The Impact of Stellar Oscillations on Doppler Velocity Planet Searches

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ABSTRACT
We present a quantitative investigation of the effect of stellar oscillations on Doppler velocity planet searches. Using data from four asteroseismological observation campaigns, we find a power law relationship between the noise impact of these oscillations on Doppler velocities and both the luminosity-to-mass of the target stars, and observed integration times. Including the impact of oscillation jitter should improve the quality of Keplerian fits to Doppler velocity data. The scale of the effect these oscillations have on Doppler velocity measurements is smaller than that produced by stellar activity, but is most significant for giant and subgiant stars, and at short integration times (i.e. less than a few minutes). Such short observation times tend to be used only for very bright stars. However, since it is these very same stars that tend to be targeted for the highest precision observations, as planet searches probe to lower and lower planet masses, oscillation noise for these stars can be significant and needs to be accounted for in observing strategies.

Key words: stars – planetary systems: star – oscillations

1 INTRODUCTION

Uncertainties in high-precision Doppler velocity measurements are now reaching $\sim 1\,\mathrm{m\,s^{-1}}$ on a regular basis (e.g. O'Toole et al. 2007; Pepe et al. 2007). The science drivers behind the quest for ever-greater precision are the detection of Earth-mass planets in short-period orbits and Solar System analogues, as well as very low amplitude stellar oscillations. Understanding both increasingly subtle instrumental variations, and intrinsic stellar variability, is now more important than ever.

The term jitter has been coined to describe the noise imposed on precision radial velocity programs by a star's intrinsic instability. Until now, only the stellar activity component of jitter has been investigated quantitatively. Wright (2005) examined the jitter of targets in the Lick and Keck Planet Searches and derived an empirical relationship based on colour, activity and absolute magnitude. This has allowed the inclusion of an additional term to the measurement uncertainties used when fitting Keplerians to velocity data, and therefore better modelling of the scatter about these fits.

The dominant oscillations in the solar-like stars are non-radial p-modes stochastically excited by turbulent convection. At least 12 stars have been observed by various groups looking for solar-like oscillations (cf. Bedding & Kjeldsen 2006). The amplitudes of these velocity variations depend on the stellar luminosity and mass and can be scaled from the Sun, at least for objects that have not evolved too far off the main sequence (Kjeldsen & Bedding 1995). These successful detections of solar-like oscillations have been in no small part due to advances in precision radial velocity techniques made by planet search teams; however, little quantitative work has been done to examine the impact of the oscillations on the detection of extra-solar planets.

Tinney et al. (2005) discussed asteroseismology as noise in the context of Doppler velocity planet searches. They suggested that exposure times of integer multiples of the peak oscillation periods could lower jitter by 1-2 $\mathrm{m\,s^{-1}}$. This was also discussed by Mayor et al. (2003), who argued that exposure times of around 15 minutes would average out oscillations. To date these suggestions have not been quantitatively investigated.

2 OBSERVATIONS

To quantify the impact of p-mode oscillations on Doppler planet searches as a function of both observing strategy and stellar properties we have analysed data from four of the published programs of high time-resolution observations obtained with the University College London Echelle Spectrograph (UCLES) that detected and analysed solar-like oscillations in α Cen A (G2V; Butler et al. 2004), α Cen B
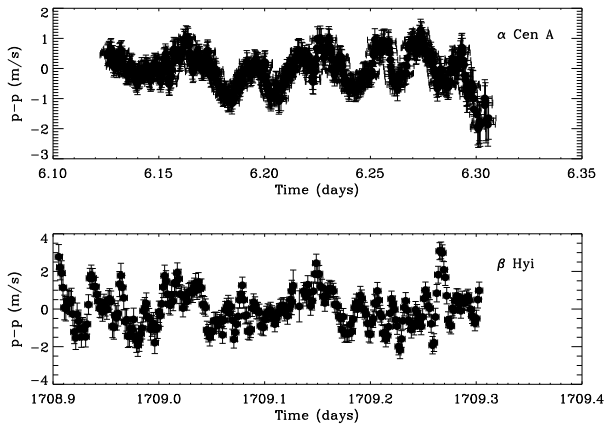
Figure 1. Moving average with $600\,\mathrm{s}$ window for a set of observations of α Cen A and β Hyi.

