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Parallax and masses of α Centauri revisited★

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ABSTRACT

Context. Despite the thorough work of van Leeuwen, the parallax of α Centauri is still far from being carved in stone. Any derivation of the individual masses is therefore uncertain, if not questionable. And yet, that does not prevent this system from being used for calibration purpose in several studies.
Aims. We aim for more accurate model-free parallax and individual masses of this system.
Methods. With HARPS, the radial velocities are not only precise but also accurate. Ten years of HARPS data are enough to derive the complement of the visual orbit for a full 3D orbit of α Cen.
Results. We locate α Cen (743 mas) right where HIPPARCOS had originally put it, i.e. slightly farther away than derived by Söderhjelm. The components are thus a bit more massive than previously thought (1.13 and 0.97 $M_\odot$ for A and B, respectively). These values are now in excellent agreement with the latest asteroseismologic results.

Key words. astrometry – binaries: spectroscopic – techniques: spectroscopic

1. Introduction

The Sun is a single star and, as such, it is among the minority of solar-like stars that are mostly within binaries or multiple systems (Duquennoy & Mayor 1991; Halbwachs et al. 2003; Raghavan et al. 2010; Whitworth & Lomax 2015). Our closest neighbour – the system comprising α Centauri A, B and Proxima Centauri – is therefore more representative. With spectral types G2 V and K1 V, α Centauri A and B (HIP 71683/1) are in a binary system with an orbital period close to 79.91 yr (Heintz 1982; Pourbaix et al. 1999; Torres et al. 2010) and a distance of 1.35 pc. The A and B pair offers a unique possibility to study stellar physics in stars that are only slightly different from our own Sun. Their masses – 1.1 and 0.9 $M_\odot$ – nicely bracket that of our neighbour star, and they are only slightly older than the Sun. Thus, α Cen is an ideal laboratory for stellar evolution (e.g. Kervella et al. 2003; Porto de Mello et al. 2008; Bruntt et al. 2010; Bazot et al. 2012), asteroseismology (Kjeldsen et al. 2008; de Meulenaer et al. 2010) and extra-solar planet searches (Dumusque et al. 2012; Rajpaul et al. 2016; Bergmann et al. 2015; Endl et al. 2015). As such it is crucial to determine the properties of the two stars in α Cen with the highest accuracy, which can be done as double-lined spectroscopic visual binaries, thus offering a hypothesis-free determination of the distance and individual masses (Pourbaix 1998). One also needs to have the most precise orbital elements to distinguish any other effects, such as oscillations or the presence of a planetary-mass companion.

Pourbaix et al. (1999) presented the first simultaneous adjustment of the relative positions and radial velocities of both components of α Cen, yielding an upward revision of the masses. Owing to the special interest of the asteroseismology community for this system, an international team was gathered later on to obtain some accurate radial velocities of both components. The outcome was a set precise radial velocities that were used to quantify the relative convective blue shift of both components, assuming the individual masses and the parallax of the system (Pourbaix et al. 2002).

Even if it turned out to be a false detection (Hatzes 2013; Rajpaul et al. 2016), the announcement of a planetary companion around α Cen B (Dumusque et al. 2012) suddenly resurrected the interest of the planet hunters for that stellar system (Kaltenegger & Haghighipour 2013). We therefore decided to determine for the first time, in a self-consistent manner, the individual masses, the parallax, and the net shift caused by gravitation and convection, using an extensive set of homogeneous and accurate radial velocities of both components from the ESO HARPS science archive. The observations are described in Sect. 2 while the adopted model used to fit them is described in Sect. 3. Results are listed in Sect. 4 and discussed in the context of asteroseismology in Sect. 5.

2. Observational data

The system α Cen has been the target of many radial velocities (RV) measurements, especially, with HARPS, the High Accuracy Radial velocity Planet Searcher at the ESO La Silla 3.6 m telescope. The vacuum and thermally isolated HARPS instrument was especially designed for high-precision radial velocities observations (Mayor et al. 2003), reaching for example a dispersion of 0.64 m s^{-1} over 500 days (Lovis et al. 2006).

