A&A 491, 531–536 (2008)
DOI: 10.1051/0004-6361:200810405

Astronomy & Astrophysics

The discovery of stellar oscillations in the K giant ι Draconis

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Received 17 June 2008 / Accepted 12 September 2008

ABSTRACT

ι Dra (HIP 75458) is a well-known example of a K giant hosting a substellar companion. We present radial velocity measurements of this star from observations taken with three different instruments spanning nearly 8 years. They show more clearly that the RV period is long-lived and coherent thus supporting the companion hypothesis. The longer time baseline now allows for a more accurate determination of the orbit with a revised period of $P = 511$ d and an additional small linear trend, indicative of another companion in a wide orbit. Moreover we show that the star exhibits low amplitude, solar-like oscillations with frequencies around 3–4 d^{-1} (34.7–46.3 μHz).

Key words. stars: individual: ι Draconis – stars: planetary systems – stars: oscillations

1. Introduction

Long period radial velocity (RV) variations have been detected in several K giants, e.g. β Gem (Hatzes et al. 2006; Reffert et al. 2006), HD 47536 (Setiawan et al. 2003), HD 13189 (Hatzes et al. 2005) and ι Dra (Frink et al. 2002). Rotational modulation can be excluded as a cause of these variations for most of these giants due to the lack of variations in photometry or line bisectors with the RV period (Hatzes & Cochran 1998). The most likely interpretation is orbiting, substellar companions.

Since the progenitor stars of planet-hosting giant stars can have masses significantly larger than 1 $M_\odot$, these giant stars offer a way to investigate planet formation around massive stars. In their evolved phase, the Doppler induced effects of a planet are easier to detect than in their main-sequence phase, due to cooler effective temperatures and lower rotational velocities.

For evolved stars the determination of the mass is more difficult. The most practical way to determine the stellar mass is to use evolutionary tracks, but those tracks converge in the region of the giant branch for stars with a wide range of masses and thus makes the derived masses uncertain.

Another way to measure the stellar mass is via asteroseismology. This requires the investigation of stellar oscillations. Photometric and RV variations with short periods from hours to days have been detected in some K and late G giants (e.g. α Boo: Retter et al. 2003, Tarrant et al. 2007; α Ari: Kim et al. 2006; ϵ Oph: de Ridder et al. 2006; ξ Hya: Frandsen et al. 2002, Stello et al. 2006; β UMi: Tarrant et al. 2008) and are consistent with solar-like p-mode oscillations. Such oscillations have also been measured for ensembles of red giants with photometry of star-rich regions or clusters (e.g. Gilliland 2008; Stello et al. 2008) which is a very efficient way to perform such asteroseismologic studies.

Solar-like oscillations have also been discovered in planet-hosting main sequence stars (e.g. μ Arae: Bazot et al. 2005; ι Hor: Vauclair et al. 2008) and in the planet-hosting K giant β Gem for which Hatzes & Zechmeister (2007) gave, in combination with interferometric measurements of the angular diameter, an estimation for the stellar mass completely independent of evolutionary tracks. In a similar way we will do this here for ι Dra.

Table 1. Stellar parameters of ι Dra.

Parameter	Value
Spectral type[a]	K2III
V^a [mag]	3.29
M_V [mag]	0.81
L [$L_\odot$]	64.2 ± 2.1
Parallax[b] p [mas]	32.23 ± 0.1
Distance d [pc]	31.03 ± 0.1
Angular diameter[c] θ [mas]	3.73 ± 0.04
Radius R [$R_\odot$]	12.38 ± 0.17

[a] ESA 1997; [b] van Leeuwen 2007; [c] Richichi et al. 2005.

2. Stellar parameters

In Table 1 we summarize some direct measurements for the K2III star ι Dra. The improved parallax from the Hipparcos catalog by van Leeuwen (2007) is given. Angular diameter estimates based on spectrophotometry are available from the CHARM2 catalog (Richichi et al. 2005).

The quantity that cannot be measured for single stars directly is the mass, which always relies on evolutionary tracks. With the online tool[1] from Girardi (see da Silva et al. 2006 and Girardi et al. 2000 for a description), we derived some values for M, $\log g$ and R. This tool uses as input parameters the visual magnitude V, parallax p, temperature T and metallicity Fe/H. For T and [Fe/H] we adopt the values in Table 2 as given by several

[1] http://stev.oapd.inaf.it/cgi-bin/param

Table 2. Stellar parameters of ι Dra from the literature (T, log g and [Fe/H]) and derived with evolutionary tracks (M, log g and R).

