UNIVERSITY OF SZEGED
FACULTY OF SCIENCE AND INFORMATICS
DOCTORAL SCHOOL OF PHYSICS

Investigation of nonradial pulsations in eclipsing binary systems

PhD thesis statements

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Szeged
2024

Scientific background

Almost all observed stars exhibit some kind of regular or irregular variability on human timescale. Regular variations are of particular interest, being easier to schedule for observations, and benefiting from a wide variety of data analysis methods than others. This holds especially for pulsating stars, the light variations of which are caused by the excitation of intrinsic oscillations through their interiors, leading to periodic contraction and expansion of their material. The pulsations can be interpreted as waves propagating through the bulk material of the stars. Their study allows the exploration of stellar interiors in the same way as Earth's interior was mapped with the help of earthquake observations. To our present knowledge this is the only way to peek inside the stars.

However, the success of this asteroseismic technique depends on our ability to properly determine the eigenmodes (eigenfunctions) of the individual pulsations, a procedure called mode identification. Pulsations occur in almost all phases of stellar evolution, allowing the mapping of internal structure for nearly all types of stars, including our Sun. The asteroseismic study of our central heavenly body proved particularly successful, given that the Sun can be easily observed with high temporal and angular resolution from dedicated space observatories. Its pulsation spectrum containing thousands of modes shows regularities that allowed the identification of most modes, leading to a detailed mapping of its internal structure, including the rotational profile. For distant, unresolved stars only quantities integrated over the whole stellar disc are observable, from which only the pulsation spectra can be inferred in terms of frequency, amplitude and phase, using time series analysis methods. The spectra of some stars show regularities similar to that of our Sun, allowing a similarly easy mode identification (though for much less modes). However, the majority of stars have wildly irregular pulsation spectra, making mode identification challenging. Of them, delta Scuti stars are particularly notorious. These are main sequence stars lying at the bottom of the instability strip of the Hertzsprung-Russell Diagram, with masses of 1.5–2.5 solar masses, periods of minutes-hours, and brightness changes ranging from millimagnitudes up to a few tenths of magnitudes. They pulsate simultaneously in dozens of radial and non-radial modes. Their irregular spectra hints to some yet unknown mechanisms preventing the excitation of some of the modes while allowing others in a non-predictable manner. Multicolour photometric and spectroscopic mode identification methods have been devised for such stars, and applied successfully for a few cases. However, these methods require detailed stellar models, therefore strongly depend on their basic like mass, radius, composition and evolutionary state, which for single stars are known with limited accuracy only. Recently the high precision space photometric data allowed the discovery of some regularities in their pulsation spectra as well.

Fortunately, more than half of the stars reside in binary or multiple stellar systems, orbiting under the laws of gravity around their common centre of mass. When their orbits are seen nearly edge-on from us, the components may periodically obscure each other, causing dips in the light curve, called eclipses. These eclipsing binary or multiple systems are extremely useful, because their photometric and spectroscopic analysis allows the determination of the absolute properties of the component stars with a high accuracy, unattainable for their single star counterparts.

Eclipsing binary stars with one or more pulsating component are a particularly fortunate configuration, due to the synergy between binarity and pulsation. First, the asteroseismic masses derived from a pulsation analysis can be calibrated with the precise masses inferred from a binary analysis. Secondly, the virtual surface sampling provided by the eclipses offers a unique possibility of empirical mode identification. During eclipses the area of the stellar disc contributing to the integrated flux varies in time, inducing modulations in the amplitudes and phases of the pulsations depending on the surface patterns describing their eigenfunctions. With the eclipse geometry available, the appropriate analysis of the modulations may lead to a reconstruction of these patterns, ultimately allowing the identification of their associated mode numbers. This approach does not require any detailed asteroseismic model; on the contrary, it works independently, and may furnish relevant mode identification results to help their improvement.

Various methods have been constructed to analyse eclipse pulsations, presented in more detail in the next section. They all required very precise data with decent time cadence and coverage for a success. Fortunately in the past one and half decade space missions like *Kepler* and *TESS* have furnished and are still furnishing data of just the required quality, making this model-independent approach feasible for appropriate objects. The majority of my research project involved the study of existing, and the construction of newer mapping methods, which were then used to analyse the pulsations in the eclipsing binary system with δ Scuti component KIC 3858884.