Figure 2. The total velocity range in an observation data set for each star, as a function of the moving average window size.

(K1V; Kjeldsen et al. 2005), β Hyi (G2IV; Bedding et al. 2001) and ν Indi (G0IV; Bedding et al. 2006).

The observations examined in this paper are described in detail in the references given above and are almost the same as used for the Anglo-Australian Planet Search (AAPS; Butler et al. 2001). Briefly, the data were taken using UCLES mounted at the coudé focus of the Anglo-Australian Telescope (AAT). An iodine absorption cell is placed in the beam, imprinting a forest of molecular iodine absorption lines onto the stellar spectrum. These lines are used as a wavelength reference to derive high-precision velocities as described in Butler et al. (1996). The integration times for each object depend on a number of factors including its brightness, its expected dominant oscillation period, P_{max} and current weather conditions. The data analysed in this paper is exactly the same as that used for the asteroseismological analyses described in the references above, including the removal of long-term drifts in the velocity time series for all stars except ν Indi (where such a correction was not found necessary).

3   THE EFFECT OF OSCILLATIONS

Observed stellar radial velocity curves show variations from several sources: those intrinsic to the star; reflex motion due to a companion; and changes and drifts in the instrumental setup. This paper investigates the observational effect of the first of these – in particular, stellar oscillations – on the second.

3.1   Oscillations as noise

To look at the impact of exposure time on the velocity variations that p-mode oscillations produce in these stars, we have calculated a moving average of our high time-resolution asteroseismology data sets. The window of the moving average was set to typical AAPS exposure times (5, 10, 15, 20, 30, 45, and 60 minutes) as well as several longer times to examine the effects of averaging an entire night's asteroseismology observations (90, 120, 180, 300, 450 and 600 minutes). An example of averaged data over time for α Cen A and β Hyi is
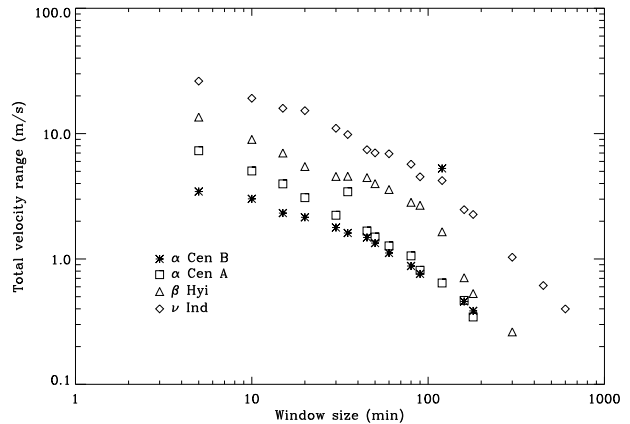
shown in Figure 1 with a window of 10 minutes. The timestamp is set to the midtime of the observations in the window. Ten minute exposures sample almost a cycle and a half of the dominant periodicity in α Cen A, but significantly less than a cycle for β Hyi (taking the dominant period as the individual mode with the highest amplitude). In both cases, there is still significant scatter in the time series when the total integration time spans ten minutes.

If we measure the total velocity range spanned by the velocity extrema for each star and each windowing time listed above, we produce the results shown in Figure 2. These extrema are measured from all nights in the time series. If we consider the 10 minute window for α Cen A shown in Figure 1, we see that the star varies by up to around $5\,\mathrm{m\,s^{-1}}$. This number decreases considerably the more cycles we "integrate" over, as suggested by Tinney et al. (2005).

The size of the variations should vary with spectral type, since oscillation amplitudes are dependent on stellar luminosity and mass. Based on equation 7 of Kjeldsen & Bedding (1995), earlier-type stars should be more affected than later-type stars, and subgiants can be expected to show the largest effects. From Figure 2 we see that this is the case and that α Cen A has higher scatter due to oscillations than the later-type star α Cen B – particularly at short total integration times. Subgiants show larger scatter due to oscillations than main-sequence stars, with the more evolved subgiant ν Ind showing more scatter than the less evolved β Hyi.

