

The next step will be an extension of RV and line sector asymmetry observations of $\alpha$ Hya in order to be able to perform a stability analysis of the modes. As pointed out by Dziembowski et al. (2001) this would help to decide about the possible driving mechanism of the modes. Mira-like and solar-like processes are on debate. A Mira-like interpretation would be related with an amplitude decrease towards higher frequencies.

Based on our data we find such a decrease only in a low frequency region around 10 $\mu$Hz. But the amplitudes raise again at higher frequencies around 78.5 $\mu$Hz in all periodograms calculated from the RV measurements and as well in the bisector velocity span measurements. Moreover the peaks are equidistant with a frequency difference of 8.09 $\pm$ 0.32 $\mu$Hz in the low frequency region and 7.69 $\pm$ 0.47 $\mu$Hz in the higher frequency region. Therefore, these pulsations are likely to be solar-like oscillations.

Our findings in $\alpha$ Hya are in good concordance with earlier detections of solar-like oscillations in red giant stars. Frandsen et al. (2002) reported of radial oscillations in $\xi$ Hya in a frequency range between 50–130 $\mu$Hz. The detected peaks were also equidistant with a separation of 7.1 $\mu$Hz. However, we also find evidences for non-radial and low-frequency oscillations in $\alpha$ Hya by analysing additionally the bisector velocity span. Both stars $\alpha$ and $\xi$ Hya have masses close to 3 M$_{\odot}$. The progenitor main-sequence star of $\alpha$ Hya is probably an early A-type star (see Schmidt-Kaler 1982). Therefore, an agreement in the oscillation frequencies and in the separation of the peaks is very likely, as both stars might have underwent a similar evolution. Further extensive theoretical modelling of the finding of oscillations in $\alpha$ Hya is beyond the scope of this report and will be presented in a forthcoming paper.

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