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Radial velocities in the globular cluster ω Centauri[★]

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ABSTRACT

We have used the ARGUS multi-object spectrometer at the CTIO 4 m Blanco telescope to obtain 2756 radial velocity measurements for 1966 individual stars in the globular cluster ω Centauri brighter than blue photographic magnitude of about 16.5. Of these, 1589 stars are cluster members. A comparison with two independent radial velocity studies, carried out by Suntzeff & Kraft and by Mayor et al., demonstrates that the median error of our measurements is below 2 km s^{-1} for the stars brighter than B -magnitude 15, which constitute the bulk of the sample. The observed velocity dispersion decreases from about 15 km s^{-1} in the inner few arcmin to about 6 km s^{-1} at a radius of $25'$. The cluster shows significant rotation, with a maximum amplitude of about 6 km s^{-1} in the radial zone between $6'$ and $10'$. In a companion paper by van de Ven et al., we correct these radial velocities for the perspective rotation caused by the space motion of the cluster, and combine them with the internal proper motions of nearly 8000 cluster members measured by van Leeuwen et al., to construct a detailed dynamical model of ω Centauri and to measure its distance.

Key words. radial velocities – Galaxy: globular clusters: individual: NGC 5139 – Galaxy: kinematics and dynamics

1. Introduction

Globular clusters have been objects of astronomical study for well over a century (e.g., Pickering 1891). They are amongst the oldest objects in the Galaxy and their stellar content provides information on star formation and evolution processes, in particular in the early lifetime of our Galaxy. Their richness and symmetry, and the complexity of their dynamical evolution through internal and external effects, make them very interesting for stellar dynamical studies (e.g., King 1966; Spitzer 1987).

Among the globular clusters, ω Cen (NGC 5139) is particularly interesting (van Leeuwen et al. 2002). The cluster was studied long ago for its variable stars (e.g., Bailey 1902; Martin 1938) and its stellar content (Woolley 1966). It is very mas-

sive (Meylan et al. 1995) and has an unusually large ellipticity of ~ 0.12 . The cluster has a tidal radius of $\sim 45'$ (Trager et al. 1995) and is structurally fairly loose, which makes it possible to study individual stars from the ground even in the dense central regions. The chemical abundance distribution is broad, with $-1.8 < [\text{Fe}/\text{H}] < -0.8$, and bimodal (Norris & Da Costa 1995; Norris et al. 1996). Recently, further evidence for multiple stellar populations was found from colour-magnitude diagrams (Anderson 2002; Pancino 2002; Bedin et al. 2004; Ferraro et al. 2004; Hughes et al. 2004) and spectroscopy (Piotto et al. 2005).

Van Leeuwen et al. (2000, hereafter Paper I) carried out a proper motion study of 9847 stars in the field of ω Cen, based on extensive photographic material obtained with the Yale–Columbia refractor between 1931 and 1983. Precisions range from 0.10 mas yr^{-1} at photographic magnitude 13 to 0.65 mas yr^{-1} at the limiting magnitude 16.5. The measurements extend out to $24'$, i.e., to nearly half the tidal radius. At a distance of 5 kpc, 0.10 mas yr^{-1} translates to about 2.5 km s^{-1} . A total of 7853 probable cluster members were identified. The astrometric measurements provide accurate estimates of two of the three components of the internal motion. They provide

[★] Complete Tables 4 and A1 are available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via

<http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/445/503>

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evidence for differential rotation, but only up to an unknown amount of solid body rotation, which is absorbed in the plate transformations required to derive the proper motions. Radial velocities of similar accuracy or better are needed to obtain the third component of the internal motion, and to characterize the rotation of the cluster.

ω Cen is an ideal cluster for a radial velocity study because of its high systemic radial velocity of 232.8 km s^{-1} (e.g., Meylan et al. 1995), which means that the cluster members are well separated from the field stars. In an effort spanning twelve years, Mayor, Meylan and co-workers obtained CORAVEL radial velocities for 471 cluster members extending to about $20'$, with mean errors of better than 1 km s^{-1} (see Mayor et al. 1997; and Sect. 2.6 below). Their data showed that ω Cen rotates, with the mean rotation reaching a peak of about 8 km s^{-1} at $8'$ from the cluster centre (e.g., Merritt et al. 1997). Suntzeff & Kraft (1996) used ARGUS to obtain radial velocities of somewhat more modest accuracy for 360 members on the giant branch between $3'$ and $23'$. Given the very large number of stars for which proper motions are now available, and given the clean member selection possible with radial velocities, we embarked on a radial velocity study with ARGUS to extend the published datasets significantly¹. Here we present the resulting radial velocities.

