Predicting radial-velocity jitter induced by stellar oscillations based on Kepler data

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ABSTRACT

Radial-velocity jitter due to intrinsic stellar variability introduces challenges when characterizing exoplanet systems, particularly when studying small (sub-Neptune-sized) planets orbiting solar-type stars. In this Letter we predicted for dwarfs and giants the jitter due to stellar oscillations, which in velocity have much larger amplitudes than noise introduced by granulation. We then fitted the jitter in terms of the following sets of stellar parameters: (1) Luminosity, mass, and effective temperature: the fit returns precisions (i.e., standard deviations of fractional residuals) of 17.9% and 27.1% for dwarfs and giants, respectively. (2) Luminosity, effective temperature, and surface gravity: the precisions are the same as using the previous parameter set. (3) Surface gravity and effective temperature: we obtain a precision of 22.6% for dwarfs and 27.1% for giants. (4) Luminosity and effective temperature: the precision is 47.8% for dwarfs and 27.5% for giants. Our method will be valuable for anticipating the radial-velocity stellar noise level of exoplanet host stars to be found by the TESS and PLATO space missions, and thus can be useful for their follow-up spectroscopic observations. We provide publicly available code (https://github.com/Jieyu126/Jitter) to set a prior for the jitter term as a component when modeling the Keplerian orbits of the exoplanets.

Key words: techniques: radial velocities—planetary systems—stars: oscillations—methods: observational

1 INTRODUCTION

The radial velocity (RV) technique has been widely used to discover exoplanets and to confirm exoplanets detected in transit surveys (see Fischer et al. 2016; Wright 2017, for recent reviews). However, RV jitter from the host stars leads to challenges, particularly, when studying the exoplanetary signals of small (sub-Neptune-sized) planets that are expected to be detected by space-based transit missions such as TESS (Ricker et al. 2014) and PLATO (Rauer et al. 2014). Several methods have been developed to mitigate effects of stellar RV jitter, including the de-correlation magnetic activity indices (Saar et al. 1998; Isaacson & Fischer 2010), time-averaging of rapid oscillations (Dumusque et al. 2011), and modeling correlated stellar oscillations using Gaussian Processes (Haywood et al. 2014; Rajpaul et al. 2015) including simultaneous photometric observations (Grunblatt et al. 2015; Giguere et al. 2016). However, as of yet there are only few quantitative tools to predict the expected level of RV jitter for a given star, which is critical to planning and prioritizing spectroscopic follow-up observations of transiting planets.

The RV jitter mainly comes from four sources: stellar oscillations, granulation (super-granulation), short-term activity from stellar rotation, and long-term activity caused by magnetic cycles (see Dumusque 2016; Dumusque et al. 2017, and references therein). For dwarfs, the oscillations and granulation have timescales on the order of minutes, while the short- and long-term activity has a longer timescale, typically greater than tens of days. In this study, we will quantify the short-timescale jitter caused by the stellar oscillations in terms of fundamental stellar properties for a wide range of evolutionary states. We emphasize that, unlike in photometry, granulation in velocity has much lower amplitude than the oscillations (Bedding & Kjeldsen 2006), and hence the results presented here can be used to predict RV jitter over a wide range of stars.

Relatively few stars so far have RV data with sufficient cadence to do seismology, so it is difficult to calibrate a RV jitter scaling relation as a function of stellar parameters. Fortunately, analysis of photometric time series can shed light on the RV jitter (Aigrain et al. 2012; Bastien et al. 2014). The Kepler photometric time se-

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ries have been widely explored to study the stellar oscillations in dwarfs and giants (see a review by Chaplin & Miglio 2013). Kjeldsen & Bedding (1995) proposed that the spectroscopic and photometric oscillation amplitudes are convertible between each other. Moreover, it has been widely demonstrated that asteroseismology is able to provide accurate estimates of stellar parameters, based on photometric data sets (see Chaplin & Miglio 2013; Hekker & Christensen-Dalsgaard 2017, for reviews). These facts suggest that asteroseismic analyses on the photometric time series allow us to estimate the RV jitter in terms of stellar parameters.

In this Letter, we provide simple relations to predict the RV jitter from stellar parameters, luminosity, mass, effective temperature, and surface gravity. We also provide public code for implementing these predictions.

