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Asteroseismic Observations of Hot Subdwarfs

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There are a number of reasons for studying hot subdwarf pulsation; the most obvious being that these stars remain a poorly understood late-stage of stellar evolution and knowledge of their interior structure, which pulsation studies reveal, constrains evolution models. Of particular interest are the red giant progenitors as in looking at a hot subdwarf we are seeing a stripped-down red giant as it would have been just before the Helium Flash. Moreover, hot subdwarfs may have formed through the merger of two helium white dwarfs and their study gives insight into how such a merger may have happened. A less obvious reason for studying pulsation in hot subdwarfs is that they provide a critical test of stellar envelope opacities and the atomic physics upon which they depend.

Keywords: stars: subdwarfs, stars: oscillations, stars: evolution, stars: binaries: general, stars: rotation

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1 INTRODUCTION

Hot subdwarfs are understood (Heber, 2009; Heber, 2016) to be core-helium burning stars, having masses of $\sim 0.5 M_\odot$ and retaining only thin hydrogen envelopes ($\sim 10^{-4} M_\odot$); they form blue extensions of Horizontal Branches seen in Hertzsprung-Russell Diagrams. Some hot subdwarfs appear to be single stars and many exist in binary systems. Two broad categories of binary system are found to host hot subdwarfs: those with short ($\sim$ 0.1 days) orbital periods (Kupfer et al., 2015) where the companion is typically a M-dwarf or a white dwarf and those with long ($\sim$ 1000 days) orbital periods (Vos et al., 2019) where the companion is a F, G or K Main Sequence star.

Binary population synthesis calculations (Han et al., 2002; Han et al., 2003) show how single hot subdwarfs may form through the merger of two helium white dwarfs, while those in binary systems have red giant progenitors whose hydrogen envelope is almost completely removed at or just before the Helium Flash. Longer period binaries are understood to be a consequence of stable Roche Lobe overflow whereas the shorter period binaries form through common envelope evolution. Clausen and Wade (2011) and Clausen et al. (2012) propose another singleton hot-subdwarf formation channel involving the merger of a helium white dwarf and a low-mass hydrogen-burning star.

Most known hot subdwarfs have effective temperatures (T_{eff}) of less than 40000K; these are referred to as subdwarf-B (sdB) stars to distinguish them from the hotter subdwarf-O stars. Greenstein (1957) argues that pulsational instability may be found in hot subdwarfs but some forty years were to elapse before this important discovery was made. The Edinburgh-Cape Survey (Stobie et al., 1997b, EC) includes photometric monitoring of sdB stars, finding $\sim 3\%$ to pulsate with periods typically between 100 and 500 s; the first pulsators identified being V361 Hya (EC 14026–2647, Kilkenny et al., 1997), EO Cet (PB 8783, Koen et al., 1997), UX Sex (EC 10228–0905, Stobie et al., 1997a) and V4640 Sgr (EC 20117–4014, O'Donoghue et al., 1997). The discovery of pulsation in a few sdB stars rejuvenated theoretical and observational hot subdwarf research, fields which had been largely dormant for the preceding two decades; there was now some prospect of studying the internal structure of stars in a poorly-understood late stage of stellar evolution.

A subsequent survey (Green et al., 2003) finds longer period (~ 1 hour) sdB pulsators which are now referred to as V1093 Her (PG 1716 + 426) stars. Further observations (Oreiro et al., 2004; Baran et al., 2005; Oreiro et al., 2005; Schuh et al., 2005) identify DW Lyn (Ballon 090100001) as a hybrid sdB pulsator, having both short and long period pulsations. Long period pulsators have $T_{\rm eff} < 30000$ K, and for those having short periods $T_{\rm eff} > 30000$ K; hybrid pulsators being found to have $T_{\rm eff} \simeq 30000$ K.

While Greenstein (1957) advocates photometric monitoring of hot subdwarfs, Charpinet et al. (1996) model pulsation instability and so anticipate the publication of pulsation having been discovered in the following year; he and his co-authors then identify (Charpinet et al., 1997) the V361 Hya stars, as they came to be known, as p-mode pulsators driven by the κ-mechanism. V361 Hya star pulsation is driven by the κ-mechanism through a metal (mostly iron) ionisation zone which OPAL (Rogers and Iglesias, 1992a; Rogers and Iglesias, 1992b) and Opacity Project (OP, Seaton et al., 1994) stellar envelope opacity revisions identify. The metal ionisation zone results in an increased opacity (known as the "Z-Bump") and Charpinet et al. (1997) argue, in the case of sdB stars, that this is enhanced through the condition of diffusive equilibrium between gravitational settling and radiative levitation.

The discovery of p-mode pulsation in V361 Hya stars prompts Charpinet et al. (2000), Charpinet et al. (2002a), Charpinet et al. (2002b) to conduct an in-depth adiabatic survey of sdB star oscillations. Basic results are provided in Paper I (Charpinet et al., 2000) of the series in which pulsational properties of a representative evolutionary model are discussed. Essential guidance in understanding pulsation mode period behaviours as functions of sdB star stellar parameters is provided in the subsequent papers; the effects of model parameters being discussed in Paper II (Charpinet et al., 2002a) and Extreme Horizontal Branch evolutionary effects in Paper III (Charpinet et al., 2002b).

Pulsations in the longer period V1093 Her stars are also driven through the κ-mechanism, although in this case they are identified as g-mode pulsators (Fontaine et al., 2003). Jeffery and Saio (2006) resolve a 5,000 K discrepancy between the observed and theoretical blue edges of the V1093 Her instability domain through the use of updated OP opacities (Badnell et al., 2005), and considering an enhancement of nickel as well as iron in the driving zone; this arises because OP predicts iron and nickel contributions to the "Z-Bump" to occur at higher temperatures. Applied to sdB star pulsation more generally, Jeffery and Saio (2007) note that κ-mechanism driving of sdB star pulsation can occur through smaller increases in the iron and nickel concentrations in the driving-zone. Bloemen et al. (2014) show in a further study that iron and nickel enhancements occur naturally in the metal-ionisation zone, without the need for artificial enhancements.

Mode identification is a further crucial step in any asteroseismic analysis. One option is to secure a photometric time-series using multi-colour photometry which ideally is longer than the longest pulsation period of interest by a large factor, the larger the better. Randall et al. (2005a) present the theoretical basis for a multi-colour photometric technique, based on the frequency dependence of an oscillation amplitude and phase being related to the degree index ℓ and other factors which may be eliminated through the amplitude ratios and phase differences arising from the brightness variation in different wavebands. Time-series spectroscopy is another technique which Schoenaers and Lynas-Gray (2006, 2008), discuss, as does Telting (2008) more generally; this has yet to be widely applied to sdB stars as short cadence high dispersion spectra, at an adequate signal-to-noise are challenging to obtain over a long enough time-interval, even with modern instrumentation.

Eclipse mapping may be used for mode identifcation when a pulsating star is in an eclipsing binary, as Reed et al. (2005) and Nuspl (2011) demonstrate. The essential idea is to model observed power spectra at selected orbital phases as their amplitudes vary in a mode-dependent way determined by pulsation and rotation axes inclinations. Given observed power spectra with an adequate signal-to-noise and frequency resolution, simulations show that low-order ($\ell \lesssim 3$) modes may be identified and radial modes ($\ell = 0$) found easily, as in the latter case power spectrum amplitudes are not dependent on orbital phase.

It quickly became clear that an adequate frequency resolution in power spectra could not be achieved with ground-based observations made at a single site; this was most obvious in the case of the longer period g-mode pulsators. Kilkenny (2010) reporting of amplitude variations in pulsating sdB stars provides further emphasis on the importance of achieving a higher frequency resolution in power spectra, because these amplitude variations could conceivably be due to beating between very close unresolved frequencies. Hot subdwarfs in the Kepler (Borucki et al., 2010) field were observed almost continuously for more than three years and the purpose of the present paper is to review this work, in the context of earlier studies with the Whole Earth Telescope (WET, Nather et al., 1990) and CoRoT (Baglin et al., 2006), as well as subsequent observations with K2 (Howell et al., 2014) and TESS (Ricker et al., 2015). The intention was to complement and update earlier reviews of sdB asteroseismology by Fontaine et al. (2008), Østensen (2010), Reed (2016), Reed et al. (2018b)

Aerts (2019) summarises the use of asteroseismology to probe stellar interiors; her figure 1 shows the positions of many known types of pulsating star, including sdB pulsators, in a Hertzsprung-Russell Diagram. Pulsating sdB stars reviewed in the present paper have been listed in **Table 1**. Left-hand columns give equatorial and galactic coordinates. A sample of the names or designations used in the literature are provided in the central three columns. The column on the extreme right identifies the type of sdB pulsator, following the scheme Kilkenny (2010) suggest with a minor adaptation.

As discussed below, observations identify some g-mode pulsators as also showing weak p-modes in their power spectra; I have identified these in **Table 1** as "sdBV$_{(sr)}$" to distinguish them from the Kilkenny classification "sdBV$_{rs}$" for

TABLE 1 | Reviewed Pulsating sdB Stars.