The velocities of both components of α Cen were retrieved from the HARPS archive maintained by ESO: 2015 velocities for A and 4303 for B. Despite the possibility of selecting the target on the ESO archive interface, a visual inspection was needed

★ Based on data obtained from the ESO Science Archive Facility under request numbers HBOFFIN/190700, Pourbaix/192287, Pourbaix/192364, Pourbaix/192404, Pourbaix/192552, Pourbaix/192630, and Pourbaix/199124.
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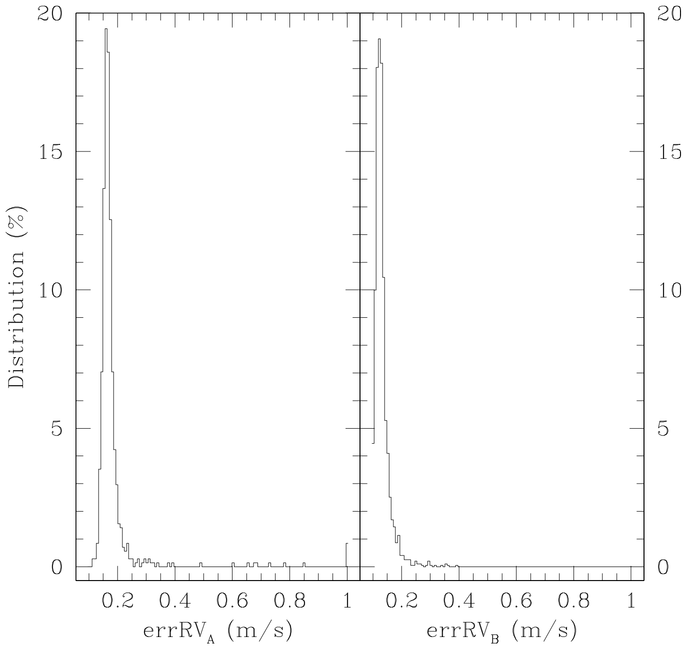

Fig. 1. Distribution of the estimated radial velocity uncertainties reported by the HARPS pipeline for components A (*left*) and B (*right*).

to assign the velocities to the right component. Further imposing that the seeing does not exceed 1 arcsec so as to avoid α Cen A contaminating α Cen B and vice versa, limited these observations to 710 and 1951 for A and B, respectively. The importance of this dataset lies in the simultaneous or quasi simultaneous observations of both components with an instrument that provides RVs on an almost absolute scale.

We used the radial velocities provided by the HARPS pipeline. For α Cen A, the RV is obtained by cross-correlating the spectra with a G2 V flux template that is the Fourier transform spectrometer (FTS) spectrum of the Sun (Kurucz et al. 1984) and is calibrated so as to have an offset in the zero-point of 102.5 m s^{-1} (Molaro et al. 2013). For α Cen B, the cross-correlation was done with a K5 template. The median of the velocity precision for A and B are 0.16 and 0.12 m s^{-1} (Fig. 1), respectively.

The HARPS data cover only 11 years (13% of the orbital period), but at the crucial time when the radial velocities cross (see Fig. 2). The HARPS data were completed with some older ESO data (Endl et al. 2001), obtained with the Coudé Echelle Spectrograph (CES) at the 1.4-m Coudé Auxiliary Telescope and later at the 3.6-m telescope, which are both in La Silla, to extend the baseline and to help improve the precision of the fractional mass ($\kappa = M_B/(M_A + M_B)$). These velocities being relative, the datasets of A and B were shifted to share the HARPS zero point.

These very accurate radial velocities were complemented with the same visual observations (both micrometric and photographic) as were used in our previous investigation (Pourbaix et al. 1999). According to its web portal, the Washington Double Star Catalog (Hartkopf et al. 2001) holds 37 additional visual observations (up to 2014.241) with respect to our original investigation. These data were kindly provided by the WDS team and added to the 1999 dataset for the sake of completeness. In practice, no parameter from the visual orbit was affected.

3. Model

The model used by Pourbaix et al. (1999) assumes that the measured radial velocities represent the radial velocities of the barycentre of each component:

$$\begin{aligned} V_A &= V_0 - K_A(e\cos\omega_B + \cos(\omega_B + \upsilon)), \\ V_B &= V_0 + K_B(e\cos\omega_B + \cos(\omega_B + \upsilon)), \end{aligned} \quad (1)$$

where V_0 denotes the systemic velocity, ω_B the argument of the periastron of component B, e the eccentricity, υ the true anomaly, and $K_{A,B}$ are the semi-amplitudes of the radial velocities of both components.

Whereas that assumption was realistic in the past when the radial velocities were precise to a few hundred metres per second, some effects pop up as soon as the precision improves. To recover the accuracy of the barycentre velocity, these effects have to be corrected for, either individually or globally. With relative radial velocities of both components, these effects would have to be modelled. With HARPS measuring both components in the same reference frame, it is possible to measure the correction to be applied globally.

Assuming that the gravitational red shift and convective blue shift of a given component do not change over the spectroscopic observation baseline, the net effect of the two shifts is just a vertical translation of the radial velocity curve. The dates of the minimums and maximums of the curve remain unchanged. No morphological change of the curve itself is anticipated. The net effect of the four shifts is therefore a vertical translation of one curve with respect to the other.

