Stars and their variability observed from space
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POTENTIAL AND CHALLENGES OF PRE-MAIN SEQUENCE ASTEROSEISMOLOGY

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Abstract.
Studying the pulsational properties of pre-main sequence (pre-MS) stars carries the potential to improve our concept of early stellar evolution and our descriptions of the input physics for theoretical models. At the same time, both the observational and the theoretical investigation of stars in their earliest evolutionary phases needs to deal with certain challenges connected to the stars' youth. In this article, I describe some of the most important challenges, suggest ways to deal with them, and summarize the potential of pre-MS asteroseismology.

Keywords: Stars: pre-main sequence, Asteroseismology, Stars: variables: delta Scuti, Stars: variables: general

1 Introduction

The properties that describe stars during their formation (such as initial mass, chemical composition and angular momentum) define how they will continue to evolve. Physical effects also influence stellar evolution even in the earliest phases after birth, and let the stars develop their characteristic properties that we detect during their later phases. For example, some stars on the zero-age main sequence (ZAMS) and in later stages possess chemical inhomogeneities in their atmospheres that cause spots to appear. But it is not clear why only a certain fraction of stars shows chemical peculiarities, nor when they are formed. It is also not understood at present how the angular momentum evolves between the birth of stars and their arrival on the ZAMS; on the main sequence and post-main sequence, stars seem to rotate rigidly and the rotation of their cores and envelopes are coupled. The question of how stars rotate near their cores during the pre-MS stages currrently remains open. It is therefore obvious that we need to improve our understanding about the processes acting in a star's pre-MS stages if we are to be able to explain the behaviour we observe in later stages.

Other open questions in the context of early stellar evolution include: How can we describe precisely the interplay between the different physical processes (e.g., convection, diffusion, rotation, angular momentum transport, magnetic fields, accretion, ...) acting in the early evolutionary stages? Can we provide more reliable age estimates for young stars? Currently, an age value of (say) five million years for a young object has a typical error of a few million years, which can translate into a relative error of up to 100%. What is the origin of the sometimes strong magnetic fields observed in some stars? What is the influence of the circumstellar environment on early stellar evolution?

Asteroseismology of pre-MS objects has the potential to contribute to finding answers to these questions. The necessary prerequisites are observational data of sufficient precision, and reliable theoretical models. Photometric time series for pre-MS pulsators are currently available from the MOST (Walker et al. 2003), the CoRoT (Auvergne et al. 2009), the Kepler K2 (Gilliland et al. 2010) and the TESS (Ricker 2014) space telescopes, where the maximum time-base available is ∼80 days. With these data it was possible to describe the pulsational properties of the class of pre-MS δ Scuti stars quite well based on 34 well-studied stars (Zwintz et al. 2014) and at least two dozen additional candidates. The first g-mode pulsating pre-MS γ Doradus stars were identified from CoRoT data of NGC 2264 (Zwintz et al. 2013), and first attempts to find Slowly Pulsating B (SPB) g-mode oscillators in their pre-MS stages were conducted, illustrating the statistical challenge to find B-type pulsators that are still in their pre-MS stage (Gruber et al. 2012; Zwintz et al. 2017).

2 Challenges for pre-main sequence asteroseismology

If we want to study pre-MS stars, we are faced with some challenges.

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2.1 Circumstellar matter

Quite often, Pre-MS stars are still surrounded by the remnants of their birth clouds. Their circumstellar disks can be a sign of the stars' youth, but at the same time they also strongly shape observational measurements. Photometric time-series show irregular variations of the order of a magnitude or more, while pulsational variability lies at the millimagnitude level and below. Fig. 1 shows the light curve of the Herbig Ae star HD 142666 as observed by Kepler; the circumstellar disk is seen edge-on and causes the large irregular variations, but HD 142666 is also a δ Scuti type pulsator with 12 detected frequeicncies in the range 5.77–28.05 d^{-1} and with amplitudes less than 3 mmag (Zwintz et al. 2009). In spectroscopic observations, the presence of a circumstellar disk is evident through strong emission lines that complicate the determination of fundamental parameters. Spectral energy distributions of pre-MS stars are typically characterized by an increased flux in the infrared, i.e., an infrared exhcess.

