Stars and their variability observed from space
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SOLAR-LIKE OSCILLATIONS: LESSONS LEARNED & FIRST RESULTS FROM TESS

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Abstract. Solar-like oscillations are excited in cool stars with convective envelopes, and provide a powerful tool to constrain fundamental stellar properties and interior physics. We provide a brief history of the detection of solar-like oscillations, focussing in particular on the space-based photometry revolution started by the *CoRoT* and *Kepler* Missions. We discuss some of the lessons learned from those missions, and highlight the continued importance of smaller space telescopes such as the BRITE Constellation to characterize very bright stars with independent observational constraints. As an example, we use BRITE observations to measure a tentative surface rotation period of 28.3 ± 0.5 days for α Cen A, which has so far been only poorly constrained. We also discuss the expected yields of solar-like oscillators from the *TESS* Mission, demonstrating that *TESS* will complement *Kepler* by discovering oscillations in a large number of nearby subgiants, and we present first detections of oscillations in *TESS* exoplanet host stars.

Keywords: Stars: oscillations, fundamental parameters, Planets and satellites: fundamental parameters

1 Introduction: A Brief History of Solar-like Oscillations

Solar-like oscillations in cool stars are excited by turbulent convection in the outer layers (e.g. Houdek et al. 1999), and most commonly described by a spherical degree l (the total number of node lines on the surface), azimuthal order $|m|$ (the number of node lines that cross the equator), and radial order n (the number of nodes from the surface to the centre of the star). Modes with higher spherical degrees penetrate to shallower depths within the star, and thus the detection of radial ($l = 0$) and non-radial ($l > 0$) modes provides a diagnostic for the interior structure and fundamental properties of stars. Solar-like oscillators typically exhibit a rich oscillation spectrum with regular spacings, enabling mode identification through simple pattern recognition (see e.g. Bedding 2011; Aerts 2019, for introductory reviews).

Following the discovery of oscillations in the Sun in the 1960s (Leighton et al. 1962), early efforts to detect oscillations in other stars focussed on ground-based radial-velocity (RV) observations. The first confirmed detection of oscillations in a star other than the Sun was made in Procyon by Brown et al. (1991), followed by the first detection of regularly spaced frequencies in η Boo by Kjeldsen et al. (1995). The greatly improved RV precision for detecting exoplanets enabled the detection of oscillations in several nearby main-sequence and subgiant stars such as β Hyi (Bedding et al. 2001; Carrier et al. 2001), α Cen A (Bouchy & Carrier 2001; Butler et al. 2004) and B (Carrier & Bourban 2003; Kjeldsen et al. 2005), and in red giant stars such as ξ Hya (Frandsen et al. 2002) and ϵ Oph (De Ridder et al. 2006).

Some of the first space-based photometric observations of solar-like oscillations were obtained by the Canadian space telescope *MOST* (Microvariability and Oscillations in Stars, Walker et al. 2003; Matthews 2007), which initially yielded a non-detection in Procyon (Matthews et al. 2004) but later confirmed a detection that was consistent with RV observations (Guenther et al. 2008; Huber et al. 2011). *MOST* also detected oscillations in red giants (Barban et al. 2007), including observational evidence for non-radial modes (Kallinger et al. 2008). Space-based observations of solar-like oscillations were also performed using the startracker of the *WIRE* (Wide-field InfrRed Explorer) satellite (Schou & Buzasi 2001; Retter et al. 2003; Bruntt et al. 2005; Stello et al. 2008), the *SMEI* (Solar Mass Ejection Imager) experiment (Tarrant et al. 2007) and the *Hubble Space Telescope* (Edmonds & Gilliland 1996; Gilliland 2008; Stello & Gilliland 2009; Gilliland et al. 2011). In total, ground and space-based observational efforts prior to 2009 yielded detections in ~ 20 stars (see left panel of Figure 1).