2 METHOD AND DATA

The two quantities we seek to predict are the RV oscillation amplitude, $v_{osc}$, and RV jitter, $\sigma_{rms, RV}$. It is important to keep in mind that the granulation background in RV is much lower than in photometry (Bedding & Kjeldsen 2006). Therefore, we cannot simply convert the jitter from the photometric time series to its counterpart in the RV time series. Instead, we must first subtract the contributions from granulation and photon noise. This is done most easily by working with the Fourier power spectrum.

First, we calculated the photometric oscillation amplitude, $A_\lambda$, which was then converted to the RV amplitude, $v_{osc}$. Specifically, the quantity $A_\lambda$ was defined as the oscillation amplitude per radial mode in this manner:

$$A_\lambda = \sqrt{\frac{H_{osc} \Delta \nu}{c}} \times \frac{1}{\sin \left(\frac{\pi v_{osc}}{2 \nu_{max}}\right)} \times (1)$$

where, $H_{osc}$ is the height of the oscillation power excess in the power spectrum, $\Delta \nu$ is the mean large frequency separation between modes of the same angular degree and consecutive radial orders, $c$ is the
effective number of modes per order, adopted as 3.04 (Bedding et al. 2010a; Stello et al. 2011). $v_{\text{max}}$ is the frequency of maximum oscillation power, and $v_{\text{Nyq}}$ is the Nyquist frequency. Note that $v_{\text{Nyq}}$ is equal to 283 $\mu$Hz for the Kepler long-cadence (29.4 minutes) time series and 8333 $\mu$Hz for the Kepler short-cadence (58.89 seconds) time series. The attenuation of the oscillation amplitude due to the integration of photons every long- or short-cadence interval was corrected with the sinc function (Huber et al. 2010; Murphy 2012; Chaplin et al. 2014).

From the photometric oscillation amplitude $A_4$, we were able to obtain the RV amplitude $v_{\text{osc}}$ via the relation given by Kjeldsen & Bedding (1995):

$$v_{\text{osc}} = (A_4/20.1\text{ppm}) (\lambda/550 \text{ nm}) (T_{\text{eff}}/5777 \text{ K})^2 [\text{m s}^{-1}] .$$

(2)

where $T_{\text{eff}}$ is the effective temperature, and $\lambda = 600$ nm was taken as a representative wavelength for the broad bandpass of the Kepler telescope.

Next, we calculated the photometric jitter $\sigma_{\text{rms, phot}}$, which was then converted to $\sigma_{\text{rms, RV}}$. Following Kjeldsen & Frandsen (1992), the quantity $\sigma_{\text{rms, phot}}$ was measured as

$$\sigma_{\text{rms, phot}} = \sqrt{\frac{\sigma_{\text{PS}} N}{4}} .$$

(3)

where $\sigma_{\text{PS}}$ is the mean ‘noise’ level of oscillations (our jitter) in the power spectrum, and $N$ is the number of data points of the time series. In practice, we calculated $\sigma_{\text{PS}} \cdot N$ from a power-density spectrum, which is the power spectrum with its power multiplied by the effective observing time (Kjeldsen et al. 2008). We evaluated the area under the oscillation power excess that can be appropriately approximated with a Gaussian. Thus, we have

$$\sigma_{\text{PS}} \cdot N = \sqrt{\frac{\pi}{4n^2}} H_{\text{env}} W ,$$

(4)

where $W$ is the full-width-at-half-maximum of the oscillation power excess.

To convert the calculated photometric jitter $\sigma_{\text{rms, phot}}$ to the RV jitter $\sigma_{\text{rms, RV}}$, we used Equation 2 by replacing $v_{\text{osc}}$ and $A_4$ with $\sigma_{\text{rms, RV}}$ and $\sigma_{\text{rms, phot}}$, respectively. Note that we distinguish the calculated and predicted $\sigma_{\text{rms, RV}}$ in this work. The former refers to the quantity we derive from Equations 2, 3, and 4, with the observables $H_{\text{env}}$, and $W$, while the latter refers to the quantity we infer from a fitted model with stellar parameters (see Section 3 for more detail). This naming distinction is also applicable to three other quantities, namely $A_4$, $v_{\text{osc}}$, and $\sigma_{\text{rms, phot}}$.

