Parallaxes and masses of α Centauri revisited

Dimitri Pourbaix1,⋆⋆ and Henri M. J. Boffin2

1 Institut d’Astronomie et d’Astrophysique, Université Libre de Bruxelles (ULB), Belgium
e-mail: pourbaix@astro.ulb.ac.be
2 ESO, Alonso de Córdova 3107 Vitacura, Casilla 19001 Santiago, Chile

Received 30/11/2015; accepted 04/01/2016

ABSTRACT

Context. Despite the thorough work of van Leeuwen (2007), 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.

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 (ESA 1997) had put it, i.e. slightly further away than derived by Söderhjelm (1999). The components are thus a bit more massive than previously thought (1.13 and 0.97 M⊙ for A and B respectively). These values are now in excellent agreement with the latest asteroseismologic results.

Key words. astrometry – (stars)binaries: spectroscopic –techniques: spectroscopy

1. Introduction

The Sun is a single star and as such is among the minority of solar-like stars which are mostly within binaries or multiple systems (Duquennoy & Mayor 1991; Halbwachs et al. 2003; Raghavan et al. 2010; Whitworth & Lumex 2015). Our closest neighbour – the system comprising α Centauri A, B and Proxima Centauri – is therefore more representative. α Centauri A and B (HIP 71683/1), with spectral types G2 V and K1 V, are in a binary system with an orbital period close to 79.91 years (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⊙ – nicely bracket that of our neighbour star, and they are only slightly older than the Sun. Thus, α Cent 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).

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.

1.1. α Centauri revisited

α Centauri A is the closest (nearly 4.3 light years) and the brightest star in the sky (absolute magnitude of 2.7) after the Sun. It was discovered in the 18th century by the Scottish astronomer James Bradley (1729). In 1914, Gaposchkin (1914) discovered three additional stars within 1 arc second of α Centauri A, known as the τ Cen proper motions. In 1921, van Rhijn (1921) showed that these three stars are part of a binary system with an orbital period close to 79.91 years (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⊙ – nicely bracket that of our neighbour star, and they are only slightly older than the Sun. Thus, α Cent 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). 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.

1.1.2. Measuring parallaxes

Concerning distances and parallaxes, even if a precise value for the parallax exists, it is difficult to know to which star the value is related. α Centauri A is the closest star to the Sun, and 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.

1.1.3. α Centauri as a laboratory for stellar evolution

α Centauri 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). 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.

2. Observational data

α Centauri 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 3.6m telescope. The vacuum and thermally isolated HARPS instrument has been 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 necessary 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 (as suggested by the referee, Xavier Dumusque), limited these observations to 710 and 1951 for A and B respectively. The importance of this data set 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 which is the Fourier transform spectrometer (FTS) spectrum of the Sun (Kurucz et al. 1984), and 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 respectively 0.16 and 0.12 m s\(^{-1}\) (Fig. 1).

The HARPS data cover 11 years only (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, both in La Silla, to extend the baseline and to help improving the precision of the fractional mass ($k = M_B/(M_A + M_B)$). 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 used in our previous investigation (Pourbaix et al. 1999). According to its web portal, the Washington double star catalogue (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:

\[
V_A = V_0 - K_A(e \cos \omega B + \cos(\omega B + v)),
\]

\[
V_B = V_0 + K_B(e \cos \omega B + \cos(\omega B + v)),
\]

where $V_0$ denotes the systemic velocity, $\omega B$ the argument of the periastron of component B, $e$ the eccentricity, $v$ 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 meters per second, some effects pop up as soon as the precision improves. In order 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 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. 2):

\[
V_B = V_0 + K_B(e \cos \omega B + \cos(\omega B + v) + \Delta V_B).
\]

It is worth pointing that, whereas Pourbaix (1998) advocated for a simultaneous adjustment of the visual and spectroscopic data, this $\Delta V_B$ 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 $\Delta V_B$, 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, 2013 is modelled in the present investigation.

4. Results

Despite the absence of visual departure between the fit of the present dataset with and without $\Delta V_B$, the parallaxes differ by 2% (smaller without shift), directly impacting the total mass by the same amount as the fractional mass remains essentially unchanged. The reduced $\chi^2$ increases from 1.01 to 1.21 without the shift. The revision of the model is thus justified. The orbital elements are given in Tab. 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 Soderhjelm (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 mass of the system perfectly matches the ‘photometric’ estimate from Malkov et al. (2012), thus indicating some possible

Fig. 1. Distribution of the estimated radial velocity uncertainties reported by the HARPS pipeline for component A (left) and B (right).
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⊙ by Lundkvist et al. (2014) over the 0.921 M⊙ based on isochrone interpolation (Boyajian et al. 2013).

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

| Element | Original | HARPS + ESO Coudé Échelle |
|---------|----------|---------------------------|
| 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 |
| V₀ (km/s) | -22.445 ± 0.0021 | -22.390 ± 0.0042 |
| σ (mas) | 747.1 ± 1.2 (adopted) | 743 ± 1.3 |
| κ      | 0.4581 ± 0.00098 | 0.4617 ± 0.00044 |
| ΔV₀ (m/s) | 0.0 (adopted) | 329 ± 9.0 |
| Mₐ (M⊙) | 1.105 ± 0.0070 | 1.133 ± 0.0050 |
| Mₐ (M⊙) | 0.934 ± 0.0061 | 0.972 ± 0.0045 |

In the particular case of this system, ΔV₀ can be interpreted as the net effect, for component B only, 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).

