Asteroseismic modelling of Procyon A: Preliminary results

G. Doğan1,⋆ A. Bonanno2 T. R. Bedding3 T. L. Campante1,4 J. Christensen-Dalsgaard1 and H. Kjeldsen1

1 Department of Physics and Astronomy, Aarhus University, Ny Munkegade, DK-8000, Aarhus C, Denmark
2 Catania Astrophysical Observatory, Via S.Sofia 78, 95123, Catania, Italy
3 School of Physics A29, University of Sydney, NSW 2006, Sydney, Australia
4 Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal

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We present our preliminary results of the modelling of the F5 star Procyon A. The frequencies predicted by our models are compared with the frequencies extracted through a global fit to the power spectrum obtained by the latest ground-based observations, which provides two different mode identification scenarios.

1 Introduction

Procyon A is a member of a binary system with a white dwarf companion, Procyon B. It is one of the very bright stars to the naked eye, and hence it has been very attractive for the observers. The observational constraints which we adopted are summarized in Section 2. It has also been of astroseismic interest for a long while (see Arentoft et al. 2008, for a summary), with a solar-like power excess in its spectrum first reported by Brown et al. (1991). However, there has been no agreement on the individual oscillation frequencies. Several authors have investigated the structure and evolution of Procyon A through an astroseismic approach (e.g., Guenther & Demarque 1993; Barban et al. 1999; Chaboyer et al. 1999; Di Mauro & Christensen-Dalsgaard 2001; Eggenberger et al. 2005; Provost et al. 2006, Bonanno et al. 2007), but there has been a need for more accurate frequencies. Recently, the star was observed through a multi-site campaign by eleven telescopes for more than three weeks (Arentoft et al. 2008). The frequency analysis is described by Bedding et al. (2010). They presented results from different approaches of frequency extraction: Iterative sine-wave fitting and global fitting to the power spectrum. In the former method, a sine wave is fitted to each mode one after the other while the corresponding sinusoid is subtracted from the time series at each step. This is repeated until the signal to noise ratio of the remaining power is lower than a given threshold. This method was used for frequency extraction of ground-based radial velocity data before (see, e.g., the analysis on solar-like star β Hyi by Bedding et al. (2007)). In the latter method, the goal is to find an overall fit to the power spectrum for all the frequencies, mode heights, and linewidths simultaneously, using some prior knowledge of oscillation properties as constraints. A similar implementation of this method was previously applied to space-based data (see, e.g., frequency analysis of CoRoT star HD 49933 by Benomar et al. (2009)). In this work, we adopted this Bayesian approach which provided us with two mode identification scenarios, referred to as Scenario A and B, with different posterior odds (for a detailed discussion, see Bedding et al. 2010). We chose the output of this analysis in order to test both scenarios. Note that Scenario B was favoured by Bedding et al. (2010; see that paper for a discussion), but here we test both scenarios.

2 Methods and Tools

We have adopted the following properties for the position of the star in the H-R Diagram: $T_{\text{eff}} = 6530 \pm 90$ K (Fuhrmann et al. 1997) and $\log(L/L_\odot) = 0.85 \pm 0.06$ (Steffen 1985). We note that there are several revised values for luminosity in the literature, such as $\log(L/L_\odot) = 0.840 \pm 0.018$ derived by Jerzykiewicz & Molenda-Zakowicz (2000) using the Hipparcos parallax and total absolute flux; however, we chose to scan a wider range, which largely covers most of the revised values. A similar argument applies also to the choice of the effective temperature. We have not put an additional constraint on the radius for the time being, although we do compare the stellar mean density inferred from the analysis with the value $0.172 \pm 0.005 \rho_\odot$, obtained from the measured radius using the angular diameter $5.404 \pm 0.031$ mas (Aufdenberg et al. 2005) and the revised Hipparcos parallax $(284.56 \pm 1.26\text{mas})$, van Leeuwen (2007), together with the adopted mass $1.463 \pm 0.033 M_\odot$, which is the mean of the two different astrometric determinations ( Girard et al. 2000, 2001b).

