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The position of confirmed pre-main sequence pulsators in the H-R diagram and an overview of their properties

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Abstract. Pre-main sequence (PMS) stars can become vibrationally unstable during their evolution to the zero-age main sequence (ZAMS). As they gain their energy from gravitational contraction and have not started nuclear fusion in their cores yet, their inner structures are significantly different to those of (post-) main sequence stars and can be probed by asteroseismology.

Using photometric time series from ground and from space (*MOST*, *CoRoT* & *Spitzer*) the number of confirmed pulsating pre-main sequence stars has increased significantly within the last years and allowed to find members of new classes of PMS pulsators. Apart from the well-established group of δ Scuti type PMS stars, members of the groups of PMS γ Doradus, PMS δ Scuti – γ Doradus hybrid and PMS slowly pulsating B (SPB) stars have been discovered. For five PMS δ Scuti candidates, space photometry has revealed that they only show irregular variability, but no pulsations.

The unique high-precision space data were combined with dedicated high-resolution spectra to probe the parameter space in the H-R diagram and study the properties of PMS pulsators in comparison to their evolutionary stage.

Keywords. techniques: spectroscopic, stars: Hertzsprung-Russell diagram, stars: pre-main sequence, stars: variables: δ Scuti, stars: oscillations

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1. Introduction

Asteroseismology of pulsating pre-main sequence (PMS) stars has the potential of testing the validity of current models of PMS structure and evolution. Although the first two δ Scuti type pulsating PMS stars were already detected in 1972 in the young cluster NGC 2264 (Breger 1972), it took more than 20 years until the existence of this new group of stars was confirmed by the discovery of pulsation in the Herbig Ae field star HR 5999 (Kurtz & Marang 1995). This first asteroseismic analysis of a PMS δ Scuti star triggered the computation of the theoretical PMS δ Scuti instability strip for the first three radial modes (Marconi & Palla 1998), because at that time it was assumed that PMS stars are purely radial pulsators with only few excited modes.

In the following years numerous studies have been devoted to the search for and investigation of oscillations in PMS stars. Soon it was clear that PMS stars pulsate with radial and non-radial modes (e.g., Zwintz *et al.* 2007) and can show rich pulsation frequency spectra (e.g., Zwintz *et al.* 2009). Hence, the theoretical PMS instability strip for the first three radial modes (Marconi & Palla 1998) has become insufficient for higher radial orders and non-radial pulsators.

The comparison of the hot and cool border of the classical instability strip with observations has been an important test for stellar structure and evolution codes. The determination of these borders by dedicated observations of PMS stars is comparably important for the theory. With the 36 known PMS δ Scuti pulsators in 2008, it was possible for the first time to investigate the instability region for PMS stars empirically and compare it with theoretical predictions (Zwintz 2008). The location of all known PMS pulsators in the H-R diagram suggested a PMS δ Scuti instability region that is slightly inclined toward the bluer (i.e. hotter) side relative to the classical instability strip under the plausible assumption that both instability regions coincide on the ZAMS. This analysis (Zwintz 2008) was based on Johnson photometric colors which has been the only common observable for all 36 stars. As young stars are often surrounded by remnants of their birth clouds, the photometric colors were often contaminated by the circumstellar matter and resulted in errors in effective temperature of up to 1000 K. Therefore, it was obvious that spectroscopic observations for all PMS pulsators were required for any further (asteroseismic) study.

2. Observational status of PMS pulsators

53 confirmed PMS δ Scuti stars are known as of September 2013 – their evolutionary stage was assessed either due to the stars' memberships to very young open clusters or because they are Herbig Ae stars; their pulsations have been studied using space or ground based photometric time series. They are radial and non-radial pulsators with periods between about 18 minutes and 6 hours. Additionally several PMS δ Scuti candidates (with ambiguous evolutionary state or low amplitude pulsations) have been found.

One PMS δ Scuti – γ Doradus hybrid (Ripepi *et al.* 2011) was discovered as well as the first two PMS γ Doradus stars (Zwintz *et al.* 2013). The presence of PMS SPB stars was suggested with two candidates in NGC 2244 (Gruber *et al.* 2012).

