# STABILITY STUDIES OF SDO MODELS

CRISTINA RODRÍGUEZ–LÓPEZ[1] , RAFAEL GARRIDO[1] , ANDRÉS MOYA[1]
*1 Departamento de Física Estelar, Instituto de Astrofísica de Andalucía–Consejo Superior de Investigaciones Científicas, E-18008 Granada, SPAIN*
ANA ULLA[2]
*2 Departamento de Física Aplicada, Universidade de Vigo, E-36310 Vigo, SPAIN*
JAMES MACDONALD
*Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, U.S.A*

**Abstract:** We present a summary of a stability analysis of 27 models of O-type hot subdwarfs (sdOs), taken from 16 complete evolutionary sequences. Our objective is the theoretical exploration of the driving mechanisms of the oscillation modes, which helps us constrain the instability strip for this recently discovered class of pulsating stars.

**Keywords:** Hot Subdwarfs – Asteroseismology – Stellar Evolution Models –Non-adiabatic Pulsations.

## 1 Introduction

Subluminous O stars (sdOs) link the extended horizontal branch and the post-asymptotic giant branch stages with low-mass white dwarfs. Their inner structure and origins are still somewhat of a mystery, despite many existing studies (see i.e. [1] and references therein). Asteroseismologic techniques provide a robust method to learn about their physical nature, and can yield information such as the mass of the star, of its envelope, and even about its inner structure through the Brunt-Väisälä frequency, provided that we know the oscillation modes present in the star.

With this in mind, an extensive observational search for pulsating sdOs [2] was carried out, with no definite results. Fortunately, a team of South African observers recently found the first sdO pulsator [3], giving real support to our theoretical exercise.

The aim of our theoretical studies is to explore the possibility of driving oscillation modes in sdO models. Our tools in the exercise were a stellar evolution code and a nonadiabatic oscillations code.

## 2 Method

The sdO models were constructed with the stellar evolution code JMSTAR [4]. They belong to 16 complete evolutionary sequences of 1 M$\odot$ stars with solar ($Z = 0.02$) and above solar ($Z = 0.05$) initial metallicity, that start on the pre-main sequence. Mass loss rates on the red giant branch are enhanced by a factor ranging from 1.60 to 1.85 so that most of the envelope is removed just after or even before the helium core flash. At the highest rates, the star undergoes helium flashes that convectively carry inner elements to the surface of the star, enriching the atmosphere. The evolution of the models is stopped when they reach the white dwarf phase, marked by the onset of the star's cooling.

A total of 27 models were used as input to the GraCo nonadiabatic oscillations code [5, 6], which predicts the theoretical spectrum of modes for each model and which of them are excited. This allows us to determine a possible instability strip.

## 3 Results

We explored with GraCo all modes from $l = 0$ to $l = 4$ and frequencies in the approximate range of 0.3 to 20 mHz, so as to cover both the regions of slow and rapid pulsations.

We found two models to be definitely unstable, and a third tentatively so. In all cases, high radial order $g$-modes are driven through the action of a $\kappa$ mechanism. This mechanism is caused by the increase in the opacity due to the partial ionization of heavy elements (in models 10 and 10.1 below) or the partial ionization of carbon-oxygen (in model 15, that we take with caution as it is still under study).

Table 1 shows a summary of the explored models with their effective temperatures, logarithm of surface gravity, metallicity in that specific moment of their evolution, and the tendency to instability of the $g$- and $p$-modes spectra. Also, we show which partial ionization zone contributes to the destabilization of the modes.

## 4 Conclusions

All of the 27 sdO models, except model 8, present a tendency to instability of the high radial order $g$-modes, that usually is associated with a driving region in the carbon - oxygen partial ionization zone. Actual driving of oscillations is achieved for model 15.

Models 10 and 10.1 also show actual excitation of high radial order $g$-modes; this time caused by the increase in the opacity associated with the ionization of heavy elements (the so-called Z-bump) in the envelope of the star. The evolutionary sequences of these models define an instability strip between 45 000 and 55 000 K in effective temperature, and 4.18 and 4.50 in logarithm of surface gravity. These parameters are still far from the preliminary determination (Roy Ostensen, private communication) of physical parameters for the first discovered sdO pulsator.

