A search for strange modes in non-linear Cepheid models

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Lívia Blanka Bárány

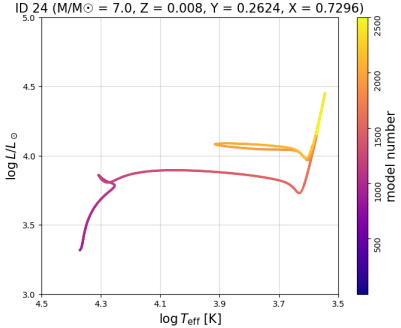
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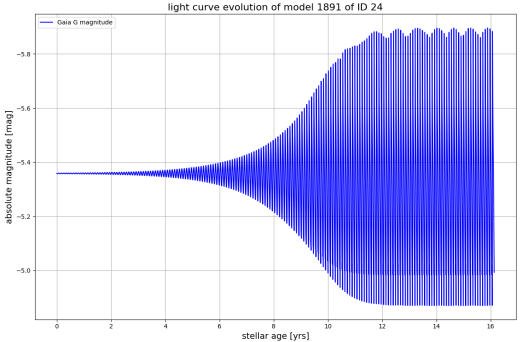
Supervisors:
Dóra Tarczay-Nehéz
László Molnár

November 6, 2026

Modeling classical Cepheids with MESA

- **MESA** (*Modules for Experiments in Stellar Astrophysics*)
- Evolutionary tracks of classical Cepheids
- **MESA-RSP**: non-linear stellar pulsation





Background and motivation

- **What are strange modes?**
  Unusual, surface-localized high-overtone pulsations in post-main-sequence stars. Occurrence in Cepheids: the 5th to 9th radial overtones, with periods: 0.6 - 6 days.
- **Previous work:** theoretical instability strip of strange modes with linear non-adiabatic (LNA) stability analysis.
- **The limitation:** linear models can identify if a mode is unstable, but can't predict amplitudes, or determine the outcome of mode selection (Tarczay-Nehéz et al. 2026).



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Stranger Things: A Grid-based Survey of Strange Modes in Post-Main Sequence Models

Dóra Tarczay-Nehéz[1,2], László Molnár[1,2,3], and Meridith Joyce[1,2,4]
[1] Konkoly Observatory, HUN-REN CSFK, MTA Centre of Excellence, Budapest, Konkoly Thege Miklós út 15-17, Hungary; tarczaynehez.dora@csfk.org
[2] MTA-HUN-REN CSFK Lendület "Momentum" Stellar Pulsation Research Group, Hungary
[3] ELTE Eötvös Loránd University, Institute of Physics, Budapest, Pázmány Péter sétány 1/A, Budapest, Hungary
[4] University of Wyoming, 1000 E University Ave, Laramie, WY, USA
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Abstract

We present a systematic survey of strange mode pulsations in Cepheids using MESA and for the linear stability analysis, MESA RSP. Our model grid spans 2–15 $M_\odot$ in mass and [Fe/H] = −0.95–0.17 ($Z = 0.0015$–0.0200) in metallicity, with four convective overshoot prescriptions. Strange modes were identified in a relatively small fraction (∼5–12.5%) of models, occurring at $n_{pg} = 5$–9, with $n_{pg} = 6$–7 as the most frequent radial modes. No unstable solutions were identified beyond $n_{pg} = 9$, in contrast to earlier studies reporting strange modes at $n_{pg} = 10$–12. We quantified the duration of the instability crossing phase ($\tau_{\rm IS}$), the strange mode phase (τ_s), and their ratio $\mathcal{T}_{\rm s} = \tau_s/\tau_{\rm IS}$. Toward higher masses, both $\tau_{\rm IS}$ and τ_s decrease, yet their ratio shows no systematic trend with mass in models that include convective core overshoot. The absolute timescales for strange modes remain short, typically $\tau_s \sim 10^{4.5}$–10^6 yr, while $\tau_{\rm IS}$ is often an order of magnitude shorter, implying that these stars may spend a larger fraction of their life in the strange mode phase than in the instability strip itself. The extended duration of the strange mode phase may enhance the detectability of strange mode pulsators, provided that observational precision is sufficient to capture their low-amplitude variability. The predicted periods (0.6–6.3 days) are well covered by a single 27-day TESS sector, making strange mode pulsators potentially detectable with current space-based photometry, although blending with nearby sources may pose challenges.