3.2   Confidence limits and an empirical relation

While the velocity range data of Figure 2 reveal the importance of stellar oscillations to precision Doppler planet searches, what is really required is an understanding of their statistical impact. That is, how can they be modelled as a source of Doppler noise for planet searches?

Doppler programs typically model their noise sources as Gaussian distributions, and in an ideal world, the "noise impact" of these stellar oscillations would be parameterised in the same way. However, as even a cursory glance at a stellar oscillation power spectrum indicates (e.g. Butler et al.
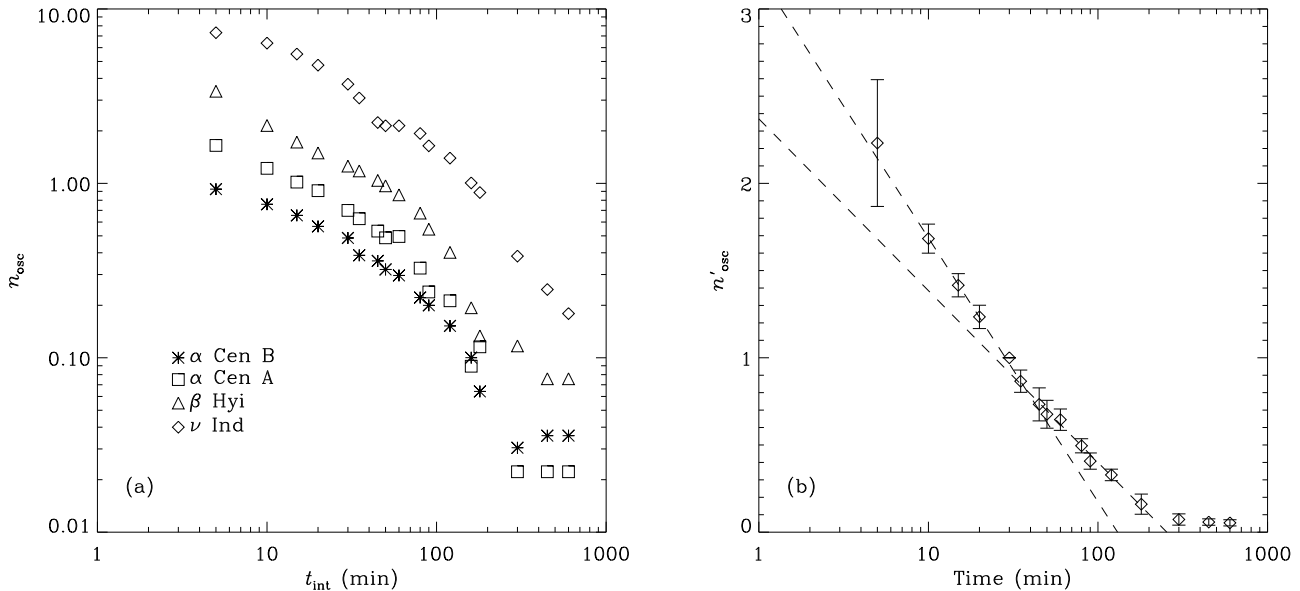
Figure 3. (a) Ninety-five percent confidence ranges ($n_{\rm osc}$) for each star as a function of simulated integration time ($t_{\rm int}$). (b) Data from the panel (a) normalised to produce $n'_{\rm osc}$ and averaged. Uncertainties represent the standard deviation; the standard error of the mean is a factor of two smaller.

2004), they are *not* a source of Gaussian noise. We have therefore parameterised the impact of oscillations using "95% confidence velocities" – i.e. the velocity range, $n_{\rm osc}$, within which 95% of the measured velocities for a given target would lie for a given simulated integration time, $t_{\rm int}$.[1]

