Asteroseismology of pre-main sequence δ Scuti stars

K. Zwintz[1*], T. Steindl[1], D. L. Holdsworth[2], D. W. Kurtz[2], M. Müllner[1], T. Medupe[3]

[1] Universität Innsbruck, Institute for Astro- and Particle Physics, Technikerstrasse 25/8, A-6020 Innsbruck, Austria
[2] Jeremiah Horrocks Institute, University of Central Lancashire, Preston, PR1 2HE, United Kingdom
[3] Department of Physics, North West University, Mmabatho, Mafikeng, South Africa

1 Introduction

Asteroseismology – the analysis of stellar oscillations – has been proven to be a successful tool to unravel details of the internal structure of different types of stars from the main sequence (MS) to the final stages of evolution (e.g., in white dwarfs). Before TESS data became available, the field of asteroseismology was revolutionized by the ultra-high precision photometric time series obtained by the space missions MOST, CoRoT and Kepler. The main focus was lying on MS and post-MS stars, but first promising results were also achieved for the pre-main sequence (pre-MS) stages.
Intermediate mass pre-MS stars can become unstable to acoustic and gravitational oscillations during their evolution from the birthline to the zero-age main sequence (ZAMS). Pre-MS stars differ from their more evolved analogues of similar mass, effective temperature ($T_{\rm eff}$) and luminosity ($L/L_{\odot}$) mostly in their interiors (Marconi & Palla 1998). As pulsation modes carry information about the inner structures of stars and show a different pattern for stars in the pre- or the (post-) MS phase (Suran et al. 2001), it is possible to use asteroseismology to constrain the evolutionary stage of a star (Guenther et al. 2007).
For a successful application of pre-MS asteroseismology we require the observational detection, resolution and identification of individual pulsation modes (i.e., high quality observational data) and accurate theories of stellar structure and evolution. For many pre-MS δ Scuti stars discovered from ground-based observations (e.g., for HD 104237; Kurtz & Müller 1999), TESS is now the first space mission delivering the high-quality, nearly uninterrupted photometric time series to fully study these stars. As our asteroseismic methods are in place, we can now tackle some of the shortcomings in our early stellar evolution theories based on TESS data for pre-MS and early ZAMS δ Scuti stars.

2 Scientific Justification

Pre-MS stars have a significantly different interior structure than their more evolved (post-)MS counterparts due to different density profiles and the lack of large amounts of processed nuclear material. It is therefore evident, that the pulsation frequency spectra for pre- and post-MS stars show different patterns and can be used to constrain the evolutionary stages of given stars (e.g., Suran et al. 2001, Zwintz et al. 2014).
Currently, the group of pre-MS δ Scuti stars is comprised of in total ~50 members that show p- mode pulsations with periods between ~15 minutes and 7 hours. Previous to the first TESS observations, about half of the stars had no photometric time series from space; earlier the pulsation properties were determined from photometric and spectroscopic ground-based campaigns (e.g., for RS Cha or IP Per).
Using the available asteroseismic data, in combination with dedicated high-resolution, high signal-to-noise spectroscopy for 34 of the pre-MS δ Scuti stars, a relation between the oscillatory properties of δ Scuti type pre-MS stars and the relative stage in their pre-MS evolution was revealed (Zwintz et al. 2014). The least evolved stars that are located close to the birthline and, hence, have the largest radii, have the longest pulsation periods. The further the pre-MS stars have progressed in their evolution towards the ZAMS, and hence the more compact they have become, the shorter their pulsation periods. A relation like this has so far only been shown for the stochastically excited solar-like oscillations in red giants (e.g., Bedding et al.

* Email: konstanze.zwintz@uibk.ac.at

2011) – a completely different type of pulsations in a different evolutionary stage. Being able to link the relative ages of heat-driven δ Scuti type pre-MS stars to their pulsational properties, is the first step in using asteroseismic methods to unravel open questions in early stellar evolution.

Until January 2020, TESS has obtained 120-second cadence data of 25 pre-MS and early MS δ Scuti stars, and FFIs are available for additional 9 objects – this adds significant observational material to earlier data obtained by the MOST (Walker et al. 2003) and CoRoT (Auvergne et al. 2009) satellites, and the Kepler K2 mission (Howell et al. 2014).

