Recent Advances in Asteroseismology of B and A Stars

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In the past few years, asteroseismology of B and A stars has advanced significantly thanks to the pristine data delivered by space telescopes such as *MOST*, *CoRoT*, *Kepler*, *TESS*, and *BRITE*-Constellation. Here I try to give an overview of some of these recent advances. Since the topic is quite broad and the achievements are numerous, I can only select a few highlights from my personal perspective and use those to illustrate the advancement of the field as a whole.

1 Introduction

1.1 Common Processes of B and A Stars

Stars of spectral types B and A are probably the most diverse group of stars in the Hertzsprung-Russell (HR) diagram as they exhibit many different physical mechanisms and features that also unite them somewhat. Pulsational instability with the excitation of both pressure (p-) and gravity (g-) modes in B and A stars is one of these processes. But to be able to analyze and interpret stellar oscillations, we have to be aware of all the other features present in B and A stars as they might influence the driving or damping of the pulsation modes under investigation. B and A stars can harbor magnetic fields (that are quite strong in some cases), display chemical peculiarities and spots in their atmospheres, show chemical gradients between their surfaces and their cores, typically rotate relatively fast, host exoplanets, and are affected by diffusion processes. All of these physical effects are a general challenge, both to observations and to theoretical models of stellar structure and evolution. Obviously they also challenge the interpretation of the oscillatory signal and the identification of pulsation modes. Recently developed methods aim to combine asteroseismology with some of the above mentioned physical effects for a more general approach. Magneto-asteroseismology interprets stellar oscillations together with the magnetic field properties. The chemical peculiarities of the stellar atmosphere are combined with the detection of chemical gradients inside stars from asteroseismology to find out how deep into the objects the peculiarity reaches. Diffusive processes contribute to the interior mixing analyzed with asteroseismology and can significantly influence stellar lifetimes, and the analysis of rotation periods measured from the surface (e.g., through rotational modulation caused by spots) is combined with the studies of angular momentum transport based on rotational splittings of pulsation frequencies and regular period spacings in g-mode pulsators.

1.2 Stellar Structure with Asteroseismology

Asteroseismology itself combines the classic observables such as effective temperature (T_{eff}), $\log g$, metallicity, distance, etc., with the asteroseismic diagnostics such as frequency of maximum amplitude, $\nu_{\max}$, small and large frequency separations, $\delta\nu$ and $\Delta\nu$, regular spacings in frequency (for p-modes) and period (for g-modes), and frequency splittings. Based on the observational detection of a set of pulsation frequencies in combination with the atmospheric parameters of the target, asteroseismologists aim to find the best fitting theoretical model explaining the observational results. The theoretical interpretation itself is based on equilibrium models of stellar structure with predictions of theoretical pulsation modes using assumptions for the micro- and macro-physics. The ultimate goal for the asteroseismic analysis is then to be able to identify the mode properties (n, l, m) of the observed pulsation frequencies. We typically simplify our theoretical models with the "basic" assumption of a non-rotating, non-magnetic star without a strong stellar wind - which is not appropriate for many of the pulsating B and A stars in particular as they often possess strong magnetic fields and tend to show high rotation velocities.

2 The "Space Photometry Revolution"

The *MOST* satellite (Walker et al., 2003) launched on June 30, 2003, was the first space telescope with asteroseismology as one of its scientific goals. Since then, time series photometry obtained from space has triggered a revolution in our understanding of the interior properties of stars in all evolutionary phases.

MOST (Walker et al., 2003) carried a 15-cm Rumak-Maksutov telescope and was able to obtain photometric time series of up to seven continuous weeks. Three different types of data could be taken:

(i) the brightest stars, i.e., with V magnitudes ranging from 0.4 to 5.5 mag, were observed through one of 36 Fabry microlenses (Reegen et al., 2006)

(ii) fainter stars with V magnitudes from 7 to 12 could be observed in the L-shaped open area of the CCD in the so-called "Direct Imaging" mode

(iii) in a similar magnitude range from 7 to 12 mag in V photometric time series of the *MOST* guide stars were taken (e.g. Zwintz et al., 2009a).

MOST was a pioneering mission which was operational until 2019.