The tendency to instability of *p*-modes is not so frequent in the analyzed models, being found in only 6 out of 27 models, but when it does occur, it is always associated with the opacity bump due to partial ionization of heavy elements.

*Acknowledgements:* This work is supported by the Spanish Ministerio de Ciencia y Tecnología under project ESP2004-03855-C03-01.

## References

[1] Ströer, A., Heber, U., Lisker, T. et al. 2007, A&A, 462, 269
[2] Rodríguez-López, C., Ulla, A., Garrido, R. 2007, MNRAS, 379, 1123
[3] Woudt, P. A., Kilkenny, D., Zietsman, E. et al. 2006, MNRAS, 371, 1497
[4] Lawlor, T. M., MacDonald, J. 2006, MNRAS, 371, 263
[5] Moya, A., Garrido, R., Dupret, M. A. 2004, A&A 414, 1081
[6] Moya, A., Garrido, R. 2007, Ap&SS, DOI:10.1007/s10509-007-9694-2

| Model number name | $T_{\rm eff}$ (K) | $\log g$ | Z | $g$-modes | $p$-modes |
|---|---|---|---|---|---|
| 1 p675_8057 | 79 000 | 5.70 | 0.07 | C/O | Z |
| 1.1 p675_9065 | 90 000 | 6.50 | 0.07 | C/O | – |
| 2 p650_7960 | 79 000 | 5.95 | 0.02 | C/O | – |
| 3 etap 685 | 55 000 | 5.89 | 0.02 | C/O | – |
| 4 etap 690 | 55 000 | 5.95 | 0.02 | C/O | – |
| 5 etap 695 | 55 200 | 5.98 | 0.02 | C/O | – |
| 6 etap 700 | 55 000 | 6.02 | 0.04 | C/O | – |
| 7 eta 600t45 | 45 000 | 4.95 | 0.05 | Z | – |
| 7.1 eta 600t70 | 70 000 | 5.95 | 0.05 | C/O | – |
| 8 eta 650t45 | 45 000 | 5.26 | 0.05 | – | Z |
| 8.1 eta 650t70 | 70 000 | 6.22 | 0.05 | C/O | – |
| 9 eta 700t45 | 45 000 | 6.13 | 0.07 | C/O | Z |
| 9.1 eta 700t70 | 70 000 | 6.34 | 0.07 | C/O | – |
| **10 eta 675t45mixi** | 45 000 | 4.18 | 0.14 | **Z** | – |
| **10.1 15773t54g45** | 54 050 | 4.50 | 0.15 | **Z** | – |
| 10.2 15873t58g47 | 58 300 | 4.77 | 0.14 | Z | – |
| 10.3 16973t69g51 | 68 900 | 5.13 | 0.16 | C/O+Z | – |
| 10.4 17773t77g54 | 77 000 | 5.39 | 0.17 | C/O+ Z | – |
| 10.5 18273t84g56 | 84 500 | 5.63 | 0.18 | C/O | Z |
| 10.6 18573t91g59 | 91 000 | 5.92 | 0.19 | C/O | Z |
| 11 eta 675t45mixnmi | 45 000 | 4.36 | 0.07 | Z | – |
| 12 eta 675t70mix1i | 70 000 | 5.16 | 0.16 | C/O + Z | – |
| 13 eta 675t70mix2i | 70 000 | 5.20 | 0.18 | C/O + Z | – |
| 14 eta 675t70mixnmi | 70 000 | 5.43 | 0.07 | C/O + Z | – |
| **15 eta 675t90mixi** | 90 000 | 5.86 | 0.19 | **C/O?** | Z |
| 15.1 18742t98g63 | 97 600 | 6.28 | 0.20 | C/O | – |
| 16 eta 675t90mixnmi | 90 000 | 6.58 | 0.07 | C/O | – |

Table 1: Effective temperature, logarithm of surface gravity, current metallicity and partial ionization zones responsible for the tendency to driving —or actual driving (models in bold)— of the $g$- and/or $p$-modes spectrum.