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Editorial: Challenges of asteroseismology in the era of space missions

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Editorial on the Research Topic
Challenges of asteroseismology in the era of space missions

New insights into the physics of stellar interiors and evolution are being made possible by asteroseismology. Moreover, asteroseismology is being increasingly applied in studies of Galactic archaeology, exoplanetary systems, and even in tests of fundamental physics. Nevertheless, more data does not always mean a better understanding, and there are long-standing problems that remain unresolved and others that have emerged as a result of the unprecedented quality of the data gathered by space missions like CNES/ESA's CoRoT (Auvergne et al., 2009), as well as NASA's Kepler/K2 (Koch et al., 2010) and TESS (Ricker et al., 2015).

With this Research Topic, our aim was to provide researchers an opportunity to publish works that tackle unresolved problems in asteroseismology from an original perspective, be it of a theoretical or observational nature. A critical point of view is needed to go beyond the limitations of our current understanding of stars and their interiors. The eleven articles published herein fulfill that role, making use of a diverse set of techniques while addressing a heterogeneous mix of subfields.

Fueled by the wealth of high-quality seismic data, the past few years have witnessed an ever-growing effort being devoted to the development of novel techniques for the estimation of fundamental stellar properties (i.e., radius, mass, and age). The focus has been placed on uniform data analysis and stellar modeling strategies, as well as state-of-the-art optimization procedures that make use of individual oscillation frequencies. In Suárez, for example, a new diagnostic diagram—the entropy spectrum (HSpec) — is proposed that makes use of the Shannon entropy to find regular patterns in the oscillation spectra of solar-like and δ Scuti stars.

Such techniques are now making it possible to estimate the precise fundamental properties of large numbers of field stars, for which such information is usually sparse. As a result, asteroseismology is having a profound impact on modern astrophysics, notably on the field of exoplanetary science. In Reda et al., a new approach is put forward that brings together the fields of asteroseismology and space weather in order to better characterize the habitability of exoplanets around solar-like stars. Another interesting application of asteroseismology is its potential use in the detection of dark matter. Ayala reviews this relatively unexplored line of research. Such applications add to the synergetic potential of asteroseismology.

The advent of high-quality, space-based photometry has also enabled the application of sophisticated inversion techniques—hitherto restricted to the field of helioseismology—to asteroseismic data sets. In Buldgen et al., the authors provide a comprehensive review of the topic of seismic inversion of the internal structures of stars, including its limitations and the prospects for future developments in view of current and upcoming space missions.

Precise fundamental stellar properties are a key output of asteroseismology. The analysis of oscillation frequencies of solar-type stars has been extremely successful in this regard. However, this is far from being reached in the case of δ Scuti stars, a class of rapidly-rotating pulsators in the main sequence. Lares-Martiz developed a new method to overcome this issue. The high-quality seismic data currently available allowed for studying small-amplitude peaks in the power spectrum of this type of pulsator. When some of these peaks are identified as resonances of higher-amplitude modes, then the study of their amplitudes and phases makes it possible to relate these quantities to the surface gravity and effective temperature of these stars.

The availability of long time series opens the possibility of carrying out time-frequency analyses. Since pulsation frequencies are not usually stable over time, their study may reveal clues about the physical processes maintaining the oscillations. This is the main motivation behind the brief research report by (Ramón-Ballesta et al.). The authors assess the benefits of the wavelet transform by monitoring the evolution of several pulsation frequencies over time for two δ Scuti stars. Although preliminary, their results show the stability of some pulsation frequencies against others that might be interacting. The development of this technique may shed new light on the excitation mechanism driving the oscillations in this type of pulsator.

Due to the lack of explanation for mode selection in some stars and a large number of pulsation frequencies in the power spectra of others, δ Scuti stars are one of the most challenging types of pulsating stars. FG Virginis is a paradigmatic case, having previously been studied as part of long ground-based, multi-site campaigns during the 1990s and early 2000s, which included multicolor photometry that made mode identification possible. This star has more recently been observed by K2 and TESS in 30- and 2-min cadences, respectively. The unprecedented quality of these data sets provides a great opportunity to shed new light on the interpretation problems characteristic to δ Scuti stars. Guzik et al. compares previous frequency analyses with the ones carried out in their study, finding good agreement regarding the identification of the modes of highest amplitude. However, they also find an increased number of detected modes that make mode identification more challenging. In addition, the presence of low-frequency modes suggests that FG Virginis might be a hybrid δ Scuti/γ Doradus variable star.

High-precision asteroseismology brought with it new questions about pulsating stars. The classical Fourier transform, commonly used to extract mode frequencies from the time-series data, has been at times criticized. Therefore, new ways of dealing with the data are being constantly sought. This is the case in the work by (Garrido et al.). The authors propose a new transform to get the most out of the observations. A new quaternionic Fourier transform is presented and applied to solar data from GOLF/SoHO, unearthing new peaks that could potentially provide insight into the deepest solar interior.

In the age of machine learning and artificial intelligence, it is a natural step to introduce these techniques for the purpose of mode identification and pattern analysis. Especially for rapidly-rotating stars, mode identification is a challenging task and several strategies have been put to the test in the past with mixed success. Mirouh reviews these strategies as well as the new efforts being made, with an emphasis on two promising developments: classification algorithms to automate mode identification and derive patterns for each subclass of acoustic modes, and the adaptation of line-profile variations to rapidly-rotating stars.

Although various types of pulsating stars populate the Hertzsprung–Russell diagram, the asteroseismology of pre-main-sequence stars has not been addressed in detail yet. Pre-main-sequence stars are usually obscured by dust and stellar activity, their pulsation properties thus being difficult to obtain observationally. The relatively short duration of this evolutionary phase makes this problem even worse. Zwintz and Steindl combine observations and theoretical modeling and review the state of the art when it comes to the study of these stars. These young stellar objects hold promise in helping us answer a number of key open questions in stellar evolution, e.g., on angular momentum transport and the formation of magnetic fields.

Intermediate-/high-mass stars are usually rapidly rotating. The effect of rotation is notoriously difficult to be accounted for fully. Although the traditional approximation works well for low-frequency gravity modes, for acoustic modes, the validity of the perturbative approach is quite limited, and the geometric deformation enforces a two-dimensional modeling of stellar structure and evolution. Reese review the cutting-edge topic of asteroseismic modeling of fast-rotating stars, linking the 2D numerical modeling effort to the direct observables in photometry (amplitude ratios and amplitude-phase diagrams in multiple bands), spectroscopy (line-profile variations), and interferometry.

As a final remark, we would like to point out that the application of open science principles together with a high level of mathematical rigor and (often) an interdisciplinary approach should be pursued in tackling the multiple challenges posed by modern asteroseismology, thus maximizing the scientific potential of future missions such as PLATO (Rauer et al., 2014) and, possibly, HAYDN (Miglio et al., 2021).

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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