Equatorial Coordinates		Galactic Coordinates		Designation(s)	PG/EC/KPD/		Space Mission		Pulsator
α(**J2000**)	δ(**J2000**)	ℓ^{II}	b^{II}	**Commonly Used**	**KUV Catalogue**		**Input Catalogue**		**Type**
00 16 54.27	+07 04 30.0	107.958740	−54.789659	EK Psc (PHL 766)	PG	0014 + 068	TIC	405212419	sdBV$_r$
00 47 29.22	+09 58 55.7	121.319967	−52.877245	HD 4539 (PHL 830)	PG	0044 + 097	EPIC	220641886	sdBV$_{(sr)}$
00 51 26.94	+09 21 32.9	122.936506	−53.512614	SDSS JJ005126.93 + 092132.9	PG	0048 + 091	EPIC	220614972	sdBV$_{(rs)}$ + F
01 04 21.67	+04 13 37.1	129.105414	−58.489796	Feige 11 (PB 6252)	PG	0101 + 039	EPIC	220376019	sdBV$_s$
01 08 26.78	−32 43 11.6	270.584263	−83.304895	CD −33° 417 (SB 459)			TIC	67584818	sdBV$_s$
01 23 43.25	−05 05 45.8	143.603685	−66.663360	EO Cet (PB 8783)			TIC	248949857	sdBV$_r$
01 56 31.90	−13 54 26.5	175.134253	−69.864921	GD 1053	EC	01541–1409	TIC	62381958	sdBV$_r$
03 45 34.58	+02 47 52.7	184.426667	−38.475269		PG	0342 + 026	TIC	457168745	sdBV$_s$
04 44 56.90	+14 21 50.2	184.190561	−19.811676	V1405 Ori	KUV	04421 + 1416	EPIC	246683636	sdBV$_{(rs)}$ + M?
05 07 20.23	−28 02 25.3	229.886388	−33.987631	CD −28° 1974	EC	05053–2806	TIC	13145616	sdBV$_{rs}$ + F/G
06 31 53.82	−00 19 13.1	210.985775	−04.493128	SDSS J063153.81–001913.0	KPD	0629–0016	TIC	36995993	sdBV$_s$
07 07 09.80	+60 38 50.2	155.677776	+25.299771	DW Lyn (Balloon 090100001)			TIC	88565376	sdBV$_{rs}$
08 20 03.36	+17 39 14.2	206.080058	+27.264486	SDSS J082003.35 + 173914.2			EPIC	211823779	sdBV$_r$ + F
08 28 32.87	+14 52 02.5	209.868554	+28.077860	UVO 0825 + 15			EPIC	211623711	He-sdBV
08 36 03.99	+15 52 16.4	209.614847	+30.137822	SDSS J083603.98 + 155216.4			EPIC	211696659	sdBV$_s$ + WD
08 36 12.03	+19 17 56.1	205.918128	+31.428427	LB 378 (EGGR 266)			EPIC	211938328	sdBV$_r$ + F
08 56 49.27	+17 01 14.7	210.568732	+35.181583	SDSS J083612.03 + 191755.9			EPIC	211779126	sdBV$_{rs}$
10 25 17.34	−09 20 40.6	253.673072	+39.164600	UX Sex	EC	10228–0905	TIC	36879659	sdBV$_r$
10 50 02.83	−00 00 36.9	250.855810	+50.170702	UY Sex	PG	1047 + 003	EPIC	248411044	sdBV$_r$
11 44 57.24	−03 56 53.3	273.077621	+55.023043		PG	1142–037	EPIC	201206621	sdBV$_s$ + WD?
12 44 20.24	−08 40 16.8	299.934029	+54.159064	HW Vir (BD −07° 3477)	PG	1241–084	TIC	156618553	sdBV$_{(sr)}$
13 17 39.21	−12 32 52.4	312.874993	+49.817059		PG	1315–123	EPIC	212508753	sdBV$_{(rs)}$ + F
13 27 48.56	+09 54 51.0	331.134760	+70.767330	QQ Vir	PG	1325 + 102	TIC	404505165	sdBV$_r$
13 38 48.15	−02 01 49.2	326.172422	+58.687745	NY Vir	PG	1336–018	TIC	175402069	sdBV$_r$ (EB)
13 40 08.83	+47 51 51.9	101.523443	+67.188615	SDSS J134008.83 + 475151.8	PG	1338 + 481	TIC	458452988	sdBV$_s$
13 55 44.72	−08 03 54.5	329.072625	+51.512995	SDSS J135544.71–080354.3			EPIC	212707862	sdBV$_s$
14 05 33.00	−27 01 34.1	322.655708	+32.991261	V361 Hya	EC	14026–2647	TIC	60793020	sdBV$_r$
16 08 03.69	+07 04 28.7	018.992818	+39.329833	V338 Ser	PG	1605 + 072	TIC	291032641	sdBV$_r$
16 19 26.60	+56 05 58.6	085.877991	+43.162539	SDSS J161926.58 + 560558.6	PG	1618 + 563B	TIC	207440585	sdBV$_r$
16 29 35.30	+01 38 18.8	016.572779	+31.949416	V2579 Oph	PG	1627 + 017	TIC	281269725	sdBV$_s$ + WD
16 49 56.23	−24 17 34.4	356.694762	+12.861245				EPIC	203948264	sdBV$_s$
17 17 22.06	+58 05 58.7	086.623052	+35.084435	V366 Dra			TIC	198412771	sdBV$_r$
17 18 03.86	+42 34 12.6	067.678153	+34.623301	V1093 Her	PG	1716 + 426	TIC	334901449	sdBV$_s$
18 24 52.41	+57 47 23.5	086.788792	+26.146641	LS Dra			TIC	353735596	sdBV$_r$
18 56 07.04	+43 19 19.3	073.257018	+17.435408				KIC	07664467	sdBV$_{(sr)}$ + WD?
19 02 21.94	+48 50 52.2	079.089792	+18.386459				KIC	11179657	sdBV$_s$ + M
19 03 37.03	+38 36 12.6	069.278167	+14.333026	SDSS J190337.02 + 383612.6			KIC	03527751	sdBV$_{sr}$
19 05 06.38	+43 18 31.2	073.878723	+15.912657				KIC	07668647	sdBV$_s$
19 09 07.15	+37 56 14.2	069.101928	+13.075789	SDSS J190907.14 + 375614.2			KIC	02697388	sdBV$_{(sr)}$
19 09 33.41	+46 59 04.1	077.730419	+16.585795				KIC	10001893	sdBV$_{(sr)}$
19 24 58.15	+47 07 53.7	078.954543	+14.236736				KIC	10139564	sdBV$_r$
19 26 34.11	+49 30 29.6	081.302431	+14.983279				KIC	11558725	sdBV$_s$
19 27 09.15	+38 10 26.4	070.883271	+09.975824	SDSS J192709.14 + 381026.3			KIC	02991276	sdBV$_{(sr)}$
19 27 15.88	+38 08 08.3	070.858605	+09.938826	SDSS J192715.88 + 380808.2			KIC	02991403	sdBV$_s$ + M
19 31 03.38	+44 13 25.5	076.730534	+12.024358				KIC	08302197	sdBV$_s$ + M?
19 32 14.81	+27 58 35.4	062.285531	+04.283443	V2214 Cyg	KPD	1930 + 2752	KIC	284692897	sdBV$_r$ + WD
19 34 39.94	+47 58 11.5	080.456691	+13.119129				KIC	10670103	sdBV$_{(sr)}$
19 38 28.03	+58 24 15.8	090.483610	+17.060368				TIC	1883989109	sdBV$_r$
19 38 32.61	+46 03 59.1	079.018765	+11.674294	2M 1938 + 4603			KIC	9472174	sdBV$_{(sr)}$ (EB)
19 45 25.47	+41 05 33.9	075.161197	+08.231124		KPD	1943 + 4058	KIC	5807616	sdBV$_{(sr)}$
19 53 08.39	+47 43 00.2	081.700956	+10.258111				KIC	10553698	sdBV$_s$ + WD
20 15 04.79	−40 05 44.1	000.805816	−32.457367	V4640 Sgr (CD −40°13747)	EC	20117–4014	TIC	355058528	sdBV$_r$
21 53 41.25	−70 04 31.4	321.130100	−40.184030	EC 21494–7018			TIC	278659026	sdBV$_s$
23 19 24.43	−08 52 37.9	068.617247	−61.611625	GD 1110 (PHL 457)			TIC	49590066	sdBV$_s$ + M
23 34 34.63	−01 19 36.9	084.174720	−58.292251	EQ Psc (PB 5450)			KIC	060018081	sdBV$_s$ + M
23 44 22.01	−34 27 00.4	001.845773	−73.871649	CD −35° 15910 (SB 815)			TIC	169285097	sdBV$_{(sr)}$

DW Lyn stars. Similarly, some p-mode pulsators have been identified as "sdBV$_{(rs)}$" because they are found to have weak g-modes in their power spectra. A qualifying upper case letter or "WD" was used to indicate an approximate companion spectral type and "(EB)" to indicate that the pulsating sdB star resides in an eclipsing binary.

2 MULTI-SITE AND WHOLE EARTH TELESCOPE OBSERVATIONS

Koen et al. (1998) identify V338 Ser (PG 1605 + 072) as an apparently single V361 Hya star with low surface gravity (log$g$) and high amplitude pulsation frequencies; these and the comparatively long period of the dominant frequency (480 s), when compared with other V361 Hya stars known at the time, made it the first V361 Hya candidate for a multi-site campaign. Kilkenny et al. (1999) observe V338 Ser over a 2 week period from five sites, well distributed in longitude, and obtain ~ 180 hours of useable photometry. Twenty frequencies are found to agree with those Koen et al. find if possible aliases of up to three-cycles per day are taken into account; these and pulsation amplitude changes emphasise the importance of multi-site observations and for the need to repeat V361 Hya star monitoring at a sequence of epochs.

O'Toole et al. (2005), Tillich et al. (2007) conduct further multi-site campaigns on V338 Ser, involving photometry and contemporaneous spectroscopy. Line profile variations are detected and measured in about 9,000 spectra from which T_{eff} and log$g$ are determined by quantitative spectral analysis based on model stellar atmospheres and line formation calculations, made assuming a static atmosphere. T_{eff} and log$g$ are obtained for eight modes with semi-amplitudes ranging from ΔT_{eff} = 880 K to as little as ΔT_{eff} = 88 K, and Δlog$g$ = 0.08 dex to as low as Δlog$g$ = 0.008 dex. Gravity and temperature vary almost in phase, whereas phase lags are found between temperature and radial velocity.

UY Sex (PG 1047 + 003) is another apparently single V361 Hya star (Billères et al., 1997; O'Donoghue et al., 1998) for which Kilkenny et al. (2002) conduct a multi-site photometric campaign over a two-week period and obtain ~ 98 hours of useful data. Eighteen frequencies are recovered with some evidence of 1 day aliasing in frequencies which the discovery data (Billères et al., 1997; O'Donoghue et al., 1998) identify, again demonstrating the value of multi-site observations which allow monitoring over an extended period. Kilkenny et al. note that four pairs of the frequencies they identify are closely spaced, separated on average by 1.05 μHz which would correspond to a rotation period of about 11.0 days; this could be the first indication that V361 Hya stars are slow rotators.

NY Vir (PG 1336–018) is a very short-period (0.101 days) eclipsing binary with a V361 Hya star primary, the secondary being a late-type dwarf of type ~ M5 (Kilkenny et al., 1998). NY Vir was arguably one of the more important V361 Hya stars to have been discovered because stellar parameters inferred from an asteroseismic analysis could be directly compared with those from analyses of light and radial velocity curves, although in this case pulsation frequency aliasing is provided by the orbital period. Kilkenny et al. (2003) therefore observe NY Vir with WET, obtaining photometry over ~172 hours; they find substantial pulsation frequency changes to have occurred since discovery with amplitude changes occurring, at least in the dominant three frequencies, on a time-scale of order one day. Power spectra based on data obtained during eclipses to eliminate aliases these cause, recover the three main pulsation frequencies although these are not adequate for mode identification. An eclipse mapping application by Reed (2006) for NY Vir, based on WET data, attempts pulsation mode identification with the pulsation axis assumed to lie in the direction of the companion, but $\simeq$20 low amplitude frequencies remain unidentified.

