Bull. Soc. R. Sci. Liege, 2023, 92(2), 1 - 13 doi:10.255118/0037-9565.11266

Kepler, K2, and *TESS* observations: ensemble and comparative asteroseismology

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Abstract

The original *Kepler* mission detected 18 pulsating subdwarf B (sdBV) stars, K2 observed 161 of our proposed targets with 41 sdB stars found to show p- or g-mode pulsations, and *TESS* has observed about 1,000 of our proposed targets. All these data should provide ∼300 sdBV stars, from which asteroseismology will provide a host of measurables. Combined with temperatures and gravities (and radii and masses from GAIA parallaxes!), we have a powerful set of observations with which to compare models. Here we review our seismology progress with sdBV stars.

1. Introduction

After the discovery of pulsating subdwarf B (sdBV) stars in 1995, we spent 15 years trying to observationally constrain pulsation modes for the application of asteroseismology. Methods included multi-site photometric campaigns (e.g. Kilkenny et al., 2003; Reed et al., 2004), time-resolved spectroscopy (e.g. Østensen et al., 2010; Telting et al., 2010; Randall et al., 2014) and multicolor observations (e.g. Baran et al., 2008; Reed et al., 2012b). These methods provided a few observationally-constrained pulsation modes, but until the high-duty-cycle observations of *Kepler*, we were largely thwarted and pulsation models remained relatively unconstrained.

The type and quality of data obtained by *Kepler* (both K1, the original mission, and K2) and *TESS* is unprecedented and transformative for observational mode identifications. A comparison of K1, K2, and *TESS* data is shown in Figure 1.

The K1 mission provided lightcurves of quality and duration previously unimaginable. The 0.95 m telescope obtained useful data on stars down to 18^{th} magnitude, nearly-continuously

