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SWIPE: Stars WIth Pulsations and Eclipses

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Abstract. Eclipses and pulsations are the two primary ways in which the physical properties of stars can be deduced and used to improve our understanding of stellar theory. An obvious idea is to combine these two analyses into the study of pulsating stars in eclipsing binaries. This is the aim of the SWIPE project. This paper summarises the scientific arguments, current status and future plans of the project.

Key words: stars: fundamental parameters — stars: binaries: eclipsing — stars: oscillations

1. Introduction

Detached eclipsing binary stars (dEBs) are our primary source of direct measurements of the physical properties of stars. It is possible to determine their *bulk properties* – mass, radius, density, surface gravity – directly from empirical measurements (Andersen, 1991; Torres et al., 2010). These quantities can be determined to accuracies surpassing 0.2%, for example AI Phe (Maxted et al., 2020) and V505 Per (Southworth, 2021a). They are a crucial check and calibration source for the theoretical stellar models on which modern astrophysics is based. As examples, dEBs have been used to study the strength of internal mixing in high-mass stars (Tkachenko et al., 2020), calibrate the mass–radius relation in low-mass stars (Chen et al., 2014), help determine the properties of transiting planets (Southworth, 2009), and as a rung in the cosmological distance ladder (Pietrzyński et al., 2019; Freedman et al., 2020). Unfortunately, very high-precision masses and radii are needed for useful constraints on stellar theory (Valle et al., 2016; Constantino & Baraffe, 2018).

Asteroseismology is another prolific route towards understanding the stars, in particular their *interior properties* (Aerts et al., 2010). Pressure- (p-) mode pulsations are widespread in solar-like oscillators, and δ Scuti (Murphy et al., 2019) and β Cephei (Stankov & Handler, 2005) stars. Gravity- (g-) mode oscillations manifest in γ Doradus stars (Kaye et al., 1999) and the slowly-pulsating B (SPB) stars (Waelkens, 1991). Of these, the g-mode pulsations offer most promise as they penetrate deep inside stars and thus are affected by physical phenomena in the stellar interior. They have been used to constrain the rotational profile of stars (Aerts et al., 2019), angular momentum transport (e.g.

Mombarg et al., 2019) and internal mixing (Pedersen et al., 2021). A limitation of this method is that the masses and radii of individual stars are not known *a priori* so useful constraints can only be obtained through analysis of significant samples of stars.

An obvious avenue for an improved understanding of the behaviour of stars is to combine the power of binarity and asteroseismology by studying pulsating stars in dEBs. Once masses and radii are precisely known, the measured pulsation frequencies become a sensitive test of theoretical models. Pulsating stars in EBs have been known for decades (Tempesti, 1971; Knipe, 1971), but the data quality for detailed analysis was only recently achieved with space missions such as *CoRoT, Kepler* and TESS (Southworth, 2021c). Examples of recent work in this area include KIC 9850387 (Sekaran et al., 2021), KIC 4142768 (Guo et al., 2019) and HD 74423 (Handler et al., 2020).

We have therefore initiated a project: *Stars WIth Pulsations and Eclipses* (SWIPE) where we aim to perform detailed analysis of a sample of pulsating stars in dEBs to determine their masses, radii, luminosities and oscillation frequencies. These will be used to constrain stellar phenomena such as angular momentum transport, rotational profiles, and internal mixing.

2. Sample selection

Early work on pulsating stars in eclipsing binaries (EBs) was hindered by the difficulty of identifying such objects, particularly in cases where the oscillation amplitudes are low and/or the frequencies are comparable to the length of an observing night. The commencement of large-scale ground-based photometric surveys primarily targeted at the detection of transiting extrasolar planets (e.g. HATNet, HATSouth, KELT and SuperWASP) has been helpful, but the low data quality and severe aliasing due to diurnal effects compromise the usefulness of observations from these surveys.

The main advances in this work have instead been realised primarily through space-based data from *CoRoT, Kepler* and TESS. Whilst *Kepler* remains the source of the best light curves, the faintness and relatively low number of its targets hinders work on pulsating dEBs. TESS (Ricker et al., 2015) has observed the vast majority of the bright stars in the sky, but in most cases the observations are split into 27-d intervals obtained in different years so have a low frequency resolution. The archives of these space missions are nevertheless suffused with pulsating stars in EBs. Gaulme & Guzik (2019) analysed the full *Kepler* database to find 303 examples, and hundreds of δ Scuti stars in EBs have been catalogued (Kahraman Aliçavuş et al., 2017, 2022; Shi et al., 2022; Chen et al., 2022).