QQ Vir (PG 1325 + 101) is seen (Silvotti et al., 2002) to be a particularly interesting V361 Hya star having large pulsation amplitudes and showing an harmonic of the main pulsation frequency; 215 hours of multi-site photometry are obtained by Silvotti et al. (2006) and fifteen pulsation frequencies identified. Charpinet et al. (2006) use the Silvotti et al. observations for an asteroseismic study; observed periods correspond to low order acoustic modes, defining a band of unstable modes in agreement with non-adiabatic pulsation theory. The hydrogen envelope mass is found to be $10^{-4.18 \pm 0.1}$ of the stellar mass of $0.50 \pm 0.01 M_{\odot}$. The rotation period is 1.6 ± 0.2 days which makes QQ Vir a slow rotator.

Multi-site campaigns are carried out for PG 1618 + 563B and PG 0048 + 091, two V361 Hya class sdB pulsators, from which Reed et al. (2007) present interesting results for both stars. Some observations of PG 1618 + 563B show a small number of stable (in amplitude) frequencies with a closely spaced pair, as would be typical for a V361 Hya star. In contrast, other data show PG 1618 + 563B to be a complex pulsator with four "regions" of power showing amplitude and phase variability; it is an obvious target for further observation, over a longer time-interval, with the view to examining its long-term frequency stability.

Reed et al. (2007) find PG 0048 + 091 to be a more complex pulsator than PG 1618 + 563B as it shows wildly variable amplitudes, while from discovery observations Koen et al. (2004) find stable pulsation amplitudes. Although an extremely rich pulsator with at least twenty-eight independent frequencies, many modes are only occasionally excited to amplitudes above the noise, often for very short lengths of time. Stochastically excited oscillations are inferred although these are not expected in a V361 Hya star where pulsations are understood to be driven by the κ-mechanism as described above.

In a later paper, Reed et al. (2012) report multi-site observations of EC 01541–1409; it turns out to be similar to PG 0048 + 091 in that both stars oscillate over a large frequency range. Thirty-four pulsation frequencies are identified in the case of EC 01541–1409, most of which are unstable in amplitude or phase. EC 01541–1409 differs from PG 0048 + 091 in that it has one high-amplitude phase-stable oscillation and, as the other frequencies are less variable in phase, stochastic excitation is not inferred in this case.

Billéres et al. (2000) find forty-four oscillations in the light curve of V2214 Cyg (KPD 1930 + 2752); it therefore has a rich frequency spectrum similar to those subsequently found in the cases of PG 0048 + 091 and EC 01541–1409 discussed above. V2214 Cyg is also found to be an ellipsoidal variable having a white dwarf as a binary companion, the binary period being 2.3 hours. Maxted et al. (2000) stimulate further interest in the system; their spectra suggest a total mass for the system of $1.47 M_{\odot}$, if the sdB star has the canonical $0.5 M_{\odot}$, making it a candidate Type Ia Supernova Progenitor as gravitational radiation will eventually result in binary component merger.

Reed et al. (2011b) report photometric observations of V2214 Cyg they make during 2003 with WET, and a smaller multisite campaign made in 2002. Sixty-eight pulsation frequencies are found in 355 hours of WET data, these showing many of the stochastic characteristics seen in PG 0048 + 091. Amplitude variations are compared with simulated stochastic data, and the binary nature of V2214 Cyg used for identifying pulsation modes using multiplet structure and a tidally induced pulsation geometry. Results suggest a complicated pulsation structure which includes a sixteen-hour amplitude variability, rotationally split and tidally induced modes, as well as some pulsations which are geometrically limited to the sdB star. Satellite observations of V2214 Cyg would have provided further insight but it lies just outside the Kepler field.

Vučković et al. (2006) highlight the pulsating sdB star EK Psc (PG 0014 + 067) as a promising candidate for a future seismic analysis, as it has a rich pulsation spectrum. As the frequency spectrum is too complex to be explained with low-degree ($\ell < 3$) p-modes without rotational splittings, a fundamental challenge to understanding its pulsation was immediately obvious. While assigning a high degree ($\ell \geq 3$) to some modes remains a possibilty, theoretical models (Kawaler and Hostler, 2005) suggest that sdB stars may retain rapidly rotating cores, resulting in the presence a few rotationally split triplet ($\ell = 1$) and quintuplet ($\ell = 2$) modes, along with radial ($\ell = 0$) p-modes. The need for a better frequency resolution to help distinguish among possible pulsation models persuades Vučković et al. to obtain WET observations of EK Psc; they find frequencies which do not appear to fit any theoretical model then available although they suggest a simple empirical relation which does match all well-determined frequencies in this star.

Baran et al. (2009) present results from a multi-site photometric campaign on the prototype hybrid sdB pulsator DW Lyn (Balloon 090100001) noted above. Forty-eight nights of data give a temporal resolution of 0.36 μHz, with a detection threshold of about 0.2 mmag in a B-filter; the subsequent analysis finds 114 frequencies, of these ninety-seven are independent and seventeen are combinations. Most of the twenty-four g-mode frequencies lie between 0.1 and 0.4 mHz; the remainder (presumably p-modes) are in four distinct groups near 2.8, 3.8, 4.7, and 5.5 mHz. The density of frequencies requires some modes to have $\ell > 2$.

Modes in the 2.8 mHz region found by Baran et al. (2009) have the largest amplitudes, the strongest is understood to be a radial mode while others in this region form two nearly symmetric multiplets: a triplet and quintuplet with rotational splitting. Splitting in both multiplets increases by $\sim 15\%$ between 2004 and 2005, implying a rotation rate dependent on latitude and highest on the equator. Torsional oscillations seem to be the only plausible explanation, though this needs to be verified by modelling. The amplitudes of almost all modes are found to vary, even within a single season.

In the case of V1093 Her stars, longer periods mean that any ground-based observations must almost necessarily be multi-site if a sufficient number of pulsation cycles are to be observed to allow a periodogram analysis. Among the V1093 Her stars, Randall et al. (2006a), Randall et al. (2006b) select V2579 Oph (PG 1627 + 017) and PG 1338 + 481 for their campaigns. V2579 Oph is a binary, the companion understood to be a white dwarf, with an orbital period ~0.83 days; Randall et al. (2006a) select it because it is relatively bright (V = 12.9), has a large pulsation amplitude and can be observed from either hemisphere. By contrast, Randall et al. (2006b) select PG 1338 + 481 for their second campaign because it is a more typical V1093 Her star understood, from spectroscopy, to be a single star.

Randall et al. (2006a) extract twenty-three pulsation frequencies for V2579 Oph, with periods between 4500 and 9,000 s, from 300 hours of useful R-band and fifty hours of simultaneous U/R differential photometry. Rotation synchronous with the binary orbit is understood to produce splitting in the highest amplitude frequencies which cluster in the period range 6300–7050 seconds. Nonadiabatic pulsation models reproduce V2579 Oph pulsation frequencies for $\ell = 2, 3$ or 4 if T_{eff} is near the lower bound its error bars indicate. But period spacing, rotational splitting and U/R photometry suggest $\ell = 1$ for at least the four highest amplitude peaks in the power spectrum, suggesting non-adiabatic effects as not being fully accounted for in adopted pulsation models.

Seven continuous weeks of observing PG 1338 + 481 at Mount Bigelow and Kitt Peak provide Randall et al. (2006b) ~250 hours of simultaneous U/R time-series photometry, as well as a further ~70 hours of R-band only data. Thirteen frequencies are extracted in the 2100–7200 second range, with amplitudes up to $\sim 0.3\%$ and $\sim 0.2\%$ in U and R respectively. An amplitude ratio comparison in the two wave-bands with those predicted by non-adiabatic pulsation theory suggests the presence of dipole modes, consistent with the highest amplitude peak period spacing. Randall et al. fix T_{eff} and $\log g$ to the spectroscopic estimates and isolate a family of optimal models reproducing measured periods to better than 1%. Preliminary stellar parameters inferred include an uncharacteristically high mass of $0.616 M_{\odot}$ and a thicker residual hydrogen envelope than those found in V361 Hya stars; this latter result is not surprising and is predicted for cooler sdB stars.

I have summarised sdB star WET and multi-site campaigns that I am aware of. Of particular note was the selection of PG 1618 + 563B, PG 0048 + 091, EC 01541–1409, V2214 Cyg, EK Psc and DW Lyn as targets for multi-site and WET observing programmes. In each case, I understood selection to have been based in part on the target being known beforehand to have a "rich pulsation spectrum", providing the hope that higher frequency resolution achievable through multi-site and WET observations would provide a high quality power spectrum from which a definitive asteroseismic analysis could follow. WET and multi-site observations showed, however, for each target in turn, that V361 Hya and DW Lyn star power spectra are highly variable and that asteroseismic analyses will be much more challenging than originally supposed.

3 MOST AND COROT OBSERVATIONS

Randall et al. (2005b) pioneer the use of spacecraft to obtain high-precision photometry of sdB stars; they monitor Feige 11 (PG

0101 + 039) for ~400 hours with the MOST Satellite (Walker et al., 2003) and identify periods of 7235, 5227, and 2650 seconds. Pulsation amplitudes which Randall et al. find are between 0.03 and 0.06% of the mean brightness, an observation which would be challenging for ground-based observers. The detection of pulsations in Feige 11 meant that the theoretical instability strip blue-edge for V1093 Her stars, as it was then understood, had to lie at higher effective temperatures as Jeffery and Saio (2006) subsequently demonstrate.

Three frequencies are, however, insufficient for a thorough asteroseismic analyis and Charpinet et al. (2010) circumvent this limitation by using CoRoT to identify seventeen pulsation frequencies in KPD 0629–0016. Longer period g-modes in sdB pulsators penetrate the deeper stellar interior, as far as the core, and asteroseismic analyses potentially reveal core masses and compositions. Van Grootel et al. (2010b) perform the second (the first being described below) asteroseismic analyses of a g-mode sdB pulsator using Charpinet et al. observations of KPD 0629–0016; they derive a core-mass and composition corresponding to an age of 42.6 ± 1.0 Myr relative to the Zero Age Horizontal Branch (ZAHB).

4 KEPLER OBSERVATIONS

Given the success of asteroseismic observations of pulsating sdB stars with multi-site ground based facilities and spacecraft, the launch of the Kepler satellite was accompanied with an understanding that further advances were about to be achieved. Østensen et al. (2010b) present results from the first two quarters of the Kepler survey, identifying nine sdB pulsators of which one is a V361 Hya star, another a DW Lyn star and seven V1093 Her stars. Below the $T_{\rm eff}$ boundary region where DW Lyn stars are found, all sdB targets are found to pulsate; with only a fraction (< 10%) of sdB stars with higher $T_{\rm eff}$ being pulsators. Østensen et al. also note that the V361 Hya pulsator (KIC 10139564) shows a low-amplitude mode in the long-period region, while several V1093 Her pulsators show low-amplitude modes in the short period region; this suggests that hybrid behaviour may be a common feature observable in many if not all sdB star pulsators.