In Sect. 2 we briefly describe the ARGUS instrument, our observations and data reduction, a comparison with earlier work, and the results of an extensive error analysis. We briefly discuss the results in Sect. 3: membership determination, rotation and velocity dispersion. The conclusions follow in Sect. 4. In the companion Paper III (van de Ven et al. 2006), we use our radial velocities to correct the Paper I proper motions for remaining overall (solid body) rotation, correct both the radial velocities and the proper motions for the perspective rotation caused by the space motion of ω Cen, and compare the resulting internal motions with anisotropic axisymmetric dynamical models, to derive an accurate dynamical distance for the cluster.

2. Observations

The observations were made with the CTIO 4 m Blanco telescope during 16 nights, on February 11–14, 1992, March 1–6, 1993, and February 26–March 3, 1994. The seeing was better than 1.5 arcsec FWHM for most of the data. We used the fiber-fed, multiple-object echelle spectrometer ARGUS to obtain a total of 2756 radial velocity measurements for 1966 individual stars (see also Appendix A).

2.1. The Instrument

ARGUS resided at the prime focus of the Blanco telescope. It consisted of 24 computer-controlled arms located around the telescope's $f/2.66$ prime focus field. Use of the red doublet corrector produced a flat field of $46'$ in diameter at a scale of 18.6 arcsec/mm . The fibers were $100 \mu\text{m}$ or $1''.86$ in diameter and carried light from the prime focus cage to a spectrograph

located in a thermally and mechanically isolated room. The movement of the fibers was in units of “steps” where a single step is $10 \mu\text{m}$ or $0''.2$. ARGUS had the ability to rapidly change the configuration of the fibers; and it had a high dispersion (6.7 \AA mm^{-1} at Mgb) which made accurate radial velocity measurements possible. For more details on ARGUS, see www.ctio.noao.edu/spectrographs/argus/argus.html and Ingerson (1988), Lutz et al. (1990).

The ARGUS echelle mode employed a 31.6 l/mm echelle grating. We used an order-separating filter to isolate a single echelle order centred on the Mgb triplet near 5175 \AA . This wavelength region also contains numerous other sharp lines and is an ideal and much used region for accurate radial velocity measurements of late-type stars.

In 1992 and 1994 we used a Reticon CCD in the blue Air Schmidt camera. It had 1240×400 pixels of $27 \mu\text{m}$ size, and a read noise of $2.94 e$. The wavelength range covered was $5083\text{--}5281 \text{ \AA}$ in 1992, and $5081\text{--}5274 \text{ \AA}$ in 1994, with a spectral resolution of 0.3 \AA ($4.2 \text{ km s}^{-1}/\text{pixel}$). Due to technical difficulties with this camera in 1993, we were forced to use a GEC CCD in the red Air Schmidt camera. The GEC CCD had 576×425 pixels of size $22 \mu\text{m}$, and a read noise of $5.18 e$. The wavelength range covered was $5133\text{--}5218 \text{ \AA}$, and the resolution was 0.6 \AA ($8.9 \text{ km s}^{-1}/\text{pixel}$).

In general the instrument worked well, although we were troubled by the poor pointing accuracy of the fibers during all three years. This required every fiber to be manually centred on a star. During 1994 we were observing at full moon, which limited how faint we could observe. Exposure times ranged from 600 to 1800 s.

Our observing strategy was to do as many stars as possible in one region of the cluster before changing the centre of the field. In each region we selected two bright stars (not necessarily cluster members) as local standards, and locked two fibers on these stars for all observations in this field. This allowed us to monitor the drift of the system without the expense of doing comparison arcs after every exposure, which were done instead at the start and end of every field (before and after any telescope motion). Comparison arcs were also done either before or after any standard star or twilight sky measurement. In 1992 we used HD 31871 ($v_{\text{helio}} = 62.3 \text{ km s}^{-1}$) and HD 43880 ($v_{\text{helio}} = 46.9 \text{ km s}^{-1}$) as radial velocity standards. In 1993 and 1994 we used HD 120223 ($v_{\text{helio}} = -26.3 \text{ km s}^{-1}$) and HD 176047 ($v_{\text{helio}} = -42.8 \text{ km s}^{-1}$).

2.2. Star selection

We originally selected the stars to be observed from the *initial preliminary* proper motion catalogue (see Paper I, Sect. 4), mainly at a distance $r \geq 3.5'$ from the cluster centre. All photographic plates that were used for that study were centred on the same position and the cluster centre is not in the centre of the plates. This enabled us to study stars that are relatively far ($>30'$) from the cluster centre at least in one direction. The *final* proper motion catalogue contains cluster giants, horizontal branch stars and field stars down to a photographic magnitude $B = 16$ in the cluster centre and 16.5 in the outer regions.

