Revised masses of α Centauri

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Abstract. With the precise radial velocities lately published (Murdoch et al., 1993), a simultaneous least-squares adjustment of all visual and spectroscopic observations of the α Centauri system is now possible and likely to yield some accurate information. Such an orbit determination leads to a mass ratio in agreement with the astrometric estimate of Kamper & Wesselink (1978) but yields upward revisions of the distance and masses. We examine the effects these revisions on the evolutionary status of the system.

Key words: stars: binaries: spectroscopic – stars: binaries: visual – stars: fundamental parameters – stars: individual: α Cen

1. Introduction

α Cen is the binary system closest to the Earth and one could think it has been studied so intensively that there is nothing new to discover. It is true that it has been visually measured for almost 250 years but its long period coupled to the poor quality of the spectroscopic measurements leads to a surprisingly large remaining uncertainty on the individual masses. Precise radial velocities lately published (Murdoch et al., 1993) have radically changed the situation. Coupling them to visual observations, one derives significant upward revisions of the distance and masses.

2. Orbits, mass ratios and parallaxes

α Cen has been subject to many independent investigations about its mass ratio, parallax (ϖ) and system's radial velocity for almost 100 years. Most have lead to discrepant results (e.g., the astrometric and spectroscopic mass ratios do not agree).

One needs the mass sum and the mass ratio to derive the individual masses. The former comes out of the visual orbit when the parallax is known whereas the latter can be derived from either astrometric or spectroscopic observations. The most recent mass determinations are based on astrometric investigations, the quality of the radial velocities of α Cen being rather poor.

The visual orbit quoted as the reference *par excellence* is still the one by Heintz (1958) (and then lately published again

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(Heintz, 1982)) even if neither takes the last 40 years of visual observations into account. For the mass ratio, the most trusted one is due to Kamper & Wesselink (1978). They derived $\kappa = 0.454 \pm 0.002$ ($\kappa \equiv M_B/(M_A + M_B)$) and $\varpi = 750 \pm 5$ mas. These values coupled to Heintz' yield $M_A = 1.10M_\odot$ and $M_B = 0.91M_\odot$. A slightly different choice of the weights lead Demarque et al. (1986) to $\varpi = 750.6 \pm 4.6$ mas. From some theoretical considerations only, Neuforge-Verheecke & Noels (1998) have lately proposed $M_A = 1.12M_\odot$ and $M_B = 0.94M_\odot$.

Though only three years are covered by the observations of Murdoch et al. (1993), they are precise enough to estimate a reliable spectroscopic mass ratio. Murdoch & Hearnshaw (1993) used these radial velocities to determine $M_B/M_A = 0.75 \pm 0.09$, just at the limit of consistency with the solution by Kamper & Wesselink (1978).

The way α Cen has been considered in the observation reduction process after Hipparcos (ESA, 1997) may be questionable. Owing to the slow apparent orbital motion of B between 1989.9 and 1993.2, both components have been reduced with the (default) single star model. The two stars were not considered as being the members of a binary system in most of the reduction. The only exception was the assumption of the uniqueness of the parallax. That yielded a solution for both components qualified as *uncertain* (sic). Multiple solutions are proposed. The adopted parallax, 742 ± 1.42 mas, is lower than all previous estimates.

3. Simultaneous spectro-visual adjustment

Instead of disjoint determinations of the visual orbit, the mass ratio and the parallax, one can advantageously undertake a simultaneous adjustment of **all** visual and spectroscopic observations (Morbey, 1975; Pourbaix, 1998). We therefore include all visual observations from the Washington Double Star Catalog (US Naval Observatory), photographic as well as micrometric, and the radial velocities from the end of last century up to those of Murdoch et al. (1993).

In order to combine radial velocity sets, we put them in the same reference frame (by adding the same correction (cf. Table 1) to all velocities of a set) and adjusted the weights according to the scatter of the set.

Table 1. Shift and standard deviations for each group of radial velocities.

Reference	Shift (km/s)	σ_{V_A} (km/s)	σ_{V_B} (km/s)
Hough (1911)	−0.661	1.27	2.01
Lunt (1918)[*]	−0.02	0.833	1.26
Campbell & Moore (1928)	+1.27	1.54	1.53
Jones (1928)	+0.610	0.718	1.11
Wesselink (1953)	+3.04	0.943	0.763
Archer (1957)	+1.70	1.10	2.57
Jones & Fisher (1984)	+0.60	0.568[**]	0.568[**]
Murdoch et al. (1993)		0.042	0.076

[*] Wright's (1904) measurements are not included.

