Re-examining the radial velocity detection of L98-59b

Executive Summary

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Introduction The radial velocity (RV) method, also known as Doppler spectroscopy, is an indirect method of exoplanet detection that observes shifts in the spectrum of a planet's parent star. This method was responsible for discovering the first convincing exoplanet around a Sun-like star with a mass similar to Jupiter. Since then, the field of exoplanet detection has grown rapidly, driven by the search for Earth-like planets outside the Solar System.

Advancements in telescopes, such as HARPS and ESPRESSO, have enabled the discovery of many terrestrial, Earth-like planets. Most notably, the detection of exoplanet L98-59b, the lowest mass planet measured so far using RVs. L98-59b is a rocky planet with half the mass of Venus and if confirmed, will reside in the middle of the habitable zone of the L98-59 system. These findings represent an important achievement in the quest for life outside the Solar System.

Detecting low-mass planets using indirect methods like the RV method is challenging due to strong stellar signals from the planet's parent star. To account for the stochastic nature of stellar activity we utilise Gaussian processes (GPs). GPs are useful in this context for several reasons:

i Stellar Activity Modelling - GPs provide a flexible framework for modelling the stochastic variations in stellar activity, which are difficult to parameterise accurately.

ii Noise Reduction - By accurately modelling the stellar noise, GPs help isolate planetary signals, which is extremely useful when detecting low mass planets such as L98-59b.

iii Non-parametric - Unlike traditionally parametric approaches to modelling, GPs adapt to the underlying structure of the data.

At their core, GPs are defined by a mean function and a covariance function. The covariance function, referred to as a kernel, determines how the values of the function relate to each other depending on positions. For RV detection, a common choice of kernel is a quasi-periodic kernel:

$$\gamma_{QP}(t_i,t_j) = A\exp\left(-\frac{\sin^2\left(\pi(t_i-t_j)/P_{\mathrm{GP}}\right)}{2\lambda_p^2} - \frac{(t_i-t_j)^2}{2\lambda_e^2}\right). \tag{1.1}$$

This kernel combines two components:

i A periodic component (sinusoidal) which captures the regular, repeating variations in the signal, such as those caused by stellar rotation (P_{rot}).

ii A decaying component which Accounts for changes over time, such as the evolution of stellar activity (λ_e).

Together, these two components model RV signals, which are often represented as decaying sinusoids. We use quasi-periodic kernels to model stellar activity to resolve planetary signals.

In this project, we closely examined the following indicators of stellar activity indicators:

i Full-width half maximum (FWHM) - The FWHM describes the width of a peak in a signal at half its maximum amplitude. It serves as a useful indicator for characterising peaks and is sensitive to chromospheric activity, such as dark spots.

ii S-index - The S-index is a measure of the fluxes observed in the Ca II H & K emission lines, these ratios measure the relative strength of the stars chromospheric emissions, correlating with the star's magnetic activity.

Project Significance The investigation of L98-59b is crucial due to its unique position as one of the lightest exoplanets detected via radial velocity methods. Additionally, L98-59b is an Earth-like planet and due to its position is a target in the search for life beyond the Solar System.

Furthermore, L98-59b is part of a system with two other transiting planets. Which offers an opportunity to study the dynamics and composition of closely-packed terrestrial planets.

This study re-examines the L98-59 system, specifically focusing on L98-59b, using a GP framework. Our goal is to challenge the detection of L98-59b and refine our understanding of using GPs in low-mass exoplanet detection, as well as to better understand the characteristics and orbital dynamics of this Earth-like planet.

Methods Our approach integrates a multi-component model with observational data from HARPS and ESPRESSO. The components include:

i Planetary Dynamics - Utilising Keplerian dynamics to model the interactions within the three-planet system.

ii Instrumental Adjustment - Correcting for data offsets when simultaneously modelling observational data from more than one instrument.

iii Stellar Activity - Implementing a GP framework to account for chromospheric activity and other noise factors, which are critical in isolating genuine planetary signals from stellar variability.

In our stellar activity model, we applied independent quasi-periodic kernels to model the observed RV and activity indicators FWHM and S-index using GPs.

Results The study confirmed the presence of planet L98-59c. L98-59b's detection was not definitive, although our derived characteristics of the planet align closely with its hypothesised parameters.

Conclusion While L98-59b's detection remains tentative, our refined modelling approach using GPs has demonstrated promising capabilities in distinguishing planetary signatures from stellar noise and marks an enhanced framework for analysing such low-mass exoplanets.

Future Work Future efforts will focus on further constraining these models, incorporating multi-dimensional GPs to better handle the complexities of stellar noise and planetary signals and extend our RV model to incorporate atmospheric considerations from recent transit surveys. This continued research is expected to solidify the detection of L98-59b, revealing more about Earth-like exoplanets and our understanding of modelling stellar activity using GPs.

Implications This work not only progresses the field of exoplanet detection but also provides a robust framework for future studies aiming to detect and analyse Earth-like planets in other solar systems. The methodologies and insights from this research can significantly impact the strategies employed in upcoming explanatory missions and the broader search for habitable worlds beyond our solar system.