The identification of KIC 10139564 as the only V361 Hya pulsator, among a sample of hot subdwarfs in the Kepler field, prompts Kawaler et al. (2010b) to present a more detailed analyis of the 30.5 days of nearly continuous time-series photometry they obtain with the Kepler spacecraft. Most of the ten independent pulsation frequencies they identify appear to be stable in phase and amplitude, providing an initial estimate for the rotation period of 2–3 weeks. With a further fifteen months of Kepler photometry, Baran et al. (2012) detect fifty-seven periodicities including several multiplets they attribute to stellar rotation, indicating a rotation period of 25.6 ± 1.8 days for KIC 10139564. A further interesting result (Baran and Østensen, 2013) is that two regions of the KIC 10139564 amplitude spectrum contain modes of degree $\ell = 3$ and $\ell = 4$. Based on thirty-eight months of almost continuous Kepler photometry of KIC 10139564, Zong et al. (2016) identify frequency and amplitude modulations as a first signature of non-linear resonant coupling occurring in V361 Hya stars which appear to follow more complicated patterns than simple predictions from current non-linear theory.

Reed et al. (2010) provide more details on the discovery of non-radial pulsations in five apparently single V1093 Her stars, based on 27 days of nearly continuous Kepler satellite photometry which Østensen et al. (2010b) report. Every sdB star cooler than $T_{\rm eff} \leq 27500$ K observed by Kepler (seven at that time) is found to be a V1093 Her or a DW Lyn pulsator. Periods range from 1 to 4.5 hours and are associated with g-mode pulsations. Three stars (KIC 02697388, KIC 03527751 and KPD 1943 + 4058 (KIC 05807616)) also exhibit short 2–5 min periods indicative of p-modes, as well as periods of 15–45 min, intermediate between the two classes. Reed et al. also find KIC 10670103 to be the longest-period V1093 Her star known and to have the lowest $T_{\rm eff}$ of 20900 K. Equally remarkable is KIC 02697388, a suspected hybrid pulsator, for which $T_{\rm eff} = 23900$ K; this turns out to have g-modes with amplitudes larger than those of its p-modes.

KPD 1943 + 4058 is one of three V1093 Her stars in which Reed et al. (2010) identify at least one short-period oscillation. Van Grootel et al. (2010a) retain eighteen pulsations in early Kepler data for their analysis, identifying these as low-degree ($\ell = 1$ and 2) intermediate-order (k = −9 through −58) g-modes. Pulsation models reproduce observed frequencies at the 0.22% level, comparable with the best results achieved in analyses of p-mode V361 Hya pulsators. Structural parameters Van Grootel et al. infer are: the sdB star mass $M = 0.496 \pm 0.002 M_\odot$, the mass of the residaul hydrogen envelope $\log(M_{env}/M) = -2.55 \pm 0.07$, the mass of the carbon-oxygen (C + O) core $\log(1 - M_{\rm core}/M) = -0.37 \pm 0.01$, and the core mass fraction $X_{\rm core}(C + O) = 0.261 \pm 0.008$; relative to the ZAHB, these correspond to an age of 18.4 ± 1.0 Myr. The Van Grootel et al. results suggest overshooting as an important process shaping the helium burning core. Further consideration of convective overshooting beyond the boundary of the helium core is discussed further below in the context of confirmed mode trapping in KIC 10553698A.

Charpinet et al. (2011a) find two very weak modulations in the low frequency range of the KPD 1943 + 4058 *Kepler* power spectrum which Van Grootel et al. use. The timescales involved are 5.7625 ± 0.0001 hours (F_1, with an amplitude of 52 ± 6 parts per million) and 8.2293 ± 0.0003 hours (F_2, with an amplitude of ~ 47 parts per million). Phase folding shows F_1 and F_2 to repeat at coherent phases throughout the entire light curve; Charpinet et al. therefore interpret these to be orbital periods of two planets orbiting KPD 1943 + 4058 at distances of 0.0060 and 0.0076 AU. The two orbiting bodies must have survived deep immersion in the envelope of any former red giant progenitor, and Charpinet et al. suggest that they could be residual dense cores of evaporated giant planets that became closer to the star during the red giant expansion phase, triggering the mass-loss necessary for sdB star formation.

KIC 02697388 is another of the V1093 Her stars in which Reed et al. (2010) identify at least one short-period oscillation and for which Charpinet et al. (2011b) make an asteroseismic analysis, following the approach Van Grootel et al. (2010a) adopt in the case of KPD 1943 + 4058. New high signal-to-noise spectra of KIC 02697388 are obtained and fitted using appropriate non-LTE model atmosphere and line-formation calculations to derive $T_{\rm eff} = 25395 \pm 227$ K, $\log g = 5.500 \pm 0.031$ and $\log N(\mathrm{He})/\mathrm{N}(\mathrm{H}) = -2.767 \pm 0.122$. Forty-three frequencies are identified in the early *Kepler* light curve, all modulations corresponding to g-mode pulsations except one high-frequency signal, typical of a p-mode oscillation. Although the presence of a p-mode is surprising considering atmospheric parameters they derive, Charpinet et al. show that it is particularly well accounted for by optimal seismic models, both in terms of frequency match and nonadiabatic properties. The seismic analysis leads to two model solutions which account for observed pulsation properties of KIC 02697388 and correspond to structural parameters similar to those Van Grootel et al. find for KPD 1943 + 4058.

Using data from the first two quarters of the *Kepler* satellite mission, Kawaler et al. (2010a) analyse two V1093 Her stars (KIC 02991403 and KIC 11179657) found to be g-mode pulsators; these also display the distinct irradiation (reflection) effect typical of sdB stars in short-period binaries with a close M-dwarf companion. Tidal locking has frequently been assumed for sdB binaries with periods less than 0.5 days and, if this has occurred, the sdB star should rotate synchronously with the orbital motion. However, Preece et al. (2018) find synchronisation time-scales to be longer than sdB lifetimes in all cases. In power spectra for KIC 02991403 and KIC 11179657 based on early *Kepler* data, Kawaler et al. find no clear evidence of the rotational splitting that would be expected if the sdB star rotation had become synchronised with orbital motion. With later *Kepler* data, obtained between 2010 March and 2011 March, Pablo et al. (2012) obtain further seismic evidence for non-synchronisation of sdB star rotation in both KIC 02991403 and KIC 11179657, strongly supporting the Kawaler et al. conclusion.

Østensen et al. (2011) identify five V1093 Her pulsators (KIC 07668647, KIC 08302197, KIC 10001893, KIC 10553698, KIC 11558725) in the second half of the *Kepler* survey phase; they also find and list (their table 7) fourteen binaries and other long-period variables which have a hot subdwarf or white dwarf as a component. Baran et al. (2011) perform time-series analyses for the five V1093 Her pulsators Østensen et al. identify, using the nearly continuous month-long *Kepler* data sets they obtain in Q3 and Q4; these data sets provide nearly alias-free photometry at unprecedented precision. Frequencies and amplitudes turn out to be typical of g-mode pulsators of the V1093 Her type, with no evidence of binarity being seen in their pulsation frequencies. Average period spacings may indicate $\ell = 1$ and $\ell = 2$ modes and possible evidence of rotational splitting needs further investigation.

Reed et al. (2011a) investigate period spacing in twelve V1093 Her stars (KIC 02991403, KIC 03527751, KIC 05807616, KPD 1943 + 4058 (KIC 05807616), KIC 07664467, KIC 07668647, KIC 08302197, KIC 09472174, KIC 10001893, KIC 10553698, KIC 10670103, KIC 11179657, KIC 11558725) and one possible DW Lyn star (KIC 02697388) they observe with the *Kepler* satellite as already referenced (Østensen et al., 2010b); in addition, they include KPD 0629–016 which Charpinet et al. (2010) observe with CoRoT. Relationships between equal-period spacings of modes with differing degrees ℓ, and periods of the same radial order n but differing degrees ℓ, are provided by asymptotic limits for g-mode pulsations; Reed et al. use these to associate observed periods of variability with pulsation modes for $\ell = 1$ and 2. A $\ell = 1$ or $\ell = 2$ constant period spacing is detected at a confidence of 95% or better for all stars except in the cases of KIC 09472174, where the power spectrum is complicated by the presence of a binary companion, and KPD 1943 + 4058 for which more subtle mode trapping in the model may be needed.

2M 1938 + 4603 (KIC 09472174) is an eclipsing binary consisting of a pulsating V1093 Her star and a cool M-dwarf companion in an effectively circular three-hour orbit; it attracts attention (Østensen et al., 2010a; Barlow et al., 2012; Baran et al., 2015b) for the same reason as NY Vir as it allows a direct comparison between asteroseismic and orbital solutions. The *Kepler* satellite light curve is dominated by a strong reflection effect. Østensen et al. (2010a) use a phase-folded *Kepler* light curve to detrend orbital effects, obtaining an amplitude spectrum of the residual light curve which reveals a rich collection of pulsation peaks spanning frequencies from ∼ 50 to ∼4500 μHz. Østensen et al. present a first analysis based on the 9.7 days commissioning light curve, augmented by ground-based photometry and spectroscopy, allowing them to derive a radial-velocity amplitude $K_1 = 65.7 \pm 0.6\,\mathrm{km s^{-1}}$, an inclination angle $i = 69^{\rm o}.45 \pm 0.20$, and component masses of $M_1 = 0.48 \pm 0.03 M_\odot$ and $M_2 = 0.12 \pm 0.01 M_\odot$ for the hot subdwarf and M dwarf respectively.

With six months of publicly available *Kepler* photometry obtained in short-cadence mode, Barlow et al. (2012) measure centroid times of primary and secondary eclipse by fitting model profiles. On average, secondary eclipses are found to occur 2.06 ± 0.12 s after the midpoint between primary eclipses, which Barlow et al. interpret as a Rømer delay; that is, the delay resulting from the light-travel-time across the binary orbit projected on to an observer's line-of-sight. Assuming circular orbits about the binary centre-of-mass, the time delay corresponds to a mass ratio $q = 0.2691 \pm 0.0018$ and individual masses of $M_1 = 0.372 \pm 0.024 M_\odot$ $M_2 = 0.1002 \pm 0.0065 M_\odot$. A very small orbital eccentricity of $e\cos\omega \simeq 0.00004$ allows Barlow et al. to reconcile their masses with those of Østensen et al. (2010a).

Thirty-seven months of 2M 1938 + 4603 *Kepler* photometry are analysed by Baran et al. (2015b). Eclipse timings from more than 16,000 primary and secondary eclipses exhibit a variation which can be fitted by one or more sinusoids, once orbital motion effects are removed, a periodic variation in the timing signal ascribed to at least one circumbinary body in the system. Upon the assumption that the third body is orbiting in the same plane as the binary, Baran et al. establish that it must be a Jupiter-mass object orbiting with a period of 416 days at a distance of 0.92 AU.

