Revisiting the Instability Strip for rapidly oscillating Ap stars

Margarida S. Cunha[1], Luis Balona[2], Daniel L. Holdsworth[3], Güenter Houdek[4], Karrine Perraut[5], Barry Smalley[6]

Abstract: More than 60 Ap stars are today known to exhibit high frequency oscillations. These are known as rapidly oscillating Ap (roAp) stars. Despite these numbers, the mechanism responsible for driving these oscillations is still under debate. Currently, the most widely accepted theory states that oscillations in this class of pulsators are excited by the opacity mechanism acting on the hydrogen ionization region, in an envelope where convection has been suppressed by a strong magnetic field. Nevertheless, this theory has been challenged in a number of ways, particularly for its difficulty in reproducing the observed red edge and the very high frequencies observed in some of the well studied pulsators. In this study we revisit the theoretical instability strip proposed by Cunha (2002) and compare the results with the observations for nearly 60 roAp stars, including 5 stars with exquisite luminosity and effective temperature determinations, derived from a combination of interferometry, parallax, and bolometric flux. The main differences with respect to the previous theoretical work is the exploitation of a larger parameter space and different input physics for the non-adiabatic models. The results show that there is an overall consistency between the position of the known roAp stars in the HR diagram and the predicted Instability strip. However, hints of disagreement are seen when comparing the range of frequencies excited in stellar models and those observed in some stars. This, in turn, points towards the need to re-think the excitation mechanism at work, at least in a sub-group of roAp stars.

Excitation mechanism in roAp stars: the problem

➢ The excitation mechanism acting on rapidly oscillating Ap (roAp) stars is still not well understood. It has been proposed that the rapid oscillations are excited in the H ionization region of stars with envelope convection suppressed by the magnetic field (Balmforth et al 2001). However, two important questions arise when comparing the model predictions with the observations, namely:

✧ Some roAp stars are placed beyond the red edge of the Theoretical Instability Strip and there are no known roAp stars close to the blue edge (Cunha 2002).

✧ Some roAp stars pulsate in frequencies that are significantly higher than those predicted to be excited by the opacity mechanism acting on the H ionization region (Cunha et al. 2013).

The goal

➢ To revisit the Theoretical Instability Strip proposed by Cunha (2002) by performing linear, non-adiabatic stability calculations for models with envelope convection suppressed and to compare the results with data on all roAp stars detected to date.

In comparison with Cunha (2002), the work is extended in the following ways:

✧ We explore a larger parameter space, in terms of stellar mass and effective temperature.

✧ We consider models with different physical properties, in particular: different surface abundance of He, different atmospheric extents, and different boundary conditions applied in the pulsation model. A detailed description of the equilibrium and pulsation models can be found in Cunha et al. (2013).

Computations

➢ The calculations were performed in three steps:

✧ A grid of models with convective overshoot was computed with the MESA code (Paxton et al. 2013, 2015), for masses between 1.4 and 2.5 Msun, in steps of 0.5Msun.

✧ For each mass track, models equally spaced in $R^{3/2}$ were selected, roughly up to the TAMS. The Mass (M), effective temperature ($T_{\rm eff}$), and luminosity (L) of these models were used as input to generate equilibrium models with envelope convection suppressed, following Balmforth et al. (2001).

✧ Linear, nonadiabatic calculations were performed to establish which models are unstable to high radial order pulsations. For each model found unstable, we identify the range of frequencies excited.

➢ For each set (M,$T_{\rm eff}$,L), four cases were considered, by changing the following one at a time: the surface abundance of He (Y_s); the minimum optical depth of the atmosphere ($\tau_{\rm min}$); the boundary condition on the pulsation code (from fully reflective to that derived for an isothermal atmosphere). The four cases are summarized in table 1.

Table 1

Case	Polar surface He	Minimum optical depth	Boundary condition
A	0.01	1.5×10^{-4}	reflective
B	0.01	3.5×10^{-4}	reflective
C	0.01	1.5×10^{-4}	transmissive
D	0.1	1.5×10^{-4}	reflective

Observations

➢ The results from our study are compared with data on 55 roAp stars. These were taken from the set of 61 roAp stars known to date (Smalley et al., 2015), after excluding 6 stars whose published parameters place them below the ZAMS.