Thus, to calculate $\sigma_{\text{rms, RV}}$ and $v_{\text{osc}}$, we need to know $H_{\text{env}}$, $W$, $v_{\text{max}}$, and $\Delta v$ for individual stars. We adopted the estimates of these global oscillation parameters from Huber et al. (2011) and Yu et al. (2018). Huber et al. (2011) measured these parameters for dwarfs and subgiants using short-cadence Kepler time series. Yu et al. (2018) determined these parameters for red giants with a homogeneous analysis of the full-length end-of-mission Kepler long-cadence data set, using the same analysis pipeline (Huber et al. 2009).

3 PREDICTING RV JITTER FROM STELLAR PARAMETERS

Figure 1a shows the calculated RV oscillation amplitude, $v_{\text{osc}}$, for dwarfs and subgiants, and giants, while Figure 1b shows the calculated RV jitter $\sigma_{\text{rms, RV}}$. This can be used to predict the RV jitter if $v_{\text{max}}$ is known. Black squares mark the measured $\sigma_{\text{rms, RV}}$ from published

![Figure 2](image-url)
RV time series for (ordered by increasing $v_{\text{max}}$) ε Tau (Stello et al. 2017), 46 LMi (Frandsen et al. 2018), β Gem (Stello et al. 2017), ξ Hya (Stello et al. 2004), 18 Del, HD 5608, 6 Lyn, γ Cep, κ CrB, HD 210702 (Stello et al. 2017), υ Ind (Bedding & Kjeldsen 2006), β Aql (Kjeldsen et al. 2008), Procyon (Bedding et al. 2010b), β Hyi (Bedding et al. 2007), α For, γ Ser (Kjeldsen et al. 2008), α Cen A (Butler et al. 2004), γ Pav (Mosser et al. 2008), 18 Sco (Bazot et al. 2011), τ Cet (Teixeira et al. 2009), α Cen B (Kjeldsen et al. 2005). The estimates of $v_{\text{max}}$ were adopted from the corresponding literature and are given in Table 2. We can see that the measured $\sigma_{\text{rms},\text{RV}}$ values are slightly higher than those of Kepler target stars at a similar $v_{\text{max}}$. This is due to the additional contributions from granulation at various timescales, as well as from instrumental and photon noise, in particular for dwarfs. We thus suggest to multiply the observed jitter $\sigma_{\text{rms},\text{RV}}$ due to the oscillations, as done in this work, by a correction factor to approximate the total RV jitter containing oscillations and granulations (see the subsequent text).

Our ultimate goal is to predict $\sigma_{\text{rms},\text{RV}}$ in terms of fundamental stellar properties. For this, we used four simple models. The first model is

$$F = \alpha \left( \frac{L}{L_{\odot}} \right)^{\beta} \left( \frac{M}{M_{\odot}} \right)^{\gamma} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{\delta},$$

where, $L$, $M$, and $T_{\text{eff}}$ are luminosity, mass, and effective temperature, respectively, and $F$ is the quantity that we seek to fit, namely one of $\sigma_{\text{rms},\text{RV}}$, $\sigma_{\text{rms},\text{phot}}$, $A_{4}$, and $V_{\text{osc}}$, by adjusting the free parameters, $\alpha$, $\beta$, $\gamma$, and $\delta$. For typical exoplanet host stars, masses may not always be available, we therefore also fitted a second model by substituting the mass, $M$, with surface gravity, $g$, and

$$F = \alpha \left( \frac{L}{L_{\odot}} \right)^{\beta} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{\delta} \left( \frac{g}{g_{\odot}} \right)^{\epsilon},$$

where $\epsilon$ is a free parameter. In addition, we fitted the following two models to cater for cases where only $T_{\text{eff}}$ and $g$, or $L$ and $T_{\text{eff}}$ are known:

$$F = \alpha \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{\delta} \left( \frac{g}{g_{\odot}} \right)^{\epsilon},$$

and

$$F = \alpha \left( \frac{L}{L_{\odot}} \right)^{\beta} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{\delta} \left( \frac{g}{g_{\odot}} \right)^{\epsilon}.$$

The last model is analogous to the one used by Wright (2005), who linked the magnitude of RV jitter with $B - V$ color and absolute magnitude of a star. In the four models, we introduced the coefficient $\alpha$ which allows for our models to not have to pass through the solar reference point. We included luminosity in the models, given that the $\text{Gaia}$ mission has provided precise parallaxes (Lindegren et al. 2018) and thus luminosities for a large number of stars observed by the Kepler telescope (Berger et al. 2018; Fulton & Petigura 2018).

