

Modeling of α Cen and Procyon using VLTI observations

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Abstract. We present a novel approach to model the nearby stars α Cen A & B and Procyon A using asteroseismic and interferometric constraints. Using the VINCI instrument installed at the VLT Interferometer (VLTI), the angular diameters of the α Centauri system were measured with a relative precision of 0.2% and 0.6%, respectively. From these values, we derive linear radii of $R[A] = 1.224 \pm 0.003 R_{\odot}$ and $R[B] = 0.863 \pm 0.005 R_{\odot}$. These radii are in excellent agreement with the models of Thévenin et al. (2002), that use asteroseismic frequencies as constraints (Bouchy & Carrier 2001; Bouchy & Carrier 2002). With the same instrument, we also measured the angular diameter of Procyon A. Using the *Hipparcos* parallax, we obtain a linear radius of $2.048 \pm 0.025 R_{\odot}$. We use this result together with spectroscopic and photometric constraints to model this star with the CESAM code. We also computed the adiabatic oscillation spectrum of our model of Procyon A, giving a mean large frequency separation of $\Delta\nu_0 = 54.8 \mu\text{Hz}$, in agreement with the seismic observations by Martić et al. (2001). Our model favours a mass around $1.4 M_{\odot}$ for Procyon A.

Keywords: interferometry, numerical modeling, asteroseismology

1. Scientific rationale

α Cen A (G2V) and B (K1V) offer the unique possibility to study the stellar physics at play in conditions just slightly different from the solar ones. Their masses bracket nicely the Sun's value, while they are slightly older. In spite of their high interest, proximity and brightness, the two main components have never been resolved by long baseline stellar interferometry, due to their particularly southern position in the sky. Their angular diameters were measured recently using the VLTI, and we have used them to constrain numerical models of these stars.

Procyon is also a binary star, with a white dwarf companion orbiting the main component in 40 years. Among the brightest stars in the sky, Procyon has been a target for a large number of spectro-



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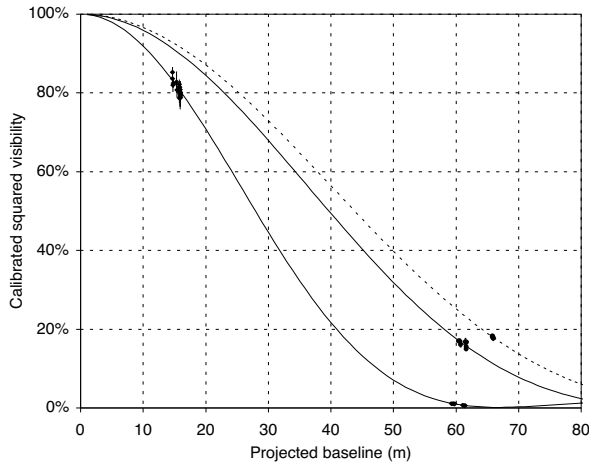


Figure 1. Squared visibilities measured with VINCI on α Cen A (bottom curve), α Cen B (middle curve) and their primary calibrator θ Cen (upper curve).

photometric calibration works. However, reproducing its position in the HR diagram has been recognized as of great difficulty (Guenther & Demarque 1993) using the classical constraints (metallicity, temperature, brightness). The addition of the asteroseismic and interferometric observational results allows to narrow very significantly the uncertainties of the evolutionary models.

2. Interferometric observations

For all our interferometric observations, we used the VLT Interferometer with its commissioning instrument, VINCI (Kervella et al. 2003c), a two telescopes beam combiner operating in the K band (2.0-2.2 μm). This instrument measures the squared visibility (V^2) of the interferometric fringes. It is related to the angular diameter of the star through the Zernike-Van Cittert theorem. Fig. 1 and 2 illustrate the V^2 measurements that we obtained on α Cen A & B, and the best-fit models that allowed us to derive their limb darkened angular sizes: 8.511 ± 0.020 and 6.001 ± 0.034 mas (Kervella et al. 2003a). Coupled with the Hipparcos parallax of 747.1 ± 1.2 mas (Söderhjelm 1999), this translates into linear radii of $1.224 \pm 0.003 R_{\odot}$ and $0.863 \pm 0.005 R_{\odot}$, respectively.