Figure 2 suggests there exists a quantifiable relationship between the jitter due to solar-like oscillations and total integration time. To examine this Figure 3(a) shows $n_{\rm osc}$ as a function of $t_{\rm int}$ for all four stars. There appears to be a consistent trend in each case, especially at periods of 5-60 min. This is not all that surprising, since while the detailed form of the stellar oscillation power spectra in these stars (e.g. fine structure splitting between modes; Kjeldsen et al. 2005) will depend on the details of their interior structure, the overall envelope of their power spectra (which is what we sample in these observations) are very similar. We have normalised each star's $n_{\rm osc}$ values at $t_{\rm int} = 30$ min (which is a typical longest exposure time in the AAPS for our very highest precision targets) to produce $n'_{\rm osc}$, which we then average over all four stars and plot in Figure 3(b); the uncertainties are a simple standard deviation. We have modelled this as two linear trends with a break point at 35 minutes. We find

$$n'_{\rm osc} = \begin{cases} 3.20 - 1.51 \log_{10} t_{\rm int} & \text{for } t_{\rm int} \lesssim 35 \, \text{min} \\ 2.37 - 0.99 \log_{10} t_{\rm int} & \text{for } 35 \lesssim t_{\rm int} \lesssim 180 \, \text{min} \end{cases} \quad (1)$$

It is clear from Figure 3 that this relationship breaks down above $t_{\rm int} \sim 180$ min. This is not surprising, as almost all of the power above this time-scale has been extracted by the high-pass filtering of the asteroseismology data to remove long-term drifts.

We expect "oscillation noise" to depend on the ratio of stellar luminosity to mass in a similar manner to the oscillations themselves (Kjeldsen & Bedding 1995). To examine this, we plot $n_{\rm osc}/4$ in Figure 4 for each star as a function of its luminosity-mass ratio (L/M), at a range of simulated exposure times. ($n_{\rm osc}/4$ is plotted as this form is more directly comparable with 1-σ noise estimates from other sources.)

That $n_{\rm osc}/4$ has approximately the same slope for each exposure time on a logarithmic scale suggests a power law relationship exists with L/M. We fit a power law at $t_{\rm int} = 30$ min and find

$$n_{\rm osc} = n'_{\rm osc} \times 10^{3.11} (L/M)^{0.92} \quad \text{for } t_{\rm int} \lesssim 180 \, \text{min} \quad (2)$$

where $n'_{\rm osc}$ is given by equation 1. The fit is overplotted in Figure 4 along with power laws scaled to the other values of $t_{\rm int}$ shown using the appropriate $n'_{\rm osc}$.

Also shown in Figure 4 are the residual root-mean-square (RMS) values for each known planet from Butler et al. (2006). The RMS represents the average deviation from a perfect fit to the radial velocity data and is made up of several components, including the various forms of jitter, instrumental variations and data quality.

The impact of oscillation jitter can be seen (in general) to skirt the lower edge of the observed exoplanetary RMS values, though for very short exposure times, or evolved stars, the noise impact reaches amplitudes of several m s^{-1}, where it clearly becomes significant and of concern.

4 DISCUSSION

We have demonstrated that the impact of p-mode oscillations on low-amplitude planet searches can be quantified. Unlike the stellar activity jitter however, oscillation jitter

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[1] Note that if the asteroseismological power spectrum *were* Gaussian, a 95% confidence velocity corresponds to a velocity range of $\pm 1.96 \, \sigma$ about the mean velocity, or that $\sigma_{\rm osc} \sim n_{\rm osc}/4$.

is dependent on the length of time spent observing a target at any given epoch, so it therefore affects the observing strategies for planet hunting.

4.1 Implications for Observing Strategies

Observing strategies should be tailored to minimise the impact of oscillations. The key factors to consider are the target's L/M value and the resulting total integration time needed to lower n_{osc} to a point where it drops below the desired photon-counting signal-to-noise ratio (SNR) requirement. It is very unlikely that lengthy asteroseismology campaigns will be staged for even a small fraction of the stars; however, one can use Equations 1 and 2 to optimise integration times. More evolved stars will have a higher L/M and will be more affected by oscillation jitter, therefore requiring longer integration times, regardless of the brightness of the object. Hekker et al. (2006) discussed radial velocity variations in giant stars and suggest that variations could be even larger than predicted here for these objects.