In 2006, the European mission *CoRoT* (Auvergne et al., 2009) was launched with two main scientific goals: the search for exoplanets and asteroseismology. With its 27-cm telescope it could obtain data in the "asteroseismology fields" for stars between 5.7^{th} and 9^{th} magnitude and in the "exoplanet fields" for stars between 11.5^{th} and 16^{th} magnitude. *CoRoT* was the next logical step in context of instrument development for high-precision photometric time series for the analysis of stellar pulsations.

Another three years later, in 2009, the NASA *Kepler* (Borucki et al., 2010) space telescope was launched with its main purpose to search for habitable exoplanets in one pre-selected field in the constellation of Cygnus. The pristine photometric time series obtained for many thousands of stars in the magnitude range from 10 to 16 was used highly successfully for asteroseismology and brought the space photometry revolution to its first culmination.

The five operational nano-satellites of the *BRITE*-Constellation (Weiss et al., 2014) mission were launched in 2013 and 2014. With their 3-cm aperture telescopes, the *BRITE* satellites focus on the variability of the brightest and most massive stars and obtain photometric time series in two colors continuously for up to half a year. More than 50% of the *BRITE*-Constellation targets are B and A type stars brighter than ∼6 mag in V.

In 2018, the NASA *TESS* mission (Ricker, 2014) was launched as a nearly all-sky survey searching for extrasolar planets and performing asteroseismology. *TESS* carries a 10.5-cm telescope and targets stars in the I-magnitude range from 4 to 13 mag. From the first results based on *TESS* observations, the next culmination of the space photometry revolution can be expected.

3 Selected Open Questions in the Field of Pulsating B and A Stars

There are currently a number of open questions in the field of pulsating B and A stars:

- How can we precisely describe the interplay between all the physical processes acting in these stars?
- Why do only ∼10% of (hot) stars possess measurable magnetic fields? What is the origin of these sometimes strong fields and why do the other stars not show detectable magnetic properties?
- Can we reliably identify the evolutionary stages, and hence, ages for B and A type pulsating stars and reliably distinguish pre-main sequence from (early) main sequence and post-main sequence objects?
- Do we classify hybrid objects as separate classes of pulsators? Shall we still keep our identification of "instability regions" in the HR diagram or has this become obsolete?
- What is the influence of accretion and the circumstellar environment on the oscillations, in particular for Be and pre-main sequence (pre-MS) stars?

4 Asteroseismology of B Stars

The intermediate-mass to massive B stars with masses between about 3 and 30 solar masses contribute significantly to the chemical enrichment of the galaxy as they explode as supernovae in their final stages of evolution. Although the space missions *CoRoT* and *Kepler* only had a few massive stars (i.e., O and B type) in their fields-of-view, these limited data sets enabled the detection of many oscillation modes, regular spacings in periods, and the first asteroseismic studies of rotational mixing and angular momentum transport. Another important addition to the space photometry revolution for massive stars is the nano-satellite mission *BRITE*-Constellation with its main science goal to study the time-dependent behaviour of the most massive and luminous stars. Nevertheless, precise ground based measurements remain an important factor in the interpretation of B type pulsators.

4.1 β Cephei Stars

One of the more recent advances for the β Cephei stars, which have masses from 7 to 20 solar masses and pulsate in low radial order p- and g-modes with periods between

$\sim$2 and 12 hours, is described in Handler et al. (2017). The authors studied the star ν Eri using data obtained simultaneously from the *BRITE*-Constellation satellites and ground-based instruments and discovered 40 p- and g-mode frequencies including 23 linear combinations. From this, they identified the pulsation modes through amplitude ratios and phase differences.

Another interesting example is the monoperiodic pulsator ξ^1 CMa which hosts a dynamical magnetic field (Shultz et al., 2017). The authors report that fitting the Hα equivalent widths with a second order sinusoid resulted in a 30-year period. The same period can be found when analyzing the magnetic field variations. The residuals to the fit of the equivalent widths phased with the pulsation period yielded an amplitude three times larger than predicted by the photospheric model, and is about 0.5 cycles out of phase.

