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Present Problem Inin AsteroseismologyAster seismology

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Abstract.

Scientific research is a continuous process, and the speed of future progress can be estimated by the pace of finding explanations for previous research questions. In this observers based view of stellar pulsation and asteroseismology, In this contribution we briefly review some of the current issues and promises for the future by asteroseismology. We are entering a new phase in this field driven by the wealth of data that has been collected and data that will soon be available for asteroseismology. Major difficulties in the descriptions of stellar interiors that arose in the second half of the 20th century may now be in part addressed and solved by asteroseismology with unprecedented precision. In this contribution we list some of the key open questions in stellar physics, the seismic data we expect to collect in the near future, and some techniques that will provide the tools to connect data and models.

***Keywords :Keywords:* Asteroseismology, physics**

Introduction

Asteroseismology is the study of the internal structures of stars by means of their intrinsic global oscillations. The characteristics of these oscillations are determined by the stellar interior and hence it is possible to infer the stellar structure from the oscillations. Stellar theory has been successful in explaining a wealth of observational data available for very different types of stars at various evolutionary stages. However, stellar physics was mainly confronted with explaining and predicting global stellar parameters such as luminosities and effective temperatures. So far, most of the strongest observational tests have come from studies of stellar clusters and helioseismology. These two methods rely on opposite philosophies. Cluster studies use large samples ofstars, for which individual processes may be averaged out. The ongoing debate about the observational evidence of convective core overshoot in stars is just one example of the difficulties addressed by this method [1]. Helioseismology, on the other hand, is concerned with the study of one star and, thus, provides information on a unique evolutionary state, and only for a specific stellar mass. Moreover, the Sun can be considered as a comparatively easier star to model: it does not have a central convective coreand is only moderately evolved. Therefore, the best solar models cannot be directly applied to other stars, whose interiors are determined by very different physical regimes. The consequence is a lack of direct constraints that can allow us to predict and explain the behaviour of these very different stars.

Classical pulsators have in some cases allowed us to go beyond standard solar physics. These stars have opened the door to the opportunities offered by doing seismology across the HR diagram. Following the success of Helioseismology, the possibility of using oscillation data for most stars is now a reality following the observational evidence that almost all stars pulsate in some way [2]. Asteroseismology has the potential, in particular, to fill in the apparent gap between helioseismology and the study of clusters. Detailed structural tests for individual stars with different masses and at different evolutionary stages will become possible with this technique. Thus, asteroseismology will provide us with much stronger constraints on the theory of stellar interiors. In particular, this technique will be fundamental in solving some of the long standing problems in stellar physics. Several physical processes have been included in models of stars and their interwoven effects on the overall structure cannot be discriminated using the currently available observational data. In Section 2, below, some of these processes will be briefly discussed.

One key aspect necessary to secure a strong impact of these new incoming data is the development of tools able to provide a direct connection between observations (oscillation mode parameters and global stellar parameters) and models. These tools have been developed successfully in helioseismology. The drive is now strong towards developing equivalent inference methods for asteroseismology (e.g. [3]). This effort can take advantage of the solar experience but the techniques are different because of the limitations in the asteroseismic data. In particular, for stars other than the Sun, we are restricted to low degree modes. Nevertheless, these modes are able to constrain the physics of the models if adequate inference tools are applied. Some of the aspects on what data we expect in the near future (Section 3) and how these data can be connected to the models (Sections 4 & 5) are also discussed below. The paper ends with a brief comment on the (expected) future of Asteroseismology.

Current issues in stellar physics

Even though the Sun is by far the best studied star, solar modelling still faces problems. If the newly revised solar heavy element abundances are to be confirmed, solar models will clearly be at odds with the observational data from helioseismology [4].

A number of physical processes that are not included in standard solar models might be relevant for solving remaining discrepancies between theory and observations. Among these are dynamical effects involving rotation and magnetic fields. In particular, a mechanism to transport angular momentum from a presumed initially rapidly rotating to a uniformly rotating solar interior is needed. Stars in different evolutionary stages are expected to contain differentially rotating interiors, for which such mechanisms must also be included in the models. As an example, the differential rotation is responsible for meridional circulation and shear-induced turbulence, which transport angular momentum and react back to the rotation [5]. These mechanisms may modify the distribution of chemical elements and the magnetic fields (e.g. [6]).