A major breakthrough, which is now widely recognized as the beginning of the space photometry revolution of asteroseismology, was achieved by the French-led *CoRoT* (Convection, Rotation and planetary Transits) satellite. *CoRoT* detected oscillations in a number of main-sequence stars (e.g. Appourchaux et al. 2008; Michel

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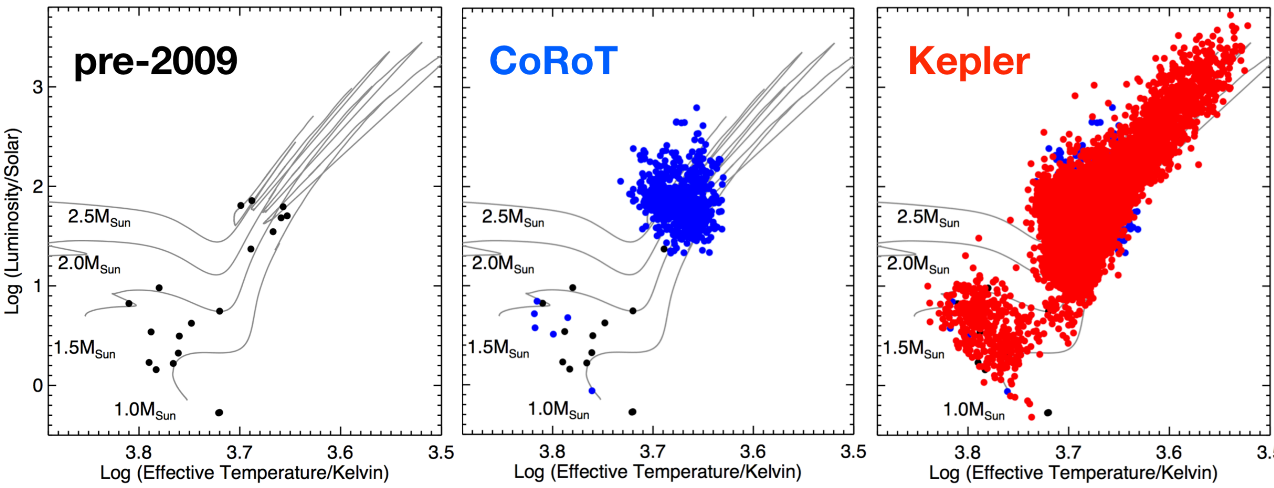

Fig. 1. H–R diagram showing stars with detected solar-like oscillations prior to 2009 (left panel), and after adding detections by the *CoRoT* (middle panel) and *Kepler* (right panel) missions. Grey lines show evolutionary tracks for solar-metallicity with masses as marked. The space-photometry revolution has increased the number of solar-like oscillators by three orders of magnitude over the past decade.

et al. 2008) and several thousands of red-giant stars (e.g. Hekker et al. 2009) (middle panel of Figure 1). In particular, *CoRoT* demonstrated unambiguously, for the first time, that red giants oscillate in non-radial modes (De Ridder et al. 2009), a result which opened the door for detailed studies of the interior structure of red giants (see Hekker & Christensen-Dalsgaard 2017, for a recent review).

Kepler, launched in 2009, completed the revolution of asteroseismology by covering the low-mass H–R diagram with detections. It detected oscillations in over 500 main-sequence and subgiant stars (Chaplin et al. 2014) and over twenty thousand red giants (Hekker et al. 2011; Stello et al. 2013; Yu et al. 2016), enabling the study of oscillations across the low-mass H–R diagram (right panel of Figure 1). The larger number of red giants with detected oscillations is due to a combination of two effects. First, oscillation amplitudes increase with luminosity (Kjeldsen & Bedding 1995), making a detection easier at a given apparent magnitude. Secondly, the majority of targets were observed with 30-minute sampling, setting an upper limit of $\log g \sim 3.5$ (since less evolved stars oscillate above the Nyquist frequency).

2 Lessons Learned from CoRoT and Kepler

CoRoT and *Kepler* yielded numerous breakthroughs for solar-like oscillators. One of the most influential discoveries was that scaling relations for global asteroseismic observables such as the frequency of maximum power, the large frequency separation, and oscillation amplitudes – all of which can be measured trivially from power spectra – are remarkably precise across nearly the entire low-mass H–R diagram (e.g. Stello et al. 2009; Huber et al. 2011; Mosser et al. 2012). The use of these scaling relations started the era of "ensemble asteroseismology" through the large-scale determination of stellar radii and masses (Kallinger et al. 2009), paving the way for the now widely successful synergy between asteroseismology and galactic archeology (Miglio et al. 2013, e.g.). Furthermore, the systematic discovery of mixed modes and rotational splittings opened up numerous breakthrough studies of the interior structure and rotation of subgiants and red giants (e.g. Beck et al. 2011; Bedding 2014; Mosser et al. 2014; Stello et al. 2016).

