Recent Insights into the Physics of the Sun and Heliosphere:
Highlights from SOHO and Other Space Missions
IAU Symposium, Vol. 203, 2001
P. Brekke, B. Fleck, and J. B. Gurman eds.

Structure of Procyon A by a seismological approach

M. P. Di Mauro

Teoretisk Astrofysik Center, Danmarks Grundforskningsfond,
Bygn. 520, Ny Munkegade, DK 8000 Aarhus C, Denmark

J. Christensen-Dalsgaard

Teoretisk Astrofysik Center, and Institut for Fysik og Astronomi,
Aarhus Universitet, DK 8000 Aarhus C, Denmark

Abstract. We consider the theoretical prediction of the power spectrum of oscillations of Procyon A, a bright subgiant star which shows solar like pulsations, comparing models computed by taking into account overshoot from the convective core, as well as diffusion of helium and heavy elements.

1. Introduction

The success of helioseismology has spurred investigators to extend this diagnostic to other stars which show multi-mode pulsations and to search for solar-type stars, which, like the Sun, show stochastically excited modes of oscillation.

Unfortunately, the seismological study of pulsating stars, known as *asteroseismology*, is currently hindered by the very small oscillation amplitudes observed in the Sun which are extremely difficult to detect in other stars with ground-based telescopes. Recently, however, Martić et al. (1999) were able to detect solar-like oscillations in Procyon A, an F5 subgiant star; the frequency spectrum showed a large frequency spacing (see below) of about 55μHz.

2. Models

Due to its proximity and brightness Procyon A has already attracted the attention of stellar seismologists (Guenther & Demarque 1993; Barban et al. 1999; Chaboyer et al. 1999). Its luminosity $\log L/L_\odot = 0.86 \pm 0.03$ (Girard et al. 1996), effective temperature $\log T_{\rm eff} = 3.8149 \pm 0.0059$ (Fuhrmann et al. 1997) and mass $M = 1.497 \pm 0.037 M_\odot$ (Girard et al. 2000) are well determined.

We have used all the observables to constrain a grid of stellar models of Procyon A based on recent physics, including the OPAL opacities (Iglesias & Rogers 1996) and Bahcall & Pinsonneault (1992) nuclear cross sections.

Figure 1 shows the resulting evolution tracks in an HR diagram; the models assumed a solar heavy-element abundance ($Z = 0.019$) and an initial helium mass fraction $Y = 0.282$. We computed models which take into account overshoot from the convective core and strong turbulent diffusion of helium and

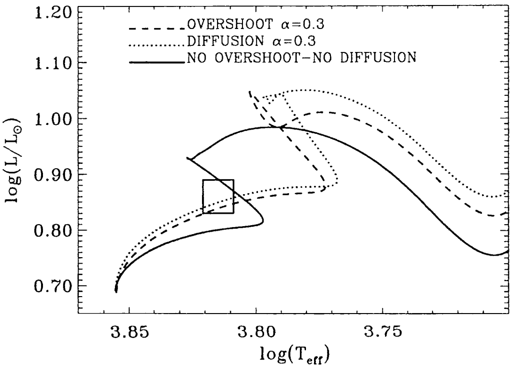

Figure 1. Stellar evolution tracks of Procyon *A* obtained for $M = 1.5M_\odot$ and Z=0.019. The rectangle defines the one-sigma error box in the observed effective temperature and luminosity .

heavy elements. The overshoot and the diffusion extend from the edge of the convective core over a distance expressed by the parameter α:

$$\ell = \alpha \min(r_{\rm c}, H_p) \ , \tag{1}$$

where H_p is the pressure scale height at the edge of the core and $r_{\rm c}$ is the radius of the convective core. Here we report results obtained by considering $\alpha = 0.3$.

The location of the star in the HR diagram identifies Procyon *A* as being in the late main-sequence phase of core hydrogen burning. All the models are identical at the ZAMS where the interior is chemically uniform, but in the domain of the observed $T_{\rm eff}$ and L at a fixed effective temperature a model which include overshoot or diffusion is less luminous and less evolved than a model without mixing outside the convectively unstable regions.

Table 1. Age, luminosity, effective temperature, radius, large frequency separation of some models of Procyon *A* with mass $M = 1.5M_\odot$ selected for pulsation calculations.

Model	*Age (Gy)*	$\log L/L_\odot$	$\log T_{\rm eff}$	$R/R_\odot$	$\Delta\nu$ (μHz)
No overshoot-No diffusion	2.09	0.87	3.81	2.19	52
Overshoot	2.03	0.85	3.81	2.12	54
Diffusion	1.34	0.86	3.81	2.15	55

3. Oscillation spectra prediction

We have calculated adiabatic eigenfrequencies of p and g modes with harmonic degree $l = 0, 1, 2, 3$. The oscillation spectrum is characterized by the large and

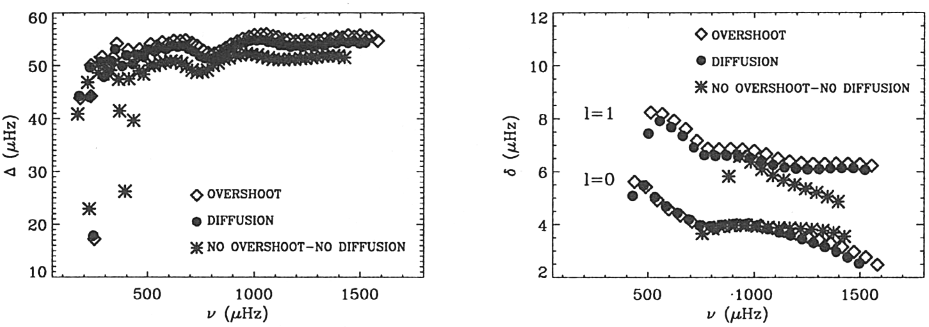

Figure 2. Large (Δ) and small (δ) frequency separations are plotted as functions of frequency, for several models of Procyon *A*.

small frequency separations which are important diagnostics of stellar properties. The large frequency separation is approximately equal to $\Delta \simeq \nu(n,l)-\nu(n-1,l)$, where $\nu(n,l)$ is the frequency of the p mode of radial order n and harmonic degree l, while the small frequency separation is $\delta = \nu(n,l) - \nu(n-1,l+2)$. In Figure 2, Δ and δ are shown as functions of frequency for some models selected for pulsation calculations, listed in Table 1. The models selected can reasonably reproduce the observed spectrum. In particular we found that the large separation is approximately 55 μHz for a model which includes both overshoot and diffusion, a value in good agreement with the observed one (Martić et al. 1999). The small separation calculated for all the models is about 4μHz for $l = 0$ and about 6.5μHz for $l = 1$. However, we note that there are subtle differences in the frequency dependence which may enable a test for overshoot or diffusion, if sufficiently precise frequencies can be determined for the star.

Acknowledgments. This work was supported by the Danish National Research Foundation through the establishment of the Theoretical Astrophysics Center.

References

Bahcall, J. N., & Pinsonneault, M. H. 1992, ApJ, 395, L119
Barban, C., et al. 1999, A&A, 350, 617
Chaboyer, B., Demarque, P., & Guenther, D. B. 1999, ApJ, 525, L41
Fuhrmann, K., et al. 1997, A&A, 323, 909
Girard, T. M., et al. 1996, BAAS, 188, 6002
Girard, T. M., et al. 2000, ApJ, 119, 2428
Guenther, D., & Demarque, P. 1993, ApJ, 405, 298
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Martić, M., et al. 1999, A&A, 351, 993