Such a vertical translation can easily be modelled with an additional term in, say, the radial velocity of component B (Eq. (1)):

$$V_B = V_0 + K_B(e\cos\omega_B + \cos(\omega_B + \upsilon)) + \Delta V_B. \quad (2)$$

It is worth pointing out that, while Pourbaix (1998) advocated for a simultaneous adjustment of the visual and spectroscopic data, this ΔV_B term has to be introduced because the solutions for V_A and V_B are obtained simultaneously! Indeed, if the two curves were modelled independently, two distinct V_0 would be obtained but K_A and K_B would represent the semi-amplitudes of the two curves. Without ΔV_B, the simultaneous fit introduces a bias on V_0, K_A, and K_B.

The orbit of the stellar system being our only goal, no short timescale variation (Dumusque et al. 2011, 2015) is modelled in the present investigation.

4. Results

Despite the absence of visual departure between the fit of the present dataset with and without ΔV_B, the parallaxes differ by 2% (smaller without shift), directly affecting the total mass by the same amount because the fractional mass remains essentially unchanged. The reduced χ^2 increases from 1.01 to 1.21 without the shift. The revision of the model is thus justified. The orbital elements are given in Table 1 together with the 2002 results and the orbit is plotted in Fig. 2.

The revised orbital parallax (743 ± 1.3 mas) is smaller than the value derived by Söderhjelm (1999) from the HIPPARCOS observations and adopted by Pourbaix et al. (2002). It is somewhat closer to the original HIPPARCOS value, 742 ± 1.42 mas (ESA 1997), and rules out the result obtained in the revision of the HIPPARCOS catalogue (van Leeuwen 2007) where the parallax is 754.81 ± 4.11 mas. Even though the parallax is different, the total

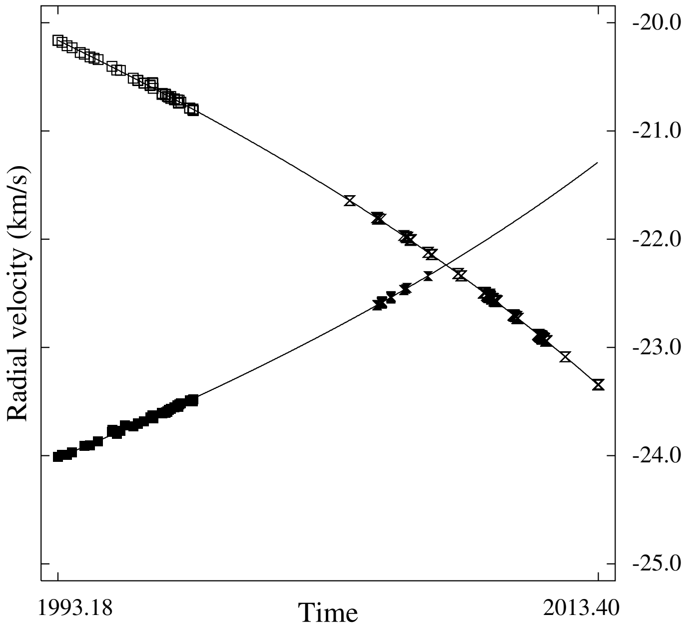

Fig. 2. Radial velocities of alpha Cen (filled for component A and open for B). Diabolos denote the HARPS archived data and squares the older ESO data (Endl et al. 2001) already used by Pourbaix et al. (2002). On this portion of the orbit, fitting ΔV_B or setting it to 0 is not visually distinguishable.

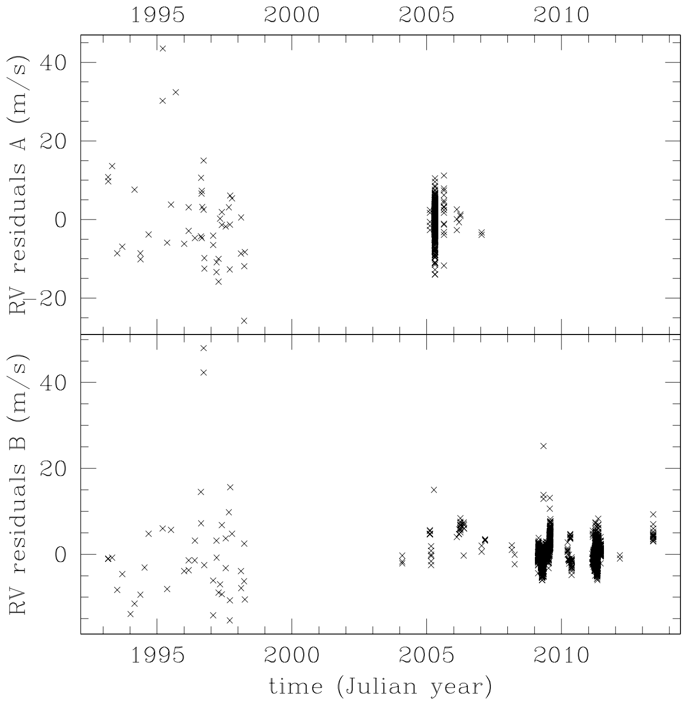

Fig. 3. Radial velocity residuals of both components (*top*: A; *bottom*: B) resulting from the orbital fit. The HARPS data are all located after 2000. The older data are from ESO Coudé Echelle (Endl et al. 2001).

