COMPARING THE OBSERVATIONAL INSTABILITY REGIONS FOR PULSATING PRE–MAIN-SEQUENCE AND CLASSICAL δ SCUTI STARS

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ABSTRACT
A comparison of the hot and cool boundaries of the classical instability strip with observations has been an important test for stellar structure and evolution models of post– and main-sequence stars. Over the last few years, the number of pulsating pre–main-sequence (PMS) stars has increased significantly: 36 PMS pulsators and candidates are known as of 2007 June. This number allows to investigate the location of the empirical PMS instability region and to compare its boundaries to those of the classical (post– and main-sequence) instability strip. Due to the structural differences of PMS and (post–)main-sequence stars, the frequency spacings for nonradial modes will be measurably different, thus challenging asteroseismology as a diagnostic tool.

Subject headings: δ Scuti — Hertzsprung-Russell diagram — stars: pre–main-sequence

1. INTRODUCTION

The pre–main-sequence (PMS) evolutionary phase is the short time span between the birth of a star from interstellar clouds and the onset of hydrogen burning on its arrival on the main sequence. Gravitational contraction is the main energy source during this stage.

Low-mass PMS stars (i.e., with masses lower than ~1.5 \( M_\odot \)) that have recently become visible in the optical range and contract along their Hayashi tracks (Hayashi 1961) presumably evolve to T Tauri stars (Joy 1942). They primarily have spectral types ranging from late F to M. Intermediate-mass young stars (i.e., with masses between ~1.5 and 10 \( M_\odot \)) evolve more rapidly to Herbig Ae/Be (HAEBE) objects (e.g., Herbig 1960; Finkenzeller & Mundt 1984) with spectral types B to early F. The evolutionary stage of a HAEBE star is ambiguous: stars with masses below ~4 \( M_\odot \) are still in their PMS phase, while hotter stars have already started nuclear hydrogen burning before they become visible in the optical range. Members of both groups, T Tauri and HAEBE stars, show regular and irregular photometric and spectroscopic variability on very different timescales, indicating that stellar activity begins in the earliest phases of stellar evolution.

A and early F type PMS stars with masses between 1.5 and 4 \( M_\odot \) have the right combination of effective temperature, luminosity, and mass to become vibrationally unstable. With the now considerably increased number of known PMS pulsators and candidates it is possible to compare the instability regions for pre– and (post–) main-sequence stars.

2. PULSATING PRE–MAIN-SEQUENCE STARS

After the discovery of the first two pulsating PMS stars in the young cluster NGC 2264 (Breger 1972), it took more than 20 yr until another PMS pulsator was found. Kurtz & Marang (1995) observed the Herbig Ae field star HR 5999 and detected δ Scuti–like pulsations with an amplitude of ~13 mmag in Johnson V and a period of ~5.0 hr in the presence of irregular 350 mmag background variability coming from the obscuring material in which the star is embedded. These measurements enabled for the first time the examination of the internal structure of a PMS star using asteroseismology and the placing of constraints on the pulsation models (Marconi & Palla 1998). Since then, several detections of pulsations in Herbig Ae field stars (e.g., Donati et al. 1997; Marconi et al. 2000), as well as in members of young clusters (e.g., Zwintz et al. 2005; Zwintz & Weiss 2006), have been published.

The PMS pulsators have the same spectral types and luminosities as the classical δ Scuti stars. Hence, it is expected that their pulsation is driven by similar mechanisms, i.e., the \( \kappa \)- and \( \gamma \)-mechanisms in the hydrogen and helium ionization zones (Marconi & Palla 1998). The unstable modes in pulsating PMS stars known so far are similar to those for classical δ Scuti stars, namely, low radial order p- and q-modes (Suran et al. 2001). Compared to post–main-sequence stars, the inner parts of PMS stars are more uniform in density and chemical composition and without the presence of nuclear reactions, which is the reason for a lack of avoided crossing (Suran et al. 2001). Frequencies of \( l = 0 \) modes with same radial order are nearly identical for pre– and post–main-sequence stars (Suran et al. 2001). For nonradial modes (\( l > 0 \)) the patterns are more complicated due to evolutionary changes in the stellar interior and allow a discrimination between PMS and (post–) main-sequence stars (Guenther et al. 2007). These are very interesting differences that can be tested with asteroseismology. Using single-site CCD time-series observations and the recently developed nonradial pulsation models for PMS stars, it was possible for the first time to identify the five significant pulsation frequencies in NGC 6383 27 as \( \ell = 0, 1, \) and 2 modes (Zwintz et al. 2007, their star No. 170).

