ABOUT MODELS AND OSCILLATIONS OF THE SOLAR-LIKE STAR PROCYON A

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ABSTRACT

Recent radial velocity observations of the solar-like star Procyon A have provided a set of frequency oscillation measurements (Martić et al 2004). We have computed new models of this star taking into account these seismic constraints, namely the large frequency separations, and the interferometric constraint, namely the new radius determination obtained with the VLT/VIINI instrument (Kervella et al 2004). We discuss the properties of these models for Procyon (age, mass and chemical compositions) and we present the characteristics of their oscillation frequencies.

1. SEISMIC OBSERVATIONS

Peaks of frequencies of acoustic modes with degrees $\ell=0$, 1, 2 have been identified in the power spectrum of Doppler shifts measurements in the frequency range 300 – 1400 $\mu$Hz (Martić et al 2004). The set of frequencies can be characterized by the large and small frequency spacings defined hereafter. At high frequency, i.e. larger than 700$\mu$Hz, the large frequency spacings do not vary much and are rather independent on the degree of the oscillation modes. We thus define the quantity $\Delta \nu$ as the mean of the large frequency spacings obtained from the frequencies with degrees $\ell=0$ and 1 and larger than 700$\mu$Hz. The observational value is $\Delta \nu \sim 53.75 \mu$Hz.

2. OBSERVATIONAL CONSTRAINTS

We use the following values of mass, effective temperature, radius and metallicity to constrain the models:

\begin{align*}
1.36 < M/M_\odot & < 1.48 \quad (\text{AP02 + Hipparcos}), \\
6480 < T_{\text{eff}} & < 6580 \quad (\text{AP02}), \\
2.023 < R/R_\odot & < 2.073 \quad (\text{Kervella et al 2004}), \\
\text{-0.08 < [Fe/H] & < -0.02} \quad (\text{AP02}).
\end{align*}

3. EVOLUTIONARY MODELS

A set of models satisfying all the above constraints have been computed with the CESAM code (Morel 1997), using the following physics: nuclear data from NACRE collaboration, EFF equation of state, OPAL...
Figure 2. Example of an echelle diagram from Procyon amplitude spectrum, computed for the modulo mean $\Delta v_0 = 54 \mu$Hz. To increase the visibility of the modes in this image the spectrum was modified by a simple normalization to the highest peak in each successive folding frequency range. The starting folding frequency for the model frequencies was shifted by $8 \mu$Hz. This figure illustrates the significant departures from the asymptotic relation, possible existence of the mixed modes due to avoided crossings (or end mode interferences with the noise). The frequencies from the model(a) of Kervella et al. (2004) are indicated by asterisk, plus sign and square respectively for $l = 0, 1, 2$, dashed lines are at $l = 0, 1, 2 \pm 11.6 \mu$Hz.

Table 1. Main sequence models (upper part) Post main sequence (lower part). (a) indicates an overshoot parameter $\zeta = 0.2$, and (b) and (c) a mixing length parameter respectively 1.05 and 1.15. All the models have a depth of the external convection zone of about 0.1 $R_\star$. The more massive models 1.44 and 1.46 and the main sequence model 1.42 have a small convective core less than 0.1 $R_\star$. All the models of the lower part satisfy the seismic constraint $\Delta \nu \sim 53.75 \mu$Hz obtained from observations. The uncertainty on the radius induces an uncertainty on $\Delta \nu$ of about 1$\mu$Hz. $\varepsilon$ characterizes the different behaviors of the large spacings for different degrees (see section 4).

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<th>Ys</th>
<th>age</th>
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4. OSCILLATIONS PROPERTIES

Adiabatic frequencies have been computed in the observed frequency range for models of Table 1. We compare the theoretical and observed large and small
Figure 3. Kinetic energy as a function of the frequency for consecutive modes of degree \( \ell = 0 \) (green), 1 (red), 2 (blue), for an evolved model \( M = 1.36 M_\odot \).

spacings:

\[ \Delta \nu_{n,\ell} = \nu_{n,\ell} - \nu_{n-1,\ell}, \]
\[ \delta \nu_{02} = \nu_{n+1,\ell=0} - \nu_{n,\ell=2}, \]
\[ \delta \nu_{01} = 2 \nu_{n,\ell=0} - (\nu_{n,\ell=1} - \nu_{n-1,\ell=1}). \]

The spectrum of the evolved models contains some modes which are no pure acoustic modes, but mixed and gravity type modes. The gravity type modes are characterized by the fact that they have a large amplitude in the core of the star and consequently a much larger energy than the adjacent acoustic modes (Figure 3). As seen in Figure 4 the surface amplitude of these modes is small, thus it is likely that they will hardly be observed. They are not included in the computation of \( \delta \nu_{02} \).

The large and small frequency spacings are given for some models respectively Figures 5 and 6. For the large spacings, all the models are in agreement with the observations for degree \( \ell = 0 \). They have a different behavior for degree \( \ell = 1 \) in the lower part of the frequency domain, below 700 \( \mu \)Hz, due to the presence for evolved models of mixed modes. These modes are seen in Figure 3. In order to characterize the different behavior of the models in this range of frequencies and degree, we introduce the quantity

\[ \varepsilon = (\Delta \nu - \Delta \nu_{\text{low}}) / \Delta \nu, \]

where \( \Delta \nu_{\text{low}} \) is the mean large frequency spacing at low frequency 500-700 \( \mu \)Hz for \( \ell = 1 \). This value of \( \varepsilon \) globally increases when \( M/M_\odot \) decreases and \( Y_1 \) decreases.

For the small spacings, except for mixed modes, \( \delta \nu_{02} \) is not sensitive to different evolved models. The behavior of \( \delta \nu_{01} \) is very different according the evolutionary stage of the models, but it is also sensitive to the core overshoot parameter, particularly in the high frequency range (Provost et al 2004).

5. CONCLUSIONS

In conclusion, these preliminary results show that main-sequence models of Procyon are excluded by
both the constraints on age and $\Delta \nu$. Possible models of Procyon A are evolved models with a mass smaller than 1.6 $M_\odot$. The actual observations are compatible with all our evolved models except for $\Delta \nu_1$ which favours models with a low values of $\varepsilon$. Detection and accurate determination of frequencies of degrees $\ell=1$ in the low frequency range (400 to 700 $\mu$Hz), where mixed modes may appear, are needed to discriminate between the models.

REFERENCES


Figure 5. Large frequency spacings for $\ell=0$ and $\ell=1$. Models 1.36 and 1.38 $M_\odot$ are in black; 1.40 $M_\odot$ in yellow; 1.42 $M_\odot$ in green; 1.44 et 1.45 $M_\odot$ in violet. Observational points are in red.

Figure 6. Small spacings $\delta \nu_{02}$ and $\delta \nu_{03}$ as a function of the frequency for some models of Table 1 and observations (red star). Green circles represent a main sequence model 1.42 $M_\odot$. The peak around 950 $\mu$Hz for $\delta \nu_{02}$ is due to the fact that despite the gravity type modes have been removed to compute $\delta \nu_{02}$, the frequencies of the adjacent modes are perturbed. Except for such modes $\delta \nu_{02}$ is not sensitive to different evolved models. The behavior of $\delta \nu_{03}$ is very different according the evolutionary stage of the models.