Reference	T [K]	log g	[Fe/H]	M [$M_{\odot}$]	log g	R [$R_{\odot}$]
Soubiran et al. (2008)	4552	2.96	0.16	1.40 ± 0.24	2.40 ± 0.10	11.82 ± 0.63
Prugniel et al. (2007)	4543	2.88	0.19	1.41 ± 0.23	2.40 ± 0.10	11.94 ± 0.62
Hekker & Meléndez (2007)	4605	2.96	0.07	1.39 ± 0.24	2.45 ± 0.10	11.19 ± 0.58
Santos et al. (2004)	4775 ± 113	3.09 ± 0.40	0.13 ± 0.14	1.71 ± 0.38	2.61 ± 0.12	10.34 ± 0.40
Gray et al. (2003)	4526	2.64	0.11	1.31 ± 0.24	2.37 ± 0.11	11.97 ± 0.65
Prugniel & Soubiran (2001)	4491	2.57	0.06	1.24 ± 0.24	2.32 ± 0.10	12.23 ± 0.65
Cenarro et al. (2001, 2007)	4498	2.38	0.05	1.24 ± 0.24	2.33 ± 0.10	12.15 ± 0.66
Allende Prieto & Lambert (1999)	4466 ± 100	2.24 ± 0.35		1.05 ± 0.36		
McWilliam (1990)	4490	2.74	0.03 ± 0.11	1.23 ± 0.24	2.32 ± 0.10	12.22 ± 0.66
Williams (1974)	4530 ± 100	2.60 ± 0.25	0.29 ± 0.20	1.40 ± 0.23	2.39 ± 0.10	12.06 ± 0.64

authors. Allende Prieto & Lambert (1999) gave no metallicity but derived a mass of $M = 1.05\ M_{\odot}$ which was used for the calculation of the companion mass in Frink et al. (2002). This value is in the lower mass range from Table 2 (1.05–1.71 $M_{\odot}$). This shows how much the tracks depend on temperature and metallicity. Furthermore, Table 2 allows a cross check of the log g-values derived from spectroscopy and from evolutionary tracks. The log g-values derived from spectroscopy are always higher, which illustrates the difficulty of reliable mass determinations for K giants.

3. Observations

For our analysis we use RV measurements for ι Dra from three independent instruments (Table 4 and Fig. 1). The data set from the 0.6 m CAT (Coudé Auxiliary Telescope) with the Hamilton Échelle Spectrograph at Lick Observatory covers nearly 8 years and thus has the longest time baseline for the orbit determination. The data up until March 2002 were published in Frink et al. (2002).

At the Thuringia State Observatory (TLS – Thüringer Landessternwarte) ι Dra was observed on 43 nights spanning 200 d. The Alfred-Jensch 2 m telescope is equipped with a Coudé Échelle Spectrograph with a wavelength coverage from 4630 to 7370 Å. These observations primarily were carried out to look for stellar oscillations with short periods. For this program on some nights up to 20 spectra (even 61 on the night of JD = 2 454 193) were taken (Fig. 3).

With a rather short time baseline of 8 days, some spectra were obtained in June 2005 with the 2.7 m telescope at the McDonald Observatory and the "2dcoude" spectrograph. This instrument provides a wavelength range from 3600 Å to 1 μm. The RVs were calculated using the "Austral" program (Endl et al. 2000). The whole data set is plotted in Fig. 4.

All three instruments have a resolving power around $R = \frac{\lambda}{\Delta\lambda} = 60\,000$ and utilize an iodine absorption cell for the wavelength reference. Table 4 lists the time coverage, time span T, number of spectra N and average precision of the radial velocity measurements σ_{RV}. These measurement errors are internal errors due to instrumental effects recorded with the iodine lines. Comparing with point to point scatter, e.g. in Fig. 3, the errors appear reasonable.

4. Orbital solution

The parameters of the orbit were determined by a weighted least squares (χ^2-fit) with the differential correction method (Sterne 1941). We simultaneously fitted five Keplerian orbital elements, a linear trend and three offsets for the combined data set as the

Table 3. Orbital parameters for the companion to ι Dra.