Østensen et al. (2014a) identify two clearly detected pulsation modes with periods of 122 and 132 seconds, as well as a few weaker modes with periods ranging from 118 to 216 seconds, in nearly 3 years of *Kepler* spacecraft photometry of the sdB star KIC 02991276. Unlike other sdB pulsators with similar high-quality *Kepler* light curves, the KIC 02991276 modes do not display long-term coherency; pulsation frequencies vary substantially in amplitude and phase on timescales of about a month, sometimes disappearing completely. Such stochastic oscillations have been suspected for V361 Hya pulsators, as Reed et al. (2007) infer in the case of PG 0048 + 091, but only with the exceptional coverage of *Kepler* data are Østensen et al. able to unambiguously establish stochastic oscillations in KIC 02991276.

Kepler satellite photometric monitoring of KIC 10553698 continued with a one-minute sampling rate for most of the mission; these results, and radial velocity variations from ground-based spectroscopy are perfectly consistent with a Doppler-beaming effect and lead Østensen et al. (2014b) to conclude that it is a spectroscopic binary with an orbital period of 3.387 days. Østensen et al. introduce the names KIC 10553698A to refer to the V1093 Her component, and KIC 10553698B to refer the $\sim 0.6 M_{\odot}$ white dwarf companion. Like most V1093 Her pulsators, KIC 10553698A displays a rich g-mode pulsation spectrum with several clear $\ell = 1$ and $\ell = 2$ multiplets that maintain a regular frequency splitting; identifying these as being due to rotation, gives a period of ~41 days, which is very much less than the binary orbital period. The detection of $\ell = 1$ modes in KIC 10553698A that interpose in the asymptotic period sequences, and provide a clear indication of mode trapping in a stratified envelope, as predicted by theoretical models, is reported by Østensen et al. for a hot subdwarf for the first time.

Ghasemi et al. (2017) note that the seismic properties of KIC 10553698A provide a test of stellar evolution models, and offer a unique opportunity to determine mixing processes. Mixing due to convective overshooting beyond the boundary of the helium burning core is considered. Chemical stratifications induced by convective shells are found to change the g-mode period spacing pattern of a sdB star appreciably, a model with moderate and small core overshooting being fully consistent with period-spacing and mode trapping Østensen et al. (2014b) observe in KIC 10553698A. Models which include small or very small overshooting with atomic diffusion lead to a decreased extreme horizontal branch lifetime and produce chemical stratification induced by convective shells during the helium burning phase.

Guo and Li (2018) argue that predicted mode trapping in V1093 Her stars is stronger than observed, although the mode trapping efficiency could be reduced by taking diffusion into account. The Helium Flash at the end of Red Giant Branch evolution causes extensive convection that extends very close to the He/H transition zone. Detailed model calculations by Guo and Li show that the mode trapping efficiency could be reduced to approximately the level observed over the whole period range, if the Helium Flash overshoot is taken into account.

Spectroscopic observations of KIC 07664467 by Baran et al. (2016), coupled with Q 5–11 and Q 13–17 *Kepler* satellite photometry to complement earlier observations which Østensen et al. (2011) report, show it to reside in a 1.56-day orbital period binary. A radial velocity amplitude of $K_1 = 57 \pm 3\,\mathrm{km s^{-1}}$ and the Doppler boosting-dominated photometric signal at the orbital period, led Baran et al. to identify the companion as a compact object, almost certainly a white dwarf. An analysis of the amplitude spectrum led to the detection of sixty-one periods, rotationally split multiplets, and an equally spaced sequence in period to facilitate mode identification. Baran et al. derive a rotation period of 35.1 ± 0.6 days for the V1093 Her pulsator, showing this to be another binary system with a subsynchronous sdB star. Spectroscopy of the sdB star gives $T_{\mathrm{eff}} = 27440 \pm 120\,\mathrm{K}$ and $\log g = 5.38 \pm 0.02$ dex with abundances following the general sdB pattern: light metals are subsolar and the iron abundance close to the solar value. Nitrogen enrichment and low carbon and oxygen abundances, resembling the CNO cycle equilibrium, are also found.

Observations over 2.75 years by the *Kepler* spacecraft of the pulsating sdB star KIC 10670103 yield 1.4 million measurements, corresponding to an impressive duty cycle of 93.8%, a frequency resolution of 0.017 μHz, and a 5σ detection limit of 0.1 parts-per-thousand (ppt). KIC 10670103 turns out to be the richest pulsating sdB star hitherto observed as Reed et al. (2014) detect 278 periodicities with frequencies ranging from 23 to 673 μHz (0.4 and 11.8 h) and amplitudes from the detection limit up to 14 ppt. Pulsation modes are identified using asymptotic period spacings and frequency multiplets which indicate a spin period of 88 ± 8 days. Of the 278 periodicities detected in KIC 10670103, Reed et al. associate 163 with low-degree ($\ell \leq 2$) pulsation modes; using these they make detailed examinations of the pulsation structure, including where the pulsation power is concentrated in radial order, over what frequency range mode trapping is inefficient, and how power switches between multiplet members. Amplitudes (and some frequencies) are not stable over the 2.75 years during which *Kepler* satellite photometry was obtained. Reed et al. also obtain follow-up spectroscopic data from which they determine that KIC 10670103 does not show significant radial velocity variations. Updated model stellar atmosphere and line formation calculations give $T_{\mathrm{eff}} = 21485 \pm 540\,\mathrm{K}$, $\log g = 5.14 \pm 0.05$ and $\log N(\mathrm{He})/N(\mathrm{H}) = -2.60 \pm 0.04$.

KIC 02697388 is a suspected hybrid (DW Lyn) pulsator with a remarkably low $T_{\mathrm{eff}} \simeq 23900\,\mathrm{K}$ (Reed et al., 2010). Kern et al. (2017) analyse 3 years of *Kepler* spacecraft short-cadence data and obtain twenty-one low-resolution spectra of KIC 02697388 giving a radial-velocity scatter of $9.5\,\mathrm{km s^{-1}}$ which, while too large to completely rule out binarity, does rule out short-period, low-inclination orbits for KIC 02697388 and any companion. From short-cadence *Kepler* data, 253 periodicities are detected, most with periods from 1 to 2.5 hours, which Kern *et al.* associate with g-mode pulsations; in addition. twenty-three periods are also detected in the short-period p-mode region. Mode identifications are made for 89% of the periodicities, most being of low degree ($\ell \leq 2$), but forty-two are identified as $\ell \geq 3$. Frequency multiplets correspond to a rotation period for the star of ~42 days. A unique feature is seen in KIC 02697388 data: in all $\ell \geq 2$ multiplets, the splittings decrease over time. If the trend continues, $\ell \geq 2$ multiplets would become singlets within a decade.

Foster et al. (2015) analyze three years of nearly continuous *Kepler* spacecraft short cadence observations of the pulsating sdB star KIC 03527751 (Østensen et al., 2010b; Reed et al., 2010). A total of 251 periodicities are detected, mostly in the g-mode domain, but also some where p-modes occur, confirming KIC 03527751 is a hybrid (DW Lyn) rather than a V1093 Her pulsator. Asymptotic period spacing relationships, frequency multiplets, and multiplet splitting separations allow 189 of the 251 periods to be associated with pulsation modes; included in these are three sets of $\ell = 4$ multiplets and a possible $\ell = 9$ multiplet. Period spacing sequences indicate respective $\ell = 1$ and 2 overtone spacings of 266.4 ± 0.2 and 153.2 ± 0.2 seconds. Frequency multiplets in the g-mode region, which sample deep into the star, indicate a rotation period of 42.6 ± 3.4 days while p-mode multiplets, which sample the outer envelope, indicate a rotation period of 15.3 ± 0.7 days. Foster et al. therefore report the first example of differential rotation for a sdB star and note that the slower core rotation is contrary to the faster core rotation Kawaler and Hostler (2005) predict.

Mode modulation in amplitude and frequency can be independently inferred by its fine structure in the Fourier spectrum, using a sliding Lomb-Scargle periodogram, or prewhitening methods applied to various parts of the light curve; Zong et al. (2018) apply these techniques to KIC 03527751, a long-period-dominated DW Lyn pulsator already discussed above. All detected modes with amplitudes large enough to be thoroughly studied show amplitude or frequency variations. Three quintuplets around 92, 114, and 253 μHz have components showing signatures that can be linked to non-linear interactions according to the resonant mode coupling theory, an interpretation further supported by many oscillation modes being found to have amplitudes and frequencies showing correlated or anti-correlated variations which may be linked to the amplitude equation formalism, where non-linear frequency corrections are determined by their amplitude variations. The results Zong et al. obtain suggest oscillation modes varying with diverse patterns are a very common phenomenon in pulsating sdB stars and close structures around main frequencies therefore need careful interpretation if a secure identification of real eigenfrequencies (crucial for seismic modeling) is to be obtained.

KIC 07668647 is a V1093 Her pulsator which Østensen et al. (2011) identify in the second half of the *Kepler* survey phase and Reed et al. (2011a) study further, as already reported in the present paper; it has a rich g-mode frequency spectrum, with a few low-amplitude p-modes at short periods, and Telting et al. (2014) therefore make a seismic study aiming to constrain its internal structure, and of sdB stars in general. From the full *Kepler* Q 06–Q 17 light curve, Telting et al. extract 132 significant pulsation frequencies and use period-spacing relations and multiplet splittings to identify the majority of modes. An internal rotation period at the base of the envelope of 46–48 days is derived from g-mode multiplet splittings, while the few p-mode splittings may indicate a slightly longer rotation period further out in the envelope. Mode-visibility considerations lead to an inclination of $\sim 60^{\mathrm{o}}$ for the rotation axis of the sdB in KIC 07668647. Another novelty in sdB-star observations made possible by *Kepler* is found by Telting et al.; there is strong evidence for a few multiplets indicative of degree $3 \leq \ell \leq 8$. With ground-based low-resolution spectroscopy, and the near-continuous 2.88 year *Kepler* light curve, Telting et al. find KIC 07668647 to be in a 14.2 day orbital period binary, the companion being a white dwarf. A radial-velocity amplitude of $39\,\mathrm{km}^{-1}$ is consistently determined from spectra, orbital Doppler beaming seen by *Kepler* at 163 parts per million (ppm), and an orbital light-travel delay of 27 s measured using pulsation timing. From their high signal-to-noise average spectra, Telting et al. find nitrogen and iron have abundances close to solar values, while helium, carbon, oxygen and silicon are under-abundant relative to the solar mixture.