Transiting exoplanets around pulsating host stars are another interesting scenario from the point of view of my research interest. By far most of the exoplanets have been discovered with the transit method, the observation of minute decreases in the central star's flux during the transit of its exoplanet in its front. The depth of the transit light curve is much less compared to an eclipse light curve, 1-2% at most, and its proper analysis required data of same quality than the study of eclipses pulsations, furnished by the same space missions (which, by the way, were conceived exactly with the goal of discovering exoplanetary transits).

Although the transits are too small to cause any observable modulation in the host star's pulsations, their analysis benefits from an asteroseismic mass of the host star determined from its pulsation on one hand. On the other hand, the presence of the pulsations may hamper a proper determination of the planetary properties, its orbit in particular, from the transit light curve. Namely, for fast rotating stars, the arising gravity darkening, causing non-uniform surface brightness distribution on the host star, allows in principle the determination of the direction in which the planet crosses in front of the star, i.e. the orientation of its orbit. An aligned orbit causes a symmetric transit curve, while an oblique orbit introduces asymmetries from which the spin-orbit angle and the tilt angle of the star can be determined. However, similar asymmetry in the transit curve can be introduced by unaccounted, small amplitude pulsations of the host star. Many of the currently known exoplanet systems do have pulsating host star, some of them being δ Scuti stars with complex multimode pulsations. Such stars may cause the most pronounced distortions in the transit curve, leading to falsely oblique orbital solutions. As part of my research work, I have closely examined this problem, with special emphasis on searching for treatments that diminish the chance of misfit.

Methods

There are a number of methods already available for the analysis of eclipsed pulsations: spatial filtering (direct fits on the isolated individual amplitude and phase variations, 4), or the fitting of the full pulsation signal assuming spherical harmonics as surface patterns (Direct Fitting, 1), or their reconstruction as more general maps, also from the full pulsation signal (Eclipse Mapping, 2). The latter two have been constructed by my supervisor, who kindly provided me the `pulzem` program suite implementing them. From these, I have worked out an alternative method for Direct Fitting (hereafter DF). Namely, the modelling of spherical harmonics requires the mode numbers (ℓ,m), which are not yet known, a dilemma which the original DF did resolve by running through all the possible partitionings of all mode numbers between the involved frequencies, and selecting the combinations that best fitted the data. However the number of possible combinations increases exponentially with the number of frequencies, quickly reaching the limits of the generally available computing resources. One workaround of my supervisor was the treatment of pulsations in separate groups according to similar amplitudes, however that iterative cleaning step is not guaranteed to give the real best solution. My approach was the stochastic sampling of the parameter space of the modes using Markov Chain Monte Carlo (MCMC) methods, implemented with Metropolis-Hastings and Gibbs algorithms. In this approach the non-numeric modes were treated as category variables with a custom ordering rule to allow the ergodic traversal of their space.

The constructed algorithms were tested on artificial data involving various single- and multimode pulsations in order to asses their capabilities and limits. Later I have used them for the analysis of KIC 3858884 alongside the original Direct Fitting and Eclipse Mapping methods. The Direct Fitting was also used to infer an orientation of the pulsation axis. In this special mode ℓ-multiplets (linear combinations of all spherical harmonics with the same ℓ) are fitted rather than single modes. Their best fitting coefficients are then treated as elements of the Wigner rotation matrix describing the transformation to the coordinate system in which the fitted multiplets can be best described with single spherical harmonics. This procedure yields the Eulerian angles of the pulsation axis, which is indispensable for Eclipse Mapping.

For the analysis of KIC 3858884 I used the short cadence photometry obtained by the *Kepler* space telescope. Mode identification requires the disentangling of the light curve into eclipsing binary and pulsation signals as a prerequisite. The former carries the contributions of the equilibrium surface brightness maps of the stars, while the latter contains the same for the pulsations, both including their own eclipse effects as well. I completed the task in an iterative manner using two programs. The binary signal was modelled using `PHOEBE` (PHysics Of Eclipsing BinariEs, 8), which is based on the popular Wilson-Devinney code [10]. The time series analysis of the pulsations was mad with the `SigSpec` [9] program capable of automated retrieval of the frequency spectrum. In the last step I have invoked a preliminary Eclipse Mapping for an improved treatment of the eight largest pulsations rather than assuming purely radial modes for them. This last step improved significantly the quality of the disentangling.

I used three methods for the identification of the source stars of various pulsations: 1) the inspection of the residuals of disentangling with all the possible combinations regarding the two strongest modes; 2) use of the phase modulation method [6] for the eight strongest modes to determine time individual time delay curves and comparing them to those of the components; and 3) a double Eclipse Mapping, also for the eight strongest modes, in which all frequencies were assumed simultaneously on both stars, and the algorithm partitioned their signal based on the light curve fitting, assigning larger amplitudes for the star of origin.