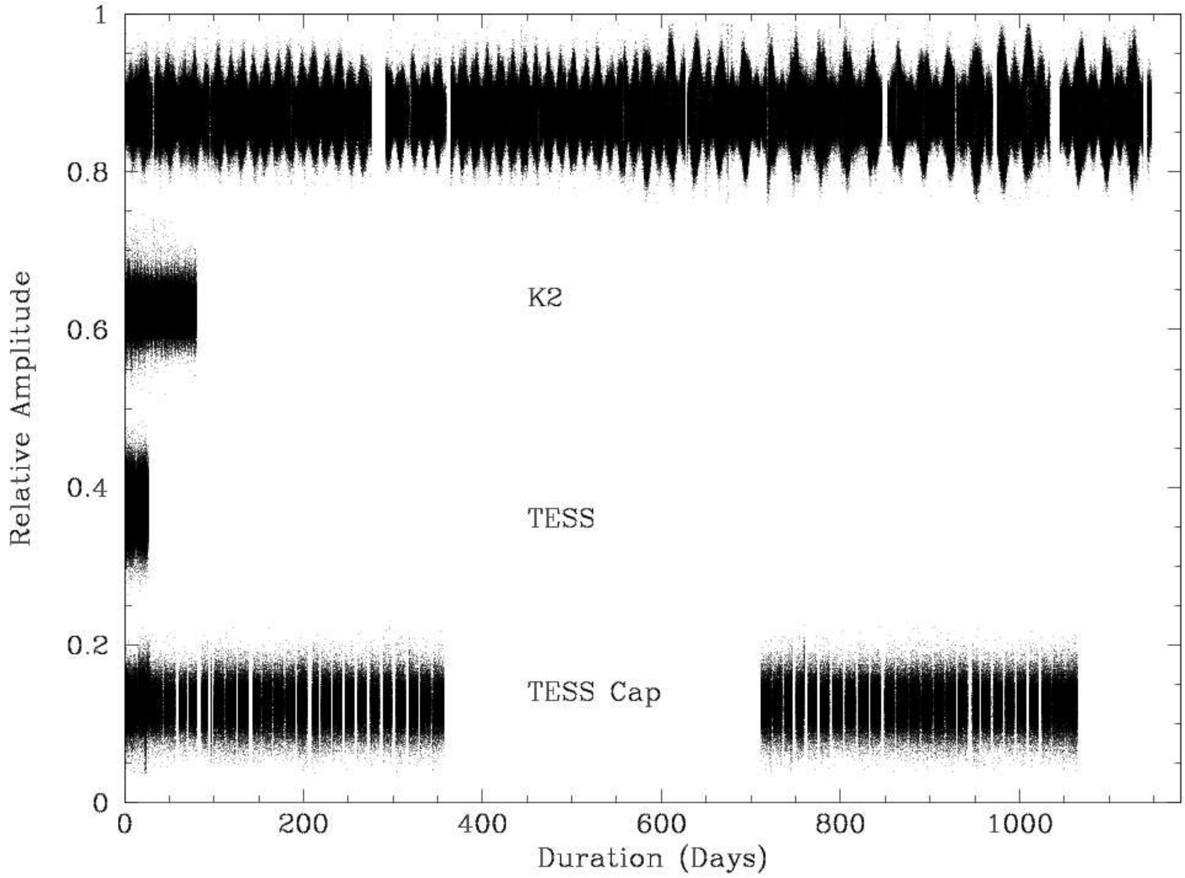

Figure 1: Lightcurves showing durations of K1, K2, and *TESS* data. Top curve shows three years of K1 short-cadence data, then a single K2 campaign, a single *TESS* sector and multi-year polar cap *TESS* data.

($>90\%$ duty cycle) for three years in short-cadence (58 s) mode. The only disadvantage was that K1 observed a single pointing of 116 square degrees. As such K1 only observed 18 sdBV stars, of which 16 were g-mode-dominated and only one was a rich p-mode-dominated pulsator (Baran et al., 2012). K1 data were transformative in that for most K1-observed sdBV stars, over a hundred pulsation periodicities were detected with $>70\%$ observationally associated with modes, providing $>1,200$ identified modes. The main seismology tools applied to sdBV stars in K1 data included g-mode asymptotic period spacings (hereafter simply period spacings; Reed et al., 2011), frequency multiplets (hereafter simply multiplets; Baran et al., 2012), and Ledoux splittings of multiplets (Reed et al., 2014). Never before had we so readily been able to identify pulsation modes, transforming sdBV seismology from one where models were poorly observationally constrained to one where so many modes are identified that period-matching models are unlikely to provide a match (Reed et al., 2012a).

The K2 mission relied upon pointings along the ecliptic, which meant durations no longer than three months. The upside is that many more stars were observed- of the 20 pointings (campaigns), only four had substantial overlap, with one pointing precisely repeated. This allowed for more stars to be observed; we proposed, and obtained, short-cadence data for nearly

200 prospective sdB pulsators with ≈ 50 estimated to pulsate (21 published to date; Reed et al., 2021; Ma et al., 2022). Importantly, six more p-mode-dominated pulsators were observed, including three previously-known from ground-based observations.

