Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

OBSERVATIONS OF INTERNAL STRUCTURES OF LOW-MASS MAIN-SEQUENCE STARS AND RED GIANTS

S. Hekker[1, 2]

Abstract. Over the past years, asteroseismic observations have been able to probe the internal structures of stars. In this review, I highlight some of the results that have been presented and some open questions that are still being addressed.

Keywords: asteroseismology, stars: interiors, stars: oscillations (including pulsations), stars: solar-type

1 Introduction

Following the advent of the space observatories CoRoT and *Kepler*, the number of stars in which solar-like oscillations have been detected has grown rapidly, and this growth is predicted to continue with data from the current TESS mission and the future Plato mission (see Fig. 1, for a schematic overview of the order of magnitude of the number of red-giant stars with asteroseismic time-series observations versus time). The different space observatories provide data with different duration and hence different resolutions in the frequency domain. These differing frequency resolutions determine the amount of information as well as the accuracy and precision with which the information regarding the stellar structure can be extracted. This in turn determines the science questions that can be answered with a specific set of observations. The data of many stars with short time series are of importance for more statistical studies where global stellar parameters are required for a large number of stars. This is, for instance, the case for galactic archaeology and planet abundance studies. The high resolution data can be used to infer information regarding the internal structure of stars. In particular, the *Kepler* data spanning nearly four years of data are suitable to study stellar internal structures. Here, I present an overview of some of the recent results in this regard and some topics that require further studies to reveal stellar internal structures.

2 Datasets

With the *Kepler* mission a couple of hundred main-sequence stars with solar-like oscillations have been observed (Chaplin et al. 2011). Out of this sample there are nearly a hundred stars that have been considered for further investigations using their individual frequencies, the so-called KAGES (Silva Aguirre et al. 2015; Davies et al. 2016) and LEGACY (Lund et al. 2017; Silva Aguirre et al. 2017) samples. In the following sections, I highlight a few examples of stellar structure information that have been obtained from (subsamples) of the KAGES and LEGACY stars.

Red-giant stars were well represented among the stars observed with *Kepler*. Catalogues of red giants with detected solar-like oscillations are presented in several papers starting with early results by Hekker et al. (2011) to the most recent public catalogue by Yu et al. (2018). These catalogues contain stars with observations of different lengths. The stars with observations covering the full timespan of the *Kepler* mission (about four years) are the ones of interest for stellar structure studies. A subset of these stars have been selected for complementary observation with the SDSS-APOGEE spectrograph and are known as the APOKASC sample (Pinsonneault et al. 2014, 2018). This sample of 6661 stars is currently one of the best studied samples of red-giant stars.

[1] Max Planck Institute for Solar system research, Justus-von-Liebig Weg 3, 37077 Göttingen, Germany
[2] Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

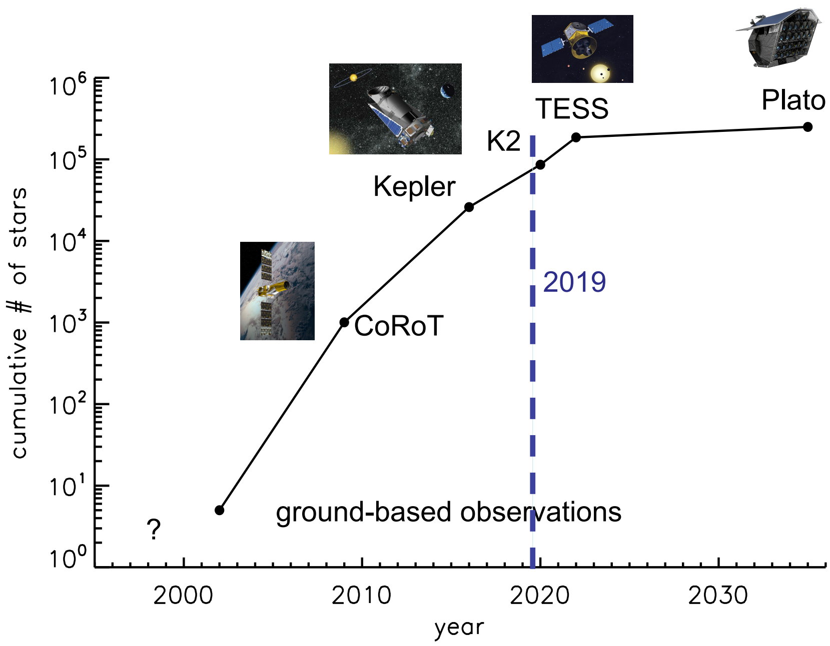

Fig. 1. The approximate cumulative numbers of red-giant stars with asteroseismic timeseries observations versus time in years. These are based on current data releases and rough estimates for K2, TESS and Plato. The blue dashed line indicates the time of the *Stars and their Variability Observed from Space* meeting in Vienna.