Unified Astronomy Thesaurus concepts: Asteroseismology (73); Blue loop (167); Cepheid variable stars (218); Delta Cepheid variable stars (368); Instability strip (798); Pulsation modes (1309); Radial pulsations (1331); Stellar evolutionary models (2046); Stellar pulsations (1625)

1. Introduction

The term "strange modes" was first introduced by Cox et al. (1980) and refers to a class of pulsation modes found in post-AGB stars. These pulsations were initially thought of as a result of strong non-adiabatic effects, and have a characteristic ultra-low amplitude (ULA) light variation on a millimagnitude scale (see, e.g., Gautschy & Saio 1996; Buchler & Kollath 2001; Saio 2009). The possibility of strange modes in hot stars was recently revisited using more modern codes by Gautschy (2025), too. However, strange modes are not limited to hot stars. They were identified in AGB star models by Wood & Olivier (2014). Buchler et al. (1997) and Buchler & Kollath (2001) showed that strange modes can exist in weakly non-adiabatic stars, like classical Cepheids, or RR Lyrae type stars, as well, even with the inclusion of turbulent convection into the hydrodynamic models. Moreover, they not only exist but may thrive in classical Cepheids.

As a Cepheid progenitor evolves from the main sequence (MS) towards the red giant branch (RGB), it undergoes the first crossing of the instability strip (IS), where coherent radial pulsations occur. During this phase, the outer regions of the star inflate, resulting in the inward shift of the partial ionization zones of H and He. In this phase, the star evolves rapidly through the Hertzsprung–Russell diagram (HRD) towards the red giant branch (RGB), spending only a short period of time inside the IS. As such, most Cepheids we know are not in the first crossing phase. In moderate- to high-mass red giant stars (>2–$3M_\odot$), the He core ignites before becoming degenerate. These stars do not experience a He-core flash, and do not descend to the red clump or the horizontal branch: instead, as the core starts to burn He, the star starts to shrink at roughly constant luminosity, while the temperature of the star starts to increase. This shift towards the bluer colors (hotter temperatures), and back after core He exhaustion, is often referred to as the "blue loop" in the literature (Lauterborn et al. 1971;

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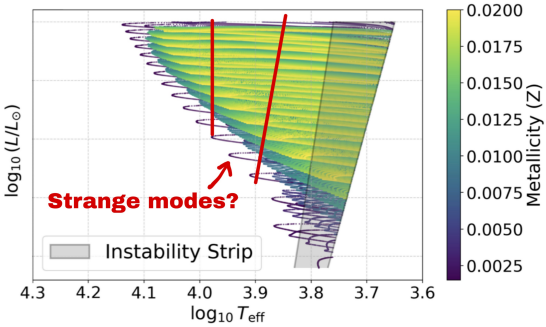
Research Objectives

Goal: to bridge the gap between theoretical models and observable reality with non-linear models.

- Determine the actual amplitudes and periods of the strange mode pulsations.
- Investigate which of the linearly unstable overtones actually survive and develop into steady pulsations.
- Map the resulting instability "islands" on the Hertzsprung-Russell diagram and compare them with stellar evolutionary tracks to filter out non-physical models.

Strange modes on the HRD

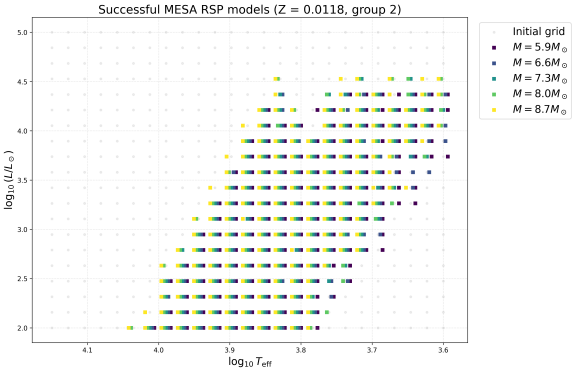
- Non-linear models will help to map out the blue (hotter) side of the blue loops.
- Strange mode pulsations are expected to form on the left side of the classical instability strip.



(Tarczay-Nehéz et al. 2026).