Parameter	Value
Period P [d]	510.88 ± 0.15
Amplitude K [m/s]	299.9 ± 4.3
Periastron time T_0 [JD]	2 452 013.94 ± 0.48
Longitude of periastron ω [°]	88.7 ± 1.4
Eccentricity e	0.7261 ± 0.0061
Linear trend [m/s/yr]	–13.8 ± 1.1
Mass function[a] $f(m)$ [$M_{\odot}$]	(4.64 ± 0.33) × 10^{-7}
Semi-major axis a [AU]	1.34
Companion mass $m \sin i$ [$M_{\rm Jup}$]	10.3

[a] $f(m) = \frac{(m \sin i)^3}{(M+m)^2} = \frac{P}{2\pi G}(K\sqrt{1-e^2})^3$.

Table 4. Journal of observations.

Data set	Coverage	T [d]	N	σ_{RV} [m/s]
CAT	2000.39–2008.38	2918	147	4.3
TLS	2006.99–2007.59	221	280	3.3
McD	2005.44–2005.46	8	62	3.9

measurements give relative velocities and the three instruments have different zero points. When weighting the measurements one has to take into account that not only do the measurement errors introduce an error in the parameter determination but so also does the jitter due to pulsations: $\sigma_i^2 = \sigma_{RV,i}^2 + \sigma_P^2$. The stellar oscillations are discussed in the next section but we mention here that σ_P is of the order of 10 m/s. We adopt this value which is larger than the typical measurement error and therefore leads to a more equal weighting of all measurements in our fit.

The resulting orbital elements are listed in Table 3 and the RV curve is plotted in Fig. 1. In the old solution the short time baseline and the unrecognizable linear trend resulted in an overestimated period ($P = 536 \pm 6$ d: Frink et al. 2002). The linear trend is −13.8 ± 1.1 m/s/yr and may be part of a longer period caused by a further companion. For the calculation of the companion mass we assumed a stellar mass of 1.4 $M_{\odot}$ (33% higher than in Frink et al. 2002).

Figure 2 illustrates the radial velocity phased to the orbital period. The total remaining scatter is 13.9 m/s for all data sets (and for the individual sets, which cover very different time scales: 15.4 m/s (CAT), 13.9 m/s (TLS) and 11.4 m/s (McD)). This scatter is a factor of 3–4 greater than the measurement errors given in Table 4 and is largely due to stellar oscillations, as we will explain below.