Another issue for which stellar models need better observational constraints, is convective core physics. All prescriptions for core overshooting or semiconvection have free parameters that must be calibrated through observations. Asteroseismology may provide additional constraints that would help to discriminate between different models/prescriptions. Similarly, the physics of convective envelopes is not fully established. One example is the evidence given by the Sun on the inadequacies of the models to reproduce the transition layer at the base of the envelope. In this case, the use of stars slightly different from the Sun may provide a clear indication on how the modelling should be improved.

Seismic frequencies of high radial orders as well as the large frequency separations are sensitive to the structure of the outer envelope of stars. Non-standard stellar processes relevant in this region include three dimensional effects of turbulent convection in the super-adiabatic layer, convective entrainment, rotation, magnetic fields and stellar winds. The study of several stars covering a wide range in effective temperature is required in order to understand the origin and impact of the surface effects on the oscillation frequencies. Seismic diagnostics complemented by 3D numerical simulations may be the only way forward to solve the questions about the near-surface physics of stars that remain unsolved, even for the Sun.

These are some examples of the current issues in stellar physics that may be addressed with the use of precise stellar seismic data.

Precise stellar data for Asteroseismology

In order to be able to confront the aforementioned issues in stellar physics with observational data it is necessary to have both accurate seismic data and global stellar parameters. The latter are important in helping asteroseismology to probe with high precision the physics of the stellar interior [7; 8]. The forthcoming GAIA mission alongside with high-precision spectroscopy and interferometry will allow the acquisition of accurate global parameters.

In the following, we focus on the present and future developments of observational asteroseismology. Current space missions with programs dedicated to asteroseismology are MOST [9] and CoRoT [10] These should be followed by Kepler [11] and PLATO [12]. From ground, the emphasis is put on the already existing high-spectroscopy facilities and on the development of new projects such as SONG [13]and SIAMOIS [14]. A more detailed description of these missions and projects can be found throughoutthis volume.

MOST

The MOST (Microvariability and Oscillations of STars) photometric satellite was launched in June 2003and has already undertaken 64 primary campaigns and obtained observations of more than 850 secondary

stars of which 180 are variable. More than half of these variable stars pulsate, with the majority beingB-type stars. MOST has detected p-modes in solar-type (e.g. red giants, yellow giants, α Cen A and B), in

pre-main sequence, roAp and δ Scuti stars. An unanticipated discovery of MOST has been the detectionof a large number of slowly pulsating B stars with variations that are characteristic of g-modes [15].

CoRoT

The CoRoT [10] photometric satellite was launched in December 2006 and has spent almost one year collecting data. The preliminary results confirm that the mission has achieved the project specificationsand is able to produce data of unprecedented quality. The first release of data to the CoRoT communitytook place at the end of 2007.

The primary goals of the CoRoT mission are to find planets and to use precise photometry for asteroseismology. A broad range of stellar types is expected to be observed from sun-like to very high mass stars. The various phases of stellar evolution will also be covered, ranging from young and main-sequence to evolved stars.

Kepler

The Kepler mission is a NASA project to be launched in 2009 with the primary science objective of finding earth-like planets. The Kepler data will also be used for a seismic study of the planet-hosting stars, because of the need to fully characterise the planetary systems being discovered.

As a by-product, Kepler will also provide precise photometry for a large number of stars in its field of view [11]. The key scientific outcome of this additional program is the possibility of doing asteroseismology for a large number of solar-type stars. This wide coverage of stellar types and stellar evolution phases will open a new window on the understanding of the physics governing the evolution of the Sun and other stars. Activity cycles [16], near-surface convection, and rotation [17] are among the issues of solar-type stars that will benefit from the constraints provided by the data to be collected byKepler.

Ground based facilities

For several years now, ground-based observations have been routinely performed to observe the variation of classical pulsators. The situation has been quite different for sun-like stars. It is well-known thatthe first breakthrough has come from the high-precision spectrograph CORALIE on the 1.5m Swiss- Telescope at La Silla [18]. Since then, single-site observations, in particular those using the HARPS spectrograph, have led to several new *p*-mode identifications [19; 20].

In parallel to these single-site observations of solar-type stars, multi-site campaigns have been organized for other stars, namely *α* Cen A and B, using the spectrographs UVES and UCLES [21], and Procyon [22]. The advantages of multi-site runs are obvious in terms of reducing the daily aliases. However their organization can be difficult. Firstly, the coordination of several telescopes depending on different organizations represents a delicate scheduling task. Secondly, the instruments that are currently able to reach sufficiently high precisions do not allow a full coverage of the sky, and therefore of all relevant targets for ground-based seismology. To overcome these difficulties the SONG project is being developed. It consists in a 8-telescope network that would allow a full sky coverage in spectroscopy.