TESS (the Transiting Exoplanet Survey Satellite) data are great but challenging for sdB seismology. *TESS* covers nearly the entire sky which means thousands of sdB stars have been observed. It uses a stack of four 10.5 cm telescopes which observes a 24 degree strip of sky 96 degrees in declination. Each pointing (sector) lasts for 27 days with stars closer to ecliptic poles being observed in multiple sectors. Single-sector data are unlikely to detect multiplets as the rotation period would need to be under ~ 13 days and most measured sdB spin periods are longer than that (Reed et al., 2021). Also, as the telescopes are much smaller than *Kepler*, the signal-to-noise is reduced and so only higher-amplitude pulsations are detected unless the star is much brighter. The right panel of Fig. 2 shows how brightness, and perhaps pulsation amplitudes, limit what can be detected. While the top panel has 12 sectors of data and a much lower detection limit (blue line), two sectors of data (bottom panel) for a brighter star, possibly with higher amplitudes, can provide better data. *TESS* spends alternate years observing north and south of the ecliptic. As such, for stars near the poles, multiple full years of data can be obtained with a one year gap in between (bottom panel of Fig. 1). During the first two years of *TESS* observations, short cadence integrations were two minutes, which effectively eliminated p-mode detections for frequencies above $\sim 6,000\,\mu$Hz because of phase smearing (integrations covering significant fractions of the pulsation period). Figure 2 shows that the observed amplitude goes to zero as the pulsation frequency approaches the integration frequency. For the extended missions which cover years three and beyond, a new “fast” cadence of 20 seconds was used, from which p-mode pulsations could more readily be detected (dashed line of Fig. 2). As such, the original mission was strongly biased *against* detecting p-mode pulsators and of the stars applied for fast cadence during the extended mission, most were previously-known p-mode pulsators. Mostly from extended mission fast-cadence data, our preliminary analyses have found just over 80 p-mode pulsators. Nearly all previously-known p-mode pulsators were observed, but unfortunately because of *TESS*’s small size, few show more than a couple periodicities.

2. Progress

Figure 3 shows Kiel diagrams of detections by mission. By the time analyses of *TESS* data are complete, there should be ≈ 300 detected sdB pulsators. For K1, where only sdB stars within a targeted $T_{\rm eff} - \log g$ range for likely pulsators were applied for, 35% of observed sdB stars were pulsators. A broader range was applied for during K2, of which $\approx$25% have been detected to pulsate (not all have been examined yet), and an even wider range was applied for to *TESS*, of which roughly 20% appear to be pulsators. A large fraction of sdB pulsators are g-mode pulsators and so spaced-observed p-mode pulsators are rare, as indicated by the black points in Figure 3 for each missions. K1 only detected three p-mode-dominated sdB pulsators, so far K2 has detected six, and our preliminary TESS reductions found eight. Note: Since this conference, Baran et al. (2023) have published the detection of 43 p-mode pulsators in TESS’s

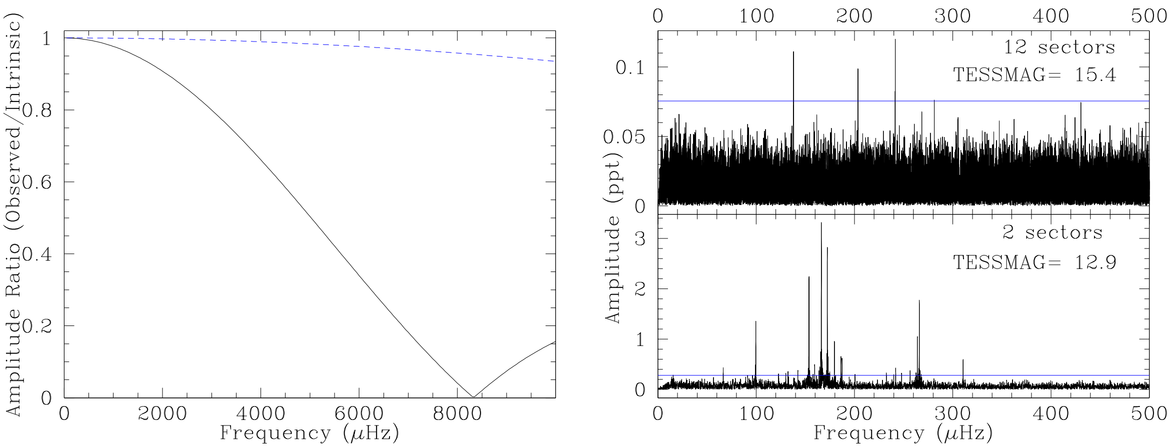

Figure 2: Left: Ratio of observed to intrinsic amplitudes for 120 second (solid black line) and 20 second (dashed blue line) integration times with pulsation frequency for simulated data. When integration times near pulsation periods, observed amplitudes are greatly reduced, making them less observable. Right: Fourier transforms of *TESS* PDCSAP (crowding-corrected) data indicating that more data is not always better as stellar brightness and pulsation amplitude can be stronger factors. In the top panel a full year of data produces a lower detection threshold but fewer pulsation peaks. Horizontal (blue) lines indicate detection thresholds.