3 Inferences from solar-like oscillations

Solar-like oscillations can be trapped in a cavity in the outer layers of a star where the restoring force is pressure and the oscillations have the nature of standing acoustic waves. These oscillation modes are referred to as p-mode oscillations. Solar-like oscillations can also be trapped in a cavity in the inner radiative region of the stars where the restoring force is buoyancy and the oscillations have the character of standing gravity waves. These are called g-mode oscillations. I shall first discuss internal structure results obtained from pure p-modes and then, I will present some of the results for more evolved subgiant and red-giant stars where non-radial modes have a mixed p-g nature as a result of the coupling, or resonance interaction, between an oscillation in the p-mode cavity and an oscillation in the g-mode cavity (e.g. Osaki 1975; Aizenman et al. 1977; Deheuvels & Michel 2010; Hekker & Mazumdar 2014).

3.1 Inferences from pressure modes

Solar-like oscillations in low-mass main-sequence stars are all p-mode oscillations. For more evolved stars the radial modes have a pure p-mode character, while for the non-radial modes, the pure p mode nature gives way to a mixed p-g nature as the effects of the buoyancy increases with evolution.

3.1.1 Acoustic depth of the He II ionisation zone and the base of the convection zone

Stellar structure changes that occur at a length scale that is short compared to the local wavelength of the oscillations cause a 'glitch' in the wave. This glitch is apparent as small periodic changes in the oscillation frequencies and can be seen in the second difference ($\Delta_2\nu(n,l)$) measurements:

$$\Delta_2\nu(n,l) = \nu(n-1,l) - 2\nu(n,l) + \nu(n+1,l) \qquad (3.1)$$

where $\nu(n,l)$ is the frequency of a mode with radial order n and degree l. Note that a 5 point difference is used in some cases.

Two well-known glitches in main-sequence stars are the HeII ionisation zone and the base of the convection zone. Each of these glitches leaves a sinusoidal trace in the second differences, which can be fitted with the following function:

$$\Delta_2\nu = a_0 + \frac{b_2}{\nu^2}\sin(4\pi\nu\tau_{\rm bcz} + 2\phi_{\rm bcz}) + c_0\nu e^{-c_2\nu^2}\sin(4\pi\nu\tau_{\rm HeII} + 2\phi_{\rm HeII}) \tag{3.2}$$

where a_0,b_2, c_0, c_2, $\tau_{\rm bcz}$, $\phi_{\rm bcz}$, $\tau_{\rm HeII}$, $\phi_{\rm HeII}$ are eight free parameters of the fit (Mazumdar et al. 2014, showed some alternative ways to extract information from the glitches). The parameters $\tau_{\rm bcz}$ and $\tau_{\rm HeII}$ are the acoustic depths of the base of the convection zone and HeII ionisation zone, respectively. In this way, these model-independent observables directly provide information on the stellar internal structure. For more details regarding the acoustic depth of the HeII ionisation zone and base of the convection zone, I refer the reader to e.g. Houdek & Gough (2007), Mazumdar et al. (2014), Verma et al. (2014a,b), Vrard et al. (2015), where the latter study concerned red-giant stars, while earlier studies were focussed on main-sequence stars.

3.1.2 Surface helium abundance

Solar-like oscillators are too cool to have helium absorption lines visible in their spectra and therefore the helium abundance can not be determined through spectroscopic observations of these stars. The prospect of determining the helium abundance from the HeII signature in the oscillation frequencies was first investigated by Basu et al. (2004) and by Broomhall et al. (2014) who specifically looked at red-giant stars. Both studies concluded that the oscillatory signal in the frequencies caused by the depression in the adiabatic index Γ_1 in the HeII ionisation zone can be used to determine the envelope helium abundance of these stars, though relative errors in the frequencies need to be small, i.e. of the order of 10^{-4} (Basu et al. 2004).