KIC 10001893 is one of nineteen sdB pulsators for which the *Kepler* spacecraft obtained time-series photometry in its primary mission; it is one of the five V1093 Her stars Østensen et al. (2011) identify from the second half of the survey and which Reed et al. (2011a) study further. In the full 993.8 days of *Kepler* photometry, Silvotti et al. (2014) find three weak peaks in the KIC 10001893 power spectrum; these are at very low frequencies and cannot be explained in terms of g-modes. Three Earth-size planets (or planetary remnants) in very tight orbits, illuminated by strong stellar radiation, are understood to provide orbital modulation and cause the low frequency peaks. Orbital periods of $P_1 = 5.273$, $P_2 = 7.807$ and $P_3 = 19.48$ h, and ratios $P_2/P_1 = 1.481$ and $P_3/P_2 = 2.495$ very close to the 3:2 and 5:2 resonances, are inferred. One of the main pulsation modes of the star at 210.68 μHz, corresponding to the third harmonic of the orbital frequency of the inner planet, leads Silvotti et al. to suggest this g-mode pulsation in KIC 10001893 is being tidally excited by a planetary companion. The planets Silvotti et al. find orbiting KIC 10001893 are similar to the two Charpinet et al. (2011a) find orbiting KPD 1943 + 4058.

Uzundag et al. (2017) provide a pulsation mode analysis for KIC 10001893, using the same *Kepler* time-series as Silvotti et al. (2014). The amplitude spectrum shows 104 g-mode frequencies between 102 and 496 μHz, as well as six p-modes above 2000 μHz. An absence of multiplets suggests a pole-on orientation; however, modal degrees and relative radial orders are assigned using asymptotic period spacing leading to the assignment of thirty-two dipole $\ell = 1$ and eighteen quadrupole $\ell = 2$ modes. With almost complete sequences of consecutive radial orders for $\ell = 1$ and 2, Uzundag et al. calculate a reduced-period diagram showing almost perfect alignment of the two sequences and in which trapped modes are clearly visible. A similar pattern is a seen in KIC 10553698A (Østensen et al., 2014b) but with all three trapped modes shifted to slightly higher periods. Mode trapping can be caused by transitions between either He/H at the base of the hydrogen envelope or convective and radiative parts of the core and their location, and particularly the spacing, provides a useful tool with which to examine the stellar interior through comparison with suitable models.

KIC 08302197 is another of the nineteen sdB pulsators for which the *Kepler* spacecraft obtained time-series photometry in its primary mission; it is one of the five V1093 Her stars Østensen et al. (2011) identify from the second half of the survey and which Reed et al. (2011a) study further. Baran et al. (2015a) base their extended analysis on *Kepler* satellite photometry from Q 5 to 17, applying a Fourier technique to extract thirty significant pulsation modes. Mode identification relies entirely on period spacing as no multiplets are found; the implication being that KIC 08302197 has a rotation period of more than 1000 days, or it has a unique (pole-on) orientation of its pulsation axis. In addition Baran et al. make spectroscopic observations and obtain twelve radial-velocity measurements, constraining a possible orbital radial-velocity amplitude to be smaller than $\sim 10\,\mathrm{km s^{-1}}$; furthermore, based on colour indices they constrain a possible companion to be a M or later type Main Sequence star, a compact or a substellar object. From their spectra Baran et al. obtain atmospheric parameters T_{eff} = 27450 ± 200 K, log$g$ = 5.438 ± 0.033 dex and $\log[N(\mathrm{He})/N(\mathrm{H})] = -2.56 \pm 0.07$ and dex for KIC 08302197, consistent with other V1093 Her stars, and abundances for C, N, O, Si and Fe, setting an upper limit for the S abundance.

Krzesinski (2015) takes another look at the Charpinet et al. (2011a) claim to have found two planets orbiting the V1093 Her star KPD 1943 + 4058. *Kepler* data obtained between Q 5 and Q 17 are analysed, giving particular attention to the low frequency 33 – 49 μHz region where Charpinet et al. find their planetary signatures. As amplitude spectra do not show clear multiplets, Krzesinski uses two stable acoustic modes to determine a theoretical width of gravity mode multiplets and their splittings; this then allows period spacing and histograms of common multiplet component separations to be used to identify pulsation modes and observed gravity mode splittings. Analysis of the low frequency region then shows that the amplitude and frequency change of the signals have similar characteristics to other g-modes. Krzesinski then concludes that the existence of two planets orbiting KPD 1943 + 4058, as Charpinet et al. (2011a) claim, must be in doubt because the two planetary signature frequencies could instead be g-mode pulsations.

Blokesz et al. (2019) demonstrate that the use of a comparison star to provide a local determination of the point-spread function, when extracting *Kepler* satellite photometry, can significantly reduce artifacts. It then appears that amplitudes of Fourier transform signals found in the low-frequency regions for KPD 1943 + 4058 (Charpinet et al., 2011a) and KIC 10001893 (Silvotti et al., 2014) depend on methods used to extract *Kepler* data. Based on their simulations, Blokesz et al. conclude that the two low-frequency Fourier transform signals found in KPD 1943 + 4058 are likely to be combined frequencies of lower amplitude pulsating modes of the star. In the case of KIC 10001893, the strongest signal decreases significantly in amplitude when KIC 10001898 is used to define the local point-spread function and the other two frequencies appear to be spurious.

5 K2 OBSERVATIONS

Following the loss of two reaction wheels, the primary mission of the *Kepler* satellite came to an end, though the same hardware is adopted for the K2 Mission as Howell et al. (2014) describe. K2 makes use of an innovative way of operating the spacecraft to observe target fields along the ecliptic; these were to be observed for approximately seventy-five days providing a unique survey to fill the gaps in duration and sensitivity between the *Kepler* and Transiting Exoplanet Survey Satellite (TESS) missions (Ricker et al., 2015). The K2 mission allows different sdB targets to be continuously monitored photometrically for up to 75 days.

Jeffery and Ramsay (2014) report K2 observations of the pulsating sdB star EQ Psc made during engineering tests in 2014 February. In addition to a rich spectrum of g-mode pulsation frequencies, a light variation with a period of 19.2 hours and full amplitude of 2% is detected. Jeffery and Ramsay propose that the latter is due to reflection from a cool companion, making EQ Psc the hitherto longest-period member of some 30 binaries comprising a hot subdwarf and a cool dwarf companion (sdB + dM).

Baran et al. (2019) present an analysis of PHL 457 and EQ Psc, two pulsating sdB stars observed during the K2 mission. Light curves of both stars show variation consistent with a hot subdwarf irradiating a cooler companion in a binary system. Baran et al. obtain new spectroscopic data with which they determine radial velocity, T_{eff}, log$g$, and $N(\mathrm{He})/N(\mathrm{H})$ for both hot subdwarfs as a function of orbital phase. A previously published spectroscopic orbit of PHL 457 (Schaffenroth et al., 2014) is confirmed, and a spectroscopic orbit of EQ Psc presented; the orbital periods are respectively 0.313 and 0.801 days. By means of multiplets and period spacing, Baran et al. classify several pulsation modes in both stars. The g-mode multiplets indicate sub-synchronous core rotation with periods of 4.6 days (PHL 457) and 9.4 days (EQ Psc). While there is no evidence of a cool companion in the spectral energy distribution (SED) of PHL 457, the SED for EQ Psc shows an infrared excess consistent with a secondary having a temperature of about 6800 K and a radius of 0.23 $R_{\odot}$; this is consistent with the correlation between T_{eff} and orbital phase in the case of EQ Psc, due to a contribution of light from the irradiated companion.

PG 0048 + 091 and PG 1315–123 are in binaries with a F-type Main Sequence companion and have amplitude spectra dominated by p-mode pulsations. Reed et al. (2019) present a spectroscopic and seismic analysis for both objects based in part on seventy-nine days of photometry with K2, giving a frequency resolution 0.22 μHz. The presence of g-modes, as well as p-modes, allows an examination of radial rotation profiles. Frequency multiplets indicate that PG 1315–123 rotates uniformly, as a solid body, while PG 0048 + 091 is rotating faster in the outer envelope. Spectroscopy shows both stars to lie at the hot end of the instability region, these high values for T_{eff} challenging pulsation driving theory, which produces g-mode pulsations only at cooler temperatures. Another challenge is the appearance of pulsations with both driven and stochastic properties.

One of the main results of WET observations by Reed et al. (2007), already mentioned above, is the possible detection of stochastic pulsations in PG 0048 + 091. With a longer-duration, evenly sampled, single-instrument K2 data set, Reed et al. (2019) now conclude that most pulsations in PG 0048 + 091 are not stochastic in nature. Amplitude variations of most peaks are too small for the sensitivity Reed et al. (2007) achieve, and peak shapes are dissimilar to those expected from stochastic oscillations. Yet seven of the Reed et al. (2007) frequencies occur in regions Reed et al. (2019) find to have stochastic properties. Variations Reed et al. (2007) observe in other frequencies were almost certainly caused by beating between closely-spaced frequencies in the rich pulsation spectrum.

A multi-site campaign on UY Sex has already been mentioned and Koen et al. (1999) identify V1405 Ori (KUV 0442 + 1,416) as a V361 Hya pulsator. Reed et al. (2020b) process and analyse K2 observations of both UY Sex and V1405 Ori, detecting ninety-seven p-mode pulsations in UY Sex and discover V1405 Ori to be a rare rich hybrid pulsator with over 100 p-mode and nineteen g-mode pulsations. From frequency multiplets, Reed et al. derive an envelope rotation period of 24.6 ± 3.5 days for UY Sex. For V1405 Ori, the p-modes give a rotation period of 0.555 ± 0.029 days, while g-modes provide a marginal determination of 4.2 ± 0.4 days. V1405 Ori is therefore found to be rotating differentially, with the core rotating more slowly than the envelope; it is also a short-period (0.398 days) binary with an envelope that is nearly but not quite tidally locked.

Reed et al. (2018a) report K2 observations during Campaign 5 resulting in the discovery of three pulsating sdB stars in binary systems. EPIC 211696659 (SDSS J083603.98 + 155216.4) is a g-mode pulsator having a white dwarf companion and a binary period of 3.16 days. EPIC 211823779 (SDSS J082003.35 + 173914.2) and EPIC 211938328 (LB 378) are both p-mode pulsators in binaries with Main-Sequence F-type companions. The orbital period of EPIC 211938328 is 635 ± 146 days and Reed et al. note that there are insufficient data to constrain the orbital period of EPIC 211823779. Rotationally induced frequency multiplets indicate all three stars to be slow rotators, with EPIC 211696659 sub-synchronous to its orbit.

A time-series analysis of the 83-day Campaign 2 short-cadence data set from K2 reveals EPIC 203948264 as a hitherto newly discovered V1093 Her star. Ketzer et al. (2017) identify twenty-two independent pulsation periods between 0.5 and 2.8 h in the EPIC 203948264 amplitude spectrum. Most pulsations fit the asymptotic period sequences for $\ell = 1$ or 2, with respective average period spacings of 261.3 ± 1.1 and 151.18 ± 0.37 s. Pulsation amplitudes are below 0.77 ppt and vary over time. Ketzer et al. also detect one possible low-amplitude multiplet, which would correspond to a rotation period of 46 days or longer, implying that EPIC 203948264 is another slowly rotating sdB star. Updated spectroscopic parameters, including atmospheric abundances and radial velocities give no indication that EPIC 203948264 is in a binary system.