Until recently, 36 pulsating PMS stars have been discovered, of which 30 are bona fide PMS pulsators and 6 remain pulsating PMS candidates because their periods could not be determined accurately enough yet. Using dedicated time-series photometry, PMS pulsation has been discovered in 18 members of 6 young open clusters and in 18 Herbig Ae field stars. A complete catalog of the presently known pulsating PMS stars and candidates including an overview of their parameters is given in Table 1. Consequently, the instability region for PMS pulsators can be investigated observationally and compared to the classical δ Scuti instability strip.

3. VERIFICATION OF PMS NATURE

The evolutionary stage of a star with given effective temperature (\( T_\text{eff} \)), luminosity, and mass may be ambiguous, as the evolutionary tracks for pre– and post–main-sequence stars intersect...
The six young open clusters that host PMS pulsators are all younger than 10 million years, indicating that their A to F type members have not reached the ZAMS yet. Hence, a basic membership criterion was the location of the targets of interest in the respective cluster HR diagrams.

In addition, proper-motion data from the TYCHO-2 (Høg et al. 2000) and the ASCC2.5 (All-Sky Compiled Catalogue of 2.5 million stars; Kharchenko 2001; Kharchenko et al. et al. 2005) catalogs were used for a verification of their cluster membership and, hence, their PMS nature. Unfortunately, for only three of the cluster stars (see Table 2) proper-motion data are listed.

Only for stars 53 and 38 in NGC 6530 have membership probabilities been published; these are 78% and 68%, respectively (van Altena & Jones 1972).

For star NGC 6383 27, Hα is in emission, and a near-infrared excess was detected by Thé et al. (1985). These features are...
characteristic for HAEBE objects (see below); hence, the PMS nature of NGC 6383 27 seems to be confirmed.

3.2. Herbig Ae Field Stars

Herbig Ae stars are known to be PMS objects because their observable characteristics (e.g., typical emission lines, infrared and ultraviolet excess) seem to originate from the protostellar material in which such young stars are still embedded. Except for V351 Ori and V1247 Lac, all pulsating PMS field stars (see Table 1) are included in the Catalog of Herbig Ae/Be stars (Thé et al. 1994).

Vieira et al. (2003) included V351 Ori (their star PDS 201) in their list of Herbig Ae/Be candidates and link this star with the Ori B star-forming region. As the observed Hα emission is quite weak for this star, Vieira et al. (2003) indicate that V351 Ori might already be a more evolved Herbig Ae star. Hence, its evolutionary stage is still disputed.

V1247 Ori (PDS 192) shows symmetric Hα emission features without, or with only very shallow absorption features (Vieira et al. 2003). It is—like V351 Ori—believed to belong to the Ori B star-forming region, and its PMS evolutionary phase is highly probable.

4. COLOR TRANSFORMATION

The observational instability strip for classical (post−) main-sequence δ Scuti stars is usually given in absolute magnitude ($M_V$) versus dereddened Strömgren ($b−y_0$) color (Rodríguez & Breger 2001). For the pulsating PMS stars only limited additional information is available, both spectroscopic and photometric. While apparent magnitudes and Johnson ($B−V$) are provided, Strömgren measurements exist for only 4 of the cluster and 7 of the field stars. Hence, for a direct comparison of classical δ Scuti and pulsating PMS stars, $M_V$ and $(B−V)_0$ had to be derived for both star groups. For the cluster stars the absolute magnitudes and dereddened colors were calculated using the cluster distances and color excess (see Table 3). The situation is not satisfactory for the 18 pulsating PMS field stars. Parallaxes are published for 16 of them, but of low quality. For part of the stars, $M_V$ based on those parallaxes yields implausible values; i.e., the stars would be located below the ZAMS. The other parallaxes have large errors. For PDS 2, e.g., the error of the parallax is 3 times larger than the parallax itself (Table 4).

Furthermore, the color excess $E(B−V)$ was not measured for any of the pulsating PMS field objects. Hence, the following general relation for reddening in the interstellar medium was applied (e.g., Voigt 1991):

$$A_V \sim 0.3 \text{ mag kpc}^{-1},$$

$$A_V = 3E(B−V),$$

where $A_V$ denotes the interstellar absorption in $V$. It has to be stressed that this can only be taken as a first estimate (see Table 4).