Using the same method (Fig. 3), we obtain an angular diameter of $\theta_{\text{LD}} = 5.448 \pm 0.053$ mas, and a linear photospheric radius of $2.048 \pm 0.025 R_{\odot}$ for Procyon A.

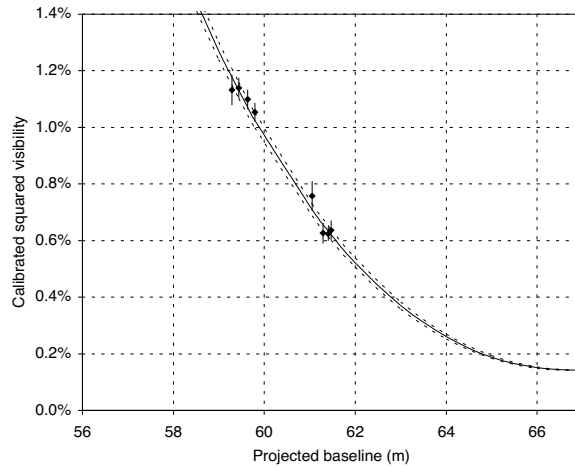


Figure 2. Enlargement of Fig. 1 showing the low visibility measurements obtained on α Cen A. They constrain the angular diameter model to a precision of $\pm 0.2\%$ (error domain limited by the dashed lines).

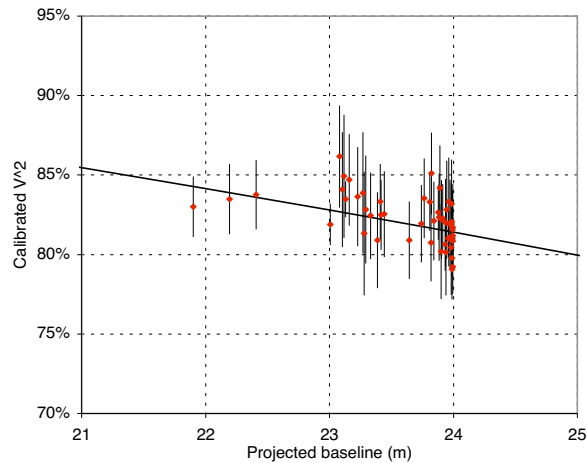


Figure 3. Squared visibility measurements obtained on Procyon with VINCI and best fit model (solid line).

3. Modeling using the CESAM code

3.1. METHOD

We have computed a series of models using the CESAM evolutionary code (Morel 1997). The evolution of each star was computed starting from the homogeneous ZAMS corresponding to their pre-estimated masses. As both α Cen and Procyon are visual binary stars with well

known orbits, it was possible to use a precise value of their masses for the input of our models. Each model (see e.g. Table I) corresponds to a different evolutionary track in the HR diagram.

The models were considered acceptable when their evolutionary track reached the center of the uncertainty domain defined by the photometric, spectroscopic and interferometric constraints. The constraint imposed by the linear radius R and the effective temperature T_{eff} is illustrated in Fig. 4 by the hatched parallelogram, while the constraint imposed by T_{eff} and the luminosity L is illustrated by the dashed rectangle. The surface of the shaded area is much smaller than the "classical" uncertainty domain, and it emphasises the advantage of using the measured R instead of L which depends of photometric calibrations and bolometric corrections.

3.2. PROCYON

Procyon was modeled using the parameters listed in Table I. Of the models that were tested, our model *a* succeeds the best in satisfying simultaneously all the observational constraints. Model *c*, based on a larger mass of $M = 1.50 M_{\odot}$, is clearly rejected by the mean asteroseismic large frequency spacing $\Delta\nu_0$ (see further for definition), as its predicted value $56.4 \mu\text{Hz}$ is incompatible with the value of $54 \mu\text{Hz}$ measured by Martić et al. (2001). Model *b* was computed without microscopic diffusion. It is still marginally compatible with the observational constraints, and it is older than model *a* by 400 Myr.

