The Discovery of Stellar Oscillations in the K Giant \textit{ι} Dra

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ABSTRACT

\textit{ι} Dra (HIP 75458) is a well-known example for a K giant hosting a substellar companion since its discovery by Frink et al. (2002). 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 \(\mu\)Hz).

Key words. Stars: individual – stars: planetary systems – stars: oscillations

1. Introduction

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

Since the progenitor stars to 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 smaller rotational velocities.

But for evolved stars the determination of the mass is more difficult. The most practical way for determining the mass is the use of evolutionary tracks, but those tracks converge in the upper part of the giant branch for stars over a wide range of masses and thus makes the derived masses uncertain.

Another possibility 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 already been detected in some K and late G giants (e.g. \textit{α} Boo: Retter et al. 2003; Tarrant et al. 2007; \textit{α} Ari: Kim et al. 2006; \textit{ε} Oph: de Ridder et al. 2006; \textit{HYa}: Frandsen et al. 2002; Stello et al. 2006; \textit{β} UMi: Tarrant et al. 2008) and are consistent with solar-like p-mode oscillations. These oscillations have also been measured for 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. \textit{μ} Arae: Bazot et al. 2005; \textit{ι} Hor: Vauclair et al. 2008) and in the planet hosting K giant \textit{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 from evolutionary tracks. In a similar way we will do this here for \textit{ι} Dra.

2. Stellar Parameters

In Table 1 we summarize some direct measurements for the K2III star \textit{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).

Table 1. Stellar parameters of \textit{ι} Dra.

| Parameter | Value |
|-----------|-------|
| Spectral type\textsuperscript{a} | K2III |
| \(V^\dagger\) [mag] | 3.29 |
| \(M_V\) [mag] | 0.81 |
| \(L/L_\odot\) | 64.2 \(\pm\) 2.1 |
| Parallax\textsuperscript{b} \(\rho\) [mas] | 32.23 \(\pm\) 0.1 |
| Distance \(d\) [pc] | 31.03 \(\pm\) 0.1 |
| Angular Diameter\textsuperscript{c} \(\theta\) [mas] | 3.73 \(\pm\) 0.04 |
| Radius \(R\) \([R_\odot]\) | 12.38 \(\pm\) 0.17 |

\textsuperscript{a} ESA (1997) \\
\textsuperscript{b} van Leeuwen (2007) \\
\textsuperscript{c} Richichi et al. (2008)

The quantity which cannot be measured for single stars directly is the mass, which always relies on evolutionary tracks. With the online tool\textsuperscript{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

\textsuperscript{1} http://stev.oapd.inaf.it/cgi-bin/param
Table 2. Stellar parameters of ι Dra from 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\太] | log g | R [R\太] |
|-----------|-------|-------|--------|---------|-------|---------|
| 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 | 0.17 | 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 |

Table 3. Journal of observations.

| Data Set | Coverage | T [d] | N | σRV [m/s] |
|----------|----------|-------|---|-----------|
| CAI      |          | 2918  | 147 | 4.3       |
| TLS      |          | 221   | 280 | 3.3       |
| MeD      |          | 8     | 62  | 3.9       |

4. Orbital Solution

The parameters of the orbit were determined by weighted least squares (χ²-Fit) with the differential correction method (Sterne 1941). We fitted simultaneously five Keplerian orbital elements, a linear trend and three offsets for the combined data sets as the 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 the measurement errors introduce an error into the parameter determination but also the jitter due to pulsations: σ² = σ²RVJ + σ²P. The stellar oscillations are discussed in the next chapter but we mention here that σP 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 4 and the RV curve is plotted in Figure 1. In the old solution the short time baseline and the unrecognizable linear trend had resulted in an overestimated period (P = 536 ± 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 1.4M\太 (33% higher than in Frink et al. 2002).

Table 4. 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 T0 [JD] | 2452013.94 ± 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* f(m) [M\太] | (4.64 ± 0.33) · 10⁻⁸ |
| Semi-major axis a [AU] | 1.34 |
| companion mass m sin i [M\太] | 10.3 |

* f(m) = \frac{(m \sin i)^3}{(M_{\star} \sin^3 i)^2} \approx \frac{a^3}{2GM_{\star}} (K \sqrt{1-e^2})^3

Figure 2 illustrates the radial velocity phased to the orbital period. The total remaining scatter is 13.9 m/s for all data sets.
Fig. 1. Radial velocity measurements for ι Dra from three data sets and the orbital solution as 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.)

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 Figures 3 and 4, respectively. Clearly one can see RV variations with an amplitude of few 10 m/s.

We performed the 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 ($\Delta f = 0.036 d^{-1}$) to 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 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 Figure 5). This prewhitening step reveals effectively 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 also drawn in Figure 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).
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.)

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).

For the McD orbit residuals an excess of power (upper panel in Figure 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 sparser sampling leading to a stronger aliasing at higher frequencies. Extracted are two frequencies, \( f_1 = 3.81 \text{ d}^{-1} \) (8.45 m/s) and \( f_2 = 4.03 \text{ d}^{-1} \) (8.90 m/s), which are also illustrated along with the periodogram of the remaining residuals in the third panel of figure 6.

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.
A more accurate mass estimation could be done with the frequency splitting:

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

since the radius can be obtained from angular diameter measurements. With the assumed mass of $1.4M_{\odot}$ for $\iota$ Dra the expected frequency splitting is around $0.33 \, \text{d}^{-1}$. 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 $\iota$ Dra. The orbital period is $P = 511 \, \text{d}$, somewhat lower than the value in the discovery paper by Frink et al. (2002). Furthermore there is a linear trend of $-13.8 \, \text{m/s/yr}$ present, possibly caused by another companion.

An excess of power around $3.8 \, \text{d}^{-1}$ 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 $M = 2.2M_{\odot}$, considerably higher than the $1.05M_{\odot}$ of Allende Prieto & Lambert (1999) or the stellar masses derived from the Girardi track ($1.2 - 1.7M_{\odot}$). However, this is a preliminary result based on limited data. Assuming $1.4M_{\odot}$ for the mass $\iota$ Dra yields a minimum mass of $10M_{\text{up}}$ for the companion.

Our RV measurements for $\iota$ 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.

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