MSc Astrophysics Project Progress Report

Investigating tidal decay and stellar structure from transit timing variations

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1 Introduction

The search for and characterisation of extrasolar planets is a rapidly developing field with wide implications for the study of planetary formation. Observing planets at various stages of a system's evolution can provide unique insights into the physics of stars and planets and can help us understand the history of our own solar system. What was once a small sample of planets to study has grown into a cosmic zoo of planetary candidates.

There are five main experimental methods employed to observe exoplanets: the "transit time" method, the "radial velocity" method, astrometry, direct imaging and gravitational micro-lensing. This project will concentrate on the transit time method, in which the transits of an exoplanet in front of its host star are observed. The change in brightness of the host star during the transit provides information about the orbital parameters of the system.

In addition to these orbital parameters, which can be directly inferred from the shape of the light-curve of a single transit, multiple such observations can be used to infer how the orbital parameters are changing over time. A change in the (otherwise usually regular) period between transit mid-points is known as a transit timing variation (TTV). Transit timing variations may be caused by either apparent or actual physical phenomena. Apparent effects include those due to proper motion and parallax, and examples of actual effects include the presence of neighbouring companion planets.

One particular physical phenomena of interest is that of tidal decay: tidal interactions in which a planet raises a tidal bulge on its host star can, under certain circumstances, cause the planet's orbital period to decrease over time. The strength of this decay is related to the distance between, and masses of, the planet and star. However it is also affected by internal properties of the star and planet. This makes it a potential tool for studying stellar and planetary composition and structure, something for which there are currently few observational techniques.

In this project I will focus on how transit observations can be used to study tidal decay and make inferences about stellar structure. Key outstanding problems include:

- Developing a statistical methodology that can leverage a wide array of data sources whilst being robust to errors and outliers.
- Confidently identifying systems where tidal interactions are occurring and distinguishing them from transit timing variations caused by other phenomena.

- Scaling the methodology to thousands of planets to allow inferences to be drawn from the resulting empirical distribution of orbital decays.
- Relating the resulting observed decay rates with theoretical models of stellar and planetary composition and structure.

My project seeks to address these outstanding problems. The main goal will be to identify instances of exoplanetary orbital evolution caused by tidal interactions and fit models to these interactions. Finally, the models will be used to infer stellar and planetary properties that can be related back to theoretical models. In doing so I hope to add to the collection of tools we have available to study stellar and planetary structure, enhance our understanding of how planetary systems form, and lay the groundwork for using transit timing variations to study other physical phenomena in a system such as the presence of neighbouring companion planets.

2 Literature review progress

What follows is a brief overview of the main topics of my literature review.

2.1 What is tidal decay? Dynamics and theory

This section will explain how tidal interactions can cause planetary orbits to decay over time and derive the equations of motion resulting from these interactions with reference to the literature. In particular the work of Darwin (1879) who provided the first quantitative description of the tidal evolution of the Earth-Moon system, and later work by Goldreich (1963) and others to apply similar techniques to other bodies in the solar system to solve problems including the origin of Pluto and the near-zero eccentricity of Triton's orbit. Finally, authors including Jackson (2008) have begun to apply the same theory to star-exoplanet systems.

Briefly, the premise is that stellar tidal decay occurs when an orbiting planet exerts a gravitational force on its host star. This creates a tidal bulge which distorts the shape of the star, making it more oblate and creating a non-Keplerian gravitational potential. Such an asymmetric potential induces a torque that acts to slow down the planet, causing it to fall into its host star. The effect is more pronounced the closer the planet is to the star, the more massive the planet is and the less massive the star. It is also affected by the internal structure and composition of the star and to a lesser extent the planet, as discussed in the introduction. The various effects at work are usually summarised into a single scalar property called the tidal dissipation factor.