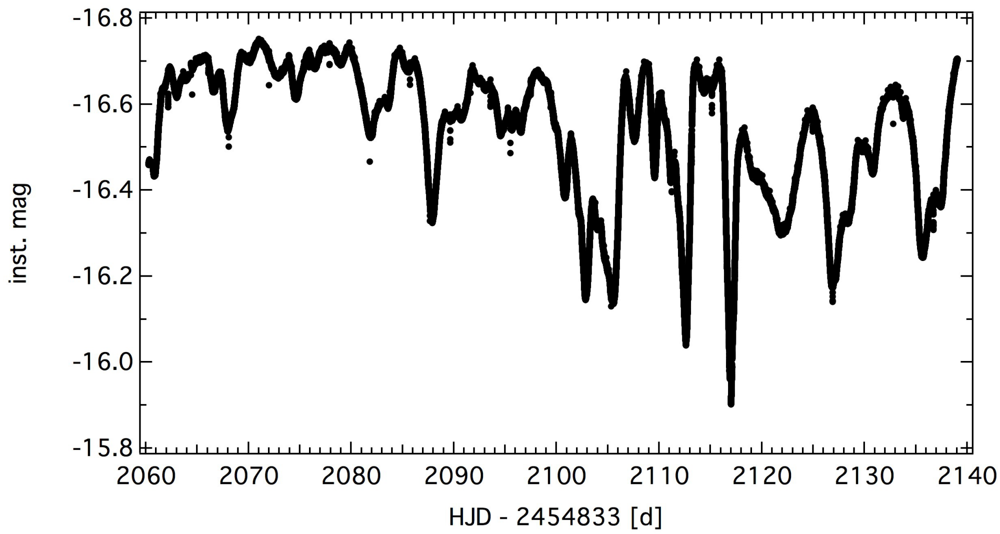

Fig. 1. Light curve of HD 142666 obtained with Kepler K2, illustrating the influence of circumstellar disks on photometric time-series of pre-MS stars.

2.2 Evolutionary stage and ages

The analysis of stars on the main sequence and in later stages can use different methods to determine the respective evolutionary stages of the objects and their ages. Apart from comparing the fundamental parameters derived from spectroscopy to the theoretically calculated evolutionary tracks or fitting isochrones, asteroseismology enables us to use the fraction of the core hydrogen, X_c, as a measure of relative age on the main sequence (e.g., Kurtz et al. 2014). For pre-MS stars it is more challenging because evolutionary tracks of pre- and post-main sequence stars of same mass, effective temperature and luminosity intersect, and isochrone fitting is usually affected by large errors even when applied to well-studied young regions like NGC 2264. Moreover, the fraction of core hydrogen, X_c, is not applicable as pre-MS stars have not processed hydrogen significantly enough yet. Hence, the identification of a pre-MS object is ambiguous, can only be based on features typical for stellar youth, and is a challenge in some cases.

2.3 Age determination

We are also faced with querying the actual zero age of a star when dealing with stars in their youngest phases. Do we set age zero at the formation of the second Larson's core (e.g., Baraffe et al. 2012), at the birthline, at the ignition of Deuterium burning, at the first hydrostatic pre-MS model, at a specified point on the Hayashi track, at the ZAMS, or at any other possible point? All of these points in early stellar evolution rely on the underlying theoretical stellar model, and thence on the corresponding input physics, and are currently used by different state-of-the-art theoretical stellar models. The effect which the choice of a given age zero-point has on stars on the main sequence – and in later stages – might be insignificant, but it has a huge impact on the determination of the ages of pre-MS stars.

2.4 Observational material and theoretical models

As mentioned above, current observational data for pre-MS stars have time-bases of up to only ∼80 days, which limits the analyses compared to what would be possible with data from (say) half a year (as for BRITE-Constellation observations) to several years (in the case of Kepler).

Theoretical models for pre-MS stars use a lot of assumptions, and trying to improve on those leads to some simple-sounding questions like, "What is the definition of the ZAMS as seen from the pre-MS side?" (for more information on a new way to define the ZAMS, see T. Steindl (PAGE). It is also not clear how the choice of the input physics influences the theoretical description of pre-MS stars. These challenges need to be tackled.

3 Potential of pre-main sequence asteroseismology

Every challenge can also be regarded as a potential invitation to overcome difficulties. The most striking potentials for the asteroseismology of pre-MS stars from my personal view are:

3.1 Pulsations on top of irregular variability

Despite the high degree of activity leading to irregular variations in the light from pre-MS stars, it was shown that disentangling irregular variability caused by circumstellar dust and gas from pulsational variability works successfully for p-mode oscillators (Zwintz et al. 2009). With a (simple) theoretical representation of the variability caused by the disk, pulsations can be identified clearly when their frequency values are higher than the frequencies induced overall by the disk (i.e., these are typically lower-range frequencies, between about 0–3 d^{-1}). It is more challenging to disentangle the two types of variability when the pulsations lie in the same frequency range as the variations from the disk (as in the case of g-modes with periods between ∼0.3–3 days; Aerts et al. 2010).