Bachulski et al. (2016) present an analysis of K2 observations of the pulsating sdB star EPIC 212707862. Thirteen significant frequencies are detected from eighty-one days of photometric monitoring during Campaign 6. As no multiplets could be identified, it was not possible to derive a rotation period although amplitude modulation allows Bachulski et al. to roughly estimate it to be 80 days. Two period-spacing sequences enable Bachulski et al. to assign $\ell = 1$ modes to six frequencies, and $\ell = 2$ to a further five. Radial velocities and the spectral energy distribution hitherto obtained are consistent with EPIC 212707862 being a single hot subdwarf. From their spectra, Bachulski et al. derive $T_{\rm eff} = 28298 \pm 162$ K, $\log g = 5.479 \pm 0.025$ and $\log[N(\mathrm{He})/N(\mathrm{H})] = -2.752 \pm 0.069$.

PG 1142–037 is a new sdB pulsator which Reed et al. (2016) discover from photometry obtained during the first full-length campaign of K2. Fourteen periodicities are detected between 0.9 and 2.5 h with amplitudes below 0.35 ppt, all of which are associated with low-degree, $\ell \leq 2$ modes. Follow-up spectroscopy shows PG 1142–037 to be in a binary with an orbital period of 0.54 days. Phase-folding the K2 photometry reveals a two-component variation, including both Doppler boosting and ellipsoidal deformation. The detection of an ellipsoidal, tidally distorted variable with no indication of rotationally induced pulsation multiplets is a surprise and suggests a sdB rotation period of longer than 45 days, even though the binary period is found to 0.54 day.

From seventy-four days of K2 photometric monitoring during Campaign 5, Baran et al. (2017) discover EPIC 211779126 to be a rare DW Lyn pulsator, having a rich pulsation spectrum in both the p-mode and g-mode regions. Baran et al. find 154 frequencies in the g-mode region as well as twenty-nine frequencies in the p-mode region; they successfully identify modal degrees and relative radial orders for most g-modes using asymptotic period spacing, and modal degrees for some p-modes on the basis of rotational splitting. An important feature for constraining theoretical models are trapped modes, which Baran et al. also detect. Ground-based spectroscopy reveals no companion, suggesting EPIC 211779126 is a single sdB star. An envelope rotation period of approximately 16 days is implied by p-mode multiplet splitting, making EPIC 211779126 the fastest rotating non-binary sdB pulsator observed with *Kepler*. However, Baran et al. do not find resolved multiplets among the high-amplitude g-mode pulsations that correspond to the envelope rotation rate inferred from the p-mode splittings, indicating a much slower core rotation rate.

Menzies and Marang (1986) identify HW Vir (BD −07°3477) to be an eclipsing binary with an extremely short (∼ 0.1 day) period. The primary is a hot subdwarf, not hitherto identified as a pulsator from ground-based photometry; the secondary is understood to be a M dwarf. Many such systems have since been discovered, as for example Kupfer et al. (2015) discuss. HW Vir has come to be regarded as "a prototype" and as its position allows K2 observations, it was an obvious target.

From seventy days of observation, Baran et al. (2018) determine the mid-times of eclipses, calculate an $(O-C)$ diagram, find the orbital period to be stable as defined by error limits and deduce a secondary minimum average shift of $\Delta T = 1.62$ s from the mid-point between two consecutive primary eclipses. If the shift is explained solely by light-travel time, the mass of the sdB primary must be $0.26\mathrm{M}_\odot$, which is too low for the star to be core-helium burning. For the sdB star mass to be canonical $(0.47\mathrm{M}_\odot)$, this could be achieved for example with an orbital eccentricity of 0.0001, given a favourable longitude of periastron (ω) so that $\cos\omega = 1$. Baran et al. therefore argue that a sdB primary mass of $0.26\mathrm{M}_\odot$ is unlikely to be be correct.

After removing the flux variation caused by the HW Vir binary orbit, Baran et al. calculate an amplitude spectrum which clearly shows periodic signals from close to the orbital frequency up to 4600 μHz, with a majority of the peaks below 2600 μHz. Peak amplitudes are below 0.1 ppt, too low to be detected with ground-based photometry, but high-precision data from the *Kepler* spacecraft reveals the HW Vir primary to be a pulsating sdB star. Multiplet structure in both p-modes and g-modes does not provide a convincing rotation period for the sdB primary. Baran et al. then argue that the HW Vir sdB pulsation spectrum differs from that in other sdB stars due to the relatively fast rotation Edelmann (2008) infers from spectroscopy which is that it is (nearly) phase-locked with the orbit.

Jeffery et al. (2017) find UVO 0825 + 15 to be a hot bright helium-rich subdwarf lying in K2 Field 5 and for which they obtain spectra using the Subaru High Dispersion Spectrograph and Nordic Optical Telescope, the latter having an intermediate dispersion ($\lambda/\Delta\lambda \simeq 2000$). Analyses of ultraviolet (from the International Ultraviolet Explorer Archive) and intermediate dispersion optical spectra rule out a short-period binary companion and provide fundamental atmospheric parameters of $T_{\rm eff} = 38900 \pm 270$ K, $\log g = 5.97 \pm 0.11$, $\log N({\rm He})/N({\rm H}) = -0.57 \pm 0.01$, $E(B-V) \simeq 0.03$, and an angular radius $\theta = (1.062 \pm 0.006) \times 10^{-11}$ radians. Jeffery et al. find Pb IV absorption lines in the Subaru spectrum, indicative of a very high lead overabundance; they also note carbon is more than 2 dex sub-solar, iron is approximately solar, and all other elements after argon in the Periodic Table are at least 2-4 dex overabundant, including germanium and yttrium. The photosphere is presumed to have a chemical structure determined by radiatively dominated diffusion. Jeffery et al. find the K2 light curve to show a dominant period around 10.8 h, with a variable amplitude, its first harmonic, and another period at 13.3 h. A preferred explanation is multi-periodic non-radial oscillation due to g-modes with very high radial order, although Jeffery *et al.* note this presents difficulties for pulsation theory; alternative explanations fail for lack of radial-velocity evidence.

Silvotti et al. (2019) nicely illustrate the value of using spacecraft to obtain long time-base high precision photometry through their detection of pulsation in the bright (V = 10.2) sdB star HD 4539 (PG 0044 + 097 and EPIC 220641886), a feat which Lynas-Gray (2012) fails to achieve with ground-based photometry using modest facilities. From the K2 light curve (78.7 days) Silvotti et al. extract 169 pulsation frequencies, 124 having a robust detection; most are found in the low-frequency g-mode region but some higher frequency p-modes are also detected, implying that HD 4539 is a hybrid (DW Lyn) pulsator. The lack of any frequency splitting in its amplitude spectrum suggests a HD 4539 rotation period longer than the K2 run, or that the star is seen pole-on. From asymptotic period spacing, many high-degree modes, up to ($\ell = 12$), are seen in the amplitude spectrum of HD 4539, with amplitudes as low as a few ppm. Silvotti et al. obtain $T_{\rm eff} = 22800 \pm 160$ K, $\log g = 5.20 \pm 0.02$, and $\log[N({\rm He})/N({\rm H})] = -2.34 \pm 0.05$ from low-resolution spectroscopy, and by fitting the spectral energy distribution they get $T_{\rm eff} = 23470 {}^{+650}_{-210}$ K, $R = 0.26 \pm 0.01 {\rm R}_{\odot}$, and $M = 0.40 \pm 0.08 {\rm M}_{\odot}$. Moreover, from eleven high-resolution spectra Silvotti et al. see radial velocity variations caused by stellar pulsations, with amplitudes of $\simeq 150\,{\rm m s}^{-1}$ for the main modes, and exclude the presence of a companion with a minimum mass higher than a few Jupiter masses having orbital periods less than ~300 days.

6 TRANSITING EXOPLANET SURVEY SATELLITE OBSERVATIONS

The NASA Transiting Exoplanet Survey Satellite (TESS, Ricker et al., 2015) was launched on 2018 April 18$^{\rm th}$. An important feature distinguishing TESS from other facilities referenced above is the intention that most of the celestial sphere will be observed during the initial two-year mission. Hot subdwarfs not accessible to MOST, CoRoT, *Kepler* and K2 may now in principle be photometrically monitored from space for an extended period. Charpinet et al. (2019) discuss the prospects for asteroseismic observations of sdB stars in more detail.

As KIC 10139564 is the only V361 Hya star Østensen et al. (2010b) find in the *Kepler* field, and subsequent searches did not find another, Prins et al. (2019) emphasise the importance of observing as many as possible with TESS, especially at the ecliptic poles where the time-base will be longest. Low-resolution Balmer-line spectroscopy is used to identify thirty-nine new sdB stars around the northern ecliptic pole ($\beta > 73^{\rm o}$); of these, twenty-nine have characteristics ($T_{\rm eff} > 28000$ K or a composite spectrum) that may put them in the p-mode instability strip, and adding to the two (LS Dra and V366 Dra) already known. Prins et al. obtain ground-based time-series photometry for most of their p-mode candidates and discover J19384 + 5824 to be a V361 Hya star in the TESS 189 days viewing zone; it has a period of 172 s and an amplitude of 0.0091 magnitudes.

Charpinet et al. (2019) present the discovery and detailed asteroseismic analysis of a new g-mode hot subdwarf pulsator, EC 21494–7018 (TIC 278659026), monitored in the TESS first sector using a 120-second cadence. The light curve analysis reveals EC 21494–7018 to be a sdB pulsator having up to twenty independent g-mode frequencies. An optimal model solution in full agreement with independent measurements provided by spectroscopy (atmospheric parameters derived from model atmospheres) and astrometry (distance evaluated from the Gaia DR2 trigonometric parallax) is obtained through a seismic analysis. Charpinet et al. derive a mass for EC 21494–7018 ($0.391 \pm 0.009 {\rm M}_{\odot}$) significantly lower than the canonical mass of sdB stars, suggesting that its progenitor had not undergone the Helium Flash and was therefore a massive ($\geq 2 {\rm M}_{\odot}$) red giant. Other derived parameters include the H-rich envelope mass ($0.0037 \pm 0.0010\,{\rm M}_{\odot}$), radius ($0.1694 \pm 0.0081\,{\rm R}_{\odot}$), and luminosity ($8.2 \pm 1.1\,{\rm L}_{\odot}$). The optimal model fit has a double-layered He + H composition profile, which Charpinet et al. interpret as an incomplete but ongoing process of gravitational settling of helium at the bottom of a thick H-rich envelope. Properties Charpinet et al. derive for the core indicate EC 21494–7018 has burnt $\sim 43\%$ (by mass) of its helium and that it is relatively large core ($M_{\rm core} = 0.198 \pm 0.010\,{\rm M}_{\odot}$), and mixed in line with trends already uncovered from other g-mode sdB pulsators. In addition Charpinet et al. make a first estimate of the core oxygen mass fraction $\left(X(\mathrm{O})_{\mathrm{core}} = 0.16\,{}^{+0.13}_{-0.05} \right)$, produced at this stage of evolution in a helium-burning core, a result which may help narrow down the still uncertain $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ nuclear reaction rate when coupled with estimates for the core-size and stellar age on the ZAHB.