Note that there is an error in Bedding et al. 2010 (Section 9); the value they give for the revised parallax is actually the original one. We also note that the uncertainty on the revised parallax is larger than the original but is presumably more reliable.
Gatewood and Han 2006). For the metallicity of the star, we allowed a wide range covering the 0.05 dex iron deficiency suggested by Allende Prieto et al. (2002), and we used the solar mixture from Grevesse & Noels (1993).

We have computed stellar models with two different evolutionary codes: ASTEC (Aarhus STellar Evolution Code) (Christensen-Dalsgaard 2008a) and GARSTEC (Garching Stellar Evolution Code) (Weiss & Schlattl 2008). The method we used is to compute several grids of standard models scanning through a parameter space formed by varying the mass, the initial metallicity at the stellar surface, their parameters summarized in Table 1. One

\[ \nu = \nu_{\text{obs}}(\ell) - \nu_{\text{model}}(\ell) / \sigma_{\nu}(\ell) \]

where \( \nu_{\text{obs}}(\ell) \) and \( \nu_{\text{model}}(\ell) \) are the model, and the observed, frequencies with spherical degree \( \ell \) and radial order \( n \). \( \sigma_{\nu}(\ell) \) represents the uncertainties in the observed frequencies.

### 3 Results

The results from the two different stellar evolutionary codes are similar; hence we present some of the selected models computed with ASTEC. The so-called \( \hat{\text{Echelle}} \) diagrams of the best models for both of the scenarios, chosen without applying any near-surface corrections are shown in Figs 1 and 2, with their parameters summarized in Table 1. One plots the \( \hat{\text{Echelle}} \) diagrams using the frequency modulo the large frequency separation, \( \Delta \nu \), in the horizontal axis. In order to allow easy comparison with the diagrams shown by Bedding et al. (2010), we use the same value, \( \Delta \nu = 56 \mu \text{Hz} \), in our diagrams.

The behaviour of the frequency differences between the models and the observations (shown in Figs 3 and 4) are quite different from that in the Sun. Kjeldsen et al. (2008) showed that the difference between observed and model frequencies of the Sun can be fitted by a power law, which can also be employed to correct the model frequencies for near-surface effects in other solar-like stars, such as \( \beta \) Hyi and \( \alpha \) Cen A. However, in Procyon, we cannot justify the application of such a surface correction to yield a significant improvement in the fit, since the frequency differences do not follow the power-law behaviour (see also Figs 16 and 17 of Bedding et al. 2010).

### 4 Discussion and Conclusion

We can argue, if Scenario A is the correct one, that the predictions of the stellar evolutionary models match the observations quite well; however, a surface correction for the model frequencies seems not to be needed, unlike in the solar case. Therefore, the effects of different near-surface properties on the high frequencies might be cancelling out in Procyon; this deserves further investigation.

If, on the other hand, Scenario B is correct, there seems to be no good agreement between the models and the ob-
Table 1  Parameters of the best models

| Parameter | Scenario A | Scenario B |
|-----------|------------|------------|
| $M/M_\odot$ | 1.50       | 1.50       |
| $Z/Z_\odot$ | 0.0235     | 0.0245     |
| $Y_i$ | 0.266     | 0.290     |
| Age (Gyr) | 1.83       | 1.51       |
| $R/R_\odot$ | 2.058     | 2.067     |
| $\rho/\rho_\odot$ | 0.1721     | 0.1698     |
| $L/L_\odot$ | 6.565     | 7.286     |
| $T_{\text{eff}}$(K) | 6446     | 6603     |
| $\alpha$ | 1.8        | 1.6        |
| $X^*_c$ | 0.1585     | 0.1995     |
| $\chi^2$ | 3.79       | 24.46      |

* Mass fraction of hydrogen remaining in the centre of the star

Fig. 3  The difference between the radial ($l = 0$) frequencies from the observations and the selected model for Scenario A. The indicated uncertainties are those from the data analysis.

Fig. 4  Same as Fig. 3, but for Scenario B

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