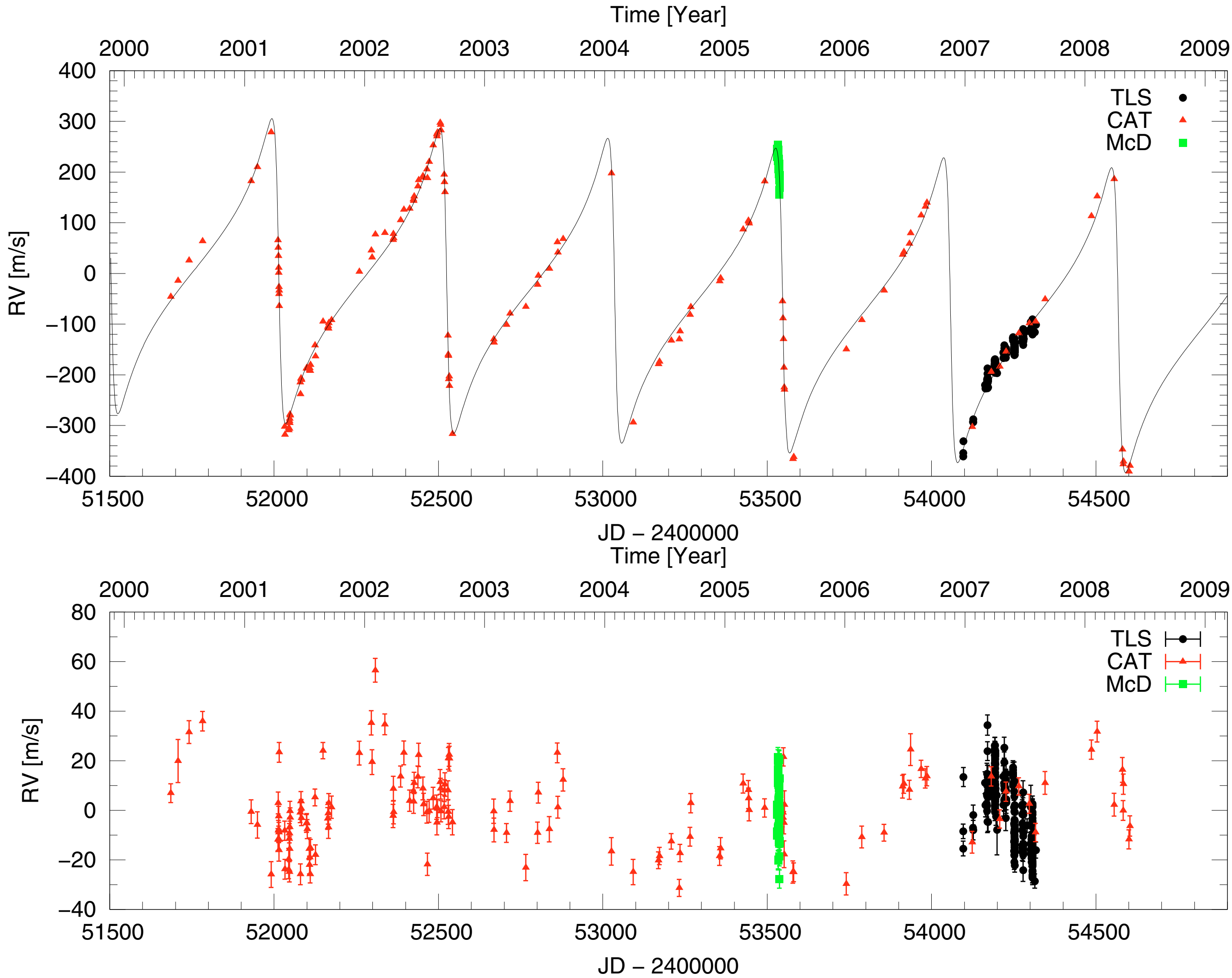

Fig. 1. Radial velocity measurements for ι Dra from three data sets. The orbital solution is given as a solid line. *The lower panel* shows the residuals after subtraction of the orbital solution and the linear trend. (See online version for a colored figure.)

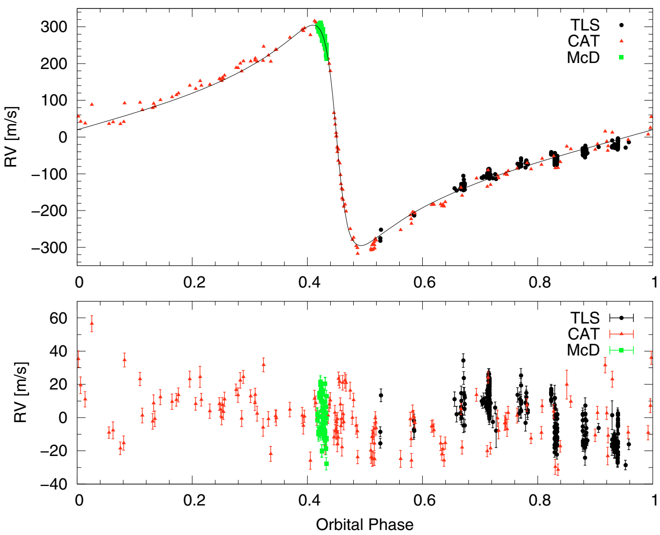

Fig. 2. Radial velocity measurements for ι Dra from three data sets phased to the orbital period. *The lower panel* shows the orbit residuals. (See online version for a colored figure.)

5. Short period oscillations

For the analysis of variations on short time scales we subtracted the trend and orbit from the data sets. The remaining residuals during some nights for the TLS and McD data sets are shown in Figs. 3 and 4, respectively. One can see RV variations with an amplitude of a few 10 m/s.

We performed a frequency analysis of the orbit residuals for each data set individually due to their different time sampling. For this we used the prewhitening procedure provided by the program Period04 (Lenz & Breger 2004). A Fourier transformation was performed for the data, the dominant frequency extracted and subtracted from the data. This procedure can be repeated on the subsequent residuals until no further significant frequencies can be found. The prewhitening has the advantage that confusing alias peaks (here mainly 1 day aliases) of the extracted frequency are removed from periodograms.