Indeed, Verma et al. (2019) could determine the envelope helium abundance of 38 stars in the *Kepler* seismic LEGACY sample. This led them to confirm that atomic diffusion does take place in solar-type stars. These authors subsequently used the measured surface abundances in combination with the settling predicted by stellar models to determine the initial abundances, which were then used to obtain preliminary estimates of the primordial helium abundance to be 0.244 ± 0.019.

3.1.3 Sound speed profiles

Structure inversions can be used to reveal the sound-speed profile in the stellar internal structure. In the early days, the only star for which enough data were available to perform structure inversions was the Sun. In recent years, some of the issues such as the less accurate determinations of mass and radius for stars other than the Sun and the limitations of only observing low-degree modes from the integrated light of stars have been mitigated. First inversion results for main-sequence stars other than the Sun, were presented based on inversions using global quantities in a series of papers by G. Buldgen and collaborators (e.g. Buldgen et al. 2015, 2016, 2019). These results were subsequently followed by structure inversions for the squared isothermal sound speed using an algorithm called 'inversions for agreement' (Bellinger et al. 2017, 2019). These results tentatively show that for stars that have similar parameters as the Sun the best-fit model shows reasonable agreement with the sound speed profile determined through inversions. On the other hand, if the structure is very different from that of the Sun, for instance owing to a convective core, the inversion results show significant differences compared to the best fit model (Bellinger et al. 2019). The cause of these discrepancies is still unknown, and is not remedied by known physics in the form of convective overshooting or elemental diffusion, thereby showing that other physical processes should be included in the models.

3.2 Inferences from mixed pressure-gravity modes

In more evolved stars with expanded envelopes and denser cores compared to main-sequence stars, the frequencies in the p-mode and g-mode cavities have similar values, which allows non-radial modes to couple and form mixed modes. These mixed modes have p-mode like properties in the outer layers and g-mode like properties in the deep layers, and hence, these mixed modes are sensitive to the stellar cores. This feature is increasingly being used to extract stellar internal structure information for evolved solar-like oscillators. For an in-depth review of giant-star seismology, I refer the reader to Hekker & Christensen-Dalsgaard (2017).

3.2.1 Distinguishing red-giant and red-clump stars

The first detection of mixed dipole modes in red-giant stars (Beck et al. 2011) was subsequently followed by the finding that the typical spacing in period between mixed dipole modes can discriminate between stars that have hydrogen-shell burning as their sole nuclear energy supply and stars that also burn helium in their core (Bedding et al. 2011; Mosser et al. 2011, 2014; Elsworth et al. 2019). The difference in the period spacing is due to the fact that the core-helium burning stars have a convective core, whilst the inert helium core in hydrogen-shell burning stars is radiative (Christensen-Dalsgaard 2014).

In addition to the spacing in period, the mixed modes also provide input on the coupling between the mode in the p and g cavity and the phase offset of the gravity modes (Mosser et al. 2017b, 2018; Hekker et al. 2018; Pinçon et al. 2019). These works reveal that the coupling is directly related to the width of the evanescent zone between the p and g cavity and therefore have different values for red-giant branch (RGB) and core-helium burning (CHeB) stars (Mosser et al. 2017b; Hekker et al. 2018). Additionally, the phase offset of gravity modes may probe the local density contrast of the core (see Fig. 10 of Hekker et al. 2018), and also appears to be related to the evolutionary phase (Mosser et al. 2018; Pinçon et al. 2019). Hence these features provide further prospects to study the internal structures of red giants.

3.2.2 Core properties

Cunha et al. (2015, 2019) showed that mixed modes in red-giant stars are affected by structural glitches near the cores of these stars. Along the red-giant branch, glitch-induced variations occur only at the luminosity bump. For the post-helium-ignition stages, glitches are only expected in the early phases of helium-core burning and at the beginning of helium-shell burning. This is due to the requirement that the structural change has to be sharp compared to the local wavelength. The local wavelength is short in the core regions and hence only in these particular phases the shell-burning feature is seen as sharp by the oscillation modes. Thus, the detection of a glitch in the mixed modes already allows us to determine the evolutionary state of the star to unprecedented detail, while extracting details of the structure of the cores awaits further development of analysis techniques.