Southern Ecliptic data.

To date the K1 observations have mostly been analyzed and published, and so some statistics can already be examined. Of the $> 1,200$ published identified modes, all but 44 were g modes, 46% were $\ell = 1$, 45% $\ell = 2$, 1.3% $\ell = 3$, 2.2% $\ell = 4$, 2.1% $\ell = 6$, and 7.6% were ambiguous $3 \leq \ell \leq 6$. The independent methods of period spacings and multiplets identified 73% and 63% of the frequencies, respectively. Multiplets were detected in all but one star, from which rotation periods could be inferred. Similar statistics have not been completed for K2 or *TESS* data though for K2 published stars, nine are g-mode only, eight are g-mode-dominated hybrids, three are p-mode-dominated hybrids, and three are p-mode only pulsators. For K1/K2, 88/74% are g-mode(-dominated) pulsators. This has led to a great observational understanding of g mode pulsators, but we are still waiting for similar clarity for the p mode pulsators.

For K2, 14 of 23 stars we have analyzed to date show multiplets. There is a selection effect here, as we have concentrated on stars with rich pulsation spectra, which are more likely to have multiplets. Of the seven *TESS* pulsators published to date, only HD 265435 (Jayaraman et al., 2022) and TIC 137908661 (Silvotti et al., 2022) have detected multiplets. Using K1 for comparison, 50% and 27% have spin periods < 45 and < 12 days which would resolve multiplets in K2 and *TESS* observations, respectively, assuming a small Ledoux constant. For g-mode pulsations, where the Ledoux constant has a significant contribution, these fractions would be even less (about half for $\ell = 1$ modes).

At this point there are a large number of mode identifications but only limited progress in model advances. Way back at sdOB5 two independent researchers used period spacings to infer diffusion models (Hu et al., 2009; Miller Bertolami et al., 2012). In 2015, Constantino et al. (2015) used deviations in asymptotic sequences (ΔP) to determine core masses. In 2017, Ghasemi et al. (2017) used mode trapping to correlate core convective overshoot, and in 2018 Guo and Li (2018) examined helium-flash convective overshoot's influence on mode trapping. Also Ostrowski et al. (2021) published some recent work using MESA comparing the effect of mixing to pre-mixing on core mass. Unfortunately these works were mostly completed by temporary investigators (graduate students and postdocs) who then moved on to other topics. As a result, there appears to be no sustained modeling effort using the now-massive amounts of observational seismic constraints to improve sdB models.

3. Comparative Asteroseismology

There are now enough sdB pulsators with mode identifications based on empirical data alone to be able to compare their seismic properties. This was most recently completed in Reed et al. (2021) and to their analyses we add some *preliminary TESS* results.

In solar-like pulsators $\Delta\nu$, $\delta\nu$, and $\nu_{\max}$ are particularly useful quantities which provide physical quantities (García and Ballot, 2019). For g-mode pulsators, these could have some translation to periods. In the left panel of Figure 4, we examine g-mode period spacings (ΔP) in a Kiel diagram. It could be inferred that trends would appear, as cooler sdB stars should have thicker envelopes, which would modify the resonant cavities and therefore the period spacings. We divided the spacings into three groups, as color-indicated in Fig. 4, and compared their averages, deviations, trend slopes and offsets. In the longest ΔP (blue/green) group, except for the coolest blue horizontal branch (BHB) star, the cooler stars have longer period spacings, yet much shorter period spacings (in the red group) also appear cooler, so it would be difficult to consider this a trend. The $T_{\rm eff}$–$\log g$ trend lines for each group are also shown, with an additional line for the blue/green group without the BHB star. The slopes for the short (red) and average (black) groups are similar with the short group trending below the average group. The longest group has a much steeper slope, but the points, except for the BHB star, have a much smaller spread in $T_{\rm eff}$–$\log g$ (noted by their proximity to the 1σ ellipse). However, at a similar slope to the other groups, there would be a trend from bottom-right to top-left from shortest to longest period spacings. The average values for each group show this trend, though their separation is within their 1σ limits. If this persists as more stars are analyzed, it would be worth investigating the cause behind it. Of the 70 stars for which we have $T_{\rm eff}$, $\log g$, and ΔP, the average spacing is 249 s, very near the "common" value of 250 s.