Figures 5 and 6 show the periodograms in each prewhitening step for the TLS and McD residuals, respectively. The TLS residuals show peaks at 0.040 d^{-1} and 0.004 d^{-1}, which seem to be 1 month aliases ($\Delta f = 0.036\,d^{-1}$) of each other. Neither frequency is found in the other data sets. However, the corresponding long periods ($P = 25$ d and $P = 250$ d) are not of

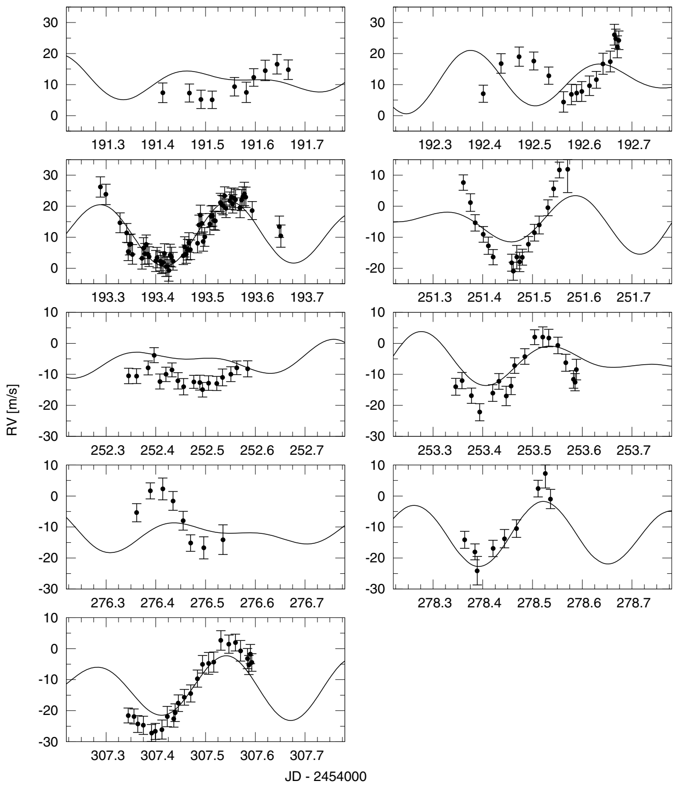

Fig. 3. Radial velocity during several good nights measured at TLS (orbit subtracted). The solid curve is the fit with the TLS frequencies (f_0, f_1 and f_2).

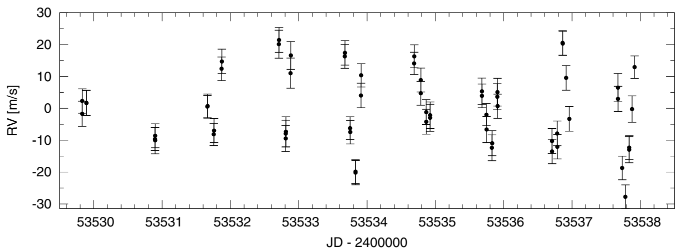

Fig. 4. Radial velocity during 8 consecutive nights measured at McD (orbit subtracted).

further interest for our investigation of short period oscillations. Subtraction of the lower frequency (f_0 = 0.004 d^{-1}, 12.33 m/s) flattens the TLS orbit residuals and removes the 1 day aliases of f_0 (second panel in Fig. 5). This prewhitening step reveals an excess at frequencies around 3.8 d^{-1}. Extraction of the two frequencies f_1 = 3.45 d^{-1} (4.77 m/s) and f_2 = 4.23 d^{-1} (4.26 m/s) lowers the excess power considerably. A third frequency f_3 = 3.75 d^{-1} (3.86 m/s) is already near an amplitude signal to noise ratio of S/N = 4 (the mean noise level is 0.865 m/s in the range of 10–20 d^{-1}). This threshold, as suggested by Kuschnig et al. (1997), can be used as a criterion for stopping the prewhitening procedure.

The fit with the frequencies is drawn in Fig. 3. Nights with many data points fit well, while some discrepancies exist for nights with sparse measurements. This may indicate that more frequencies are present or that the modes have a finite lifetime due to stochastic excitation mechanisms (e.g Barban et al. 2007).