Reed et al. (2020a) report TESS observations showing CD $-28^{\circ}1974$ to have an amplitude spectrum in which g-modes dominate, making it a hybrid (DW Lyn) pulsating sdB star; it has thirteen secure periods that form a $\ell = 1$ asymptotic sequence near the expected period spacing. Typical $\ell = 1$ g-mode periods in sdB stars lie between 3300 and 10000 seconds, whereas in CD $-28^{\circ}1974$ Reed et al. find them between 1500 and 3300 seconds, indicating a somewhat different internal structure. CD $-28^{\circ}1974$ has a F or G-type Main Sequence companion with Gaia proper motions indicating a comoving pair at the same distance (395 ± 7 pc) at which the separation of 1.33 arcsec would correspond to 530 ± 10 au and an orbital period of $\sim 10^4$ years.

Sahoo et al. (2020) report the detection of pulsations in three pulsating sdB stars SB 459 (TIC 067584818), SB 815 (TIC 169285097) and PG 0342 + 026 (TIC 457168745) monitored by TESS during single sectors, giving time-series covering twenty-seven days. Six longer period (266.8–387.2 seconds) p-mode frequencies are identified in SB 815 and in all three stars, at least twenty-two frequencies in the g-mode domain are seen. As no multiplets are found, mode identification in these stars is based on an asymptotic period relation; $\ell = 1$ or $\ell = 2$ being assigned to g-modes. Trapped modes are also identified which signify a non-uniform internal chemical profile. Using high precision trigonometric parallaxes from the Gaia mission and spectral energy distributions, Sahoo et al. derive stellar parameters from their atmospheric counterparts. Radii, masses, and luminosities are close to their canonical values for extreme horizontal branch stars. In particular, the stellar masses are close to the canonical 0.47 $M_{\odot}$ for all three stars but with large uncertainties.

7 SUMMARY AND FUTURE PROSPECTS

A better understanding of the late stages of stellar evolution is one of the main reasons for probing the internal structure of hot subdwarfs with asteroseismology. The point is very well expressed by Van Grootel et al. (2010a) who in the concluding part of their paper write: "As all helium-burning cores have similar characteristics, pulsating sdB stars are found to be excellent probes of Horizontal Branch star internal properties in general, an intermediate stage of stellar evolution experienced by the vast majority of stars." In reviewing papers mentioned above, I was very impressed by the wide diversity among the sdB stars various authors study with the *Kepler* satellite. While similarities exist and are mentioned, every sdB appeared to have its distinguishing characteristics. Diversity was to me at least, a good argument for a binary origin: evolution of binary systems depends on masses, separations and compositions of the two components as well as how that binary formed originally.

Having all too briefly highlighted the enormous contribution to the asteroseismic study of sdB stars achieved through observations made by the *Kepler* satellite, during the main mission and the K2 mission that followed, it was gratifying to find that further time-series data collected by TESS will very probably continue the advance. In this closing section, I have therefore attempted to distill the essential facts about sdB stars that have been learnt from the *Kepler* Missions:

- Precision time-series photometry obtained with the *Kepler* satellite, almost continuously over nearly four years, has allowed some apparently single V1093 Her pulsators to be identified as binaries. KIC 07668647 and KIC 10553698 are found to have white dwarf companions from an orbital signature in the power spectra. M dwarf companions of KIC 02991403, KIC 08302197 and KIC 11179657 are identified from reflection effects seen in raw light curves. 2M 1938 + 4603 turns out to be an eclipsing binary, possibly having a Jupiter-mass object orbiting the binary at a distance of 0.92 AU
- Evidence of trapped modes is found in power spectra of KIC 10001893, KIC 10553698 and KPD 1943 + 4058. Guo and Li (2018) argue that the Helium Flash, at the end of the red giant stage, causes convection extending very close to the He/H transition zone and a convective overshoot during this stage smooths the chemical profile in the He/H transition zone. Detailed model calculations show that the mode trapping efficiency is then reduced to agree with observation.
- For a number of V1093 Her stars observed by *Kepler*, core rotation rates are found to be lower than the corresponding envelope rotation rate. In cases where the V1093 Her star is also known to be in a binary, the orbital time was shorter than its rotation period, indicating that rotation is generally not synchronised with orbital motion. The slow envelope rotation is consistent with a V1093 Her star having a red giant progenitor and the finding by Mosser et al. (2012) that the mean red giant core rotation significantly slows down in the last stages of Red Giant Branch evolution. A slower core rotation rate is consitent with results by Tayar et al. (2019) who find a rapid transfer of angular momentum from the core, to the surrounding envelope, during the core helium burning phase.
- According to Miller Bertolami et al. (2020), stochastic excitation of pulsations in sdB stars are asteroseismic signatures of an earlier helium core flash. Stochastic excitations are identified in WET observations of PG 0048 + 091 and, for some frequencies, confirmed by later K2 observations. In the case of KIC 02991276, *Kepler* observations confirm the presence of stochastically excited pulsations. A new opportunity to study the helium core flash has thus been established.
- Although early *Kepler* observations of KIC 10139564, the only V361 Hya star in the *Kepler* field, suggest pulsations with stable frequencies and amplitudes, the analysis of thirty-eight months of contiguous short-cadence data (Zong et al., 2016) highlights mode multiplets induced by rotation which show intriguing behaviour. For example, Zong et al. find a triplet at 5760 μHz, a quintuplet at 5287 μHz and a ($\ell > 2$) multiplet at 5412 μHz, all induced by rotation, showing clear frequency and amplitude modulations typical of the intermediate regime of a resonance between components.

Identified frequency and amplitude modulations are signatures of non-linear resonant couplings occurring in pulsating sdB stars. Resonances occurring in pulsating sdB stars appear to follow more complicated patterns than the simple predictions from current non-linear theoretical frameworks; results which should motivate further development of non-linear stellar pulsation theory.

Diversity among the sdB star population means that a point Heber (2009) makes in his review is still valid; every sdB star needs to be studied and its distinguishing characteristics identified. More and better observations will be needed as well as theoretical developments and so the following future developments are proposed:

- In order to study every sdB star, it is first necessary to find them and distinguish pulsators from non-pulsators; several facilities are becoming available to expedite this search. The All-Sky Automated Survey for Supernovae (Kochanek et al., 2017) consists of twenty-four observing stations distributed in latitude and longitude across the globe; each observes with Johnson V, R and I filters and in principle allows the entire celestial sphere to be surveyed to $V \leq 16$ every twenty-four hours. Evryscope (Law et al., 2015, 2016) is deployed in Chile and California and images the entire visible sky every two minutes to $V \leq 16$. The Large Synoptic Survey Telescope (Tyson, 2002; Ivezić et al., 2019) will obtain deep images in six optical bands, with each sky location visited close to 1000 times over 10 years.
- Given the *Kepler* mission success, it is important for TESS to monitor as many sdB pulsators as feasible and for as long as possible, so as to maximise the time-base; this is already in hand. To some extent the asteroseismology community is fortunate because for as long as the current interest in exoplanets persists, and the prospect of finding an Earth-like planet harbouring life continues, satellites will be needed to continue these searches. PLATO (Rauer et al., 2016) is one such mission and so obtaining high quality time-series photometry of hot subdwarfs may be expected to continue.
- Apart from work on the AA Dor secondary (Vučković et al., 2016) there has hitherto, and to the best of my knowledge, been no detailed study of M dwarf companions of pulsating hot subdwarfs in binary systems. Once completed, such studies would help with understanding associated hot subwarf power spectra. The James Webb Space Telescope (Gardner et al., 2006) could in principle be used to obtain transmission spectra immediately before and after primary and secondary eclipses in HW Vir-type systems.
- Atmospheric parameters and element abundances in sdB star atmospheres are an essential guide to the interpretation of asteroseismic time-series. Continued observation of sdB stars in spectroscopic surveys, such as LAMOST (Luo et al., 2016), are therefore needed. Follow-up high dispersion spectroscopy could then be obtained as necessary.
- Derived element abundances in the solar photosphere are compromised, if three-dimensional radiative transfer and hydrodynamic effects are neglected in the atmosphere. Atmospheres of pulsating hot subdwarfs are non-static, almost by definition, and temperature as well as pressure changes which accompany pulsation imply that these quantities are not constant at a given optical depth. I therefore propose that pulsating hot subdwarf atmospheric parameters and element abundances be based on model stellar atmospheres and line formations calculations incorporating hydrodynamics and three-dimensional radiative transfer.
- Stellar evolution calculation results are known to be dependent on the approximation used to model radiation transfer in the stellar atmosphere (VandenBerg et al., 2008). Coupling one-dimensional stellar evolution with three-dimensional hydrodynamical simulations of the stellar surface are now also being extended to asteroseismology (Mosumgaard et al., 2020); the resulting new models are able to predict observed frequencies without additional corrections and are able to do so consistently for all stellar parameters. As far as I am aware, the Mosumgaard et al. technique has not yet been applied to pulsating hot subdwarfs.
- Lynas-Gray et al. (2018) summarise our understanding of astrophysical opacities as it was in 2018. Of particular note is an experimental measurement by Bailey et al. (2015) of iron absorption in plasma conditions existing at the base of the solar convection zone, using the Sandia Z-Facility. When compared with the OP prediction, the Bailey et al. measurement implies an increase in the Rosseland mean opacity of $7 \pm 3\%$. In advance of any new theoretical initiative, it is essential that the Bailey et al. measurement be repeated with a different facility and Perry et al. (2020) report progress towards doing so with the National Ignition Facility.
- In view of various modulation patterns time-series observations of sdB stars uncover, Zong et al. (2018) encourage further developments in the field of non-linear stellar oscillation theory. The idea is hardly new as Cox (1976) proposes the full development of non-linear stellar oscillation theory and, although widely recognised as a difficult problem, its development would allow information in pulsation amplitudes to be more fully exploited. Stars such as KIC 10139564 now offer remarkable test-beds against which new non-linear pulsation theory may be benchmarked.

I end this review with a cautionary note. In the last sentence of their abstract, Zong et al. (2018) write “It also raises a warning to any long-term project aiming at measuring the rate of period change of pulsations caused by stellar evolution, or at discovering stellar (planetary) companions around pulsating stars using timing methods, as both require very stable pulsation modes”.

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The author confirms being the sole contributor of this work and has approved it for publication.

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