4.2 Slowly Pulsating B Stars

The data obtained by the *Kepler* mission advanced our knowledge about the intermediate mass Slowly Pulsating B (SPB) stars which show significant high order g-modes with periods between $\sim$0.5 and 3 days. Since pulsators with periods close to one day are particularly difficult to study with ground-based data due to the day-night cycle, the continuous photometric time series from space were needed to make progress in the field. The four year-long *Kepler* data revealed long sequences of nearly equidistant period spacings (e.g., 19 equally spaced dipole modes with rotationally split triples for KIC 10526294, Pápics et al., 2014). These provided constraints to the ages through the measurement of the central hydrogen fraction, X_C, (e.g., Moravveji et al., 2015), and enabled detailed studies of the effects of diffusive mixing and core overshooting (e.g., Moravveji et al., 2015) in SPB stars.

Buysschaert et al. (2018) investigated the SPB-type pulsating, magnetic star HD 43317, and inferred its interior properties from 35 pulsation frequencies. The authors concluded from the frequency shifts of the pulsation modes caused by the Lorentz and the Coriolis forces that the magnetic field has a lower impact than rotation for this star. With a mass of 5.8 solar masses, HD 43317 is also the most massive g-mode pulsator with seismic models to date.

4.3 Be Stars

The big breakthrough in the investigations of Be stars and their different types of variabilities came from the data obtained by the *BRITE*-Constellation mission. During their evolution, Be stars may be faced with an excess angular momentum problem which they seem to solve by a regular pulsation-driven ejection of matter that carries away angular momentum to the stars' circumstellar disks (e.g., Baade et al., 2017a,b). The main reason seems to be large amplitude difference (combination) frequencies of non-radial g-mode pulsations (e.g. Baade et al., 2018).

4.4 Pre-main Sequence and Early ZAMS SPB Stars

B stars with masses lower than $\sim$6 solar masses have an optically visible pre-main sequence (pre-MS) phase (e.g., Gruber et al., 2012) which is quite short. The analysis of true pre-MS SPB type stars has the potential to tell us about the interior structure in stars that are about to change their main energy source from gravitational contraction to full-equilibrium hydrogen core burning. But in this mass range, stars are less than about one million years old when they start core hydrogen burning. The first attempts to find pre-MS SPB stars used data from the space telescope *MOST* (Gruber et al., 2012; Zwintz et al., 2017) and the K2 mission (Ketzer & Zwintz, 2020, to appear in the proceedings to the conference "Stars and their variability observed from space", Vienna, August 2019).

5 Asteroseismology of A Stars

The challenge in studying pulsations in A stars is the strong interaction of many physical processes (e.g., rotation, convection, magnetic fields, pulsation, exoplanets, etc.) that complicate the asteroseismic mode-identification. Based on a few successful cases, we aim to learn more about the physical processes, improve their descriptions in our theoretical models, and yield more accurate identifications of pulsation modes, and consequently, fundamental parameters for the pulsating A stars.

5.1 δ Scuti Stars

δ Scuti stars in the mass range from 1.2 to 2.5 solar masses (Aerts et al., 2010) can be found in three different evolutionary stages: on the pre-main sequence, the main sequence and the post-main sequence. Space data (in particular from *CoRoT* and *Kepler*) revealed thousands of significant frequencies and triggered discussions about their origins. Explanations include, for example, granulation (Kallinger & Matthews, 2010), rotationally split frequencies (e.g., Kurtz et al., 2014) or linear combinations (Breger et al., 2012). The very long time series also led to the discovery of variability in some of the pulsation amplitudes. An excellent overview of the different origins of amplitude variability in δ Scuti stars can be found in Bowman et al. (2016).

One of the big success cases is KIC 11145123 which shows p-mode triplets and quintuplets, but also g-mode triplets (Kurtz et al., 2014). The star's asteroseismic analysis yielded a rotation period of ∼100 days, and a central hydrogen fraction, X_C, of only 0.033 which is a clear indication that KIC 11145123 is in its Terminal Age Main Sequence (TAMS) contraction phase (Kurtz et al., 2014).

Another recent novelty in δ Scuti star research is the discovery of the first clearly detected magnetic field in the δ Scuti star HD 18874 (Lampens et al., 2013; Neiner & Lampens, 2015). A second potentially magnetic δ Scuti star was proposed by Escorza et al. (2016) based on the detected chemical peculiarities of the rare earth elements from high-resolution spectroscopy.