Southworth & Bowman (2022a) presented a catalogue of 26 high-mass pulsators in EBs, based on TESS data and including preliminary analyses of 18 of these objects. This sample of stars was identified visually via inspection of the

TESS light curves of known EBs. We found eight objects showing stochastic low-frequency (SLF) variability (Bowman et al., 2019), 16 definite or possible β Cephei stars, and 11 definite or possible SPBs. Eze & Handler (2024) have since presented a catalogue of 78 β Cephei stars in EBs using TESS data.

Whilst there are many δ Scuti stars known in EBs (see references above), eclipsing SPB and γ Dor stars appear to be much rarer. This reflects the prevalence of these objects in the single-star population. Southworth & Van Reeth (2022) presented the discovery of γ Dor pulsations in four known dEBs (CM Lac, MZ Lac, RX Dra and V2077 Cyg), again from visual inspection of TESS data. A fifth, V456 Cyg, was analysed in more detail as we found it to be only the second object known with tidally perturbed high-order g-mode pulsations (Van Reeth et al., 2022). A set of five more EBs showing tidally perturbed g-mode pulsations has been analysed by Van Reeth et al. (2023). We have since discovered more dEBs containing signatures of SLF, β Cephei, SPB, δ Scuti and γ Dor pulsations.

3. A SWIPE status report

Early results for several objects have been published, concentrating on the higher-mass objects in our sample. Two examples are the first and second β Cephei pulsators with a precise mass measurement: V453 Cyg and VV Ori (Southworth et al., 2020, 2021); in both cases the stars were well-studied dEBs whose TESS data led to the discovery of the pulsational signature. A subsequent study of VV Ori by Budding et al. (2024) used extensive spectroscopy to revise the mass measurements upwards by a statistically significant amount (masses of $M_1 = 11.56 \pm 0.14$ and $4.81 \pm 0.06\,\mathrm{M}_\odot$ compared to $M_1 = 10.9 \pm 0.1$ and $4.09 \pm 0.05\,\mathrm{M}_\odot$ from Terrell et al. 2007).

An emerging trend is the prevalence of pulsations affected by binarity, specifically showing evidence for tidal excitation, perturbation or tilting. Theoretical analyses of these phenomena have been described by Fuller et al. (2020) and Guo (2020). Spectroscopic follow-up has been obtained for nine of the objects in the catalogue of Southworth & Bowman (2022a) and all five γ Dor EBs named above, among other objects, and analysis of the data for AR Cas, AL Scl, V453 Cyg, V446 Cep and RX Dra has begun. Tab. 1 summarises our published work to the present. A basic webpage[1] has been established to document the project, but remains a work in progress. Spectroscopic observations have been obtained for approximately 20 systems in addition to those mentioned above, using the Isaac Newton, William Herschel, Mercator, Nordic Optical and Calar Alto 2.2 m telescopes .

In the near future the PLATO satellite (Rauer et al., 2024) will obtain light curves of *Kepler*-like quality over a much larger field of view, to detect

[1] https://www.astro.keele.ac.uk/jkt/swipe/

Table 1. EBs containing pulsating stars where a reasonably detailed analysis has been published as part of the SWIPE project, given in decreasing order of mass.

Target	Pulsation	Spectral type	Period (d)	Ref.
V1765 Cyg	SLF	B0.5 Ib + B1 V	13.374	(1)
V453 Cyg	β Cep, tidal	B0.4 IV + B0.7 IV	3.889	(2)
V346 Cen	Tidally excited	B1 III + B2 V	6.322	(3)
VV Ori	β Cep, tidal	B1 V + B4 V	1.485	(4)
V1388 Ori	β Cep or SPB	B2.5 IV + B3 V	1.485	(5)
IQ Per	SPB	B8 V + A6 V	1.744	(6)
KIC 4851217	γ Dor, δ Sct, tidal	A7 V + A7 IV	2.470	(7)
V1229 Tau	δ Sct	A0 Vp(Si) + Am	2.461	(8)
RR Lyn	γ Dor, δ Sct, tidal	A6 IVm + F0 Vm	9.945	(9)
KIC 9851944	γ Dor, δ Sct, tidal	F1 V + F2 IV	2.164	(10)
V456 Cyg	γ Dor, tidal	A2 Vm + F3 V	0.892	(11)
GK Dra	γ Dor, δ Sct	F1 V + F2 IV	9.974	(12)

References: (1) Southworth (2023); (2) Southworth et al. (2020); (3) Pavlovski et al. (2023); (4) Southworth et al. (2021); (5) Southworth & Bowman (2022b); (6) Southworth (2024b); (7) Jennings et al. (2024b); (8) Southworth et al. (2023); (9) Southworth (2021b); (10) Jennings et al. (2024a); (11) Van Reeth et al. (2022); (12) Southworth (2024a).

Earth-like planets via the transit method. The PLATO Multiple Star Working Group (MSWG) has been established to co-ordinate work on multiple stars using PLATO observations (Southworth & Maxted, these proceedings).

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