Consider, for example, the bright, slightly evolved star μ Ara (HD 160691; V=5.12; $L = 1.75 L_\odot$; $M = 1.15 M_\odot$) which has been the subject of numerous planet discovery papers, and has been claimed to host up to 4 planets, the smallest producing velocity amplitudes as low as $3\,\mathrm{m\,s^{-1}}$. This star is very bright, and so requires integration times of only a few minutes to reach a SNR sufficient to achieve $\sim 1\,\mathrm{m\,s^{-1}}$ precision or better with the AAT and UCLES. At $t_{int} = 1$ & 5 min, we find $n_{osc}/4 = 0.58, 0.39\,\mathrm{m\,s^{-1}}$ – sufficient to make constraining the innermost planet in this system difficult or impossible. Observations of $t_{int} > 15\,\mathrm{min}$ are required to reduce $n_{osc}/4$ below $0.26\,\mathrm{m\,s^{-1}}$, and of $> 60\,\mathrm{min}$ to reduce $n_{osc}/4$ below $0.11\,\mathrm{m\,s^{-1}}$.

As seen above, the scale of the effect these oscillations have on Doppler velocity measurements is smaller than that produced by stellar activity, but is most significant for giant and sub-giant stars, and at short integration times (i.e. less than a few minutes). Such short observations times tend to be used only for very bright stars. However, as planet searches target lower and lower masses, it is these very same stars that tend to be targeted for the highest precision observations. So oscillation noise for these stars can be important and needs to be accounted for in observing strategies.

4.2 Avenues of Further Investigation

Apart from solar-like oscillations and stellar activity, what other stellar noise sources remain to be quantified? Two sources of potential noise are stellar activity cycles and stellar convection. The activity metric of Wright (2005) is useful and has been widely adopted; however, it does not include a time-varying component, which is certainly present (e.g. Metcalfe et al. 2007). The timescales of these variations though are much longer than oscillations – the order of years rather than minutes. Incorporating a time dependence into jitter measurements is worthy of investigation, especially since stellar activity timescales are similar to Jupiter's orbital period.

Sun-like stars have large convective cells or granules where material is dredged up from lower layers and mixed to the surface. The process involves many random surface motions that even when averaged over time are almost certainly
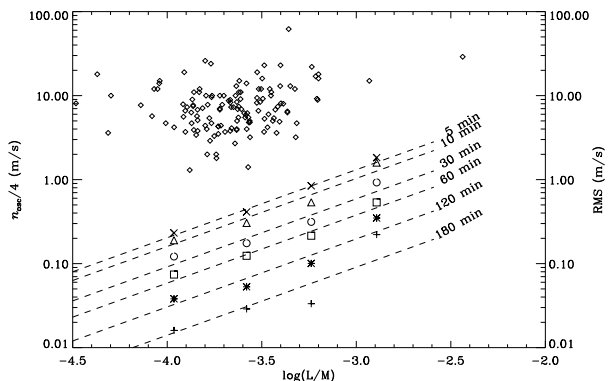

Figure 4. Oscillation jitter ($n_{osc}/4 \approx \sigma_{osc}$) of the UCLES asteroseismology targets as a function of $\log_{10}(L/M)$ for various simulated integration times: 5 minutes (crosses); 10 min (triangles); 30 min (circles); 60 min (squares); 120 min (asterisks); 300 min (plus signs). Overplotted are the power laws dervied from Equation 2. Finally, the residual RMS values for known planets from Butler et al. (2006, small diamonds) are also shown.

large enough to affect planet search measurements. Variations are expected to be around 1-2 $\mathrm{m\,s^{-1}}$ (Dravins 1999) and may have already been observed in μ Ara (Bouchy et al. 2005). Granule lifetimes are typically tens of minutes which is similar to the exposure times used in planet searches. Despite these characteristics, the impact of convection has not been quantitatively investigated.

These two effects will form the focus of our ongoing investigation of the noise sources limiting precision Doppler planet searches.

5 CONCLUSIONS

We have shown that the noise impact of stellar oscillations on precision Doppler velocities obtained in the search for extra-solar planets can be significant in some circumstances. We have used asteroseismological data sets to derive relations which quantify that impact as a function of integration time, and stellar luminosity-to-mass ratio. These can be used to improve the quality of Keplerian fits to planet search data. But most importantly, these relations can drive observing strategies in the search for the lowest-mass planets around bright and evolved stars.

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