With the relations given in Caldwell et al. (1993) the $(b−y)_0$ colors of the classical δ Scuti stars were transformed into $(B−V)_0$ values. Any transformation is affected by errors, but they are smaller when transforming intermediate-band to broad-band photometry than vice versa. Consequently, we transformed the $(b−y)_0$ colors of the δ Scuti stars to $(B−V)_0$.

5. COMPARING PMS PULSATORS TO CLASSICAL δ SCUTI STARS

It is now possible to compare classical δ Scuti to pulsating PMS stars in a common parameter space, $M_V$ versus $(B−V)_0$ (Fig. 1). For the δ Scuti stars $M_V$ is taken from (Fig. 1, open circles) Rodriguez & Breger (2001), and for the PMS pulsators and candidates $M_V$ was computed from the cluster distances (Fig. 1, filled and open diamonds; Table 3) and parallaxes of the field stars (filled squares; Table 4). For the majority of PMS field pulsators the published parallaxes either place the stars below the ZAMS or have large (i.e., > 10%) errors (Table 4).
Hence, only two pulsating PMS field stars are selected for the H-R diagram: $\beta$ Pic and HD 104237, with errors in the parallaxes of 1% and 6%, respectively. According to Figure 1, PMS pulsators and $\delta$ Scuti stars seem to populate the same instability region in the H-R diagram. A lack of pulsating PMS stars is visible at the “cool” corner of the instability region for classical $\delta$ Scuti stars. Whether this is only a selection effect caused by poor number statistics or has some astrophysical reason can only be speculated about.

Figure 1 shows also the uncertainties in $M_V$ and $(B-V)_0$ for the PMS pulsators. For the pulsating PMS cluster stars the errors in $M_V$ were computed from the errors in distance (Table 3) and the $(B-V)_0$ errors were either taken from the literature, if available, or propagated from the listed errors in the $V$ and $B$ measurements. In an analogous manner, the $M_V$ errors for the pulsating PMS field stars were calculated from the errors in the parallax (Table 4). As the parallax errors are typically larger than 10%, only two of the 18 pulsating PMS field stars with accurate enough parallaxes could be used for the comparison of PMS pulsators and $\delta$ Scuti stars in the H-R diagram. For the pulsating PMS field stars errors for $(B-V)$ are scarce in the literature and we estimated them as standard deviations of independently measured and published $V$ and $B$ magnitudes. Note that the computed errors in $(B-V)_0$ for the field stars are at least 5 times larger than for all other stars.

For NGC 6823 230 ($open$ $diamond$) only a single value for $V$ and $B$ can be found in the literature without any error information. Hence, no errors in $(B-V)_0$ and also in $M_V$ can be determined for this star. It is remarkable, that—despite the large formal errors—most PMS pulsators are located within the instability strip. This fact may indicate an excessively pessimistic error estimate for these stars.

Two outliers can clearly be identified: the PMS cluster stars, NGC 6823 230 ($open$ $diamond$) and NGC 6823 279, are located blueward of the blue border of the classical instability strip. The distance of NGC 6823 has the largest error compared to the other clusters containing pulsating PMS stars. The general cluster $E(B-V)$ of 0.845 mag adopted for the two PMS stars seems to be overestimated considering their position in a rather unobscured region of the cluster.

6. SUMMARY AND CONCLUSIONS

For 36 PMS stars ($\delta$ Scuti–like) pulsations were discovered by different authors within the last few years. The PMS evolutionary