For the McD orbit residuals an excess of power (upper panel in Fig. 6) can be seen in the same region as for the TLS data. The peaks at frequencies >15 d^{-1} in the McD data set are due to the

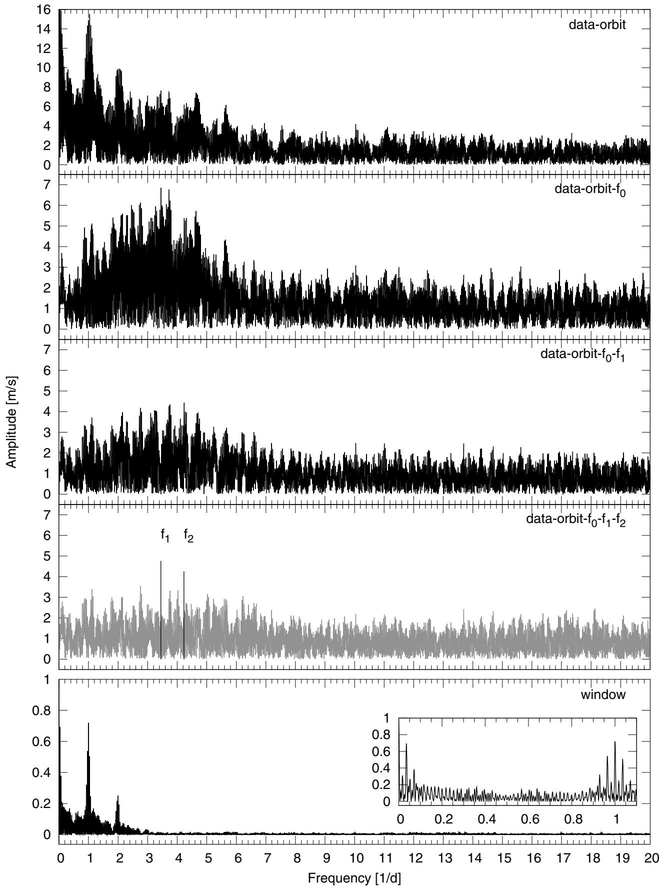

Fig. 5. Amplitude periodograms of the TLS RV data at each prewhitening step. The fourth panel shows the periodogram of the residuals in comparison to the extracted frequencies and the last panel shows the window function. The inset is an enlargement where the one month alias can be seen.

sparser sampling leading to a stronger aliasing at higher frequencies. Two frequencies are extracted, f_1 = 3.81 d^{-1} (8.45 m/s) and f_2 = 4.03 d^{-1} (8.90 m/s), which are also illustrated along with the periodogram of the remaining residuals in the third panel of Fig. 6.

The higher amplitudes of the frequencies in the McD data may be an effect of the short time baseline and the finite mode lifetime of solar-like oscillations seen in main sequence stars and red giants (Stello et al. 2006; Carrier et al. 2007).

The CAT residuals show a 555 d period, which is close to the orbital period. However the data set has insufficient time resolution to look for short period variability (<1 day) since its Nyquist frequency is only 0.5 d^{-1}.

6. Discussion

We compare our results with the scaling relations for solar-like oscillations from Kjeldsen & Bedding (1995). The oscillation velocity amplitude $v_{\rm osc}$ and the frequency $f_{\rm max}$ of the strongest mode of the 5-minute-oscillations in the sun scales to other stars as:

$$v_{\rm osc} = \frac{L/L_\odot}{M/M_\odot} \cdot 0.234\,{\rm m/s} \qquad (1)$$

$$f_{\rm max} = 62\,{\rm d}^{-1} \frac{(T/5777\,{\rm K})^{3.5}}{v_{\rm osc}/\,{\rm m\,s^{-1}}}\,. \qquad (2)$$