At this time there is no known correlation in period for $\delta\nu$, other than the $\delta\nu$ of frequency multiplets which provides rotation periods. However the $\nu_{\max}$ analog, $\mathrm{P}_{\rm Amax}$, does show a trend with $T_{\rm eff}$ (right panel of Fig. 4). For hotter stars, their highest-amplitude period is shorter. The trend is consistent with a near-constant core mass and a distribution of envelope masses (as indicated in Jeffery and Saio, 2006). While the overall trend is quite clear, the actual distributions and deviations have yet to be explored. In Reed et al. (2020a) it was posited that two stars which deviated from the trend might have dissimilarly-sized cores (in mass). In Fig. 4, those g mode stars would appear below the trend, yet there are more stars deviating *above* the trend. *If* (and this is highly speculative) the trend is near-constant core mass, then perhaps those above the trend indicate larger cores. A cautionary note to this procedure is shown in the bottom right panel of Fig. 4. Fourier transforms of three sectors of the same star are shown. In S15, the highest-amplitude frequency is $\approx 230\mu$Hz whereas during S20 and S21, it is near 80μHz.

Beyond the two comparisons shown here, others have appeared in publications including a rotation-$T_{\rm eff}$ relation (Reed et al., 2014) and non-radial indices (ℓ, m) with reduced period as a proxy for how pulsation power is distributed (Reed et al., 2014; Foster et al., 2015). Three K1-observed examples of the latter are shown in the bottom-left panel of Fig. 4. The notion is that where pulsations are most easily driven, they will have higher amplitudes, and therefore are more easily detected.

4. Results

Once initial K1 data were available, sdB asteroseismology fundamentally changed. It went from a model-driven, observation-starved field to an observationally-constrained, incomplete modeling one. Prior to K1, g modes were poorly observed and essentially not understood past the point that they *are* g modes. Ground-based work concentrated on p-mode pulsators, which could more easily be observed, but even those observations went little beyond simply cataloging frequencies. Post-K1, commonly-measured seismic constraints include mode identifications for the majority of periodicities, period spacings, and rotation rates. While papers have been written matching models to *initial* data releases (Van Grootel et al., 2010; Charpinet et al., 2019) or specific features (such as mode trapping; Guo and Li, 2018; Ghasemi et al., 2017), *no* papers have been written which include the full set of observational mode constraints for any given sdB pulsator. That still remains a challenge.

Along with the benefits of ample mode identifications, long-term photometric observations have provided a wealth of unexpected, but interesting, features. Although already known, extreme amplitude variability is more easily detected when extended observations have near-to 100% coverage. The bottom-right panel of Fig. 4 shows the same star during three *TESS* sectors. Even in adjacent sectors, the second highest peak (in S20) is nearly gone in the subsequence sector (S21) and P_{Amax} has shifted from 4,300 to over 12,000 s (230 to 82μHz) between S15 and S20. This indicates that *what* you detect has a dependence on *when* you look. While very complex, it could lead to advances in non-linear pulsation theory (Zong et al., 2016; Ma et al., 2022).

