Semi-parametric methods to aid in the detection and characterization of distant worlds around small stars

by

Ryan Cloutier

A thesis submitted in conformity with the requirements
for the degree of Doctor of Philosophy
Graduate Department of Astronomy & Astrophysics
University of Toronto

Abstract

Semi-parametric methods to aid in the detection and characterization of distant worlds around small stars

Ryan Cloutier
Doctor of Philosophy
Graduate Department of Astronomy & Astrophysics
University of Toronto
2019

Statistical studies of the exoplanet population have provided key insights into their formation histories and evolution. Developing an understanding of the planet formation process requires both accurate and precise measurements of fundamental planetary parameters such as their masses, radii, and orbital characteristics. Planetary systems orbiting low mass stars represent superlative opportunities to characterize exoplanets in detail as they are plentiful within the solar neighbourhood and they are known to commonly host multi-planet systems of terrestrial to Neptune-sized planets that are more easily detectable than similar planets around Sun-like stars. One major deterrent to the characterization of such planets is stellar activity and its manifestation in radial velocity (RV) measurements that can mask and even mimic planetary signals.

In this thesis, I develop and implement a formalism aimed at enabling the detection and precise and accurate characterization of planetary systems around low mass stars. This formalism is based around semi-parametric Gaussian process (GP) regression models that are used to simultaneously model planets, in both RV and transit light curve observations, and the temporal covariance structure arising from stellar activity produced by magnetically active regions on the stellar surface. The GP formalism is applied to synthetic RV datasets emulating the upcoming planet detection survey using the near-infrared spectropolarimeter SPIRou and to synthetic optical and near-infrared measurements of the expected population of transiting planets discovered with TESS. I also apply the GP formalism to activity modelling in the K2-18 planetary system from which an accurate and precise planetary mass of its transiting temperate sub-Neptune is inferred along with the presence of an additional planet in the system using RV measurements from HARPS and CARMENES. Lastly, I extend the GP formalism to the treatment of stellar photometric variability and systematic effects in TESS light curves and uncover a number of candidate transiting planets around low mass stars in the first two TESS sectors.

Applications of GPs for the detection and characterization of exoplanets will prove to be a crucial tool

for developing a global understanding of planet formation and in revealing how common the conditions for life like our own are within our galaxy.

To my wife and future children.

Acknowledgements

Contents

List of Tables

List of Figures

Chapter 1

Appendix: summaries of additional papers not presented in this thesis

The following is chronological list of papers that include direct contributions from myself and have not been included as chapters in this thesis. Lead author papers in the following subsections are accompanied by a brief paper summary whereas papers for which I was a contributing author are accompanied by descriptions of those contributions.

1.1 Prospects for Detecting the Rossiter-McLaughlin Effect of Earth-like Planets: the test case of TRAPPIST-1b and c (Cloutier & Triaud, 2016)

The Rossiter-McLaughlin (RM) effect, or spectroscopic transit, is an observable effect that is sensitive to the sky-projected spin-orbit angle λ of a planet's orbital plane relative to the host star's spin axis (see Fig. 1.1). The measurement of λ may be used to inform formation models and planet dynamical histories. Notably, it has yet to be measured for any terrestrial-sized exoplanet ($\lesssim 1.6$ R$_\oplus$) owing to their typically shallow transit depths. In this paper, which followed shortly after the discovery of at least three terrestrial-sized planets orbiting the ultracool dwarf TRAPPIST-1 (Gillon et al., 2016), we argued that the two innermost planets represent ideal targets for being the best terrestrial-sized exoplanets amenable to the detection of the RM effect discovered to date. Due to the small size of TRAPPIST-1, its short rotation period (i.e. large $v \sin i_s$), and its relatively low level of activity compared to other ultracool dwarfs, we expect the semi-amplitudes of the TRAPPIST-1b and c RM effects to be $\sim 40-50$ m s^{-1} which is an order of magnitude greater than the amplitude of the Doppler reflex motion induced by the planets on their host star. Simulations of the RM effect showed that if the planets are well-aligned, then λ can be measured with a precision of $\lesssim 10°$ in an RV time series with typical measurement uncertainties of 2 m s^{-1}, although multiple transits will be required due to the faintness of TRAPPIST-1 ($J = 11.4$).