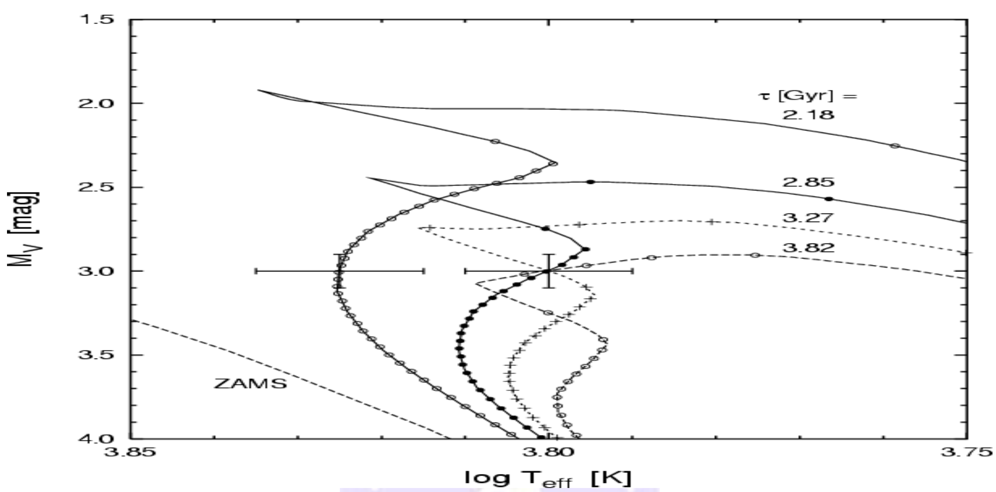

Figure 1. HR diagram showing the location of two hypothetical observations at (log $T_{\rm eff}$, M_V) = (3.825, 3.0) and (3.800, 3.0).

There are other projects being developed/implemented with the primary goal of doing precise asteroseismology from the ground. The use of the South Pole is such an example (e.g. [14]) or the development of a new generation of detectors for high precision spectroscopy for existing and future telescopes.

The link between observations and models

In 1993, nearly ten years before the first reliable measurement of individual *p*-modes in *α* Cen A, Brown & Christensen-Dalsgaard, in an article not so metaphorically entitled *How may seismological measurements constrain parameters of stellar structure?* [23], proposed a prospective study that aimedat estimating the impact of asteroseismology on theoretical models. Today, thanks to the ever growing amount of available data, a not-so prospective answer to this question has to be sought. This implies, in particular, developing the necessary methods for inference of the model parameters.

Choosing a method to estimate stellar parameters is in itself a non-trivial problem. An illustration ofthis situation is given in Fig. 1. The isochrones show a typical non-linear behaviour in the HR diagram,undergoing a hook when convective cores start to develop in the innermost regions of the corresponding stars. The rightmost set of observables in Fig. 1 can be reproduced by several isochrones.

The number of free parameters necessary to describe a stellar model is significant. If one considers a so-called "standard model" for a sun-like star, the minimum number of input parameters is given by the mass, the age and the initial chemical composition (i.e. the initial helium and metal abundances) of the star. In the framework of the mixing-length theory, which describes convection, the mixing- length parameter should be included, which adds up to five parameters to be taken into account. It is therefore of no surprise that the solution to this inverse problem can be degenerate. The situation is even more complex if we consider that many non-standard effects could be added in the stellar models which usually introduce additional free parameters (e.g., turbulence, rotational mixing, accretion, winds. Although the relevant physical parameters may change from one type of star to the other, thisstatement remains valid.
Adding seismic constraints to the set of observational data certainly reduces the number of possible solutions, but the general difficulty of searching the multi-dimensional space of stellar input parameters remains. It is thus worth exploring the different available methods to estimate these parameters and theirrespective advantages and limitations.

CONCLUSION

As it has been so well put by Laurent Eyer [2], *now is the time to be an Asteroseismologist*! After reviewing the list of contributions presented at the HELAS II conference in Göttingen the authors can only agree that the wealth of results that are starting to appear, as a consequence of the new data made available by ground based and space missions, is marking the beginning of a new era for stellar physics. The forthcoming years in this field are expected to see a major breakthrough, as the "wave" of new data inundating the community will lead undoubtedly to a much deeper understanding of the physics of stars. It may a big "wave", but the contributions presented at the HELAS II conference clearly show that the community is prepared to surf this wave (as the Sun has proved to be a good training ground). We look forward to the bright future of asteroseismology

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