Theoretical studies had indicated that sdB stars should be quickly rotating (Kawaler and Hostler, 2005), but observations have shown otherwise, with rotation periods typically being tens of days. Frequency splittings have also been found to vary in some stars (Kern et al., 2017, 2018), which again could be a non-linear effect as investigated by Zong et al. (2016) and comparing p- to g-mode splittings (in the few hybrids to show multiplets in both) also compares envelope to deeper rotation. This has found both solid-body-like (Baran et al., 2012; Kern et al., 2017; Reed et al., 2019) and radially differential rotation (Baran et al., 2017; Foster et al., 2015; Reed et al., 2019, 2020b; Baran et al., 2019; Ma et al., 2022; Silvotti et al., 2022). For the radially-differential rotators, the surprising discovery has been that the envelope rotates faster, which is contrary to expectations. It is unfortunate that very few stars are likely to have detectable p- and g-mode multiplets with current data sets, as this inhibits investigating the cause for rotational differences.

5. Future directions

The most obvious item for continued work is to complete seismic analyses of K1, K2, and *TESS*-observed pulsators. As only $\approx 1/6$ of that has been completed thus far, there is still a long way to go. *TESS* is still obtaining observations and, most importantly, continues to improve its sampling, which is vital for examining p-mode pulsators. Still, as pointed out in the introduction, sampling and duration differences will complicate analyses and particularly comparisons of pulsators detected from the various sets. While *TESS* has observed, and is still observing, thousands of sdB stars, the brightness and duration limitations will greatly constrain what can be learned.

On the plus side, new non-seismic parameters are being obtained, from which seismic ones can be compared. Likely the most notable of these are Gaia parallax measurements. Eventually radii and masses will be determined for thousands of sdB stars, which can then be compared to seismic properties of the subset of pulsators. Additionally, while somewhat piece-meal, model advances and comparisons, mostly using MESA (Paxton et al., 2011), will increase understanding of sdB stars, and by extension all horizontal branch stars. That, of course, is the goal of stellar astronomy and our subgroup within it.

Acknowledgments

The Missouri Space Grant, funded by NASA, provided funding for undergraduate students to work on this project. Financial support from the National Science Centre in Poland under projects No. UMO-2017/26/E/ST9/00703 and UMO-2017/25/B/ST9/02218 is acknowledged. This paper includes data obtained by the *Kepler* mission. Funding for the *Kepler* mission is provided by the NASA Science Mission directorate. Data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts. This paper includes data collected by the *TESS* mission. Funding for the *TESS* mission is provided by the NASA Explorer Program.

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R. H. Østensen: Data analysis, investigation, writing - review & editing.
J. H. Telting: Data analysis, investigation, writing - review & editing.
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Conflicts of interest

The authors declare no conflict of interest.