Our model *a* shows that using the given set of parameters and given physics, Procyon A is currently finishing to burn its central hydrogen, and is at the phase where the convective core is disappearing. The error on the measured radius gives a narrow uncertainty of 10 Myr on the deduced age. Provencal et al. (2002) have discussed the cooling time of the WD Procyon B and found that the progenitor ended its lifetime 1.7 ± 0.1 Gyr ago. We derive an age of 2 314 Myr for Procyon A. Subtracting the cooling age of the WD companion to our determination of the age of Procyon A leads to a lifetime of about 600 Myr for the progenitor of Procyon B. This indicates that the mass of the progenitor is approximately $2.5 M_{\odot}$. This value yields in turn a mass of $\sim 0.57 M_{\odot}$ for the core of the corresponding Thermal-Pulsating-AGB star (for $Z=0.020$) (Bressan et al. 1993), which is the minimum possible value for the final mass of the WD (see also Jeffries 1997). This estimate of $0.57 M_{\odot}$ agrees very well with the mass of Procyon B that we deduced from Girard et al. (2000) using the Hipparcos parallax. We note that the age obtained with model *c* is younger than the cooling age of Procyon B.

Table I. Procyon A models (without overshoot) lying within the uncertainty box in the HR diagram. The corresponding evolutions in the HR diagram are shown on Fig. 4. The subscripts “_i” and “_s” respectively refer to initial values and surface quantity at present day. “_c” refers to the central value. The model *a* is the most probable (see text).

Model	<i>a</i>	<i>b</i>	<i>c</i>
m/M_{\odot}	1.42	1.42	1.50
Y_i	0.3012	0.2580	0.345
Y_s	0.2209	0.2580	0.202
$\left(\frac{Z}{X}\right)_i$	0.03140	0.0218	0.0450
$\left(\frac{Z}{X}\right)_s$	0.02157	0.0218	0.0220
diffusion	yes	no	yes
X_c	0.00051	0.00000	0.2180
age (Myr)	2 314	2 710	1 300
T_{eff} (K)	6524	6547	6553
$\log g$	3.960	3.967	3.994
$[\text{Fe}/\text{H}]_i$	+0.107	-0.051	+0.264
$[\text{Fe}/\text{H}]_s$	-0.055	-0.051	-0.043
$\log(L/L_{\odot})$	0.8409	0.8405	0.8390
R/R_{\odot}	2.0649	2.0495	2.0420
$\Delta\nu_0$ (μHz)	54.7	55.4	56.4

This argument suggests a mass lower than $1.5 M_{\odot}$ for Procyon A and strengthens the asteroseismology results.

Further progress on the modeling of Procyon will be possible when the accuracy on the flux of the star is improved to less than 1%. Waiting for such accuracy, the uniqueness of the solutions resulting from computed models fitting a narrow box in the HR diagram will come from future detailed asteroseismic studies. For example, other linear combinations of frequencies such as the small frequency spacings (see e.g. Gough 1991) will constrain the age and the mass of the star.

Large uncertainties also come from the adopted chemical abundance mixture Z_s which is still rather uncertain. Only a few chemical element abundances are measured today and most of them with a low accuracy. This uncertainty on Z_s is the largest source of error on the estimated initial helium content Y_i and on the age of Procyon. Thus, we recommend that surface abundances should be derived from 3D atmosphere studies, in particular for oxygen and other important donors of electrons.

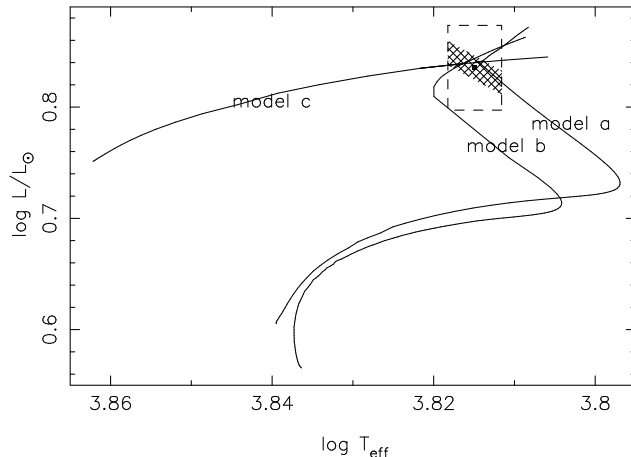


Figure 4. Evolutionary tracks in the HR diagram of three models of Procyon A (see Table I for the corresponding parameters). The dashed rectangle delimits the uncertainty domain for luminosity and effective temperature, while the hatched area delimits the uncertainty domain for effective temperature and the interferometric radius. Model *a* is the most probable model for this star (see text).