Space-based observations of solar-like oscillators also uncovered several new challenges. For example, *CoRoT* and *Kepler* demonstrated that mode lifetimes decrease strongly for hot stars, causing an increase in the line-widths which hampers identification of radial and non-radial modes. The "bloody F star" problem has been partially addressed through the phase offset ϵ (White et al. 2012), but remains a major obstacle for carrying out asteroseismology of hot stars. In addition, the transition of solar-like oscillators to classical pulsators remains only poorly understood, and causes major uncertainties when predicting amplitudes and thus detection yields for current and future space-based missions such as *TESS* and PLATO.

Another major challenge for *Kepler* was that the majority of oscillating stars are relatively faint, and thus lack independent observational constraints that are required to fully exploit the information provided by individual frequencies. For example, the potential of the *Kepler* "legacy" sample to constrain the convective

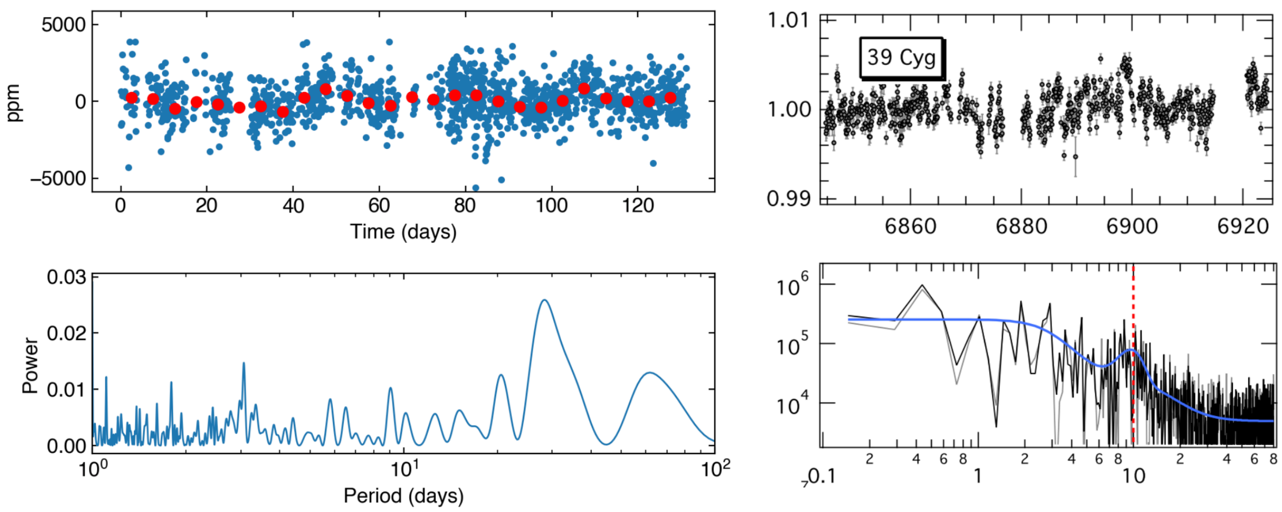

Fig. 2. *Left:* BRITE Constellation light curve of α Cen obtained in 2014 (top), binned into one-orbit (blue circles) and one-day (red circles) averages. A periodogram shows a significant peak at 28.3 ± 0.5 days, which may correspond to the rotation period of α Cen A (see text). *Right:* BRITE Constellation light-curve and power spectrum of the red giant 39 Cyg, showing the clear detection of solar-like oscillations. Adapted from Kallinger et al. (2019).

mixing length parameters (Silva Aguirre et al. 2017) and initial Helium abundances (Verma & Silva Aguirre 2019) is at times limited by the lack of fundamental constraints such as temperatures, radii and masses from interferometry and/or binary systems.