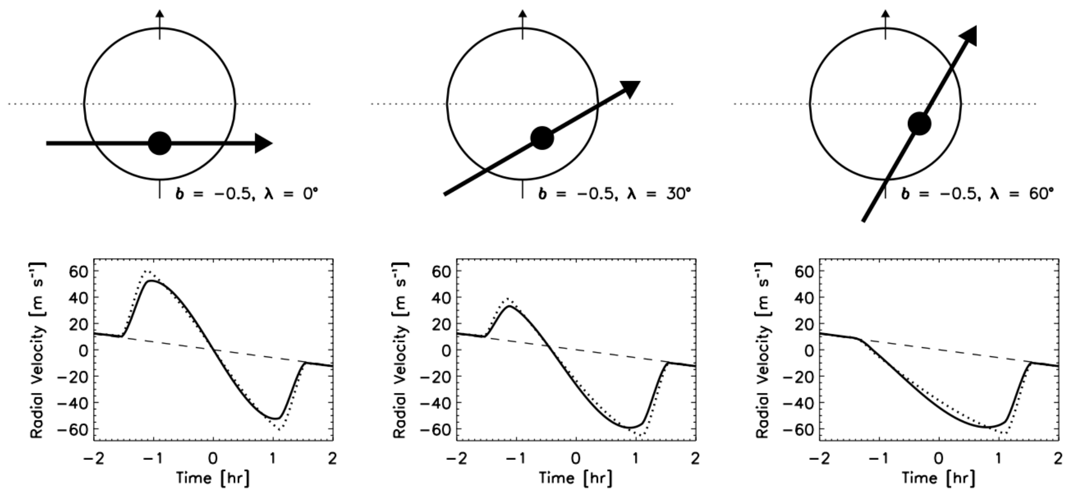

Figure 1.1: Dependence of the anomalous RV waveform from the Rossiter-McLaughlin effect on the sky-projected spin-orbit angle λ. All depicted trajectories during the planetary transit have the same impact parameter $b = -0.5$. The solid and dashed curves correspond to different assumed limb darkening coefficients. (Image credit: Gaudi & Winn, 2007)

1.2 On the Radial Velocity Detection of Additional Planets in Transiting, Slowly Rotating M dwarf Systems: The Case of GJ 1132 (Cloutier et al., 2017)

M dwarfs are known to frequently host multi-planet systems such that we can reasonably expect to find additional planets with RVs around M dwarfs that are known to host at least one transiting planet. In this paper we focused on one such system, namely the nearby mid-M dwarf GJ 1132, which hosts a small transiting planet at $P = 1.6$ days. This system is amenable to deep RV follow-up both for the precise mass measurement of GJ 1132b and for the search for non-transiting planets in the system. We created synthetic RV time series by injecting planets from the empirical M dwarf occurrence rates plus physical models of stellar activity. We then applied our GP formalism for modelling stellar activity (Sect. **??**) to attempt to recover those planets. From these calculations we compute our sensitivity to the detection of additional planets in the GJ 1132 planetary system as a function of the number of RV measurements. We show that at 1 m s^{-1} precision, $\sim 50\%$ of all non-transiting planets from the expected planet population can be detected with ~ 50 measurements.

Indeed there turns out to be at least one additional planet in the GJ 1132 planetary system that is not transiting and is presented in Sect. 1.5.

1.3 Near-InfraRed Planet Searcher to Join HARPS on the ESO 3.6-metre Telescope (Bouchy et al., 2017)

This paper summarized the current status of the up-coming near-IR spectrograph NIRPS (*Near-InfraRed Planet Searcher*) including an overview of its design and primary science goals. As an instrument paper all science team members were added as co-authors including myself as a Canadian collaborator. I did however contribute directly to the discussion of the NIRPS science goal of searching for new RV planetary systems in the southern sky that may be amenable to direct imaging with ELTs. Those specific contributions were calculations of the expected NIRPS planet yield. These calculations were based on the simulations presented in Chapter **??** for the SPIRou Legacy Survey-Planet Search after modifications to the simulated observing strategy and instrument performance were made as they pertain to NIRPS.