[**] Since there is only one observation, these σ are just the residuals.

Here are the sources of radial velocities coupled to the data after Murdoch et al. (1993) to compose the most extended radial velocity set:

- Hough (1911) and Jones (1928) published two sets of radial velocities taken at the Cape Observatory in 1904–1908 and 1908–1924.
- Lunt (1918) took some spectra between 1904 and 1912.
- Campbell & Moore (1928) compiled the radial velocities obtained at Santiago between 1904 and 1922. The authors gave empirical corrections to apply to individual measurements depending on who obtained them, where and when.
- Wesselink (1953) took some spectra around the extrema of the radial velocities. Unfortunately, although the epoch of the extrema had been known for a long time (Jones, 1928), very few spectra were taken at that epoch.
- Archer (1957) obtained some points in the steepest part of the radial velocity curves, just after the extrema.
- Jones & Fisher (1984) determined just one radial velocity of each component in 1972, almost coincident with the secondary extrema.

The shift applied to each set as well as the standard deviations of the radial velocities within each group are summarized in Table 1.

Each term of the objective function (Pourbaix, 1998) incorporates the weight associated to the observation. Although one may have a different weight for each observation, we assign the same weight to a group of observations. The weight of such a group is given by the inverse of the standard deviation of the members of the group. We thus adopt the values of Table 1 (Columns 3 and 4) for the radial velocities. We also set different weights for the polar and Cartesian observations. There is no need for relative weights of the radial velocities with respect to the astrometric data (Eq. 17 in (Pourbaix, 1998))

The orbit we derive is given in Table 2 and plotted in Fig. 1. We notice upward revisions of the distance and masses (6% and 7% for A and B respectively with respect to the estimates of Kamper & Wesselink (1978)). The new mass ratio is fully consistent with the astrometric one by Kamper & Wesselink (1978). We have thus obtained the first agreement between the
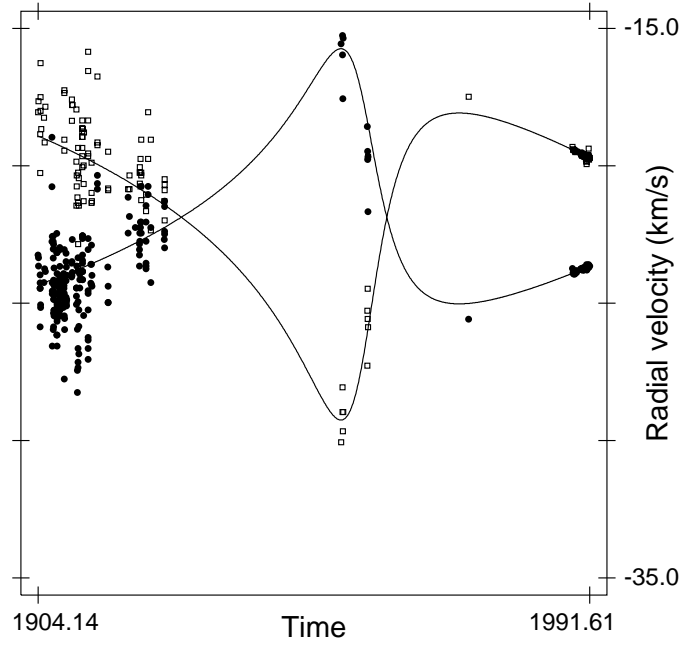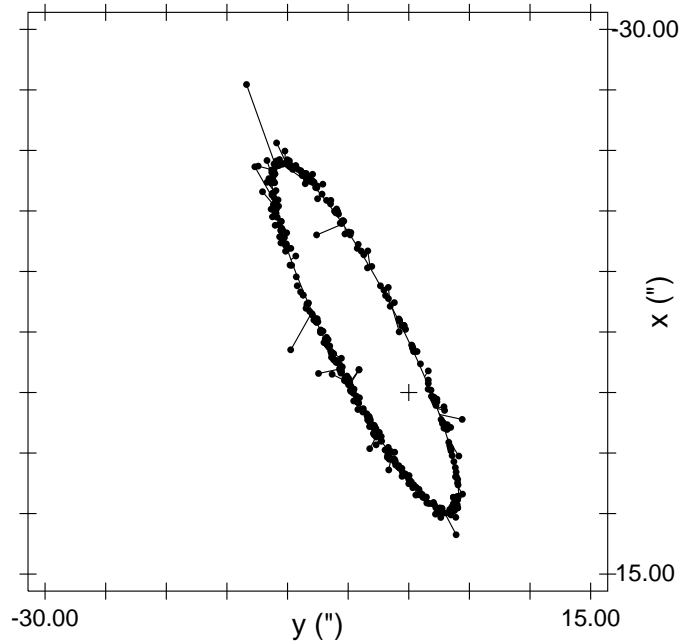