Table 1. Orbital solutions from Pourbaix et al. (2002) and from this work using HARPS together with some older ESO Coudé Echelle velocities (Endl et al. 2001).

Element	Original	HARPS + ESO Coudé Echelle
a ($''$)	17.57 ± 0.022	17.66 ± 0.026
i (°)	79.20 ± 0.041	79.32 ± 0.044
ω (°)	231.65 ± 0.076	232.3 ± 0.11
Ω (°)	204.85 ± 0.084	204.75 ± 0.087
e	0.5179 ± 0.00076	0.524 ± 0.0011
P (yr)	79.91 ± 0.011	79.91 ± 0.013
T (Julian year)	1875.66 ± 0.012	1955.66 ± 0.014
V_0 (km s^{-1})	−22.445 ± 0.0021	−22.390 ± 0.0042
ϖ (mas)	747.1 ± 1.2 (adopted)	743 ± 1.3
κ	0.4581 ± 0.00098	0.4617 ± 0.00044
ΔV_B (m s^{-1})	0.0 (adopted)	329 ± 9.0
M_A ($M_\odot$)	1.105 ± 0.0070	1.133 ± 0.0050
M_B ($M_\odot$)	0.934 ± 0.0061	0.972 ± 0.0045

mass of the system matches the so-called photometric estimate from Malkov et al. (2012) perfectly, thus indicating some possible flaw in their mass-luminosity relation. Our value of the mass of component B seems to favour the asteroseismology-based 0.97 ± 0.04 $M_\odot$ by Lundkvist et al. (2014) over the 0.921 $M_\odot$ based on isochrone interpolation (Boyajian et al. 2013).

In the particular case of this system, ΔV_B can be interpreted as the net effect, but only for component B, of the differential gravitational redshift, differential convective blue shift and template mismatch. Indeed, the template used for component A is a G2 mask calibrated against asteroids. The radial velocities of A are therefore as close to absolute as possible. Component B was reduced using a K5 mask instead of K1 (the commonly accepted spectral type).

The velocity residuals against the orbit have a standard deviation of 4.56 for A and 3.26 m s^{-1} for B (Fig. 3). For the HARPS data alone, the standard deviations are 3.44 and 2.74 m s^{-1} with the latter likely overestimated owing to some outliers in 2009 that were not filtered out by the constraint on the seeing. Those values, especially for B, are consistent with the residuals obtained by Dumusque et al. (2012) before they corrected for other effects (e.g. rotational activity, . . .).

5. Discussion

Thévenin et al. (2002) could not find any asteroseismologic model consistent with the masses obtained by Pourbaix et al. (2002) and, instead, proposed 1.100 ± 0.006 $M_\odot$ and 0.907 ± 0.006 $M_\odot$ for α Cen A and B, respectively. These results were somehow confirmed by Kervella et al. (2003) through measuring of the angular diameter of both components and adopting the parallax by Söderhjelm (1999). Combining their own results with those of Thévenin et al. (2002), they also derived a likely parallax of 745.3 ± 2.5 mas.

Using asteroseismology alone, Lundkvist et al. (2014) obtained 1.10 ± 0.03 $M_\odot$ and 0.97 ± 0.04 $M_\odot$, which is very consistent with our values. They also derived 1.22 ± 0.01 $R_\odot$ and 0.88 ± 0.01 $R_\odot$ for the radius of components A and B, respectively, matching the values obtained by Kervella et al. (2003). Adopting the angular diameters from the latter (8.511 ± 0.020 mas and 6.001 ± 0.034 mas for A and B) and our revised parallax yields 1.231 ± 0.0036 $R_\odot$ and 0.868 ± 0.0052 $R_\odot$ for the radii of A and B, also in good agreement with Lundkvist et al. (2014).

6. Conclusions

As stressed by several authors (Torres et al. 2010; Halbwachs et al. 2016), obtaining stellar masses at the 1% level is crucial for astrophysics. Accounting for ΔV_B made it possible to reach that level of precision (and hopefully of accuracy as well) for α Cen without any ad hoc assumption over so short a timescale.

The revised distance and masses match the values independently derived by astroseismology.

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