2.2 How to observe tidal decay? Experimental methodology for observing transit timing variations

In this section various techniques used to observe tidal decay will be discussed, primarily focusing on how the transit method can be used to spot deviations from regular periodic orbits and how models can be fitted to these deviations to identify a variety of physical phenomena, such as tidal interactions, companion planets and oblateness of bodies.

In the case of tidal decay, exoplanet transits are expected to occur ever so slightly closer together than might otherwise be expected under the assumption of a constant period.

Typically the deviations are very small so and barely distinguishable when plotting transit time against transit number, but when light curves are phase folded a systematic shift over time may become apparent.

Maciejewski (2018), Patra (2020), Hagey (2022) and others have modelled transit timing variations using transits recorded by both ground and space-based telescopes and used these observations to constrain tidal decay rates, and in some cases the tidal dissipation factors of stars. Meanwhile Jackson (2009) has used frequentist methods examining occurence rates of planets to provide evidence for the destruction of close in planets due to tidal decay, and Turner (2020) used newly acquired TESS transits to confirm the decay of WASP-12b, the only planet to date for which statistically significant decay has been observed.

2.3 How does stellar structure relate to tidal decay? Modelling tidal dissipation factors from first principles

As discussed, a scalar property known as the tidal dissipation factor is a key determining factor of the rate of tidal decay. The final section of the literature review focuses on how this factor is determined by the internal structure of the star. Notably, it will touch on work by Ogilvie (2014) and Barker (2020) in which they consider how stellar material responds under the influence of a harmonic driving force caused by an external orbiting body. They discuss rates of energy dissipation caused by movement of stellar material in various stellar zones and how this relates to the tidal dissipation factor.

Whilst internal structure cannot be directly inferred from these measurements due to various degeneracies in the modelling, making connections between internal structure and tidal dissipation factors may be useful for complementing and enhancing existing stellar modelling techniques.

3 Project goals

The goals of my project are to:

- Identify hot Jupiter exoplanet candidates that exhibit statistically significant transit timing variations.
- Determine which are good candidates for follow up study of tidal decay.
- For those systems undergoing tidal decay, measure the strength of tidal dissipation.
- Classify tidal dissipation factors by stellar properties, such as age and position on the main sequence, and use the results to test and inform models of stellar structure.

To do this I will make use of publicly available transit data for large close-in hot Jupiter exoplanets from a variety of professional telescopes and citizen-scientist sources. Deviations in these transit times from what might be expected under the assumption of no orbital evolution, known as "transit timing variations" will be computed and used to identify orbital decay. Modelling the decay of these planets will be useful for testing the theory of tidal interactions, as well as investigating stellar structure. Some of the techniques developed in the process will be useful in understanding other orbital evolution phenomena too.

So far, I have completed the following preliminary milestones:

- Used tidal decay theory to rank planets by predicted orbital decay rate.
- Fitted an orbital decay model to TESS light-curve data for WASP-12b, the only planet confirmed in the literature to be decaying.
- Developed a new method based on Bayesian multivariate regression to fit orbital decay models more efficiently than MCMC.
- Fitted decay rates to over 400 planets using publicly available transit data from TESS, ExoClock, the Exoplanet Transit Database, and the Transit Timing En Masse archives.

Remaining project outline:

- Improve the ability of the fitting process to handle outliers and discern transit timing variations caused by other physical phenomena.
- Validate the fitting process by mocking up transit times and recording the fitted model's accuracy and false positive decay detection rate for different scenarios and magnitudes of observational noise.
- Relate the fitted decay rates and tidal dissipation factors to stellar properties like age and temperature.
- Investigate whether constraints on stellar structure can be made using these fitted factors, or whether the factors can be used to improve the uncertainty in existing stellar structure models.

4 Conclusion

This project will focus on using the transit method to study the orbital evolution of close-in Hot Jupiter exoplanets. In particular, the project is motivated by a desire to better understand the physics of stars, and I will discuss how modelling one class of evolutionary effects - tidal interactions - could serve as a possible new tool with which to investigate stellar (and possibly planetary) composition and structure.