3.2.3 Radial differential rotation

Different mixed modes have different sensitivities to the p or g cavity, which allows for probing radial differential rotation in case the mixed modes are also rotationally split. Beck et al. (2012); Deheuvels et al. (2012, 2014); Di Mauro et al. (2016); Triana et al. (2017); Di Mauro et al. (2018) analysed a small set of stars and showed that the cores of subgiants and red giant branch stars rotate faster than their surfaces (see also Marques et al. 2013; Goupil et al. 2013). Furthermore, Deheuvels et al. (2015) reported only weak radial differential rotation in six intermediate-mass core helium-burning stars. The results of individual stars are complemented by ensemble results for both red-giant branch and core helium-burning stars by (Mosser et al. 2012; Gehan et al. 2018). The latter works show that the core rotation rate is almost constant along the RGB, while cores of CHeB stars rotate about six time slower. Sills & Pinsonneault (2000) showed that this change in core rotation rate can't be fully explained by the expansion of the core indicating that internal momentum has been transferred from the core to the envelope.

Angular momentum transport in stellar interiors (see for a recent review Aerts et al. 2019, and references therein) continues to be difficult to understand. As shown by, e.g., Cantiello et al. (2014) reproducing the observed rotation rates requires some new physics to be included in the modelling. Recent suggestions, such as extraction of angular momentum from the core by mixed modes (Belkacem et al. 2015a,b), magnetic instabilities (Eggenberger et al. 2019) or the magnetic Tayler instability (Fuller et al. 2019) could bring the models more in line with the observations.

4 The road ahead

As the state-of-the-art results show, we are now inferring information on the stellar structure through the global oscillation modes, in other words asteroseismology is effective. Despite the achievements, there are still many open questions. One of the issues that is currently being worked on is measuring and identifying oscillation modes in the thousands of red-giant stars that have time-series data. Kallinger (2019) released frequencies and mode identifications of all stars in the APOKASC sample based on the AɜʙA code. Additionally, Themeßl et al. (these proceedings contribution 5o12) provide first results from the TACO (Tools for Automated Characterisation of Oscillations) code that has been developed to analyse the power spectra of solar-like oscillations in an automated way. The parameters of the identified oscillation modes are essential inputs for further stellar structure studies.

One of these further studies involves the (unusual) structure of red-giant stars with suppressed dipole modes (e.g. Fuller et al. 2015; Stello et al. 2016; Cantiello et al. 2016; Loi & Papaloizou 2018). One of the current hypotheses is that these could be caused by large magnetic fields in the cores of stars with masses larger than the Sun which rotated faster during their main-sequence phase. The scenario proposed by Fuller et al. (2015) was based on the presence of a poloidal magnetic field in the core of red-giant stars which would completely damp the mixed modes. However, Mosser et al. (2017a) refuted this argument by showing that some mixed modes are still present in the observed spectra. Loi & Papaloizou (2018) proposed to mitigate this by adding a toroidal field. Since it is not possible to observe these magnetic fields in the core directly, the cause of the suppressed dipole modes is still debated. One of the alternative hypotheses could be a connection to binarity as indicated by Themeßl et al. (2017).

Another ingredient of stellar structure that is still under investigation is the convection which drives and damps solar-like oscillations. Progress, partly using 3-D simulations, has recently been made by, e.g., Samadi et al. (2012), Belkacem et al. (2019), Houdek et al. (2019), Zhou et al. (2019). Additionally, overshooting at convective boundaries is also still being actively investigated using solar-like oscillations. It is generally believed that overshoot is a necessary ingredient in models in order to match observational constraints. Angelou et al. (submitted) have shown that overshooting can be estimated from seismic data using frequency ratios. These again may lead to interesting findings regarding the internal structures of stars with solar-like oscillations.

5 Final remarks

About 10 years after the launch of *Kepler* the asteroseismic revolution may be over, however asteroseismology of solar-like oscillators has just begun. Inferences about the internal structures of these stars are ongoing and with the current data from MOST (Matthews et al. 2000), CoRoT (Baglin et al. 2007), *Kepler* (Borucki et al. 2009), K2 (Howell et al. 2014), BRITE-Constellation (Weiss et al. 2014), SONG (Grundahl et al. 2008) and TESS (Ricker et al. 2016) and the data that we still expect from BRITE-Constellation, SONG, the TESS extended mission as well as the planned Plato (Rauer et al. 2014) mission, we will be able to increase our knowledge and understanding further.

I am grateful for comments by Sarbani Basu and Yvonne Elsworth on earlier versions of this manuscript, which improved it significantly.