1.4 Quantifying the Evidence for a Planet in Radial Velocity Data (Nelson et al., 2018)

The paper presents the results of a collaborative study that was conceived in a breakout session during the *Extremely Precise Radial Velocities III* conference at Penn State. When searching for planets in an RV dataset $\mathbf{y}$, robustly quantifying the detection of a planet requires the Bayesian evidence $\mathcal{Z}$ of an RV model M, that contains that planet, to be greater than the evidence of a competing model M' that does not. If the model is parameterized by a set of model parameters θ then the evidence integral is written as

$$\mathcal{Z}(\mathbf{y}|M) = \int_\theta \mathcal{L}(\mathbf{y}|\theta, M)\Pi(\theta|M)\mathrm{d}\theta \tag{1.1}$$

and requires one to integrate the product of the data likelihood $\mathcal{L}(\mathbf{y}|\theta, M)$ and full model parameter prior $\Pi(\theta|M)$ over the full model parameter space θ. The evidence integral is expensive to compute accurately and many computational methods have been proposed to calculate or approximate $\mathcal{Z}$.

In this study, a number of astronomers from differing RV groups were given identical synthetic RV datasets with injected planets that we participants were agnostic to. The groups were tasked with using our favourite methods to calculate or approximate $\mathcal{Z}$ using those datasets and a consistent set of priors. This paper was comparative study of those methods.

My contribution was to test two non-Bayesian methods that operate analogously to the Bayesian evidence ratio (i.e. ratio of two model evidences $\mathcal{Z}_1$ and $\mathcal{Z}_2$) for the purposes of model comparison. These methods were leave-one-out cross-validation and time-series cross-validation. Instead of calculating $\mathcal{Z}$ they are used to compute the predictive power of a given model such that if a model containing $N+1$ planets demonstrates more predictive power on previously unseen RV measurements (i.e. it is more accurate), then $N+1$ planets are favoured in the dataset than just N planets where $N = 0, 1, 2$ in the study. The two methods were shown to perform comparably to the median Bayesian method when comparing their model comparison diagnostics to Bayesian evidence ratios.

1.5 Radial Velocity Follow-up of GJ 1132 with HARPS: a Precise Mass for Planet 'b' and the Discovery of a Second Planet (Bonfils et al., 2018)

This paper presents the results of an intensive RV follow-up campaign with HARPS of the GJ 1132 mid-M dwarf planetary system. My contribution to this work was to conduct an independent analysis of the RV time series using my GP formalism. This analysis was complementary to those performed by the lead authors which were based on more traditional methods that lacked a treatment of temporally correlated stellar activity signals. With the results of my analysis we measured a precise mass of the known transiting planet GJ 1132b of 1.66 ± 0.23 $M_\oplus$ (i.e. a 7.2σ mass detection). We also detected an additional signal at ~ 8.9 days that favours a second terrestrial mass planet as postulated by my work in Sect. 1.2. Yet another significant signal was seen in the RVs at ~ 177 days although its interpretation as planetary or as an activity-induced signal remains an open question.

1.6 A Second Terrestrial Planet Orbiting the Nearby M Dwarf LHS 1140 (Ment et al., 2019)

This paper presents the results of another intensive RV follow-up campaign with HARPS. This time of the LHS 1140 mid-M dwarf planetary system. LHS 1140 was known to host a small transiting HZ planet ($P = 24.7$ days, $r_{p,b} = 1.73$ $R_\oplus$) discovered from the ground with the MEarth telescope array (Dittmann et al., 2017). Our RV follow-up campaign, which included an independent analysis from myself using my GP formalism, resulted in a significant improvement to the measurement precision of the planet's mass and also revealed a second strong periodic signal at ~ 3.8 days. Re-investigation of the MEarth photometry by the lead authors revealed a second small transiting planet that was missed in the initial light curve analysis, and with an orbital period that was consistent with the 3.8 day RV signal. Through my reanalysis of the RV data now including two planetary signals we recovered the planet masses and confirmed the presence of at least two terrestrial planets around LHS 1140.