Small space telescopes such as BRITE Constellation play an important role by filling the gap left by the inability of most space instruments to observe very bright stars. A prominent example is α Cen: while fundamental properties of both components have been exceptionally well constrained using astrometry and asteroseismology, their rotation periods still remain a matter of debate. Figure 2a shows the BRITE light-curve of α Cen obtained 2014. The continuous coverage over 120 days reveals variability with a period of 28.3 ± 0.5 days. α Cen is not resolved in BRITE observations, but – based on the activity cycle of both components (Ayres 2018) – the period that is observed probably corresponds to α Cen A. That period is consistent with, but significantly more precise than, previous estimates from asteroseismic splittings (21 ± 9 days, Fletcher et al. 2006), and when dilution by component B is taken into account the amplitude of the spot modulation (~ 370 ppm) is consistent with that of relatively quiescent solar-type stars (van Saders et al. 2019). BRITE follow-up observations in 2018 provided only a preliminary confirmation of this signal, tentatively attributed to change in the spot coverage. The period identified in the 2014 dataset should therefore be viewed with caution.

BRITE has also detected oscillations in bright red giants such as 39 Cyg (Fig. 2, right, Kallinger et al. 2019). 39 Cyg ($V = 4.4$) is eight magnitudes brighter than the average *Kepler* red giant, thus providing an excellent opportunity to study oscillations in red giants with well determined independent parameters.

3 First Results from the *TESS* Mission

3.1 Target Selection

The NASA *TESS* Mission (Ricker et al. 2014) was launched in April 2018. Located in a 2:1 lunar resonance orbit, *TESS* observes 24×96 degree fields for 27 days, with continuous coverage near the ecliptic poles. In addition to downloading the entire FOV every 30-minutes (full-frame images, FFIs), *TESS* also observes a subset of targets in a 2-minute cadence, which is suitable for the detection of oscillations in solar-type stars.

The selection of asteroseismology targets for the *TESS* prime mission was coordinated within the TESS Asteroseismic Science Consortium (TASC). To select solar-like oscillators, we calculated a detection probability given estimates of effective temperature, luminosity, apparent *TESS* magnitude and the expected number of observed sectors for all stars in Hipparcos and Gaia DR2 following the method by Chaplin et al. (2011), modified for the *TESS* mission. The resulting Asteroseismic Target List (ATL) for the *TESS* mission is described in detail in Schofield et al. (2019).

Figure 3 shows an expected representative yield of solar-like oscillators from *TESS* compared to ground-