References

Aerts, C., Mathis, S., & Rogers, T. M. 2019, ARA&A, 57, 35

Aizenman, M., Smeyers, P., & Weigert, A. 1977, A&A, 58, 41

Baglin, A., Auvergne, M., Barge, P., et al. 2007, in AIPCS, Vol. 895, Fifty Years of Romanian Astrophysics, ed. C. Dumitrache, N. A. Popescu, M. D. Suran, & V. Mioc, 201–209

Basu, S., Mazumdar, A., Antia, H. M., & Demarque, P. 2004, MNRAS, 350, 277

Beck, P. G., Bedding, T. R., Mosser, B., et al. 2011, Science, 332, 205

Beck, P. G., Montalban, J., Kallinger, T., et al. 2012, Nature, 481, 55

Bedding, T. R., Mosser, B., Huber, D., et al. 2011, Nature, 471, 608

Belkacem, K., Kupka, F., Samadi, R., & Grimm-Strele, H. 2019, A&A, 625, A20

Belkacem, K., Marques, J. P., Goupil, M. J., et al. 2015a, A&A, 579, A31

Belkacem, K., Marques, J. P., Goupil, M. J., et al. 2015b, A&A, 579, A30

Bellinger, E. P., Basu, S., Hekker, S., & Ball, W. H. 2017, ApJ, 851, 80

Bellinger, E. P., Basu, S., Hekker, S., & Christensen-Dalsgaard, J. 2019, ApJ, 885, 143

Borucki, W., Koch, D., Batalha, N., et al. 2009, in IAU Symposium, Vol. 253, Transiting Planets, ed. F. Pont, D. Sasselov, & M. J. Holman, 289–299

Broomhall, A. M., Miglio, A., Montalbán, J., et al. 2014, MNRAS, 440, 1828

Buldgen, G., Farnir, M., Pezzotti, C., et al. 2019, A&A, 630, A126

Buldgen, G., Reese, D. R., Dupret, M. A., & Samadi, R. 2015, A&A, 574, A42

Buldgen, G., Salmon, S. J. A. J., Reese, D. R., & Dupret, M. A. 2016, A&A, 596, A73

Cantiello, M., Fuller, J., & Bildsten, L. 2016, ApJ, 824, 14

Cantiello, M., Mankovich, C., Bildsten, L., Christensen-Dalsgaard, J., & Paxton, B. 2014, ApJ, 788, 93

Chaplin, W. J., Kjeldsen, H., Christensen-Dalsgaard, J., et al. 2011, Science, 332, 213

Christensen-Dalsgaard, J. 2014, Asteroseismology of red giants (Cambridge University Press, pages = 194, adsurl = https://ui.adsabs.harvard.edu/abs/2014aste.book..194C, adsnote = Provided by the SAO/NASA Astrophysics Data System)

Cunha, M. S., Avelino, P. P., Christensen-Dalsgaard, J., et al. 2019, MNRAS, 490, 909

Cunha, M. S., Stello, D., Avelino, P. P., Christensen-Dalsgaard, J., & Townsend, R. H. D. 2015, ApJ, 805, 127

Davies, G. R., Silva Aguirre, V., Bedding, T. R., et al. 2016, MNRAS, 456, 2183

Deheuvels, S., Ballot, J., Beck, P. G., et al. 2015, A&A, 580, A96

Deheuvels, S., Doğan, G., Goupil, M. J., et al. 2014, A&A, 564, A27

Deheuvels, S., García, R. A., Chaplin, W. J., et al. 2012, ApJ, 756, 19

Deheuvels, S. & Michel, E. 2010, Ap&SS, 328, 259

Di Mauro, M. P., Ventura, R., Cardini, D., et al. 2016, ApJ, 817, 65

Di Mauro, M. P., Ventura, R., Corsaro, E., & Lustosa De Moura, B. 2018, ApJ, 862, 9

Eggenberger, P., Buldgen, G., & Salmon, S. J. A. J. 2019, A&A, 626, L1

Elsworth, Y., Hekker, S., Johnson, J. A., et al. 2019, MNRAS, 489, 4641

Fuller, J., Cantiello, M., Stello, D., Garcia, R. A., & Bildsten, L. 2015, Science, 350, 423

Fuller, J., Piro, A. L., & Jermyn, A. S. 2019, MNRAS, 485, 3661

Gehan, C., Mosser, B., Michel, E., Samadi, R., & Kallinger, T. 2018, A&A, 616, A24

Goupil, M. J., Mosser, B., Marques, J. P., et al. 2013, A&A, 549, A75

Grundahl, F., Christensen-Dalsgaard, J., Arentoft, T., et al. 2008, Communications in Asteroseismology, 157, 273

