Stellar Oscillations in Planet-hosting Giant Stars

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Abstract. Recently a number of giant extrasolar planets have been discovered around giant stars. These discoveries are important because many of these giant stars have intermediate masses in the range 1.2 – 3 \( M_\odot \). Early-type main sequence stars of this mass range have been avoided by radial velocity planet search surveys due the difficulty of getting the requisite radial velocity precision needed for planet discoveries. Thus, giant stars can tell us about planet formation for stars more massive than the sun. However, the determination of stellar masses for giant stars is difficult due to the fact that evolutionary tracks for stars covering a wide range of masses converge to the same region of the H-R diagram. We report here on stellar oscillations in three planet-hosting giant stars: HD 13189, \( \beta \) Gem, and \( \iota \) Dra. Precise stellar radial velocity measurements for these stars show variations whose periods and amplitudes are consistent with solar-like p-mode oscillations. The implied stellar masses for these objects based on the characteristics of the stellar oscillations are consistent with the predictions of stellar isochrones. An investigation of stellar oscillations in planet hosting giant stars offers us the possibility of getting an independent determination of the stellar mass for these objects which is of crucial importance for extrasolar planet studies.

1. Introduction
Precise stellar radial velocity (RV) measurements have shown spectacular success at finding extrasolar planets around other stars. The vast majority of these discoveries have been around main sequence stars with masses \(< 1.5 \ M_\odot \). We thus know little about the process of planet formation around stars that are significantly more massive than our sun. Precise stellar radial velocity measurements of main sequence stars in this mass range are difficult due to the high effective temperatures and a paucity of stellar lines. Furthermore, these lines are often broadened by high rates of stellar rotation. These result in a typical RV precision of several hundreds \( \text{m s}^{-1} \) for early-type stars, too poor to detect planetary companions. It is for this reason that RV surveys have focused primarily on main sequence stars later than about spectral type F6.

One way to find planets around stars with masses \( > 1.5 \ M_\odot \) is to search around more massive stars after they have evolved off the main sequence. G–K giant stars are cool (lots of spectral lines) and have slow rotational rates (narrow lines) that are amenable to RV measurements. RV surveys have discovered a number of giant planets in orbit around giant stars ([1], [2], [3], [4]). The study of planets around this class of stars can thus give us valuable clues as to the process of planet formation around stars more massive than the sun; however, the determination of an accurate mass for a giant star is problematical. Evolutionary tracks of main sequence stars spanning a wide range of masses all converge to the giant branch in the color magnitude diagram. One has to rely on stellar evolutionary tracks which are model dependent, and these in turn rely
Figure 1. RV measurements for the planet-hosting star HD 13189 taken over 8 consecutive nights from TLS. The solid line shows a least squares sine-fit with a period of 4.89 days. The deviations of the data from this sine function indicates the presence of additional periods in the data.

on accurate determinations of such stellar parameters as effective temperature, surface gravity, abundance, and absolute luminosity.

The most accurate means of measuring stellar masses, outside of dynamical means, is via asteroseismology. It is well known that many cool giants can exhibit short period RV or photometric variations with periods ranging from hours (e.g. [5], [6], [7]) to days (e.g. [8], [9]). These periods are consistent with p-mode oscillations in giant stars. The fact that extrasolar planets have been discovered around a class of stars known to exhibit stellar oscillations opens up the exciting possibility of using these stellar oscillations as an independent means of deriving important properties of the planet host star. In particular, an accurate determination of the stellar mass is important for extrasolar planet studies. Here we present observations of stellar oscillations in 3 known planet-hosting giant stars.