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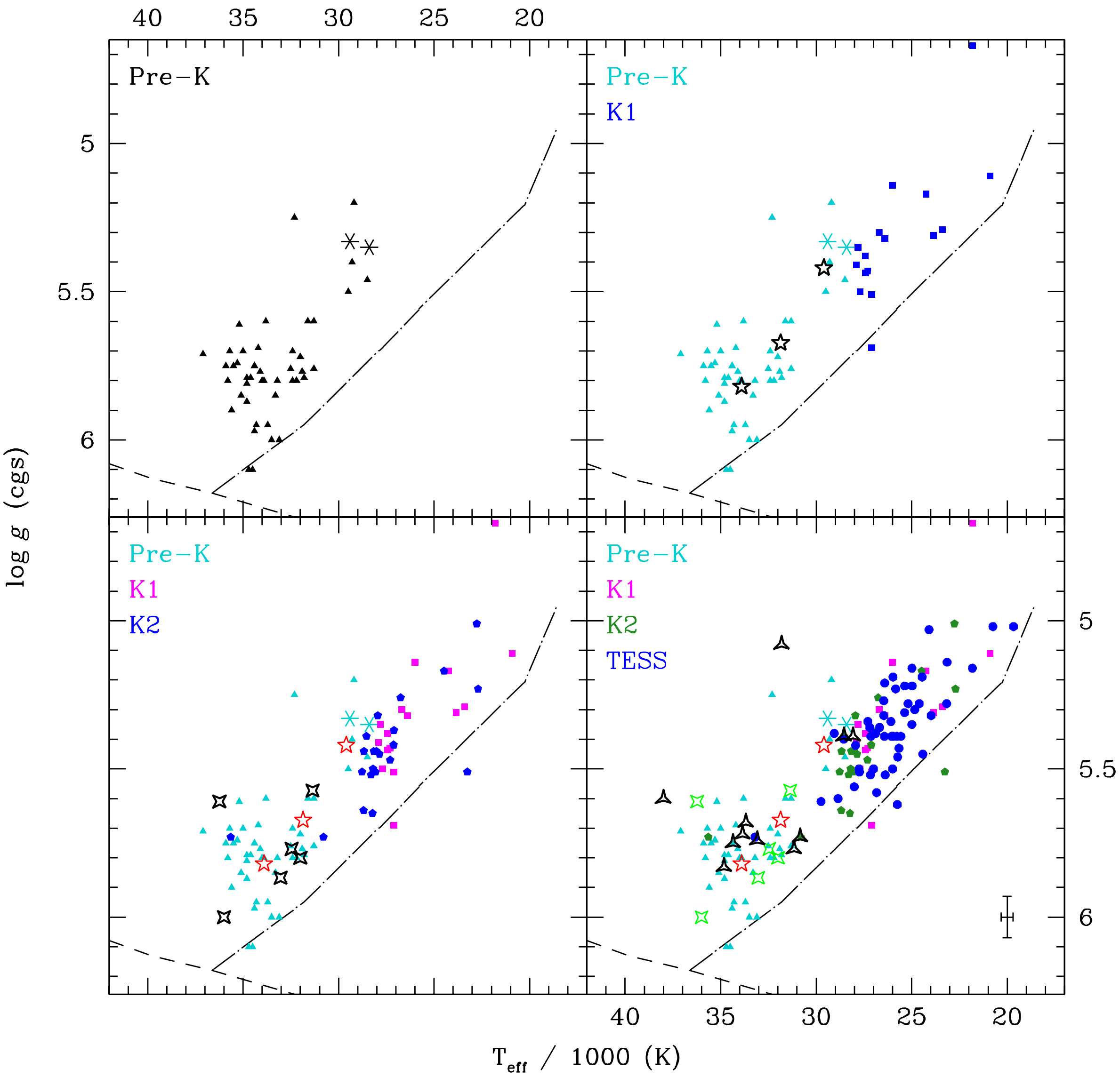

Figure 3: Kiel diagrams showing *Kepler* and *TESS* progress with particular emphasis on p-mode pulsators, which are shown as black points in initial panel of each data set. Top left panel shows ground-based p-mode pulsators, labeled as Pre-K(epler). Asterisks are hybrids DW Lyn and Balloon09 but no g-mode pulsators are shown. K2 only includes published pulsators and *TESS* pulsators are preliminary from our Guest Investigator program. Errorbars for average errors are indicated in the bottom-right panel, long-dashed line indicates the zero-age-helium main sequence for a core mass of 0.47M$_\odot$ with varying envelope thicknesses and the short-dsahed line is for a single envelope mass of 10^{-4}M$_\odot$ and varying core masses.