Hekker, S. & Christensen-Dalsgaard, J. 2017, A&A Rev., 25, 1

Hekker, S., Elsworth, Y., & Angelou, G. C. 2018, A&A, 610, A80

Hekker, S., Gilliland, R. L., Elsworth, Y., et al. 2011, MNRAS, 414, 2594

Hekker, S. & Mazumdar, A. 2014, in IAU Symposium, Vol. 301, Precision Asteroseismology, ed. J. A. Guzik, W. J. Chaplin, G. Handler, & A. Pigulski, 325–331

Houdek, G. & Gough, D. O. 2007, MNRAS, 375, 861

Houdek, G., Lund, M. N., Trampedach, R., et al. 2019, MNRAS, 487, 595

Howell, S. B., Sobeck, C., Haas, M., et al. 2014, PASP, 126, 398

Kallinger, T. 2019, arXiv e-prints, arXiv:1906.09428

Loi, S. T. & Papaloizou, J. C. B. 2018, MNRAS, 477, 5338

Lund, M. N., Silva Aguirre, V., Davies, G. R., et al. 2017, ApJ, 835, 172

Marques, J. P., Goupil, M. J., Lebreton, Y., et al. 2013, A&A, 549, A74

Matthews, J. M., Kuschnig, R., Walker, G. A. H., et al. 2000, ASPCS, Vol. 203, Ultraprecise Photometry from Space: The MOST Microsat Mission (ASP Conference Series), 74–75

Mazumdar, A., Monteiro, M. J. P. F. G., Ballot, J., et al. 2014, ApJ, 782, 18

Mosser, B., Barban, C., Montalbán, J., et al. 2011, A&A, 532, A86

Mosser, B., Belkacem, K., Pinçon, C., et al. 2017a, A&A, 598, A62

Mosser, B., Benomar, O., Belkacem, K., et al. 2014, A&A, 572, L5

Mosser, B., Gehan, C., Belkacem, K., et al. 2018, A&A, 618, A109

Mosser, B., Goupil, M. J., Belkacem, K., et al. 2012, A&A, 548, A10

Mosser, B., Pinçon, C., Belkacem, K., Takata, M., & Vrard, M. 2017b, A&A, 600, A1

Osaki, Y. 1975, PASJ, 27, 237

Pinçon, C., Takata, M., & Mosser, B. 2019, A&A, 626, A125

Pinsonneault, M. H., Elsworth, Y., Epstein, C., et al. 2014, ApJS, 215, 19

Pinsonneault, M. H., Elsworth, Y. P., Tayar, J., et al. 2018, ApJS, 239, 32

Rauer, H., Catala, C., Aerts, C., et al. 2014, Experimental Astronomy, 38, 249

Ricker, G. R., Vanderspek, R., Winn, J., et al. 2016, SPIE Conference Series, Vol. 9904, The Transiting Exoplanet Survey Satellite (SPIE), 99042B

Samadi, R., Belkacem, K., Dupret, M. A., et al. 2012, A&A, 543, A120

Sills, A. & Pinsonneault, M. H. 2000, ApJ, 540, 489

Silva Aguirre, V., Davies, G. R., Basu, S., et al. 2015, MNRAS, 452, 2127

Silva Aguirre, V., Lund, M. N., Antia, H. M., et al. 2017, ApJ, 835, 173

Stello, D., Cantiello, M., Fuller, J., et al. 2016, Nature, 529, 364

Themeßl, N., Hekker, S., & Elsworth, Y. 2017, in EPJ Web of Conferences, Vol. 160, EPJ Web of Conferences, 05009

Triana, S. A., Corsaro, E., De Ridder, J., et al. 2017, A&A, 602, A62

Verma, K., Antia, H. M., Basu, S., & Mazumdar, A. 2014a, ApJ, 794, 114
Verma, K., Faria, J. P., Antia, H. M., et al. 2014b, ApJ, 790, 138
Verma, K., Raodeo, K., Basu, S., et al. 2019, MNRAS, 483, 4678
Vrard, M., Mosser, B., Barban, C., et al. 2015, A&A, 579, A84
Weiss, W. W., Rucinski, S. M., Moffat, A. F. J., et al. 2014, PASP, 126, 573
Yu, J., Huber, D., Bedding, T. R., et al. 2018, ApJS, 236, 42
Zhou, Y., Asplund, M., & Collet, R. 2019, ApJ, 880, 13