2. Data Acquisition

Precise Radial velocity (RV) measurements were made of planet hosting giant stars using the coude echelle spectrograph of the 2m Alfred Jensch Telescope of the Thuringer Landessternwarte (Thuringia State Observatory, or TLS). A high measurement precision was achieved by using an iodine absorption cell placed in the optical light path to provide the wavelength reference. This method enables us to achieve an RV precision of \( \approx 3 \, \text{m s}^{-1} \) on bright late-type stars. A detailed description of the instrumental setup and data reduction and analysis process can be found in Hatzes et al. [4].
3. Results

3.1. HD 13189

HD 13189 is a K-type star that was observed as part of the Tautenburg Planet Search Program. Simbad lists the spectral type as K2 but with no luminosity class. Our high resolution spectra established that this star was most likely a giant with a spectral type of K2 II. HD 13189 being a luminous giant is consistent with the visual $V$-mag = 7.57 for this star and the Hipparcos-measured distance of 1.85 kpcs (absolute magnitude $\approx -3.8$). Our RV measurements revealed variations with a period of 472 days and a $K$ amplitude of 173 m s$^{-1}$. These variations are consistent with a planetary companion having a minimum mass of $m \sin i = 8 - 20 \, M_{\text{Jup}}$ [4]. The large range in companion mass results from the uncertainty in the mass of the host star which can range between 1 and 7 $M_{\odot}$.

The RV measurements for this star showed an rms scatter about the orbital solution of $\approx 50$ m s$^{-1}$, which was about a factor of 10 larger than the RV measurement error. Figure 1 shows the RV measurements for this star on 8 consecutive nights. There are clear sinusoidal variations due to stellar oscillations. It is impossible for these variations to be due to a short-period planet since the orbital radius would be well within the photosphere of the star. The solid line shows a sine-function fit to the data with a period of 4.89 days. Note that the RV measurements deviate from the pure sine wave indicating the presence of additional periods. Unfortunately, the data is too sparse to determine reliably the periods of the additional modes. Multi-periodic variations with periods of several days is typical for K giant stars with radii, $R \sim 20 - 60 \, R_{\odot}$ ([8], [10]) and confirms the giant status for the host star.

Figure 2. RV measurements of $\beta$ Gem on one night. The solid line represents a fit with four sine functions whose periods and amplitudes given in Table 1.
| Table 1. Oscillation Modes for $\beta$ Gem |
|------------------------------------------|
| Mode | Per. (hrs) | Amp. (m s$^{-1}$) |
|------|-----------|-----------------|
| $f_1$ | 3.2 | 5.8 |
| $f_2$ | 12.4 | 4.2 |
| $f_3$ | 2.7 | 4.3 |
| $f_4$ | 4.5 | 2.4 |

| Table 2. Oscillation Modes for $\iota$ Dra |
|------------------------------------------|
| Mode | Per. (hrs) | Amp. (m s$^{-1}$) |
|------|-----------|-----------------|
| $f_1$ | 6.7 | 8.9 |
| $f_2$ | 10.9 | 4.7 |
| $f_3$ | 15.9 | 2.6 |
| $f_4$ | 4.7 | 2.4 |

3.2. $\beta$ Geminorum

Long period RV variations in $\beta$ Gem with a period of 545 days were first reported by Hatzes & Cochran [11]. One proposed explanation was that these were due to a planet with a minimum mass of 2.9 $M_{Jup}$, assuming a stellar mass of 2.8 $M_{\odot}$. However, due to the extended atmospheres of giant stars it was not clear if these RV variations could be caused by surface features or an exotic form of stellar oscillations. Hatzes et al. [12] used RV measurements for this star spanning 26 years to confirm that these variations were in fact due to an orbiting planet with a revised period of 590 days. Using a stellar mass of 1.7 $M_{\odot}$ [13] resulted in a companion mass of 2.3 $M_{Jup}$.

