PHYS3900 Report Plan – Surface Mapping of the Primary Star in DI Herculis

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TOPIC

We can obtain unique surface maps of stars in eclipsing binary systems using new computational techniques.

PARAGRAPH

Low-mass stars are known to have complex surface features due to magnetic interactions in their upper layers, which in turn affects the local surface brightness. As such, a time-series of its brightness will vary quasi-periodically as the star rotates, bringing dark star spots in and out of view. Some high mass binary star systems have exhibited similar behaviour in their light curves, which raises questions as to the underlying physics involved as magnetism is poorly understood in such stars. DI Herculis is one such binary system, where the primary star is understood to have these star spots which may even be clouds of light-absorbing heavy metals in the stellar atmosphere. Using the Python package `starry`, we infer a unique mapping of the surface of the primary star, using a family of spherical harmonics to fit a model to the light curve. In doing so, the magnetic and radiative properties of high mass, chemically peculiar stars will be better constrained which will help our understanding of stellar physics in extreme regimes.

KEY IDEAS AND RESOURCES

For the key points of the report, I will show that by fitting a model to time-series flux data, we can infer more physics about the DI Her binary system than meets the eye. For example, we've likely found buoyancy-driven stellar pulsations in at least one component of DI Her by analysing the residual error of the model fit – a result that wasn't even considered at the beginning of the project. This was only possible due to the precision in the model fit, which subsequently allowed us to infer the behaviour of chemical clouds in the stellar atmosphere of a hot star.
The `starry` model is remarkably fast and accurate. By analysing the model behaviour during eclipses, we can assess how well the maps fit the surface of the stars. During the secondary eclipse (the shallower dip in brightness), we observe only the primary (hotter and more massive) star as the dimmer star passes behind the primary. During the primary eclipse, the secondary star passes over star spots on the primary star and so is an invaluable tool in breaking degeneracies in the family of possible fits (since it constrains the position of star spots to high accuracy). Figure 2 shows that the residuals during the primary eclipse is, at worst, only on the order of 0.2% out of agreement with the data which suggests that the spot size and position is well fit. Similarly, the residuals during the secondary eclipse show minimal variation (during each eclipse) which means that surface overall is well modelled (discounting the vertical and horizontal shifts which are the result of external effects).

Below are the key figures that I intend to include in the report. They may be changed slightly, and I may omit them and include others pending supervisor feedback and research developments.

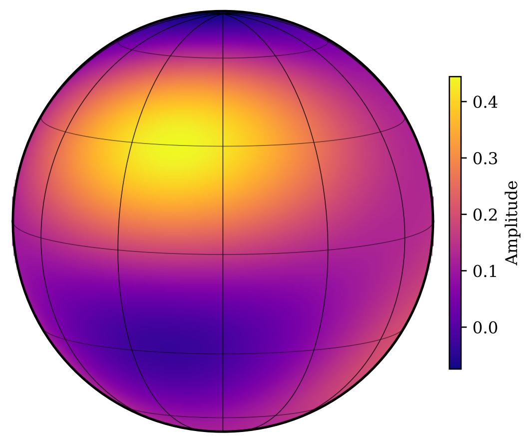

FIG. 4. Best-fit surface map of the DI Her primary star. The inclination is as it appears in the plane of the sky. The amplitude is in arbitrary units, and is only to show relative brightness of surface features. The other side of the sphere mapping is mostly homogeneous in amplitude, and a full, rectangular projection of the mapping is available on the project GitHub repository, as well as an animation of the surface across one rotation.