To implement the fit, we used the non-linear least-square minimization code, LMFIT, with the Levenberg-Marquardt algorithm (Newville et al. 2016). We fitted separately giants and dwarfs using $v_{\text{max}} = 500 \mu\text{Hz}$, or equivalently log $g \sim 3.5$ dex as the dividing point. We calculated luminosities, masses, and surface gravities for the stars in Huber et al. (2011), using the well-known seismic scaling relations (Ulrich 1986; Kjeldsen & Bedding 1995). For red giants, we took the stellar parameters from Yu et al. (2018), which are based on the same relations. Effective temperatures used in this work were taken from Mathur et al. (2017).

Figure 2 shows the comparison between the calculated and predicted $\sigma_{\text{rms},\text{RV}}$ (See Section 2 for the definitions). We can see from Figures 2a and 2b that luminosity, mass, and temperature can be used to make quite good predictions of the RV jitter $\sigma_{\text{rms},\text{RV}}$ for both dwarfs and giants. The comparison returns a median fractional residual of 4.4% with a scatter of 17.9% for dwarfs, and a median fractional residual of 3.3% with a scatter of 27.1% for giants. To test the model, we computed $\sigma_{\text{rms},\text{RV}}$ for 21 stars, as listed in Table 2, from their real RV time series. Note that the predicted RV jitter are only from oscillations. Thus, we removed granulation contributions from the computed $\sigma_{\text{rms},\text{RV}}$ for the 21 stars by dividing a correction factor of 1.9. The correction factor was taken to be the median ratio between the measured $\sigma_{\text{rms},\text{RV}}$ from RV time series, and the predicted $\sigma_{\text{rms},\text{RV}}$ using the model of Equation 5 with $L$, $M$, and $T_{\text{eff}}$ from Table 2. The agreement as shown in black squares is very
Figure 3. log g vs. $T_{\text{eff}}$ diagram color-coded by the RV jitter $\sigma_{\text{rms, RV}}$. Approximate $\nu_{\text{max}}$ is labeled in the right vertical axis. The solid lines show evolutionary tracks from PARSEC (Bressan et al. 2012), with the masses from 0.8 to 2.0 $M_\odot$ and the metallicity [Fe/H] = -0.096 equal to the median value of the whole sample.

We estimated RV jitter in terms of fundamental stellar properties. We calculated the RV jitter $\sigma_{\text{rms, RV}}$ due to stellar oscillations using the global oscillation parameters, the height $H_{\text{env}}$, and width $W$ of oscillation power excess, measured with Kepler data. We then predicted the RV jitter in terms of stellar parameters for both dwarfs and giants. Using four sets of stellar parameters, we obtained the following predictions (i.e., standard deviations of fractional residuals):

(i) $L$, $M$, $T_{\text{eff}}$: 17.9% for dwarfs and subgiants, 27.1% for giants.
(ii) $L$, $T$, $g$: 17.9% for dwarfs and subgiants, 27.1% for giants.
(iii) $T$, $g$: 22.6% for dwarfs and subgiants, 27.1% for giants.
(iv) $L$, $T$: 47.8% for dwarfs and subgiants, 27.5% for giants.

A comparison between our calculated RV jitter $\sigma_{\text{rms, RV}}$ and those directly computed from RV time series indicates that the predicted $\sigma_{\text{rms, RV}}$ is globally smaller than observed in RV data. This is due to the observed $\sigma_{\text{rms, RV}}$ values including the extra contributions from granulation, as well as photon noise and instrumental noise. We stress that the RV jitter predicted from this work are only from stellar oscillations, representing the lower limit. A correction factor is suggested to be applied to our predicted $\sigma_{\text{rms, RV}}$, so as to approximate the whole RV jitter including both oscillations and granulation. By calibrating on long RV time series, we recommend to increase the estimates by using a factor of 1.9 when using the models of Equation 5 and 6, and factors of 2.0 and 1.9 when using the models of Equation 7 and 8, respectively.

The predicted RV jitter $\sigma_{\text{rms, RV}}$ can provide guidance to the follow-up spectroscopic observations for the exoplanets to be found by transit surveys, such as the TESS and PLATO space missions. They can also be used to set a prior for the jitter term as a component when modeling Keplerian orbits (e.g., Eastman et al. 2013; Fulton et al. 2018). We provide publicly available code to estimate the RV jitter $\sigma_{\text{rms, RV}}$.

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