The modelling, fitting an assessment of exoplanet transit curves with pulsating host stars required multiple work phases. The light changes of the equilibrium brightness were synthesised with the `FITSH` program [7], and the pulsations were generated using a variant `pulzem` developed by my supervisor for the specific case of exoplanetary transits. The combined synthetic data set was analysed using `TLCM` (Transit Light Curve Modeller, 3). Two configurations were used: aligned orbit, and free orbit with gravity darkening. The pulsations, rendered as 'other' astrophysical signal, were handled by a wavelet-based method built into `TLCM` that treated them as red noise and fitted them alongside the transit curve. The feasibilities of the results were evaluated using various information criterion numbers and with two different accounts for red noise – 'yn' (yes, noise in the model) and 'nn' (no noise in the model) depending on whether they were regarded as part of the model, or not.

Theses

1. I implemented a custom method using stochastic sampling for mode identification of pulsations in eclipsing binaries. Following its validation, I have determined its applicability limits with test data. (Bókon and Bíró, 2020)

1.a. I have constructed and MCMC procedures based on Metropolis-Hastings and Gibbs algorithms for the stochastic sampling of the parameter space of eclipsed pulsations in binary systems. The novelty of the methods consists in handling the modes described by a pair of numbers (ℓ, m) as category variables. The method was successfully tested on synthetic data involving multiple pulsations. It was found that in favourable eclipse configurations the method shows the same mode selectivity as the full survey approach of `dffit`, but with much lower computational needs. In non-selective cases the method could successfully identify the equivalent modes, attributing probabilities of similar magnitudes to them.

1.b. At the same time it was also established that the identification is less successful for the weaker pulsations when the amplitudes are distributed across many orders of magnitude, suggesting that for stars showing richer pulsations and iterative application of the analysis in groups of two or three frequencies would be more appropriate.

2. I investigated the possible distortion effect of non-radial pulsations of host stars on the parameters of their exoplanets derived from their transit light curves, with particular emphasis on the occurrence of false tilted orbital configurations. (Bókon et al, 2023)

2.a. I generated synthetic transit light curves caused by exoplanets orbiting pulsating stars in an artificial system, with the goal of determining the amplitude and phase modulations of various pulsation modes during the transit. I could establish that the amplitude would vary at most 2–5% while the phase would show variations less than 2 degrees, therefore in real conditions these modulations are much lower than the measurement errors, therefore they practically can be ignored and treated as simple harmonic signals.

2.b. I investigated whether the presence of pulsations does introduce any error in the determined transit parameters during a fit. There could be cases where the nature of the observations does not allow a proper modelling and subtraction of the pulsations prior to the transit curve analysis (e.g. signal too low, data too short). In order to assess it, I generated synthetic transits with stars showing single and multimode pulsation for a variety of configurations, using the TLCM program, allowing it to handle the pulsations as red noise. Based on the results I concluded that single mode pulsations are properly handled with the red noise algorithm of TLCM, which correctly restores the aligned configurations even under the non-zero gravity darkening assumption.

2.c. TLCM returned the correct result for most cases even in the presence of multimode pulsations. However, for cases with some frequencies close to and orbital resonance, the fits returned oblique configurations even for aligned input setups. Nevertheless, it turned out that such false results can be successfully detected and filtered out using the 'yn' variant of the BIC (Bayesian Information Criteria) number, giving hope for detections in real cases.

2.d. Configurations similar to typical δ Scuti stars, on the other hand, are improperly handled by the red noise algorithm, yielding uncertainties 6-10 times larger than normal. In this case the elimination of pulsation signal by any possible means before a transit analysis is highly desirable.

3. I made a detailed analysis of the eclipsing binary system with pulsating component KIC 3858884 based on its space photometric data, and performed mode identification using several independent methods. (Bókon, Bíró and Derekas, 2024, submitted)

3.a. I used an own, iterative procedure for the disentangling of the data set into eclipsing binary and pulsation components. The uniqueness of my approach consists of invoking a preliminary Eclipse Mapping procedure as a last step to model the modulations more realistically than just radial modes. This procedure has also led to an improvement in the model parameters of the eclipsing binary.

3.b. I did an investigation regarding the source star of the dominant pulsations, using multiple methods: inspection of the residuals, phase modulation analysis, and double Eclipse Mapping. As a result, it was found with fair certainty that the eight larger pulsations originate from the secondary, contrary to the conclusions of Manzoori [5] that the two strongest signals would come from differing components.

