Spots on Adolescent Stars: Remapping the Extreme Binary DI Herculis with New Techniques

PHYS3900 Project Proposal

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1 Introduction

A significant proportion of the stellar systems in the Milky Way galaxy are composed of two or more stars, which can often have peculiar interactions which influence the systems as a whole. Among these binary systems is the curious case of DI Herculis: two young, high-mass, rapidly rotating stars on an extremely eccentric and close orbit to one another [1]. Conveniently for astrophysicists, this is an eclipsing binary system, where the stars periodically occlude each other and cause a significant 'dip' in the observed total luminosity of the system [4]. This aids in the analysis of key surface parameters of the component stars, as the edges of the eclipse offer an important probe into the surface features on each star. The most notable of these features is the presence of gravity darkening and likely star spots on the surface of each star (perhaps due to chemical clouds in the stellar atmospheres) [2]. This suggests a lack in understanding of massive star behaviour, as star spots are a by-product of an outer convective shell stellar interior. Since massive stars are understood to be primarily radiative as opposed to convective, there is a clear gap in the current understanding of stellar physics.

Results published in a recent paper suggested that the primary star in the DI Her system, DI Her A, has two significant star spots (both in size and luminosity-reduction) that were responsible for a periodic variability in the luminosity-time curve of the system [2]. Unfortunately, the best-fit model derived by Liang et al (for this curve) was subject to systematic residual error. This provides a suitable use-case for the new and highly accurate Python package `starry` to produce a best-fit luminosity mapping of the surface of the primary star, or both stars in the DI Her system.

2 Significance

Understanding the behaviour and physics of high mass stars is integral in extrapolating that understanding to other areas of astronomy that rely on it as a prerequisite. Scientists working to further understand stellar evolution, planetary systems, binary interactions and even astrobiology (to name a few) would stand to gain from more definite models of stars in extreme regimes such as that seen in the DI Herculis system. Hot, massive stars are observed to have more stable star spots, and so they are an ideal laboratory to test emerging techniques (as opposed to late type, cooler stars that display more time-varying surface features). With a suitable test of techniques in a stable environment, they can be extrapolated to those cooler stars where we (the community) want to observe exoplanets and the extreme magnetism the stars are characterised by.
Liang et al alludes to the potential of chemical peculiarity in the DI Her system as a possible explanation for the observed star spots. Constraining the parameters (namely size, location, and delta luminosity) of the spots more accurately than in previous work is a must in order to more determine the cause of such variability. Using the recent `starry` package, we will fit a closer-matching model to the system light curve, accounting for the contributions from each star. In the process, the obtained parameters of the model will allow for a more statistically significant spot-mapping on each of the component stars.

As a secondary deliverable of the project, we will understand how to apply the `starry` package to systems with complex features. If the implementation is as smooth as claimed, we expect to be able to analyse similar systems (in terms of observed quasiperiodic variability in the time-series luminosity data) at scale in any future implementations.

3 Method

Using publicly available data from the Transiting Exoplanet Survey Satellite (TESS) Sector 26, a spot-transit model (accounting for both limb darkening and gravity darkening) will be formulated for each of the primary and secondary components of the DI Her system. The rotational modulation of the lightcurve allows us to fit a family of solutions to the surface features of the stars, where the eclipses inherent in the system provide an opportunity to break the degeneracies and arrive at a unique solution for a mapping. The analysis will be carried out in Python, using Markov Chain Monte Carlo (MCMC) methods to generate the posterior distributions of the fit-parameters in conjunction with the `starry` package. Due to the analytic implementation of the starry algorithms [3], the model fitting is expected to be feasible on a scale of merely hours of compute time. Once the maximum-likelihood parameters are obtained, we will use the starry functionality to map the corresponding star spots to the stellar surface and generate a plot displaying this.

The timeline of the project and expected duration of each component is outlined below (Table 1).

Task	Semester Week											
	2	3	4	5	6	7	8	9	10	11	12	13
Literature Review												
Project Proposal												
Familiarisation with `starry`												
Model Fitting												
Project Report Plan												
Student Talks (incl. Preparation)												
Project Report Writing												

Table 1: Projected Timeline and Project Milestones

4 Expected Outcomes

Although there has been a model fit of the light-curve of DI Her in Liang et al, we're confident that we can produce a more comprehensive fit with `starry` that significantly reduces the systematic error in the fit residuals. This will be done with the analytic methods in `starry`, allowing for a unique spot-map fitting which uses the eclipses to break degeneracies in the set of potential fits. In doing so, we'll be able to map any star spots far more accurately which will be invaluable in determining their origins.

The process here is, in principle, applicable to other eclipsing binary systems that display quasiperiodic luminosity variation. By analysing DI Her with `starry`, we're confident that we'll lay the foundations for analogous analyses in similarly peculiar star systems.

References

[1] Kassandra R. Anderson and Joshua N. Winn. "Were the Obliquities in DI Herculis Excited by an Unseen Tertiary Companion?" In: *The Astrophysical Journal* 928.1, 96 (Mar. 2022), p. 96. DOI: `10.3847/1538-4357/ac5623`. arXiv: `2202.08275 [astro-ph.SR]`.

[2] Yan Liang, Joshua N. Winn, and Simon H. Albrecht. "DI Herculis Revisited: Starspots, Gravity Darkening, and 3D Obliquities". In: *The Astrophysical Journal* 927.1, 114 (Mar. 2022), p. 114. DOI: `10.3847/1538-4357/ac4f65`. arXiv: `2201.11699 [astro-ph.SR]`.

[3] Rodrigo Luger et al. "starry: Analytic Occultation Light Curves". In: *The Astronomical Journal* 157.2, 64 (Feb. 2019), p. 64. DOI: `10.3847/1538-3881/aae8e5`. arXiv: `1810.06559 [astro-ph.IM]`.

[4] James J. Marshall, Edward F. Guinan, and George P. McCook. "Possible Low Amplitude Light Variations of DI Her". In: *Information Bulletin on Variable Stars* 4161 (Feb. 1995), p. 1.