As pre-MS stars are partly still embedded in the remnants of their birth environments, they can possess circumstellar disks. A typical example is shown in Figure 1: TESS observations of the Herbig Ae star HD 104237 which shows large irregular light variability and δ Scuti type pulsations on the millimagnitude level. In situations like this, the variations caused by the disk have to be carefully disentangled from those coming from pulsations.

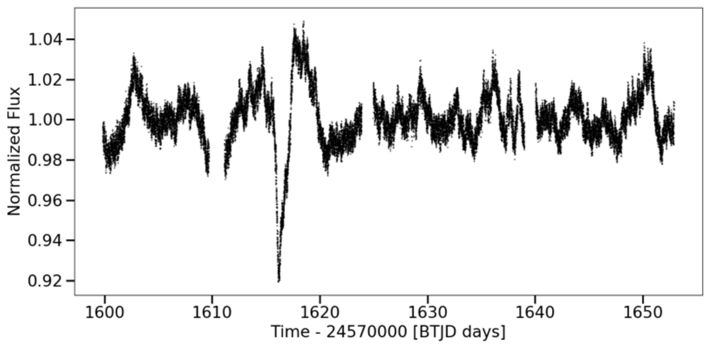

Figure 1: TESS observations of the Herbig Ae star HD 104237 exhibiting irregular light variability and pulsations.

As δ Scuti pulsations can be as short as 15 minutes, we apply for TESS observations with 2-minute cadence.

3 Analysis Plan

We have already developed several software tools that allow us to extract and analyze TESS data: The package SMURFS (https://github.com/MarcoMuellner/SMURFS) allows to download and extract light curves from the TESS FFIs using existing pipelines (e.g., Eleanor: https://adina.feinste.in/eleanor/) or the SC-pipeline data if they are available. In a second step, the TESS data can be fully analyzed with SMURFS based on selectable parameters. SMURFS can be used as standalone tool or implemented in other existing software.

Additionally, one of us (MM) is currently developing a second-level automatic classifier to identify pre-MS stars in context of the TESS Data for Asteroseismology (T'DA) Working Group.

Theoretical pre-MS stellar models will be computed using the open source MESA stellar evolution code (e.g., Paxton et al. 2011). We will use the open source GYRE stellar oscillations code (Townsend & Teitler 2013) to model the pre-MS pulsations. Recent work focused on the theoretical definition of the ZAMS, which is an important calibration point for pre-MS evolution (Steindl & Zwintz 2020).

For most of the known pre-MS δ Scuti stars that are the subject of this proposal, spectroscopic data are already available allowing us to constrain their positions in the Hertzsprung-Russell diagram (e.g., Zwintz et al. 2014). Some of the pre-MS δ Scuti stars included in our target list are new discoveries from the TESS Primary Mission. For the most promising candidates, we will apply for ground-based complementary high-resolution spectroscopy at state-of-the-art facilities and instruments, such as UVES@ESO-VLT, or the Mc Donald 2.7m telescope with the cross-dispersed Robert G. Tull spectrograph. These high-resolution spectra will be used to determine the atmospheric parameters $T_{\rm eff}$, surface gravity (log *g*), projected rotational velocity (*v* sin *i*), metallicity (Fe/H), and abundances of individual chemical elements. These observational parameters will allow us to place the pre-MS δ Scuti stars discovered in the TESS Primary Mission in the Hertzsprung-Russell diagram and constrain the calculation of theoretical models for them.

4 Technical Feasibility

Although the pulsation amplitudes of pre-MS δ Scuti stars can be as low as a few μmag, the pristine TESS data allow us to address all the science cases described above, even with the minimum observing period of 27 days. An example is given in Figure 2. More detailed asteroseismic analyses will be possible for stars observed in more than one sector, as the longer time bases yield lower noise levels and will let us investigate smaller amplitude pulsations.