TABLE 4

| Name           | Parallax (mas) | Error (mas) | $M_V$ (mag) | $(B-V)$ (mag) | Ref. $(B-V)$ (mag) | $E(B-V)$ (mag) | $(b-y)_0$ (mag) |
|----------------|---------------|-------------|-------------|--------------|------------------|----------------|---------------|
| PDS 2          | 9.69          | 29.60       | 5.66        | 0.38         | 1                | 0.01           | $0.234$       |
| IP Per         | 42.29         | 29.70       | 8.48        | 0.34         | 2                | 0.00           | $0.208$       |
| UX Ori         | 0.69          | 2.47        | -0.13       | 0.16         | 2                | 0.15           | 0.055         |
| HD 34282       | 5.89          | 1.62        | 3.68        | 0.33         | 2                | 0.02           | $0.189$       |
| V346 Ori       | 1.39          | 2.01        | 0.97        | 0.20         | 2                | 0.07           | $0.066$       |
| HD 35929       | 0.66          | 0.93        | -2.78       | 0.45         | 2                | 0.15           | 0.267         |
| V351 Ori       | 3.55          | 1.59        | 1.66        | 0.38         | 2                | 0.03           | 0.120         |
| CQ Tau         | 10.00         | 2.00        | 5.60        | 0.50         | 2                | 0.04           | $0.319$       |
| BF Ori         | 0.66          | 1.79        | -0.78       | 0.25         | 2                | 0.15           | $0.129$       |
| V1247 Ori      | 32.4          | 25.10       | 7.38        | 0.34         | 2                | 0.00           | $0.210$       |
| $\beta$ Pic    | 52.00         | 0.50        | 2.43        | 0.20         | 2                | 0.00           | 0.085         |
| HD 104237      | 8.54          | 0.52        | 1.24        | 0.25         | 2                | 0.01           | 0.124         |
| HD 142666      | 3.29          | 10.89       | 1.40        | 0.56         | 2                | 0.03           | $0.343$       |
| HR 5999        | 4.88          | 0.87        | 0.53        | 0.31         | 2                | 0.02           | 0.154         |
| VV Ser         | 2.27          | ...         | 3.65        | 0.93         | 3                | 0.90           | $0.561$       |
| WW Vul         | 47.7          | 26.89       | 8.99        | 0.38         | 2                | 0.00           | $0.237$       |
| PX Vul         | ...           | ...         | ...         | ...          | 2                | 0.00           | $0.458$       |
| V375 Lac       | ...           | ...         | ...         | 0.88         | 3                | 0.00           | $0.527$       |

Notes.—Name, parallax, error in parallax, and the computed absolute magnitude $M_V$, $(B-V)$, and $(b-y)_0$, where values marked with an asterisk were calculated using the transformations given by Caldwell et al. (1993). Parallaxes and their errors are taken from the Hipparcos catalog (Perryman et al. 1997) and the ASCC 2.5 Catalog (Kharchenko 2001; Kharchenko et al. 2005); except for VV Ser for which the parallax was computed from the distance given in Ripepi et al. (2007). The $(B-V)$ values were taken from (1) Vieira et al. (2003), (2) the ASCC 2.5 Catalog (Kharchenko 2001; Kharchenko et al. 2005), and (3) the Third Catalog of Emission-Line Stars of the Orion Population (Herbig & Bell 1988). The measured $(b-y)_0$ values are taken from Hauck & Mermilliod (1998).
phase of these stars has been assessed from observational evidence: either they are members of young open clusters or Herbig Ae stars. Although only limited information is available in the literature for pulsating PMS stars, it is possible to explore their positions in the observational H-R diagram. These positions and the observed period range support predictions of driving mechanisms for PMS pulsation that are similar to those of δ Scuti stars. Furthermore, the hot and cool boundaries of the δ Scuti instability strip seem to coincide with the borders for the pulsating PMS stars.

Note that in general the determination of fundamental parameters for pulsating PMS stars is still unsatisfactory. For only two of the 18 pulsating PMS field stars the parallaxes are accurate enough to be useful for a comparison to the δ Scuti stars. Young clusters frequently exhibit strong differential reddening, and field Herbig Ae stars are often surrounded by circumstellar gas and dust, which severely limits the determination of \((B - V)_0\). Temperature calibrations using \((B - V)\) colors exist for stars on the ZAMS (e.g., Reed 1998), but their applicability to PMS stars that have luminosity classes III–V is questionable. Consequently, no \(T_{\text{eff}}\) and \(L/L_\odot\) data are provided in this paper.

With a dense enough observed pulsation frequency spectrum it will be possible to discriminate directly between evolutionary stages using asteroseismology, as recently has been successfully demonstrated by Guenther et al. (2007). This avoids hazards with poorly determined distances and photometric indices.

The question of whether the lack of PMS pulsators in the “cool” corner of the classical instability strip has an astrophysical background or is due to poor number statistics calls for dedicated observations.

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1 See http://www.univie.ac.at/webda.

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