3.2 Discovery of empirical scaling relations

Asteroseismic scaling relations are powerful tools that connect the masses and radii of stars theoretically to their asteroseismic properties (e.g., frequency separations or frequency of maximum power), and are mostly tuned to the Sun and solar-like oscillators (e.g., Kjeldsen & Bedding 1995). With a large enough number of pre-MS pulsators that have well-studied pulsational frequencies and a reliable determination of fundamental parameters (effective temperature, $\log g$, $v \sin i$), group properties can be studied. For the pre-MS δ Scuti stars, an empirical relation between the p-mode oscillation properties and the evolutionary stage can be identified, illustrating that the highest excited p-mode frequency is smallest close to the birthline and increases towards the ZAMS (Zwintz et al. 2014). It illustrates that finding new pre-MS pulsators, in particular for the γ Doradus and SPB classes and populating the HR diagram with them, has the potential to investigate whether similar relations exist for the other types of stars as well. Consequently, asteroseismic scaling relations for pre-MS stars can connect the pulsational properties of young stars to their fundamental parameters, enabling us to test theoretical models of early stellar evolution; they therefore have a power similar to that for more evolved solar-like oscillators.

3.3 g-mode period spacings in pre-main sequence stars

By detecting g-mode period spacings, it is possible to study the angular momentum transport near the stellar core and to investigate whether the envelope and the core rotate rigidly or not (Aerts et al. 2017). This was done quite successfully for main-sequence and post-main sequence objects (e.g., Van Reeth et al. 2015). For pre-MS stars, the first g-mode period spacings have recently been discovered using Kepler K2 data of the Lagoon Nebula (see L. Ketzer, PAGE). In particular, g-mode period spacings in pre-MS stars have the potential to extend earlier studies of angular-momentum transport from the main sequence to the earlier evolutionary phases and to investigate when the strong coupling occurs between the surface and the core of a star.

3.4 What was our Sun like in its youth?

The presence of stochastic, solar-like oscillations in pre-MS stars has been predicted by theory (Samadi et al. 2005; Pinheiro 2008). As pre-MS stars in this mass regime are characterized by high degrees of activity and mostly fall into the class of T Tauri stars, the observational detection of solar-like oscillations is even more challenging. The amplitudes of solar-like oscillations are generally smaller than those driven by the heat engine mechanism (such as δ Scuti and γ Doradus pulsations). And although we are faced by several of the previously mentioned challenges (including a lack of sufficient observational material), searching for pre-MS solar like oscillators has the potential of recognizing what the Sun was like in its early phases and investigating how its interior structure changed with time.

3.5 Automated selection of pre-MS stars

The identification of the pre-MS nature of a given star can be quite challenging and ambiguous (see Section 2.2). Pre- and post-main sequence evolutionary tracks for masses lower than ~ 6 solar masses intersect several times, and there is no unique identifier that enables us to distinguish a pre- from a post-main sequence star. Several features that are attributed to an early evolutionary stage must therefore be used for a possible identification of stellar youth. This process is typically carried out manually on a case-by-case basis.

In the context of space missions like TESS or (in the future)PLATO (Rauer et al. 2014), where thousands of stars will be measured, such a selection of potential pre-MS stars has to be done in an automatic way. An appropriate variability classifier is currently being developed for application to TESS data, with an additional possibility of an extension to PLATO data in the future. It combines known catalogues of young stellar objects, features attributed to pre-MS stars and information provided by *Gaia* (Gaia Collaboration et al. 2016). It applies machine learning to carry out automatic classification of a pre-MS object. More information can be found in the article by Müllner (PAGE).

4 Conclusions: The power of pre-MS asteroseismology

Despite the challenges we face when applying asteroseismic methods to pre-MS stars (e.g., influences of the circumstellar disk and accretion), the subsequent power of asteroseismology of the youngest pulsating stars is evident.

- The evolutionary stage of a given pulsating star, i.e., if it is a pre- or a post-main sequence object, can be identified from its frequency pattern *only*.
- The oscillation properties of pre-MS stars are related to their relative evolutionary stage during their pre-MS phase (i.e., between the birthline and the ZAMS).
- When we overcome the lack of long enough photometric time series for pre-MS pulsators - e.g., through observations with TESS and in the future with PLATO - we will reveal many more oscillatory features typical for the pre-MS stages similar as it was possible in red giant asteroseismology. Consequently, we will be able to find the "young Sun", i.e., pre-MS solar like oscillators that are currently only theoretically predicted.
- Current work concentrates on improving the input physics for starsu in their pre-MS phases, e.g. by modelling warm and cold accretion (Vorobyov et al. 2017). With the expected advances in our theoretical concept of early stellar evolution together with theoretical models of pre-MS oscillations, we will test the influences of the choice of the input physics and learn more about the physical effects acting in young stars.

Pre-MS asteroseismology allows to connect the early stages of stellar evolution with the later evolutionary phases and has the potential to improve our descriptions of the physical effects acting in young stars. This is essential because only if we understand how stars pass through their pre-MS stages, we will be able to derive a complete picture of stellar evolution.

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