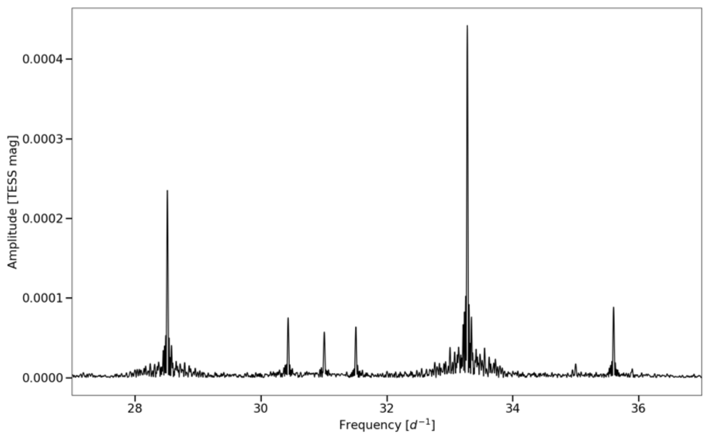

Figure 2: Amplitude spectrum of the pre-MS δ Scuti star HD 104237 observed by TESS in the Primary Mission.

For some stars (e.g., β Pictoris, HD 104237), TESS has already delivered observations in its primary mission which we will combine with the new observations from Cycle 3 to extract more precise measurements for our interpretation. The combination of the future Cycle 3 data with previous measurements is in particular important for the study of evolutionary period rate changes.

Pulsation periods can be as short as 15-18 minutes (e.g., HD 34282; Casey et al. 2013), hence a cadence of 2-minutes is needed to sample the pulsation completely.

Our target list is comprised of 30 previously known pre-MS δ Scuti stars in the Southern Ecliptic hemisphere, and 14 pre-MS δ Scuti stars newly discovered from long cadence data of the TESS Primary Mission. For all our targets, we apply for 2-minute cadence data to be able to fully sample the highest excited p-mode frequency, f_{max}, which can be at values of 80 or 90 d^{-1}.

5 Expected Impact

An increase in the observational time bases for pre-MS δ Scuti stars in 2-minute cadence and a combination with previous TESS observations – if already available – will allow for a homogeneous observational study of intermediate mass pre-MS δ Scuti stars, and provide constraints for, and an improvement of, our state-of-the-art theoretical models for early stellar evolution. Some of the expected science returns will focus around the following topics:

- The relation between the pulsation properties of pre-MS δ Scuti stars and their relative evolutionary phase (Zwintz et al. 2014) is unique for the early evolutionary phase and does *not* apply to the more evolved (post-)MS stars of the same $T_{\rm eff}$, $L/L_\odot$ and mass in the same way. Based on the TESS data, we aim to confirm this relation and extend it. The next logical step is then to convert this dependence into a scaling relation for pre-MS stars that connects the asteroseismic properties of young stars (e.g., f_{max}) to their masses, radii, and, ultimately, ages.
- Pre-MS asteroseismology can be used as a novel age indicator for stellar astrophysics because it provides an observable that is changing sensitively and smoothly with age (i.e., the pulsations). It also requires the availability of suitable calibration objects (i.e., the brightest early ZAMS star β Pictoris or the two pulsating components of the Herbig Ae binary RS Cha), an experimental or

numerical inversion of the age dependence, and the possibility to provide errors (Barnes 2007). An asteroseismic age will also be independent of distance.

- The investigation of regularities in frequency of the p-modes will significantly help to identify the modes of the observed δ Scuti frequencies, compare to the results of theoretical pulsation models and improve their input physics.
- As young stars undergo structural changes in their interiors during their relatively fast evolution from the birthline to the zero-age main sequence (ZAMS), it is possible to measure changes in their pulsation periods after several years. Such measurements can only be attempted for stars with a sufficiently long observational time base (i.e., on the order of 20 to 30 years) including several independent determinations of the pulsation periods. The first attempt to investigate the speed of pre-MS evolution was conducted using V 588 Mon and V 589 Mon – the very first discovered pre-MS δ Scuti stars. Based on theoretical computations (Breger & Pamyatnykh 1998), pre-MS δ Scuti stars are expected to show an evolutionary period rate change in the range of about -50 to $-150 \cdot 10^{-8}$ yr^{-1}. First measurements for V 589 Mon using a time span of nearly 30 years and a new Bayesian approach yielded period changes of about $-70 \cdot 10^{-8}$ yr^{-1} which agrees well to the theoretical predictions (Zwintz & Kallinger 2020, in preparation). Additional data from TESS will allow us to check the first calculations and improve the accuracy of our measurements.
- Our improved tools for extraction and analysis of TESS data will be openly available through a github repository and shared with the scientific community. Additionally, our pre-MS variability classifier will be added as a second-level classification to the T'DA algorithms and with it also provide a selection method assisting in the discovery of new pre-MS δ Scuti stars.