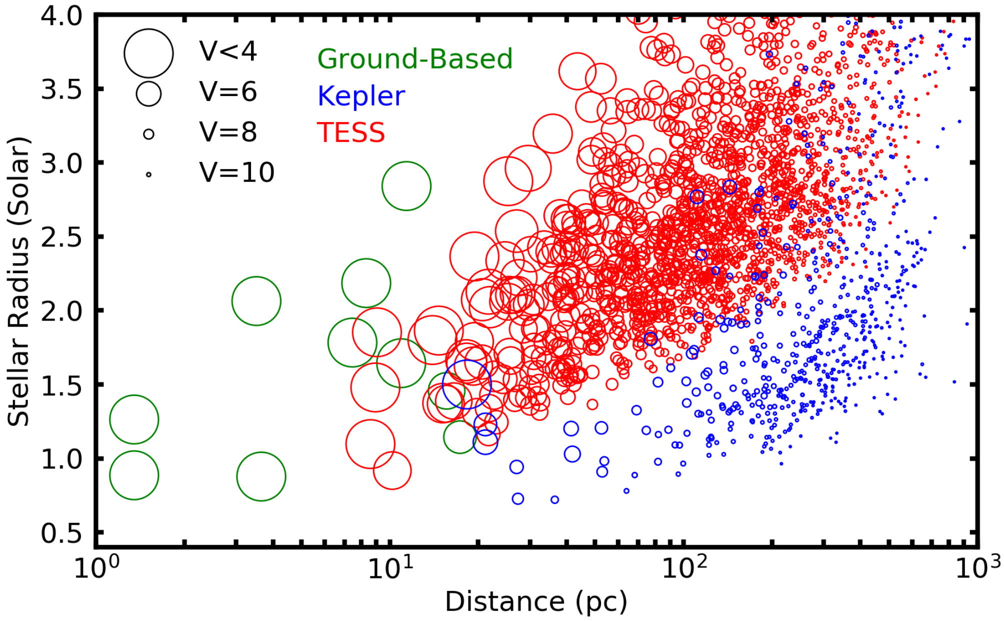

Fig. 3. Stellar radius versus distance for solar-like oscillators detected using ground-based observations (green circles), *Kepler* (blue circles), and a representative expected yield from *TESS* (red circles) based on the *TESS* Asteroseismic Target List (ATL, Schofield et al. 2019). Symbol sizes scale with the apparent V-band magnitude, as indicated on the plot. The brightest and closest *Kepler* detections are θ Cyg (Guzik et al. 2016) and 16 Cyg A and B (Metcalfe et al. 2015). *TESS* is expected to complement the *Kepler* yield by detecting oscillations in bright, evolved stars.

based observations and the *Kepler* mission. Owing to its smaller aperture, the average *TESS* detection is expected to be $\sim$5 magnitudes brighter, more evolved, and closer compared to *Kepler*. *TESS* is thus expected to complement the parameter space explored by *Kepler* which yielded a substantial number of solar-type stars that were relatively faint. Based on preliminary performance, the total yield of solar-like oscillators from *TESS* in the prime mission is expected to range between 1000–2000 stars, a 2–4-fold increase in yield over the *Kepler* mission.

3.2 Asteroseismology of *TESS* Exoplanet Host Stars

The search for solar-like oscillations with *TESS* initially focussed on exoplanet host stars, for which light-curves were first made publicly available to facilitate ground-based follow-up observations. The first claimed detection of oscillations was made for the solar-type star π Men (Gandolfi et al. 2018), which hosts the first transiting exoplanet discovered by *TESS* (Huang et al. 2018). Subsequent analysis of the π Men light-curve showed that the power spectrum noise level is twice as large as the predicted oscillation amplitude*, thus demonstrating that the claimed detection of oscillations by Gandolfi et al. (2018) could not have been correct.

The first confirmed detection by *TESS* of solar-like oscillations was made in the exoplanet host-star HD 221416 (TESS Object of Interest 197, TOI-197), a $V = 8.2$ mag late subgiant star (Huber et al. 2019). The power spectrum (Figure 4, left) shows a clear detection of mixed dipole modes. Asteroseismic modelling combined with spectroscopic $T_{\rm eff}$ metallicity and *Gaia* luminosity yielded a precise characterization of the host-star radius ($R_\star = 2.943 \pm 0.064 R_\odot$), mass ($M_\star = 1.212 \pm 0.074 M_\odot$) and age ($4.9 \pm 1.1$ Gyr), and demonstrated that it has just started ascending the red-giant branch. The combination of asteroseismology with transit modelling and RV observations showed that the planet is a "hot Saturn" ($R_{\rm p} = 9.17 \pm 0.33 R_\oplus$) with an orbital period of $\sim$14.3 days, irradiance of $F = 343 \pm 24 F_\oplus$, moderate mass ($M_{\rm p} = 60.5 \pm 5.7 M_\oplus$) and density ($\rho_{\rm p} = 0.431 \pm 0.062\,{\rm g\,cm^{-3}}$). The properties of HD 221416 b showed that the correlation between host-star metallicity and planet mass found in sub-Saturns (Petigura et al. 2017) does not extend to larger radii, indicating that planets in the transition between sub-Saturns and Jupiters follow a relatively narrow range of densities. With a density measured to $\sim$15%, HD 221416 b is one of the most carefully characterized Saturn-sized planets