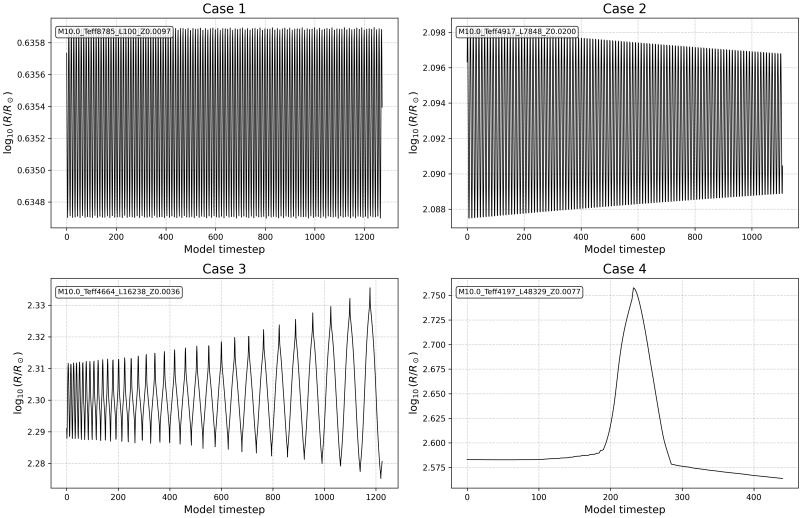
The simulation grid

- **Software:** MESA RSP (Radial Stellar Pulsation)
- **Parameter space:** a grid of 100,000 models, with masses ranging from 2.5 to 15.5 $M_\odot$ and metallicities between $Z = 0.0015$ and 0.020.

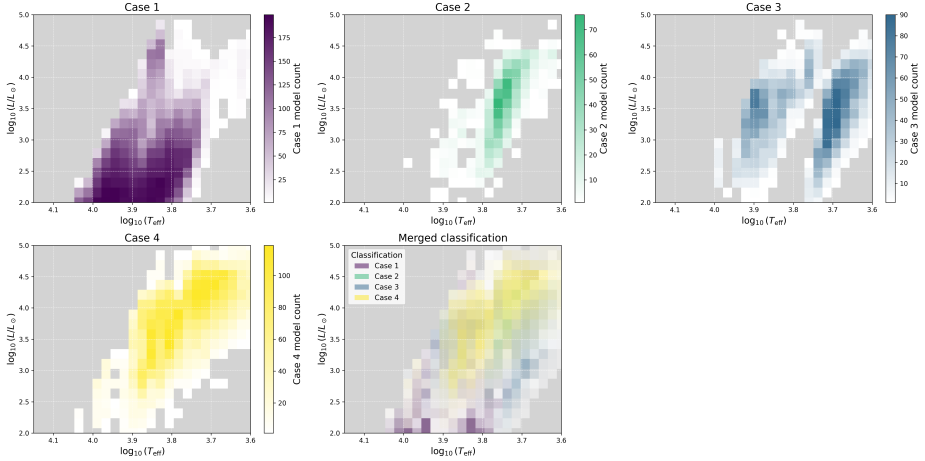


Data processing

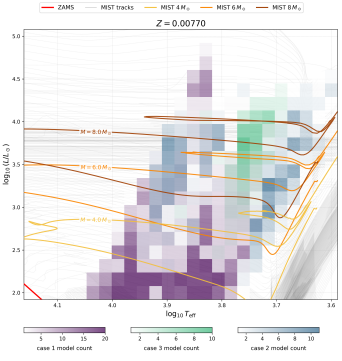
- Sorting algorithm in Python
  1. **Stable** (Case 1)
  2. **Decaying** (Case 2)
  3. **Growing** (Case 3)
  4. **Other** (Case 4)



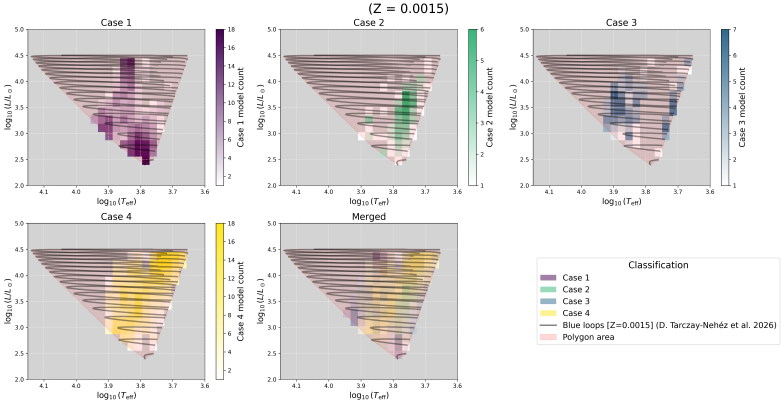
Results: classification



Results: comparison with MIST and blue loop tracks



MIST database
A. Dotter (2016); J. Choi et al. (2016)



Future steps

- **Light curve analysis:** calculate exact pulsation amplitudes and periods from the filtered non-linear model light curves.
- **Observational comparison:** compare model results with observational data from SMC and LMC Cepheids. $\Rightarrow$ Gaia DR4.
- **Software development:** implement and refine my custom algorithm.
- **TDK thesis & publication:** Summarize the results in an upcoming TDK research paper, with the ultimate goal of submitting a major article.