3.3. α CENTAURI

As emphasized by Thévenin et al. (2002), the seismic observations give strong constraints on masses and on the age of the system when combined with spectro-photometric measurements. To achieve this, one derives from the set of oscillation frequencies, one “large” and two “small” frequency spacings. The large frequency spacing is a difference between frequencies of modes with consecutive radial order n : $\Delta\nu_\ell(n) \equiv \nu_{n,\ell} - \nu_{n-1,\ell}$. In the high frequency range, i.e. large radial orders, $\Delta\nu_\ell$ is almost constant with a mean value $\Delta\nu_0$, strongly related to the mean density of the star, i.e. to the mass and the radius. The small separations are very sensitive to the physical conditions in the core of the star and consequently to its age. These frequencies measured for the star α Cen A have led to decrease the masses of the stellar system, leading to the following values: $M_A = 1.100 \pm 0.006 M_\odot$ and $M_B = 0.907 \pm 0.006 M_\odot$ (Thévenin et al. 2002) close to those adopted by Guenther & Demarque (2000). The mass of the B component departs significantly by 3% from the value published by Pourbaix et al. (2002).

Using radial velocity measurements, Pourbaix et al. (2002) have derived the masses of each components ($M_A = 1.105 \pm 0.007 M_\odot$, $M_B = 0.934 \pm 0.006 M_\odot$). We note that Thoul et al. (2003) have recently proposed a model of the binary system using these masses and spectro-photometric constraints different from that of Thévenin et al. (2002). They were able to reproduce the seismic frequencies of α Cen A, but the

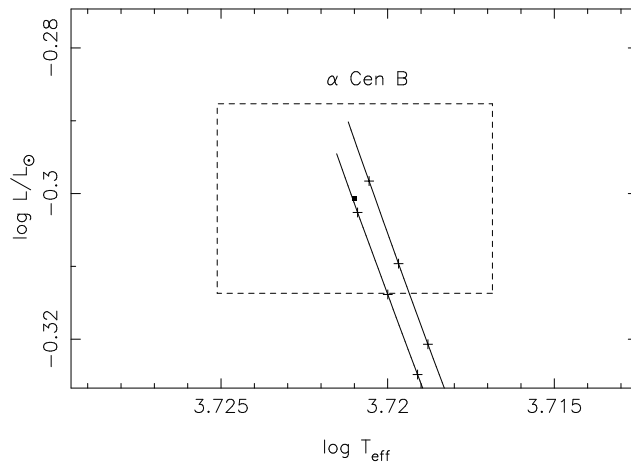


Figure 5. Evolutionary tracks of α Cen B in the HR diagram. The line on the right corresponds to a mixing length of $\lambda = 0.96$ and $M = 0.909 M_{\odot}$, the line on the left corresponds to the values published by Thévenin et al. (2002): $\lambda = 0.98$, $M = 0.907 M_{\odot}$.

model they propose does not take into account the helium and heavy elements diffusion.

The masses derived by Thévenin et al. (2002), $M_A = 1.100 \pm 0.006$ and $M_B = 0.907 \pm 0.006 M_{\odot}$ allowed us to compute evolutionary models that match simultaneously all constraints, including the linear diameter and asteroseismic large frequency spacing. These modifications do not change the calibration of α Cen A. We took care in this process to keep the star B in its error box on the HR diagram (Fig. 5). It results from this new mass a diameter that is closer to the interferometric one: $0.863 D_{\odot}$ or 5.999 ± 0.050 mas (parallax from Söderhjelm 1999). The effective temperature is found to be 5262 K, identical to the adopted spectroscopic value $T_{\text{eff}} = 5260$ K. Our results confirm that the mass of the B component is probably close to $0.907 M_{\odot}$, as reported by Thévenin et al. (2002).

As shown on Fig. 5, it is possible to refine the agreement by changing slightly the hypothesis of the model, in particular for B. The future availability of the large frequency spacing of α Cen B will complete the calibration of the system. While B is still on the Main Sequence with an hydrogen fraction at center of $X_{\text{center}} = 0.43$, α Cen A is currently near the end ($X_{\text{center}} = 0.18$), owing to its larger mass. This also explains its larger diameter compared to the lower Main Sequence M-R relation (Kervella et al. 2003d).

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