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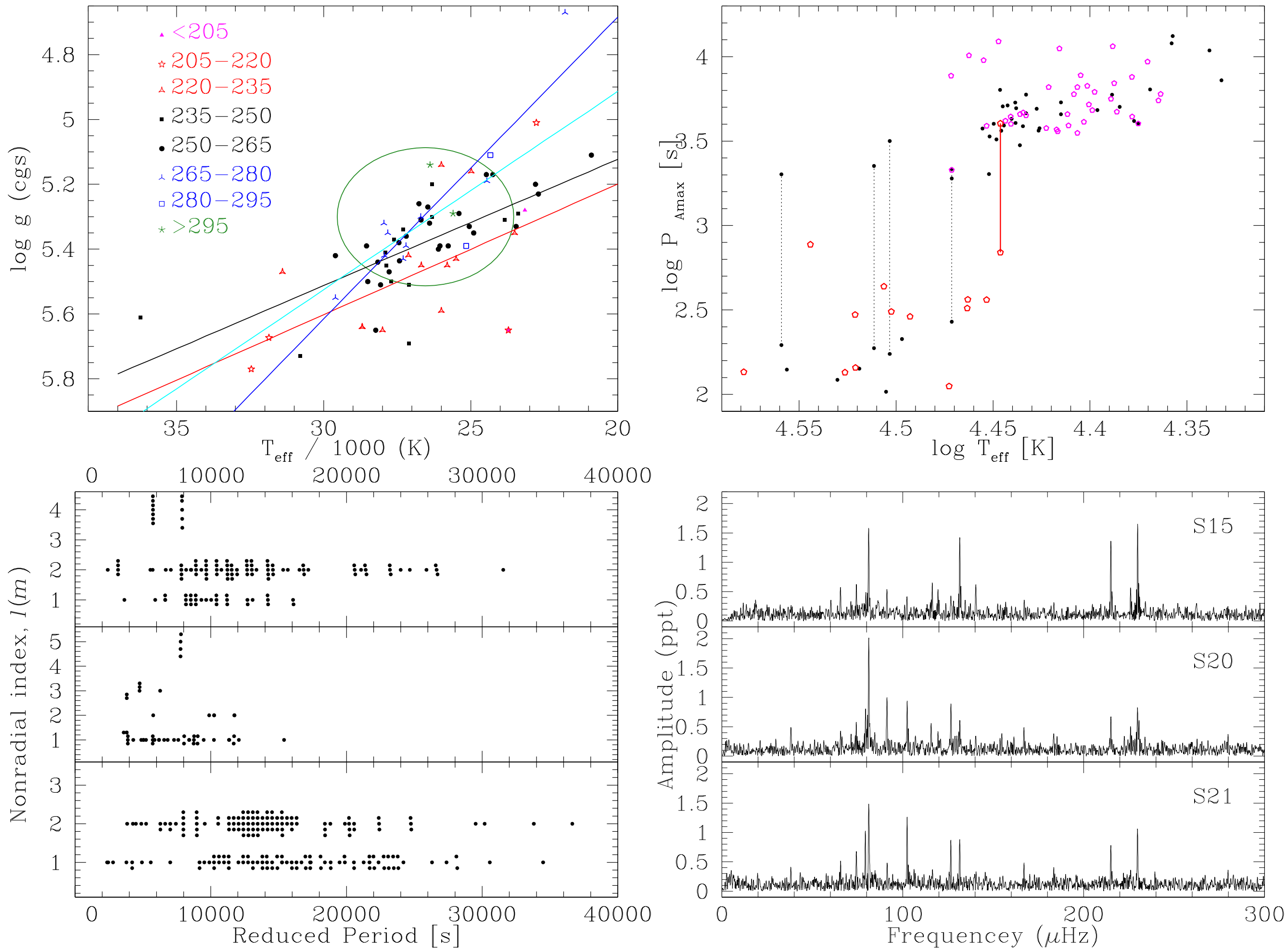

Figure 4: Top: Left: Kiel diagram with g-mode period spacings (in seconds) indicated. The green ellipse is the 1σ error on $T_{\rm eff}$ and $\log g$ centered at the average value and the red, black, and blue lines are linear regression fits to the points in those groups. The cyan line is for the blue group omitting the blue horizontal branch star in the very top right. Right: Period of highest amplitude pulsation ($P_{\rm Amax}$) compared with effective temperature. Filled symbols are K1 & K2-observed stars and open symbols are (preliminary) *TESS*-observed stars. P-mode-dominated hybrid pulsators also have their highest-amplitude g mode period indicated (connected by a line). Again, filled points are K1/K2-observed and open red and magenta points are *TESS*-observed stars. Bottom: Left: Non-radial indices (enumerated as $\ell + 0.1m$) are compared with reduced period to indicate pulsation power. Right: Fourier transforms of the same star observed during three different *TESS* sectors.