3.c. The quantity and quality of *Kepler* measurements about the target enabled a more elaborate investigation of the modulated pulsations with the help of échelle diagrams. It was found that only a few peaks are modulated during the primary eclipses, and at levels that were too low to be analysed in the present work. Most of the modulations happen during the secondary eclipses. It also turned out that only a subset of the dominant peaks show such modulation, the rest being unaffected by any of the eclipses and are probably combination frequencies. On the other hand two additional peaks turned up as hidden modes, with small amplitudes outside the eclipses and pronounced amplifications during them. As a result, I managed to select the peaks worth of attempting mode identification: F1, F2, F3, F6, F15, F44 and F52.

3.d. An ℓ-multiplet fit was made for the frequencies selected in 3.c., using the Direct Fitting method, in order to infer the orientation of the pulsation axis. The best fitting angles were found as 22° for the azimuth and 22° for the tilt angle, which can be regarded basically as an aligned configuration.

3.e. I applied various methods to reconstruct and identify modes for the selected frequencies. The methods used were: modelling with spherical harmonics (Direct Fitting, DFClEAN), the stochastic approach (YLMCMC) presented in **T1**, and the more general reconstruction program, Dynamic Eclipse Mapping. The synthesis of the results yielded mode numbers for the selected frequencies. The two strongest signals F1 and F2 are most probably sectoral modes (2,-2) and (3,3); contrary to my a priori expectation, none of them is radial. Their non-radial nature is also supported by the structure an position of their side peaks. The different methods yielded diverging results for them, which could be explained either by the deviation from spherical harmonics of these strongest pulsations, or an insufficient knowledge of the pulsation axis orientation. F3 and F15 were found beyond doubt as radial modes, with F15 being possibly related to F3 by combination. Another retrograde sectoral mode (1,-1) was found for F6. Finally, the last two frequencies F44 and F52 were found to be bona fide hidden modes with numbers (3,-1) and (2,1). To my knowledge, this is the first time that hidden modes were detected and identified among pulsations in eclipsing binaries.

Publications

Publications associated with the thesis

Refereed papers:

- **Bókon, A**. and Bíró, I. B., *A stochastic sampling method for the analysis of eclipsed pulsations*, Bulgarian Astronomical Journal, 33, 47 (2020).

- **Bókon, A.**, Kálmán, S., Bíró, I. B., and Szabó, M. G., *Stellar pulsations interfering with the transit light curve: configurations with false positive misalignment*, arXiv e-prints, arXiv:2305.00440 (2023).

- **Bókon, A.**, I. B. Bíró and A. Derekas „Eclipse mapping study of the eclipsing binary KIC 3858884 with hybrid δ Sct/γ Dor component". A&A. submitted. arXiv: 2408.14464 (2024, submitted).

Other matters related to the topic of the thesis

Refereed papers:

- Kálmán, S., **Bókon, A.**, Derekas, A., Szabó, G. M., Hegedűs, V., and Nagy, K., *Gravity darkening and tidally perturbed stellar pulsation in the misaligned exoplanet system WASP-33*, A&A, 660, L2 (2022).

- Derekas, A., Murphy, S. J., Dálya, G., Szabó, R., Borkovits, T., **Bókon, A.**, Lehmann, H., Kinemuchi, K., Southworth, J., Bloemen, S., Csák, B., Isaacson, H., Kovács, J., Shporer, A., Szabó, G. M., Thygesen, A. O., and Mészáros, S., *Spectroscopic confirmation of the binary nature of the hybrid pulsator KIC 5709664 found with the frequency modulation method*, MNRAS, 486, 2129 (2019).

Conference talks:

- Bókon, A.: *Application of Eclipse Mapping and Direct Fitting method on KIC 3858884 eclipsing binary system* – KOLOS 2017, 7-9 December 2017; Stakcin, Slovakia

- Bókon, A.: *A stochastic sampling method for the analysis of eclipsed pulsations* – Joint Conference of SREAC & BgAS, Bulgaria, 4-8 June 2019; Sofia, Bulgaria

- Bókon, A.: *A stochastic sampling method for the analysis of eclipsed pulsations* – KOLOS 2019, 5-7 December 2019; Stakcin, Slovakia

- Bókon, A.: *A stochastic sampling method for the analysis of eclipsed pulsations* – PIMMS Workshop, 18 - 22 January 2021; University of Surrey, United Kingdom; online

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