Fig. 1. Plot of the orbit corresponding to the best adjustment of all visual and spectroscopic data. The radial velocities of component B are represented with open squares. The radial velocities of Murdoch et al. (1993) are those after 1988

astrometric and spectroscopic mass ratios. The orbital parallax is discrepant with all previous estimates, the Hipparcos one being the closest to ours.

Our estimates of a and i are very close to those of Heintz (1958). The noticed reduction of the parallax and the corresponding increase of the masses are therefore due to an increase

Table 2. Orbital parameters and their standard deviations of α Cen after the simultaneous adjustment of all visual observations and the radial velocities

Element	Value	Std. dev.
a ($''$)	17.59	0.028
i ($°$)	79.23	0.046
ω ($°$)	231.8	0.15
Ω ($°$)	204.82	0.087
e	0.519	0.0013
P (yr)	79.90	0.013
T (Besselian year)	1955.59	0.019
V_0 (km/s)	-21.87	0.054
ϖ (mas)	737.0	2.6
κ	0.45	0.013
mass A ($M_\odot$)	1.16	0.031
mass B ($M_\odot$)	0.97	0.032

of at least one radial velocity amplitude. There is nothing puzzling with that since our spectroscopic orbit is one of the first one which takes all spectroscopic observations into account.

4. Evolutionary models of α Cen A and B

What are the consequences of these new masses? Does it remove the discrepancies noted by Popper (1997) when the fit of an isochrone is undertaken?

Two theoretical evolutionary models have been computed with the assumption that the two stars have a common origin, i.e. the same age and the same chemical composition. For a given stellar mass (M_A or M_B), a theoretical model of α Cen A or B contains the following parameters: the age t of the system, its initial hydrogen content X, its initial metallicity Z and the convection parameter (α_A or α_B), when convection is treated in the mixing length approximation. These parameters have to be adjusted so that the models reproduce the available observables within their error bars. Such models are referred to as calibrated models. The observables constraining the models are: the visual apparent magnitudes $m_{v,A} = -0.01 \pm 0.005$, $m_{v,b} = 1.33 \pm 0.005$ (Hoffleit & Jaschek, 1982), the effective temperatures $Te_A = 5830 \pm 30$ K, $Te_B = 5255 \pm 50$ K (Neuforge-Verheecke & Magain, 1997), the surface gravities $\log g_A = 4.34 \pm 0.05$, $\log g_B = 4.51 \pm 0.08$ (Neuforge-Verheecke & Magain, 1997) and the logarithmic abundance ratio of heavy elements to hydrogen, relative to the corresponding ratio for the Sun, $[Z/X] = 0.25 \pm 0.06$ (Neuforge-Verheecke & Magain, 1997).

Our models are calculated with the Liège stellar evolution code based on a first version originally developed by Henyey et al. (1964). The Debye-Huckel corrections (Noels et al., 1984) are included in the equation of state of Bodenheimer et al. (1965), the nuclear reaction rates are those of Fowler et al. (1975), the treatment of the photospheric layers is taken from Krishna-Swamy (1969). The interior opacities are OPAL opacities taken from Iglesias & Rogers (1996), the low-T opacities ($T \leq 10^4$K) are from Neuforge (1993) and the bolometric cor-

Table 3. Model parameters (mass, initial hydrogen content, initial metallicity, age and convection parameter) and physical characteristics (visual magnitude, effective temperature Te (in K), central hydrogen content X_c, central temperature T_c (in K) and central density ρ_c (in g/cm^3)) of the calibrated models of α Cen A.