These 55 stars are organized in three different groups:

✧ Stars for which interferometric data are available (blue symbols).

✧ Stars for which Hipparcos parallaxes, but not interferometric data, are available (green symbols).

✧ All stars from Smalley et al (including the stars from the samples above), with parameters from that publication, except for 6 stars that according to those parameters would be placed below the ZAMS (red symbols).

Results of the non-adiabatic analysis

✧ High radial order excitation is found in models with temperatures lower than the previous theoretical red edge (see Fig. 1).

✧ All 55 roAp stars considered are positioned within the theoretical instability strip, given the 1-sigma uncertainties (see Fig. 2).

✧ Out of 5 stars with very accurate global parameters, 2 pulsate in frequencies that are not in agreement with the model predictions (see Fig. 3).

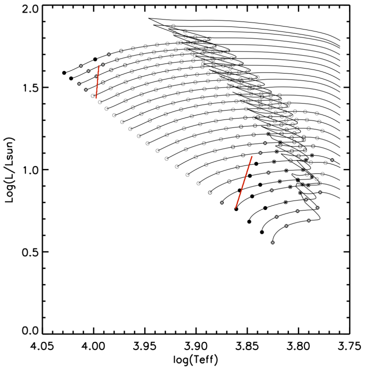

Fig 1: Results of the stability analysis

- **Open circles: Models are unstable to high radial modes in at least 3 out of the 4 cases considered**
- **Filled circles: Models are stable to high radial order modes in all 4 cases**
- **Open circles with black star over-plotted: Models are unstable to high radial modes in 2 out of 4 cases considered.**
- **Filled circles with white star over-plotted: Models are unstable to high radial modes in 1 out of 4 cases considered.**

- red lines: limits of the instability strip found with the models considered in Cunha (2002).

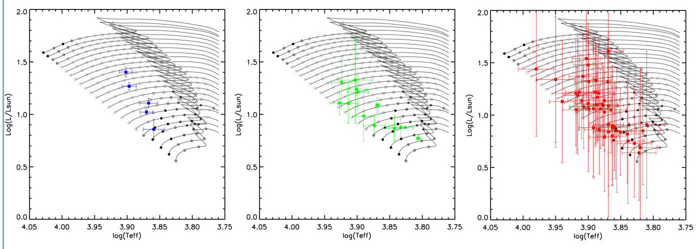

Fig 2. Position of known roAp stars in the HR diagram.
Left panel: Stars for which interferometric data are available; Middle panel: Stars for which Hipparcos parallaxes, but not interferometric data, are available; Right panel: All stars from Smalley et al. (2015) (except for 6 stars: see Observations section for details).

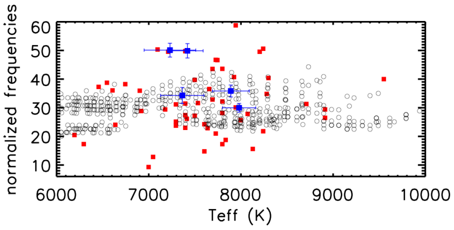

Fig 3: Comparison between the characteristic frequencies excited in the models and the observed frequencies. All frequencies are normalized by $M^{1/2}/(2\pi R^{3/2})$

Open circles: model results
Blue squares: stars with interferometry
Red squares: stars from Smalley et al. (2015), except for 6 stars (see text for details) and for the stars with interferometry. The typical vertical error bar of the red squares is larger than the total extent of the y axis.

Conclusions

✧ There is a good agreement between the position of the known roAp stars in the HR diagram and the predicted instability strip, but a clear disagreement is found when comparing the observed and mode predicted frequencies for some of the stars.

1 Instituto de Astrofísica e Ciências do Espaço, Centro de Astrofísica da Universidade do Porto, Portugal
2 South African Astronomical Observatory, South Africa
3 University of Central Lancashire, UK
4 Stellar Astrophysics Centre, Aarhus University , Denmark
5 Université Grenoble Alpes, and CNRS, IPAG, Grenoble, France
6 Keele University, UK

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