δ Scuti stars can also host exoplanets, as in the case of β Pictoris (Koen, 2003; Koen et al., 2003). A recent study based on data obtained from space with *BRITE*-Constellation and *SMEI* (e.g. Eyles et al., 2003), and from the ground with bRing (Stuik et al., 2017) and ASTEP (Abe et al., 2013) yielded the mass and radius of this exoplanet host star to an accuracy of better than 3% (Zwintz et al., 2019).

A first empirical relation for δ Scuti stars connecting the effective temperature with the frequency of maximum power (ν_{max}) was proposed by Barceló Forteza et al. (2018) based on 1055 objects observed by *CoRoT* and *Kepler*. Recently, Murphy et al. (2019) used data for 15000 δ Scuti stars observed by *Kepler*, calculated their luminosities based on *Gaia* (Gaia Collaboration et al., 2016) data, and revised the location of the δ Scuti instability strip.

The study of pre-MS δ Scuti stars often faces the challenge that they might be surrounded by the remnants of their birth clouds, which sometimes causes quite strong, irregular variability on the order of a magnitude and more (e.g., in HD 142666 Zwintz et al., 2009b). At the same time, the pulsation amplitudes are on the millimagnitude level and have to be disentangled from the variations caused by the circumstellar disk.

The investigation of δ Scuti stars in their pre-MS phase of evolution identified a relationship between the oscillation properties and the relative evolutionary stage of the pre-MS pulsator (i.e., its point of evolution between the birthline and the ZAMS; Zwintz et al., 2014).

5.2 Rapidly Oscillating Ap (roAp) Stars

Rapidly oscillating Ap (roAp) stars are considered to be test beds for modelling the physical processes that lead to element segregation such as gravitational settling and levitation. Currently the most widely accepted theory proposes that these oscillations are driven by an opacity mechanism in the hydrogen ionization layers in stars where the strong magnetic field is capable of suppressing envelope convection, at least in some region around the magnetic poles (i.e., the Oblique Pulsator Model Kurtz, 1982).

Recent advances in the field of roAp stars include the identification of a repetition of the frequency spacings of the principal pulsation peak around its harmonics which is a sign of non-linear mode coupling (Holdsworth et al., 2018). Another significant recent achievement was a study of 83 roAp stars (including five new roAp objects) in Sectors 1 and 2 of the *TESS* mission by Cunha et al. (2019) used to populate the roAp instability region in the HR-diagram and identify the fastest known roAp pulsator, TIC 35146296, with a pulsation period of only $\sim$4.7 minutes.

6 Interior Angular Momentum of B and A Stars

One of the major uncertainties in our current theory of stellar evolution is the distribution of angular momentum inside stars and how it changes during the stars' lifetimes. Aerts et al. (2017) investigated the core rotation rates versus the spectroscopic $\log g$ for eight B-type and 59 A- and F-type stars and found rigid rotation on the main sequence, independent of the core rotation and the evolutionary stage from the main sequence to the red giant phases. This points towards a strong coupling between the core and the envelope. How and when this coupling starts is a matter for ongoing research.

One possibility to explain the observed core-to-envelope rotation is that internal gravity waves are responsible for the angular momentum transport (Mathis, 2011; Rogers, 2015). Currently, its full implementation in stellar structure models is too computationally demanding, so some analytical treatments are needed.

7 Summary and Conclusions

The data obtained from space telescopes for B and A stars have led to a revolution for selected object groups: one of the big successes of space photometry is the detections of g-mode period spacings that allow us to study the stars' core-to-envelope properties. But the big revolution is yet to come in the fields of, for example, massive stars, magnetic stars and pre-MS stars.

Our theoretical models need improved input physics to enable a similar revolution to occur in theoretical asteroseismology of B and A stars. First steps have been taken through the implementation of diffusive mixing or angular momentum transport through internal gravity waves. But there are still some long-standing problems for the theoretical models of stellar structure and evolution, such as the physically correct way to describe convection, rotation and the influence of magnetic fields.

The main goal for the future should be to put the specific classes of B and A pulsators into a global, evolutionary context. Then we will be able to advance our knowledge of stellar structure and evolution and all the involved processes and bring it to the next level.

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Grant Hill (left) and John Landstreet (right) demonstrate that stars are, indeed, roughly spherical.