	Model 1	Model 2
Model parameters		
M_A	1.17	1.09
X	0.686	0.680
Z	0.030	0.030
t	2.7	6.2
α_A	1.9	2.3
Physical characteristics		
$m_{v,A}$	-0.01	-0.01
Te_A	5848	5826
X_c	0.359	0.006
T_c	1.725E7	1.873E7
ρ_c	1.271E2	3.003E2

rections are from Flower (1996). Our models do not include diffusion and settling.

For $M_A = 1.17\,M_\odot$ and $M_B = 0.96\,M_\odot$, the observables are reproduced with the following model parameters: $X = 0.686 \pm 0.054$, $Z = 0.030 \pm 0.004$, $t = 2.7$ Gyr, $\alpha_A = 1.86 \pm 0.80$, $\alpha_B = 2.1 \pm 0.80$. The error bars on the model parameters result from the uncertainties affecting all the observables, including the masses (see (Brown et al., 1994) for the details of the calculations). These uncertainties are huge on the age and have not been quoted here. This means that the age is not very well constrained by the observations. The parameters and the physical characteristics of our α Cen A model, chosen at the center of the error bars, are presented in Table 3. Table 3 also shows the characteristics of a previous model (Model 2) calculated with the same input physics and obeying to the same observational constraints except for the orbital parameters, which have been taken from Kamper & Wesselink (1978), Heintz (1982) and Demarque et al. (1986). Both α Cen A models lie in the main-sequence band: they are burning hydrogen in their central layers, although Model 2 is very close to the end of the main sequence. Model 1 has a small convective core as a result of its higher mass. The problem in isochrone fitting (Popper, 1997), which was probably due to the use of a fixed chemical composition, has been removed here. The comparison between the models and the observational results may seem to be a never ending quest, since the models are continuously being improved and the error bars on the observations allow most of the time satisfactory models to be found. The hope is that asteroseismology will bring additional constraints which will be able to reduce the number of possible models (Brown et al., 1994).

We also computed the p-mode oscillation frequencies in both models for $l = 0, 1, 2, 3$ and for 1300 μHz $\leq \nu_{nl} \leq$ 3300 μHz. Although no ambiguous detection has been reported yet, oscillation data of low degree might nevertheless soon be

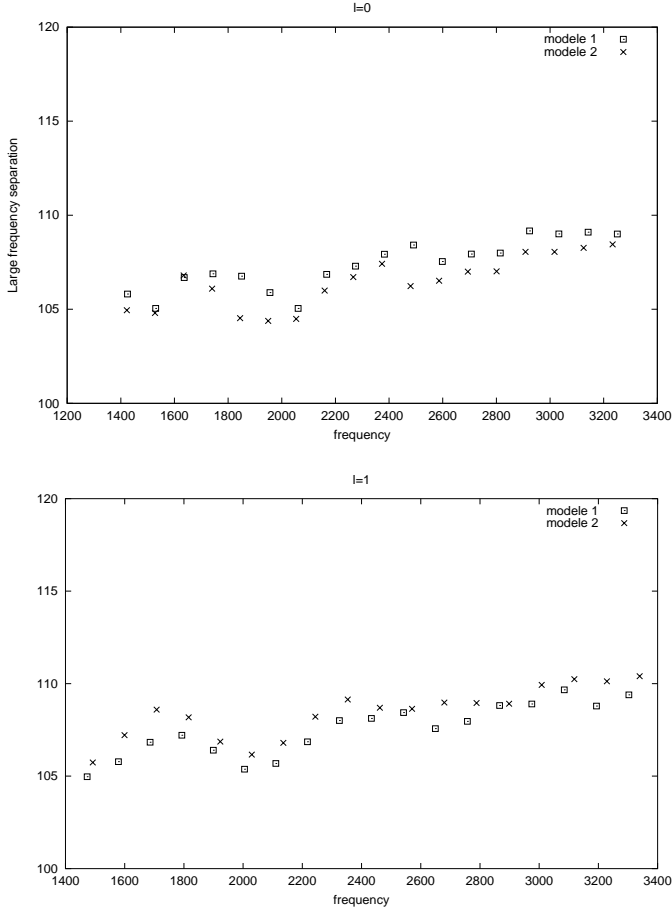**Fig. 2.** $\Delta\nu$ (l=0) as a function of ν (in μHz) for Model 1 (squares) and Model 2 (crosses). The *top panel* is for l=0 and the *bottom* one for l=1
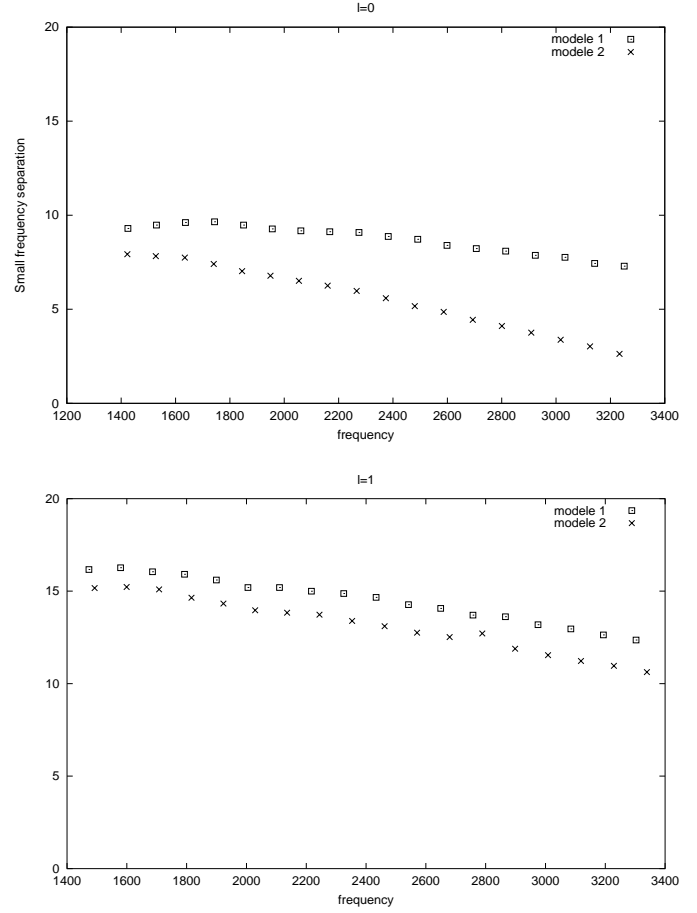
Fig. 3. $\delta\nu$ (l=0) as a function of ν (in μHz) for Model 1 (squares) and Model 2 (crosses). The *top panel* is for l=0 and the bottom one for l=1