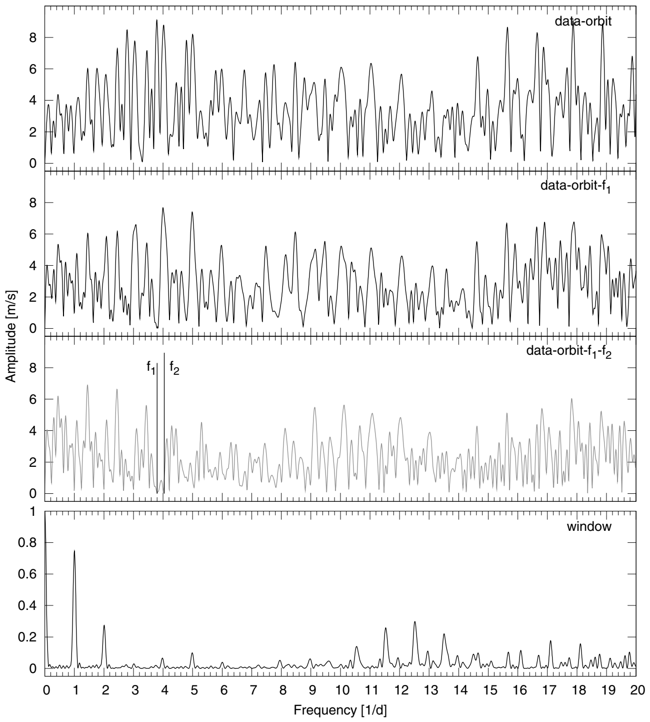

Fig. 6. Amplitude periodograms of the McD RV data at each prewhitening step. *The third panel* also shows the extracted frequencies and *the last panel* shows the window function.

These relations are valid for a wide range of convective stars (Bedding & Kjeldsen 2003) and seem to be valid for other K giants (Stello et al. 2008). For a power excess frequency of around 3.8 d^{-1}, which is present in two data sets, the expected amplitude should be 6.75 m/s according to Eq. (2) (based on T = 4490 K, McWilliam 1990). This agrees with the excess power seen in the periodograms and is comparable to the amplitude of f_1 (4.77 m/s (TLS) and 8.90 m/s (McD)). So this frequency satisfies the relation between amplitude and frequency typical for solar-like oscillations.

Under the assumption that the simple scaling relations are valid, the combination of both equations to $L/M \propto T^{3.5}/f_{\max}$ implies a luminosity to mass ratio of $L/M = 29\ L_\odot/M_\odot$ for this frequency. Using $L = 64.2 \pm 2.1\ L_\odot$ from the Hipparcos catalog one would estimate a mass of 2.2 $M_\odot$ (or with $f_{\max} \propto g/\sqrt{T}$ a log g of 2.54). Even if we roughly estimate an uncertainty of ±0.6 $M_\odot$ due to strong 1 day aliasing (i.e. derived from $\Delta f_{\max} = \pm 1\,\mathrm{d}^{-1}$), this value seems too high in comparison with Table 2. For a mass of 1.4 $M_\odot$ the expected frequency is 2.4 d^{-1}. We cannot exclude that we miss such a mode as 0.42 d periods are difficult to detect in short nights with single site observations.

A more accurate mass estimation could be made with the scaling relation for the frequency splitting:

$$\Delta f_0 = \sqrt{\frac{M/M_\odot}{(R/R_\odot)^3}} \cdot 11.66\,\mathrm{d}^{-1} \tag{3}$$

since the radius can be obtained from angular diameter measurements. With the assumed mass of 1.4 $M_\odot$ for ι Dra the expected frequency splitting is around 0.33 d^{-1}. But the examination of the frequency splitting needs more effort and much more data for the identification of many modes. Unfortunately, our current data sets are not suitable for this kind of analysis.

7. Conclusion

We revised the orbit solution for the companion of ι Dra. The orbital period is P = 511 d, somewhat lower than the value in the discovery paper by Frink et al. (2002). There is a linear trend of −13.8 m/s/yr present, possibly caused by another companion.

An excess of power around 3.8 d^{-1} was found independently in two data sets, taken at different times and with very different sampling. The amplitude and the location of the power excess are consistent with solar-like oscillations.

Our analysis of the short period oscillations indicates a somewhat high stellar mass of M = 2.2 $M_\odot$, considerably higher than the 1.05 $M_\odot$ of Allende Prieto & Lambert (1999) or the stellar masses derived from the Girardi track (1.2−1.7 $M_\odot$). However, this is a preliminary result based on limited data. Assuming 1.4 $M_\odot$ for the mass ι Dra yields a minimum mass of 10 M_{Jup} for the companion.

Our RV measurements for ι Dra indicate that it shows multiperiodic stellar oscillations. This means that an asteroseismic analysis can yield an accurate mass. This is best done by measuring the frequency splitting in the p-mode oscillation spectrum which requires more measurements and better sampling than the data presented here.

Acknowledgements. We gratefully acknowledge assistance from Debra Fischer and Geoffrey Marcy in obtaining precise radial velocities at Lick Observatory, and we thank the staff at Lick Observatory for their extraordinary dedication and support. In addition, we would like to thank the CAT observers David Mitchell, Saskia Hekker and Christian Schwab for obtaining some of the observations used in this work. We thank the anonymous referee for constructive criticism and valuable hints which helped improve this paper.

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