DESCRIPTION OF THE PROPOSED PROGRAMME

A- Scientific Rationale

The curious case of warm Jupiters:
Since the very first exoplanet detections of hot Jupiters ($P_{\rm orb} < 10$ days) were made (Mayor & Queloz 1995) it was clear that our previous understanding of planet formation based entirely on our own solar system may not represent the full picture. Most theories suggest that giant planets cannot form interior to the snow line and so must have migrated inwards to their observed orbit (Dawson & Johnson 2018). While some progress has been made in understanding the formation and migration pathways of hot Jupiter planets, it is the warm Jupiters ($10 < P_{\rm orb} < 200$ days) which pose the biggest challenge to our understanding: their short semi-major axes challenge in situ migration models, while their eccentricity distribution does not match most migration theories.

Two different migration pathways:
One proposed mechanism is so-called disk migration. Here, giant planets form beyond the snow line and migrate inward through the disk. However, this set of theories generally predicts low orbital eccentricities for warm Jupiters, as interactions between planet and disk tend to damp the eccentricity (Bitsch et al. 2013 & Dunhill et al. 2013). This appears to be in contrast with observations of highly eccentric warm Jupiters (see Figure 1, left panel). Some planets may have increased their eccentricities through scattering events *after* their disk migration was complete, but even such a scenario cannot generally explain the higher end of observed warm Jupiter eccentricities (e.g., Petrovich et al. 2014).

An alternative set of theories, that better matches the wide range of observed orbital eccentricities, is known as high-eccentricity migration (e.g., Wu & Murray 2003). In this type of model, planets form at long periods and their orbital eccentricity is excited through a mechanism such as planet-planet scattering (Rasio & Ford 1996) or secular chaos (Kaib et al. 2013). The highly eccentric planet passes close to the star during pericentre, which results in orbital circularisation and tidal shrinking. This type of model suffers from the opposite challenge as disk migration models: the observed warm Jupiter eccentricities are generally too *low* to get close enough to their star to further shrink their orbits. Nevertheless, high-eccentricity migration models can be 'rescued' by invoking Kozai-Lidov oscillations (e.g. Takeda & Rasio 2005, Dong et al. 2014). Here, a planet's orbital eccentricity and inclination changes (oscillates) due to interactions with a perturber. This implies that a planet can periodically reach a high eccentricity (facilitating orbital shrinking) while being at a moderate or low eccentricity most of the time (matching the observed eccentricity distribution of warm Jupiters). **If this idea is correct, then these warm Jupiters must have perturbing companions external to their orbit. In this pilot study, we will seek to detect or rule out these companions.**

Testing the prediction: do warm Jupiters have massive companions?
If warm Jupiters are the result of Kozai-Lidov interactions, these planets must have companions acting as a perturber. Furthermore, these companions need to be massive and nearby to result in perturber-coupled high-eccentricity migration (Dong et al. 2013). Therefore, detecting or ruling out the presence of such companions for warm Jupiter planets is a direct test of this promising formation theory. Recent detailed simulations show that a dedicated radial velocity (RV) study of warm Jupiters is capable of detecting or ruling out the vast majority of relevant perturbers (Jackson et al. 2021). In particular, detailed simulations show that 20 RV observations with a precision of 1 m s^{-1} over a 3-month baseline can detect 77% of perturbing companions – only massive companions at relatively short periods outer to the warm Jupiter are capable of exciting eccentricity oscillations – to a synthetic population of bright stars with transiting warm Jupiters (Jackson et al. 2021). With a longer baseline, the detectability further increases, as does limiting the sample to warm Jupiters with periods less than 50 days. Despite previous RV observations of a number of warm Jupiters, such a detailed RV study has not yet been performed. Most RV studies of warm Jupiters are primarily aimed at measuring the mass of the planet, and are insufficiently precise to detect or rule out these companions. **In this pilot study, we will target 10 warm Jupiter planets with HARPS and ESPRESSO to detect or rule out potentially perturbing companions. If perturber-coupled high-eccentricity migration is an important formation pathway for these planets, several companions will be detected – if, by contrast, none are detected, this theory will be falsified.**

B- Immediate Objective

In this proposal we seek to obtain high-resolution spectroscopic observations of 10 stars hosting warm Jupiter planets to detect or rule out the presence of perturbing companions. We will do so by acquiring a minimum of 20 high-precision spectroscopic observations per star over a > 3-month baseline, with the exposure time per spectrum calculated to reach a minimum precision of each individual RV measurement to be better than 1 m s^{-1}. The 4 brightest stars in are sample will be targeted by the HARPS instrument, whereas the 6 other stars require the superior capabilities of the ESPRESSO instrument to meet our science goals.