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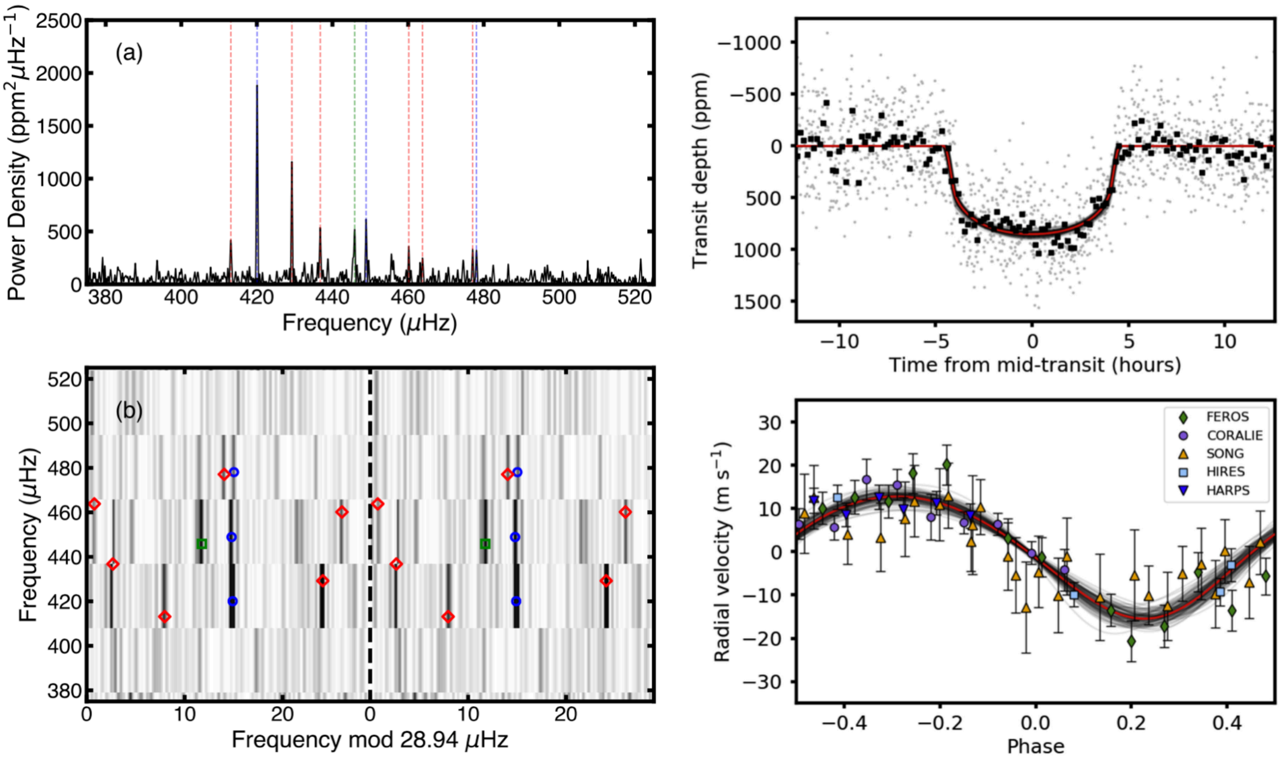

Fig. 4. Detection of solar-like oscillations in HD 221416 (TESS Object of Interest 197, TOI-197), the first *TESS* asteroseismic exoplanet host star. Left: power spectrum and echelle diagram of the *TESS* time-series after removing the planetary transits. From Huber et al. (2019); © AAS, reproduced with permission. Right: Phase-folded transit light-curve and RV follow-up observations using six different instruments. The combination of asteroseismology, transits and RV measurements constrained the density of the planet to $\sim$15%, making the planet one of the most carefully characterized Saturn-sized planets to date.

to date.

In addition to recognizing stars that are hosting transiting planets, *TESS* has detected oscillations in stars previously known to host planets and which were discovered using the Doppler method (e.g. Campante et al. 2019). *TESS* is expected to yield a significant number of both new and known exoplanet hosts that are amenable to asteroseismic characterization (Campante et al. 2016), including new discoveries of transiting planets around oscillating red-giant-branch stars (e.g. Grunblatt et al. 2019).

4 Conclusions

Asteroseismology of solar-like oscillators has undergone an exciting revolution over the past decade. This review has discussed how small space-based missions such as the BRITE Constellation is, and will remain, a critical component in characterizing the brightest stars, as akready achieved (for example) through measuring the poorly constrained rotation period of α Cen A, or asteroseismology of bright red giants. Current and future large space-based mission such as *TESS* and PLATO will continue the *CoRoT* and *Kepler* legacies, filling in the parameter space of nearby solar-like oscillators including the systematic characterization of exoplanet host stars.

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