Radial velocity measurements of this star were made over 10 nights in late 2006 and early 2007. Almost 900 RV measurements were made with a total coverage of over 60 hrs. Hatzes & Zechmeister [14] presented a preliminary analysis using three nights of the data and they found up to 6 modes present in the data, with the dominant one at $\nu = 87 \mu$Hz. Figure 2 shows the RV measurements from one of these nights. A period analysis of the data shown in Fig. 2 was made using the program Period04. This program enables one to perform a pre-whitening procedure, i.e. a dominant period is found and subtracted from the data before searching for more periods in the data. Period04 can then do a simultaneous fit to the data using all the found periods. This analysis shows that on this night at least 4 periods are present with periods and amplitudes ($P$, $K$): ($P_1$, $K_1$) = (3.2 hrs, 5.8 m s$^{-1}$), ($P_2$, $K_2$) = (12.4 hrs, 4.2 m s$^{-1}$), ($P_3$, $K_3$) = (2.7 hrs, 4.3 m s$^{-1}$) and ($P_4$, $K_4$) = (4.5 hrs, 2.4 m s$^{-1}$). These modes are listed in Table 1. A analysis of the full data set is currently in preparation and this shows that the 3.2 hr mode is the dominant mode and that up to 10 modes may be present in this star. The derived frequency spacing of the modes is $\approx 7.2 \mu$Hz.
Figure 3. RV measurements of the planet hosting star $\iota$ Dra on 3 consecutive nights. The solid line represents a fit with four sine functions whose periods and amplitudes given in Table 2.

3.3. $\iota$ Draconis
The planetary companion to the K2III star $\iota$ Dra was discovered by Frink et al. [15]. It has an orbital period of 536 days and an eccentricity of 0.70. Allende Prieto & Lambert [13] determined a stellar mass of $M = 1.05 M_\odot$ using stellar isochrones. This stellar mass results in a minimum companion mass ($m \sin i$) of 8.9 $M_{\text{Jup}}$.

Figure 3 shows our RV measurements for this star over 3 nights taken with the coude spectrograph of the TLS 2m telescope. A frequency analysis yields 4 periods with periods and amplitudes ($P, K$): ($P_1, K_1$) = (6.7 hrs, 8.9 m s$^{-1}$), ($P_2, K_2$) = (10.9 hrs, 4.7 m s$^{-1}$), ($P_3, K_3$) = (15.9 hrs, 2.6 m s$^{-1}$), and ($P_4, K_4$) = (4.7 hrs, 2.2 m s$^{-1}$). Table 2 lists the oscillation modes found in this data. The solid line in the figure shows the multi-component fit to the data using these periods.

3.4. Stellar Properties and Predicted Oscillation Periods
The scaling relations of Kjeldsen & Bedding [16] can be used to test if the oscillation modes we have detected are consistent with the frequency and amplitudes of p-mode oscillations. Kjeldsen & Bedding showed that these relations are valid for stars covering a wide range of masses and luminosity classes. Their expression for the frequency of the maximum power of the stellar oscillations is

$$v_{\text{max}} = \frac{M/M_\odot}{(R/R_\odot)^2 \sqrt{T_{\text{eff}}/5777 K}} \, 3.05 \, \text{mHz}$$

and for the amplitude

$$v_{\text{osc}} = \frac{L/L_\odot}{M/M_\odot} \times (23.4 \pm 1.4) \, \text{cm s}^{-1}.$$
Table 3. Stellar parameters and oscillation modes of the program stars.

| Star    | Per. (days) | Amp. (m s⁻¹) | \( R \) (\( R_{\odot} \)) | \( M \) (\( M_{\odot} \)) | \( L \) (\( L_{\odot} \)) | Per. (pred.) (days) | Amp. (pred.) (m s⁻¹) |
|---------|-------------|--------------|-----------------|----------------|----------------|-------------------|---------------------|
| HD 13189 | 4.89        | 85.2         | 42.7            | 1.17          | 3980          | 5.0               | 800                 |
| \( \beta \) Gem | 0.13        | 5.8          | 8.8             | 1.94          | 42.8          | 0.14              | 5.2                 |
| \( \iota \) Dra | 0.28        | 8.9          | 12.2            | 1.37          | 70.5          | 0.63              | 12.0                |

The stellar radius of \( \beta \) Gem has been measured with long baseline interferometry. Nordgren et al. [17] determined an angular diameter of 7.96 ± 0.09 mas which corresponds to a radius of 8.8 ± 0.1 \( R_{\odot} \) using the Hipparcos distance of 96.74 ± 0.94 mas. McWilliam [18] derived an effective temperature of 4850 K for this star. The mass of \( \beta \) Gem was estimated using a library of theoretical isochrones [19] and a modified version of the Bayesian estimation method implemented by Jorgensen & Lindegren [20]. A detailed description of this method is given by da Silva et al. [21]. Girardi has implemented a web-interface for calculating stellar parameters from isochrones (http://stev.oapd.inaf.it/~lgirardi/cgi-bin/param). This method yields a stellar mass of \( M = 1.955 \pm 0.192 \, M_{\odot} \).