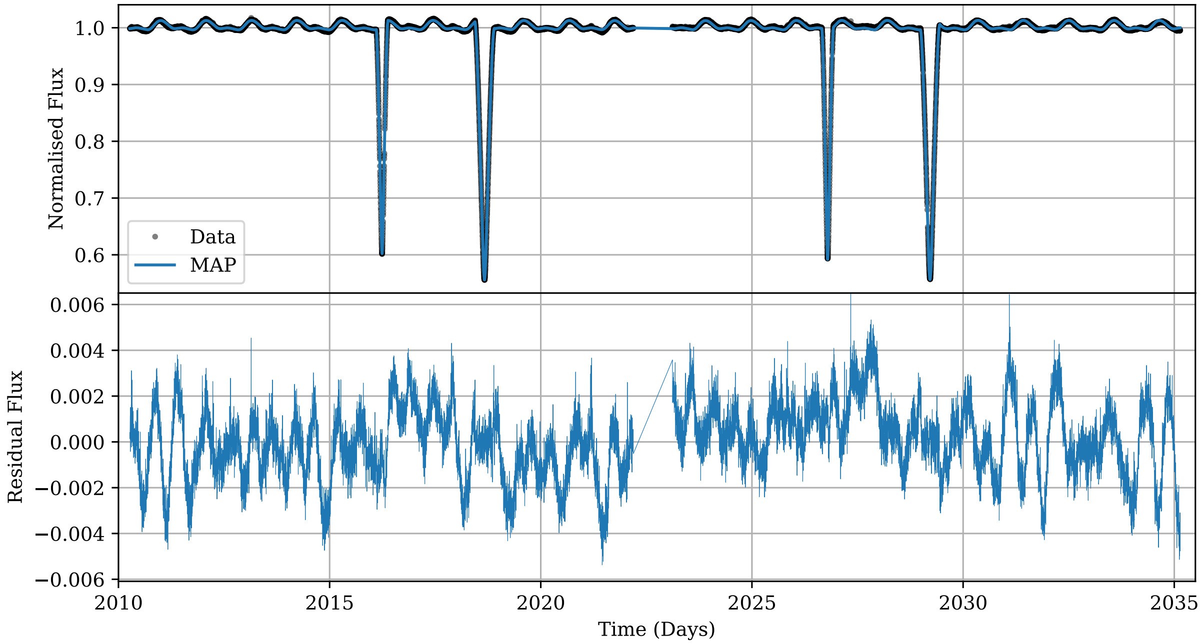

FIG. 1. Top: raw data with the maximum a posteriori fit of the model overlaid in blue. The data were normalised to the median flux value in arbitrary flux units. We see two sets of eclipses, each with a secondary and primary eclipse respectively. The time-series data was obtained from TESS uploads to MAST using the `lightkurve` Python package. Bottom: residuals from the model fit. We see some quasi-periodic oscillations both on short and long time scales (hours to days).

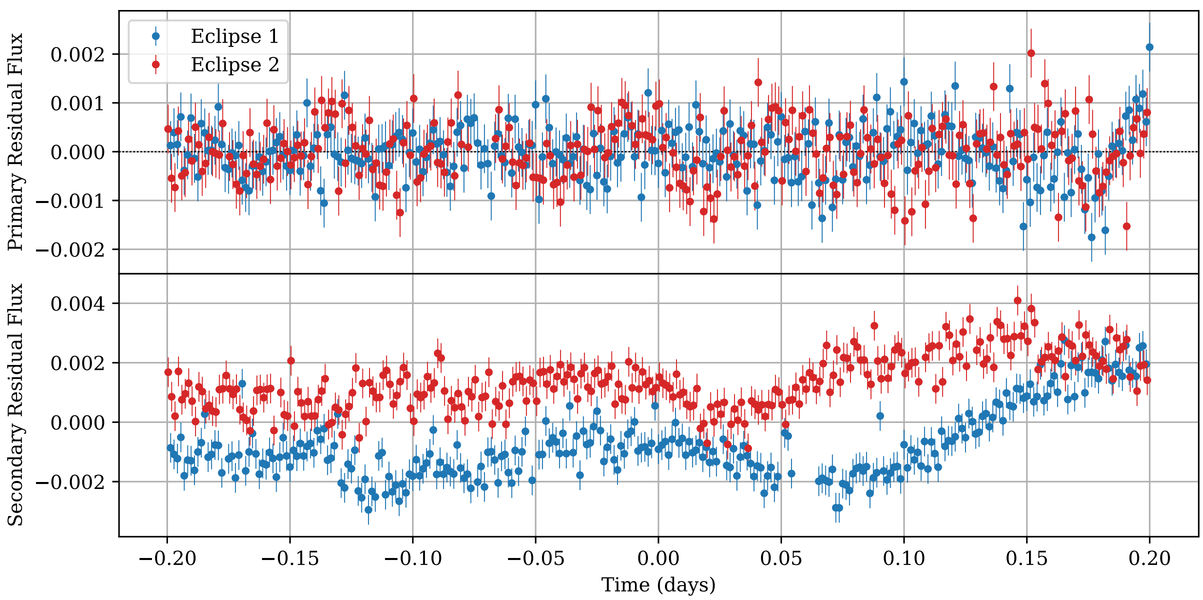

FIG. 2. Residuals of the model during all four eclipses. The time axis represents the time since the minimum brightness of each eclipse. The duration of the primary and secondary eclipses are different, with the primary eclipses occurring from about $-0.2 \leq t \leq 0.2$ days, and the secondary eclipses about $-0.14 \leq t \leq 0.14$ days.

REPORT OUTLINE

Introduction

- Introduce the current understanding of star spots in relation to magnetism and mass of stars. Further, explain how star spots influence the observed light curve of a star. Briefly touch up on other influences on a light curve, namely stellar pulsation, beaming, and reflection.