Based on this observing strategy and the detailed simulations by Jackson et al. (2021), we expect to find at least 77% of companions that can be responsible for perturber-coupled high-eccentricity migration. We therefore expect that if this pathway is significant or dominant, we should detect several such companions, whereas not detecting any companions among 10 planets will significantly constrain this theory. The perturbers will be detected as a linear or quadratic trend, which we will separate from stellar activity through a careful study of activity indicators (e.g., FWHM, BIS, differential line width, S-index, Halpha). This study is envisioned as a pilot study to provide the first data for the PhD project of the PI – if perturbing companions are detected, we anticipate a further larger study to more precisely quantify their occurrence and to better constrain their orbits through longer-baseline RV monitoring.

All targets have been carefully selected to meet the scientific goals of this proposal. Several of the planets are well-known warm Jupiters whose masses have been previously measured using RV observations, but this data is insufficiently precise to detect or rule out perturbing companions. The other targets are more recently discovered planets and planet candidates discovered by the NASA TESS mission (Ricker et al. 2014). They have been carefully vetted to ensure their veracity, using a variety of ground-based follow-up images and spectra within the TESS follow-up consortium (TFOP). The systems span a range of orbital periods and eccentricities (see Figure 1), making them most suitable to test the theoretical predictions.

Additional Science Opportunities: The exceptionally high-precision RV data that will be acquired in this proposal will be further used to measure the mass and eccentricity of the warm Jupiters themselves. This will significantly improve the precision of these parameters for all systems targeted here. The eccentricities are often poorly constrained when only lower-precision RV data are available, and are themselves key to understand the formation history (see above). The planetary masses will be directly relevant for atmospheric studies of these planets, which are key targets for e.g., transmission spectroscopy using the James Webb Space Telescope (JWST, Gardner et al. 2020) scheduled for launch in December 2021.

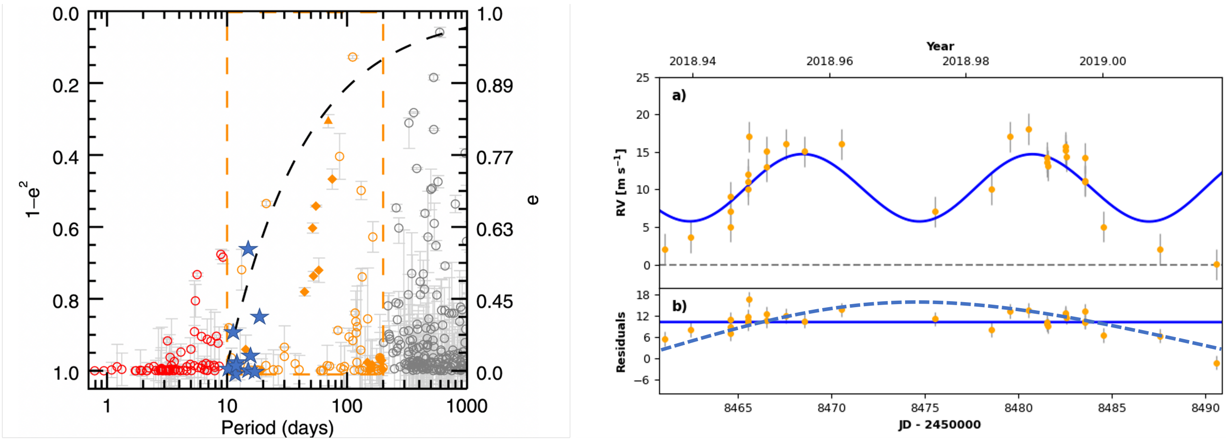

Figure 1. Left: Adapted from Jackson et al. (2021). The warm Jupiter population of exoplanets (orange) in the context of hot (red) and cold (gray) Jupiters. Open circles represent planets with no known companions, closed diamonds (triangles) represent planets with companions detected via RVs (Transit Timing Variations). The black dashed line represents the tidal circularization track that a migrating warm Jupiter would follow if it were to end its migration as a circular hot Jupiter on a 10 day orbit. Kozai-Lidov oscillations may explain the observed eccentricity distribution, which would lead to detectable companions. The blue stars show the proposed targets, with short periods to improve detectability and a range of periods. Right: Illustration (based on real data) of our proposed method. We will model the known warm Jupiter (top panel) and search whether additional trends (bottom panel) are present (dotted line) or absent (solid line). This highlights the need for precise RV points and the increased precision that comes with a longer baseline of observations (baseline of 30 days shown for illustration, we will seek longer baseline of 90 days to confirm trends).

References

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