There are no interferometric measurements of the angular diameters for HD 13189 and \( \iota \) Dra. For \( \iota \) Dra we used the value from CHARM, the Catalog of High Angular Resolution Measurements [22] which gives an angular diameter of 3.58 mas. This corresponds to a radius of \( R = 12.2 \, R_{\odot} \) given the Hipparcos-measured distance of 31.92 pcs. Girardi’s method gives a stellar mass of 1.37 \( M_{\odot} \) which is larger than the value of 1.05 \( M_{\odot} \) derived by Allende Prieto & Lambert [13]. McWilliam [18] derived an effective temperature, \( T_{\text{eff}} = 4480 \, \text{K} \).

CHARM lists no angular diameter for HD 13189. We rely stellar isochrones that give \( R = 42.7 \, R_{\odot} \) and \( M = 1.17 \, M_{\odot} \). Schuler et al. [23] derived an effective temperature of 4180 K for this star. Table 3 lists the stellar parameters for our 3 stars as well as the predicted period and amplitudes (last columns) for the highest amplitude modes according to Eqs. 1 and 2.

4. Discussion

There is good agreement between the observed periods and amplitudes and those predicted from p-mode oscillations. This suggests that we are seeing solar-like p-mode oscillations in these stars. Discrepancies between the predicted and observed frequencies are probably due to the fact that given our sparse data we may have not detected the mode with maximum power. A more reliable method would be to compare the predicted and observed frequency spacing of the modes, but this requires considerably more data. In the case of \( \beta \) Gem, however, we do detect a frequency spacing of \( \approx 7.2 \, \mu \text{Hz} \) which is consistent with the radius and mass listed in Table 3.

The predicted amplitude of HD 13189 is at least a factor of 10 higher than the observed values. One explanation for this large discrepancy is that the Kjeldsen & Bedding relations only hold for high order modes. If the estimated radius and mass for this star are correct, then a 4.89 day oscillation mode corresponds to the period expected for the second harmonic of a radial mode. Thus the order is low (\( n \approx 2 \)) so the Kjeldsen & Bedding relations may not be valid. Another, more likely explanation is the poorly known stellar parameters for HD 13189, in particular the distance. The Hipparcos parallax for this star is \( \pi = 0.54 \pm 0.93 \, \text{mas} \), i.e. the error exceeds the measured value. If the true parallax were \( \pi = 1.47 \, \text{mas} \) (1σ difference) then the luminosity of HD 13189 would be \( L = 537 \, L_{\odot} \) and this results in predicted pulsational amplitude of \( \approx 100 \, \text{m s}^{-1} \) which is more consistent with the observed amplitude of 85 m s⁻¹.

The fact that these stars show oscillation modes consistent with the predicted masses and
radii of these stars from stellar isochrones is encouraging. Multi-periodic variations seems to be a common phenomenon in giant stars and the study of stellar oscillations in giant stars can thus be used to determine fundamental parameters for the stars, and in particular the stellar mass which is important for extrasolar planet investigations. Interferometric observations can yield the angular diameter of the star, and the derivation of the frequency splitting via asteroseismic measurements can yield the stellar mass. The measured mass and radius of the star can then be used to calibrate stellar isochrones. Ideally, one would like to perform asteroseismic studies for every planet hosting star, but that would be difficult given the large amount of observations that are required. Currently, hundreds of giant stars are being surveyed for extrasolar planets and many discoveries are expected. Calibrated stellar isochrones can be used to determine the stellar mass needed by extrasolar planet studies.

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