1.7 A Hot Terrestrial Planet Orbiting the Bright M dwarf GJ 4332 Unveiled by TESS (Astudillo-Defru et al. in prep.)

Shortly after the release of the first light curves from TESS sector 1, the TESS science team reported a transiting planetary candidate (TOI-134.01) around the nearby early M dwarf GJ 4332. The orbital period and size of the planet candidate ($P = 1.4$ days, $r_{p,b} = 1.58$ $R_\oplus$) make it a hot terrestrial-sized planet that would be a very promising target for atmospheric spectroscopy measurements in emission using JWST/MIRI[1]. As a formal members of the *TESS Follow-up Observing Program*, the HARPS and PFS (*Planet Finder Spectrograph*) RV teams combined their data to confirm the planetary nature of this candidate and measure its mass. Yet again I performed an independent analysis of all available RV data using separate GPs to model the activity signals from each spectrograph based on the methods used to jointly analyze the HARPS and CARMENES data presented in Chapter ??. At ~ 1.6 $R_\oplus$, GJ 4332b

[1] https://jwst-docs.stsci.edu/display/JTI/Mid+Infrared+Instrument

will be one of the first terrestrial planets to contribute to the completion of the TESS level one science requirement[2].

1.8 Characterization of the L 98-59 Multi-Planetary System with HARPS: Two Confirmed Terrestrial Planets and a Mass Upper Limit on the Third (Cloutier et al. in prep.)

Similarly to the announcement of the planetary candidate around GJ 4332, the TESS team also reported a compact system of three transiting planet candidates orbiting the mid-M dwarf L 98-59 from sector 1 (i.e. TOI-175.01,02,03). From follow-up observations including ground-based photometry, reconnaissance spectroscopy, high-resolution imaging, and dynamical stability arguments, Kostov et al. (2019) statistically validated each of the three planets. I led the HARPS RV follow-up of this system and applied my usual analysis techniques to measure precise planet masses for the two outermost planets ($r_{p,c} = 1.37, r_{p,d} = 1.48$ R$_\oplus$) and place an upper mass limit on the smallest inner planet ($r_{p,b} = 0.77$ R$_\oplus$).

Similarly to the dynamical analysis performed on the K2-18 two-planet system, I ran a suite of N-body simulations of the L 98-59 planetary system to constrain their eccentricities. These results supplemented the orbital eccentricity constraints from the RVs themselves and together placed upper limits on each planet's orbital eccentricity of < 0.1 at 95% confidence to ensure a dynamically stable system given their newly measured masses.

[2]To measure the masses of 50 TESS planets smaller than 4 R$_\oplus$.

Bibliography

Bonfils, X., Almenara, J.-M., Cloutier, R., et al. 2018, A&A, 618, A142

Bouchy, F., Doyon, R., Artigau, É., et al. 2017, The Messenger, 169, 21

Cloutier, R., Doyon, R., Menou, K., et al. 2017, AJ, 153, 9

Cloutier, R., & Triaud, A. H. M. J. 2016, MNRAS, 462, 4018

Dittmann, J. A., Irwin, J. M., Charbonneau, D., et al. 2017, Nature, 544, 333

Gaudi, B. S., & Winn, J. N. 2007, ApJ, 655, 550

Gillon, M., Jehin, E., Lederer, S. M., et al. 2016, Nature, 533, 221

Kostov, V. B., Schlieder, J. E., Barclay, T., et al. 2019, arXiv e-prints, arXiv:1903.08017

Ment, K., Dittmann, J. A., Astudillo-Defru, N., et al. 2019, AJ, 157, 32

Nelson, B. E., Ford, E. B., Buchner, J., et al. 2018, ArXiv e-prints, arXiv:1806.04683