![Fig. 2. Radial velocities of alpha Cen (filled for component A and open for B). Diablos 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 Δ V₀ or setting it to 0 is not visually distinguishable.](image1)

The velocity residuals against the orbit have a standard deviation of 4.56 and 3.26 m s⁻¹ for A and B respectively (Fig. 3). For the HARPS data only, the standard deviations are 3.44 and 2.74 m s⁻¹ with the latter likely overestimated due to some outliers in 2009 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. rotation activity, . . . ).

![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 Échelle (Endl et al. 2001).](image2)

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⊙ and 0.907±0.006 M⊙ for α Cen A and B respectively. These results were somehow confirmed by Kervella et al. (2003) through the measurement 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 only, Lundkvist et al. (2014) obtained 1.10 ± 0.03 M⊙ and 0.97 ± 0.04 M⊙, very consistent with our values. They also derived 1.22 ± 0.01 R⊙ and 0.88 ± 0.01 R⊙ for the radius of component 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 1.231 ± 0.0036 R⊙ and 0.868 ± 0.0052 R⊙ 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 $\Delta V_B$ made it possible to reach that level of precision (and hopefully of accuracy as well) for $\alpha$ Cen without any ad-hoc assumption over a so short timescale. The revised distance and masses match the values independently derived by asteroseismology.

Acknowledgements. We thank the referee, Xavier Dumusque, for his suggestion about filtering the HARPS dataset according to the seeing. This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory and the Simbad data base, operating at CDS, Strasbourg, France.

References

Bazot M., Bourguignon S., Christensen-Dalsgaard J., 2012, MNRAS, 427, 1847
Bergmann C., Endl M., Hearnshaw J.B., Wittenmyer R.A., Wright D.J., 2015, International Journal of Astrobiology, 14, 173
Boygajian T.S., von Braun K., van Belle G., et al., 2013, ApJ, 771, 40
Brunth H., Bedding T.R., Quirion P.O., et al., 2010, MNRAS, 405, 1907
de Meulenaer P., Carrier F., Miglio A., et al., 2010, A&A, 523, A54
Dumusque X., Udry S., Lovis C., Santos N.C., Monteiro M.J.P.F.G., 2011, A&A, 525, A140
Dumusque X., Pepe F., Lovis C., et al., Nov. 2012, Nature, 491, 207
Dumusque X., Pepe F., Latham D.W., 2015, ApJ, 808, 171
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Endl M., Kürster M., Els S., Hatzes A.P., Cochran W.D., 2001, A&A, 374, 675
Endl M., Bergmann C., Hearnshaw J., et al., 2015, International Journal of Astrobiology, 14, 305
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Halbwachs J.L., Mayor M., Udry S., Arenou F., 2003, A&A, 397, 159
Halbwachs J.L., Boffin H.M.J., Le Bouquin J.B., et al., 2016, MNRAS, 455, 5003
Harfst W.J., McAlister H.A., Mason B.D., 2001, AJ, 122, 3480
Hatzes A.P., 2013, ApJ, 770, 133
Heintz W.D., 1982, Observatory, 102, 42
Kaltenegger L., Haghighipour N., 2013, ApJ, 777, 165
Kervella P., Thévenin F., Ségransan D., et al., 2003, A&A, 404, 1087
Kjeldsen H., Bedding T.R., Arentoft T., et al., 2008, ApJ, 682, 1370
Kurucz R.L., Furenld J., Braulj, J., Testerman L., 1984, Solar flux atlas from 296 to 1300 nm, National Solar Observatory
Lovis C., Pepe F., Bouchy F., et al., 2006, In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 6269 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 0
Lundkvist M., Kjeldsen H., Silva Aguirre V., 2014, A&A, 566, A82
Malkov O.Y., Tamazian V.S., Docobo J.A., Chulkov D.A., 2012, A&A, 546, A69
Mayor M., Pepe F., Queloz D., et al., Dec. 2003, The Messenger, 114, 20
Molaro P., Monaco L., Barbieri M., Zaggia S., 2013, The Messenger, 153, 22
Porto de Mello G.F., Lyra W., Keller G.R., 2008, A&A, 488, 653
Pourbaix D., 1998, A&AS, 131, 377
Pourbaix D., Neuforge-Verheecke C., Noels A., 1999, A&A, 344, 172
Pourbaix D., Nidever D., McCarthy C., et al., 2002, A&A, 386, 280
Raghavan D., McAlister H.A., Henry T.J., et al., 2010, ApJS, 190, 1
Rajpaul V., Aigrain S., Roberts S.J., 2015, ArXiv e-prints
Söderhjelm S., 1999, A&A, 341, 121
Thévenin F., Provost J., Morel P., et al., 2002, A&A, 392, L9
Torres G., Andersen J., Giménez A., 2010, A&A Rev., 18, 67
van Leeuwen F., 2007, Hipparcos, the new Reduction of the Raw data, Springer
Whitworth A.P., Lomax O., 2015, MNRAS, 448, 1761