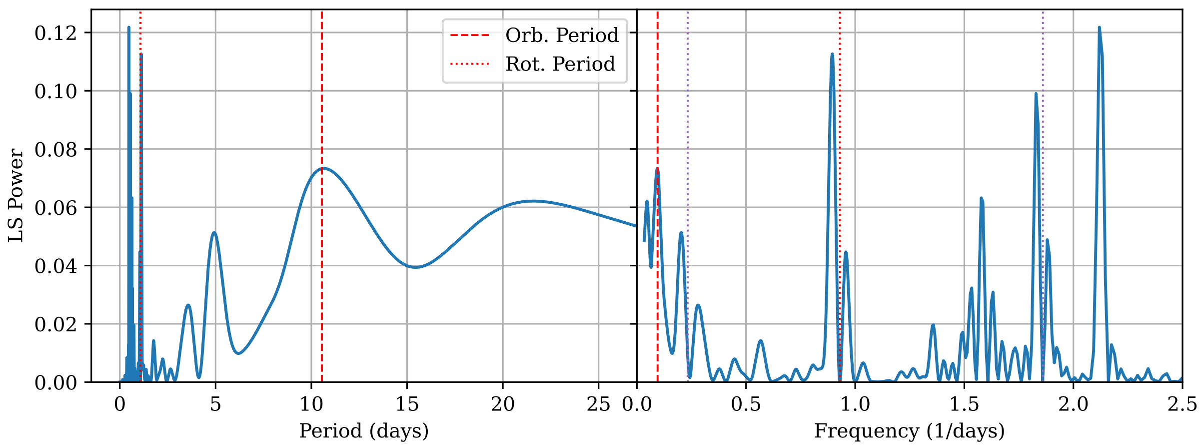

FIG. 3. A Lomb-Scargle Periodogram of the residual flux in the model, in both the period and frequency domains. Dashed lines correspond to peaks at the orbital period, red dotted lines peaks at the primary star rotation period, and purple dotted lines represent harmonics (integer multiples) of the primary rotation period.

- Introduce chemical peculiarity as a likely cause for star spots in high mass stars where there shouldn't be any significant convection.

- Very briefly describe the prominence of binary systems and why they're worth studying. DI Herculis is a perfect system to analyse the phenomena of chemical peculiarity/star spots in high mass stars. It is composed of two closely orbiting, high mass stars which periodically eclipse each other on short timescales. These eclipses are integral in being able to uniquely infer a surface map of the star, as they break degeneracies in a model.

- Explain previous work done with DI Her in Liang et al [2]. Their method of arbitrarily placing a dark spot is inaccurate at best. Fitting spots with use of spherical harmonics would be more accurate and rigorous, as non-radial stellar pulsations (g-modes!) are described by these.

Methods and Results

- How did we get the data? Briefly describe TESS and why it is so important, namely the 2 minute cadence in the timeseries data and the ~ 27 day period of data collection.

- Introduce the Python package `starry`, and very briefly describe how it fits a surface map with spherical harmonics. Describe the parameters that we allowed to vary in the model fit and why we did this/how they impact the fit.

- Most likely a small table of the maximum a posteriori parameter values, or a small paragraph listing the values. Explain how these values match the literature, and explain any differences/alignments. If the Markov Chain Monte Carlo (MCMC) is working by the report date, include a table of the parameter fit values with uncertainty.

- Include the above figures throughout the text, most likely in the order they appear in this plan (figures 1 to 4). Here, detail that we see from the bottom of Figure 1 that this model fit is state of the art, and at worst is better than the previous best fit in Liang et al.

- To assess how well the model fits a surface map, we look at the residuals during eclipse as this is when we see primarily only one of the two stars (and so the light received corresponds to (approximately) one star). This is Figure 2, and here we state that we've significantly reduced the periodic error shown in Liang et al. The secondary eclipse residuals are slightly horizontally offset due to orbital and rotational period misalignment - other inconsistencies signify time evolution of the surface spots.

- We observe multiple seemingly periodic variations in the residuals in each figure. Creating a Lomb-Scargle periodogram shows the prominence of periodic behaviour in these residuals, and from that we can infer shortfalls in the model. We see peaks at the orbital period (maybe due to relativistic beaming and/or reflection), at the harmonics of the rotational period of the primary star (due to time evolution of the star and limitations in the spherical harmonic model), and two other main peaks. The peak at $f \approx 2.1$ days^{-1} is likely due to g-mode pulsations, making at least one of the two DI Her stars a slowly pulsating B star (SpB variable). We see another, time evolving peak at $f \approx 1.6$ days^{-1}, which may be due to *"unstable modes of low degree"* as described in Balona et al [1].

Discussion

- Even though the starry model fit is the best yet, it is still hindered by error on the order of the rotation period. Modelling spot evolution (potentially via linear interpolation between a start and end surface map) could minimise this error. Suggest further improvements for the starry package.

- An MCMC was attempted but abandoned due to software and time constraints. Performing an MCMC in the future would be imperative to help constrain the system properties (like orbital characteristics, star mass, etc) as the MAP fit does not give posterior distributions. Similarly, modelling gravity darkening was abandoned from software constraints. Would this have made much of an impact?

- What does the surface map say about chemical peculiarity, and on a broader scope, spots on stars with no significant convective layer? Relate the findings to binary systems and hot stars in general.

Conclusion

- We've successfully fit a state of the art surface map to DI Her A – reiterate what this implies about the physics of high mass stars and how it can be applied in other situations and on known chemically peculiar stars.

- Further reiterate shortfalls and how they could be solved in the future (i.e. next steps).

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[1] L. A. Balona and D. Ozuyar. Pulsation among TESS A and B stars and the Maia variables. *Monthly Notices of the Royal Astronomical Society*, 493(4):5871–5879, 03 2020.

[2] Y. Liang, J. N. Winn, and S. H. Albrecht. DI Herculis Revisited: Starspots, Gravity Darkening, and 3D Obliquities. *The Astrophysical Journal*, 927(1):114, Mar. 2022.