All of the above-mentioned science questions can only be addressed if sufficient observational material with short enough cadence (i.e., 2 minutes) is available and the asteroseismic properties of the individual members of the group of pre-MS δ Scuti stars can be determined precisely. To increase the number of confirmed pre-MS δ Scuti stars, at the University of Innsbruck we have an ongoing project that searches for new members in all available TESS data.

6 Work Plan

The main asteroseismic analysis and interpretation of the TESS data together with the calculation of theoretical models with MESA and GYRE will be done as part of the PhD thesis of Thomas Steindl. Smaller sub-projects (such as the data extraction and frequency analyses of selected pre-MS δ Scuti stars and the combined analysis with previously obtained data) will be carried out as part of future master or bachelor theses in the "Stellar Evolution and Asteroseismology" research group of Konstanze Zwintz at the University of Innsbruck.

We will use our own SMURFS tool together with available tools from the TESS Science Support Center to extract and analyze the TESS data. In the future, we aim to use the light curves extracted from FFIs based on the algorithms developed in the T'DA working group which are best suited for the analysis of asteroseismic data. We will also investigate the instrumental behavior of TESS during the respective observations to understand any systematic or instrumental effects and exclude them from any astrophysical interpretation.

7 References

Auvergne, M., Bodin, P., Boisnard, L., et al. 2009, *Astronomy & Astrophysics*, **506**, 411
Barnes, S. A. 2007, *Astrophysical Journal*, **669**, 1167
Bedding, T. R., Mosser, B., Huber, D., et al. 2011, *Nature*, **471**, 608
Breger, M. & Pamyatnykh, A. 1998, *Astronomy & Astrophysics,* 332, 958
Casey, M. P., Zwintz, K., Guenther, D. B., et al. 2013, *Monthly Notices of the Royal Astronomical Society*, **428**, 2596
Guenther, D. B., Kallinger, T., Zwintz, K., et al. 2007, *Astrophysical Journal*, **671**, 581
Howell, S. B., Sobeck, C., Haas, M., et al. 2014, *The Publications of the Astronomical Society of the Pacific*, **126**, 398
Kurtz, D. W. & Müller, M. 1999, *Monthly Notices of the Royal Astronomical Society*, **310**, 1071
Marconi, M. & Palla, F. 1998, Astrophysical Journal, **507**, 141
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, *Astrophysical Journal Supplement Series*, **192**, 3
Steindl, T. & Zwintz, K. 2020, in *Proceedings* of the conference „Stars and their variability observed from space", Vienna, August 2019, C. Neiner, W. Weiss, D. Baade, E. Griffin, C. Lovekin, A. Moffat (eds)
Suran, M., Goupil, M., Baglin, A., et al. 2001, *Astronomy & Astrophysics,* **372**, 233
Townsend, R. H. D. & Teitler, S. A., 2013, *Monthly Notices of the Royal Astronomical Society*, **435**, 3406
Walker, G., Matthews, J., Kuschnig, R., et al. 2003, *The Publications of the Astronomical Society of the Pacific*, **115**, 1023
Zwintz, K., Fossati, L. Ryabchikova, T., et al. 2014, *Science*, **345**, 550

8 Target Table

The target table below shows some of the most prominent pre-MS δ Scuti stars that are subject to this proposal for 2-minute cadence TESS observations. The full table including 44 targets is submitted electronically.

TIC ID	**Common Name**	**RA (deg)**	**Dec (deg)**	**TESS mag**	**Obj. Type**	**Comments**
270577175	beta Pic	86.821216583	-51.06650357	3.6935	Exoplanet host star with δ Scuti pulsations	2 min cadence
323292655	RS Cha	130.80082442	-79.07010172	5.8258	Pre-MS δ Scuti spectroscopic and eclipsing binary	2 min cadence
220281554	V 589 Mon	99.868599449	9.7011009528	9.9546	Pre-MS δ Scuti star in NGC 2264	2 min cadence
220249462	V 588 Mon	99.774597826	9.6842879383	9.4935	Pre-MS δ Scuti star in NGC 2264	2 min cadence