obtained for α Cen A (Kjeldsen & Bedding, 1997). We computed the large and the small p-mode frequency separations, $\Delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l}$ and $\delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2}$. ν is the frequency of the p-mode and n, l are respectively its order and its degree. $\Delta\nu$ is an indicator of the mean density of the star. $\delta\nu$ decreases as the star evolves and gives clues to its evolutionary status. $\Delta\nu_{n,l}$ and $\delta\nu_{n,l}$ are given as functions of ν in Figs. 2 and 3, for l=0 and l=1.

Model 1 is more massive and therefore younger and less evolved than Model 2 as indicated by its higher central hydrogen content and its small frequency separations. The small frequency separations of this model differ from those of Model 2 by amounts much larger than the expected observational error bars ($\simeq 1$ μHz, (Brown et al., 1994)). The two models could thus be discriminated. If asteroseismology favors the lower mass model, could the mass difference be explained by the presence of a planet?

star A (or B) plus an unseen companion. The more massive the companion, the lesser massive the star.

The question of the detection of a possible planet orbiting around α Cen A or B rose with the drastic improvement of the spectroscopy. Dynamical simulations show that a planet could remain bound (Benest, 1988; Wiegert & Holman, 1997) but no spectroscopic campaign has revealed such a companion (Murdoch et al., 1993; Hatzes et al., 1996).

What would be the effect of a planet on the radial velocity of α Cen A? If one assumes $10^{-2}M_{\odot}$ for the mass of the planet (ten times the mass of Jupiter), 3 A.U. for the semi-major axis of the orbit (the upper bound for a stable circular orbit (Wiegert & Holman, 1997)) and co-planar orbits, we obtain an amplitude of 136 m/s. Such an amplitude is reachable with the most up to date spectroscopic techniques. Therefore, it is very unlikely that even one percent of the mass of α Cen A comes from a planet.

5. On the possibility of a planet around α Cen A or B

In the previous sections, we assumed that the mass we obtain for components A and B are the masses of stars A and B. Actually, one cannot reject the possibility for component A (or B) of being

6. Conclusions

Current visual and spectroscopic observations yield component masses larger than previous estimates. Further observations, especially very accurate radial velocities, are needed to confirm

those results. We urge southern spectroscopists to put a high priority on α Cen.

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