A large part of these discoveries is based on space photometry obtained by the *MOST* (Walker *et al.* 2003) and *CoRoT* (Baglin 2006) satellites. Data for a total of 46 PMS pulsators are available from these two space telescopes. Observations were taken also within the CSI2264 project (Cody *et al.* 2013), which targeted the young cluster NGC 2264 and involved simultaneous observations of the four satellites *MOST*, *CoRoT*, *Spitzer* (Werner *et al.* 2004) and *Chandra* (Weisskopf *et al.* 2002).

The pulsational characteristics for all these stars have been determined well from the high-precision photometric time series. But PMS pulsators were lacking reliable fundamental parameters that are crucial for an asteroseismic interpretation, for a correct determination of their positions in the H-R diagram and for stellar evolution studies in context with pulsations.

2.1. *Non-pulsating PMS stars*

From the list of 36 PMS pulsators published in Zwintz (2008), for five stars dedicated *MOST* space photometry revealed that they only show irregular variations but no pulsations. The previously conducted ground based photometric observations on relatively short time bases of a few hours mimicked a periodic signal that in fact originates from large irregular variability caused by circumstellar material. BF Ori, UX Ori and WW Vul have effective temperatures ranging from 8500 K to 9500 K, while HD 35929 and PX Vul are on the cooler side with effective temperatures of 6800 K and 6700 K, respectively. A detailed study will be given in Zwintz *et al.* (2013, in preparation).

3. Spectroscopic observations

High resolution, high signal-to-noise spectroscopic observations were taken for all PMS pulsators, for several irregular variable PMS stars and some known constant comparison stars using the McDonald 2.7-m telescope and Tull echelle spectrograph, ESO VLT with UVES, ESO 3.6-m telescope with HARPS and CFHT with ESPaDOnS. Literature data were available for additional 15 objects.

The spectroscopic analysis was performed using the LLMODELS model atmosphere code (Shulyak *et al.* 2004), the VALD database (Kupka *et al.* 1999) and SYNTH3 for computation of synthetic spectra (Kochukhov 2007). Use was made of an updated version (N. Piskunov, 2013, priv. comm.) of the SME software package (Valenti & Piskunov 1996) that uses a LLMODELS model atmosphere grid and CM treatment of convection.

4. Results

4.1. *PMS δ Scuti pulsators*

PMS δ Scuti stars basically populate the same instability region as their classical, (post-) main sequence counterparts. The previously suggested slight inclination of the region towards the hotter (i.e., bluer) side might still be seen, while the gap at the lower red corner suggested in 2008 could not be confirmed. Masses of PMS δ Scuti stars range from 1.5 to $\sim$3.5 $M_{\odot}$; $v \sin i$ values lie between 10 and 190 km s^{-1}. There is no correlation between the position of the stars in the H-R diagram and their $v \sin i$ values.

4.2. *PMS γ Doradus stars and PMS δ Scuti – γ Doradus hybrid(s)*

CoID 102699796 (Ripepi *et al.* 2011) is the first PMS δ Scuti – γ Doradus hybrid, which is nicely positioned between the δ Scuti and the γ Doradus instability regions. NGC 2264 VAS 20 and NGC 2264 VAS 87 are the first two PMS γ Doradus stars (Zwintz *et al.* 2013). With effective temperatures of 6220 K and 6380 K they are cooler than the predicted cool border of the PMS γ Doradus instability region (Bouabid *et al.* 2011). Several more candidates for both groups discovered in NGC 2264 are currently under investigation.

4.3. *PMS Slowly Pulsating B (SPB) stars*

PMS SPB stars are more massive than the PMS δ Scuti stars, hence have a much shorter PMS evolutionary phase and are located much closer to the ZAMS. The discovery and analysis of PMS SPB type stars allows to investigate the stars' transition phases from the pre- to the main sequence evolutionary stage, i.e. from gravitational contraction to the onset of hydrogen core burning. The first two candidates of SPB type objects among PMS stars, GSC 00154-01871 and GSC 00154-00785, have been found in the young open cluster NGC 2244 (Gruber *et al.* 2012). Additional data for young B type objects are provided by the recent *MOST* observations of the young cluster NGC 2264. At least five new candidate SPB stars close to the ZAMS have been revealed and are currently under investigation.

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