¹ Radial velocities were obtained for nearly 5000 stars in the central three arcmin of ω Cen with the Rutgers imaging Fabry-Perot spectrometer (Xie, Gebhardt, et al., in prep.).

Table 5 of Paper I lists their properties, including B magnitude and $B - V$ colour (when available). Because we selected objects from the initial catalogue which was somewhat larger than the final catalogue, we measured radial velocities of some stars that are not present in Table 5 of Paper I. We discuss these in Appendix A.

In Paper I, each star was assigned a class on a scale from 0 to 4, based on visual inspection of the stellar image on the photographic plates, and ranging from no disturbance by a neighbouring star (0) to badly disturbed (4). Over 83% of our stars are of class 0, and the remainder is divided nearly equally between classes 1 and 2 (mildly disturbed).

In selecting stars for radial velocity measurement, we wanted to be careful not to introduce any kinematic bias. Thus we avoided selecting stars on the basis of any proper motion value, in order to avoid truncating the observed radial velocity distribution function.

We also elected not to select on the basis of location in the colour-magnitude diagram, other than that imposed by the lack of spectral lines in blue stars. In what follows, we restrict ourselves to stars with $B - V \geq 0.4$. We specifically did not exclude stars from the sample which did not fall in the giant and sub-giant region of the colour-magnitude diagram, in order to have as complete a sample as possible. The price of not imposing such selection criteria is that we ended up observing a considerable number of field stars. In Appendix A we return to the stars with $B - V < 0.4$ and those without colour information.

In 1992, instrument problems forced us to work in the “inner” region ($3'5 < r < 8'0$) only, and we obtained 649 observations of 564 stars. In 1993 and 1994 we worked in both the inner and outer regions (from $3'5$ to $38'$), and obtained 1673+944 observations of 1256+707 stars.

2.3. Data reduction

After trimming the raw images and correcting for overscan and fixed pattern bias, we divided the spectra of 1993 and 1994 by a “milk” flat field to remove pixel-to-pixel variations (see ARGUS web page). The different spectra on each frame were identified, traced and extracted using the IRAF APSUM task. For the 1992 data, we ran APSUM before we applied the flat field corrections, because we used a quartz lamp flat field. After continuum subtraction, we rebinned the spectra onto a log wavelength scale.

We used the IRAF RV package (Tody 1986) to cross-correlate the spectra against high S/N template spectra of two radial velocity standard stars of similar spectral type (Tonry & Davis 1979). The displacement of the peak of the correlation function gives the velocity of the star relative to the template. We filtered out obvious bad velocities by noting the value of the cross correlation coefficient below which the scatter in repeat observations increased significantly. As reported by Côté et al. (1994), the correlation task FXCOR in IRAF tends to overestimate the uncertainties in the derived radial velocities by as much as a factor of two.

Table 1. Mean radial velocities and standard errors for stars with more than 10 repeat measurements. The table gives: year of observation; Leiden identification number from Paper I; ROA number from Woolley (1966); photographic B -magnitude of Paper I; number of measurements n ; mean velocity $\langle v \rangle$; standard deviation $\sigma_{\langle v \rangle}$ of the mean velocity.

Year	Star nr	ROA nr	B mag	n	$\langle v \rangle$ km s ⁻¹	$\sigma_{\langle v \rangle}$ km s ⁻¹
1992	46024	40	12.77	47	215.95	1.20
	60087	20	11.08	38	-23.04	0.26
1993	62015	36	12.66	22	-30.30	1.08
	93011	–	12.47	23	-26.25	2.61
1993/4	11014	242	12.54	53	9.45	1.59
1994	27009	409	13.22	17	46.42	0.81
	32138	48	12.98	20	222.08	0.70
	48049	76	13.04	20	219.16	1.28
	65014	413	13.80	17	-44.90	1.60

2.4. Repeat measurements

A number of factors contribute to the uncertainty of the velocities: the errors in the individual measurements, the error in the fiber-to-fiber velocity zero point, and the zero point of the velocity system with respect to the standard stars. In addition, the radial velocity of some stars will vary in time due to orbital motion in a binary.

We carried out simple Monte Carlo simulations using 18 bright known cluster members. These stars were measured in one frame and, before processing, we copied this frame 24 times and added random noise to each frame using the IRAF MKNOISE task, simulating the same conditions (read noise, gain etc.) as the real data. In this way, we simulated 24 measurements of 18 bright stars. We found a standard deviation $\sigma_{\text{sim}} \lesssim 1 \text{ km s}^{-1}$.

Stars with 10 or more measurements are listed in Table 1. Their standard errors range from less than 0.3 to 2.6 km s⁻¹. Column 1 indicates the year in which the observations were taken; Cols. 2 and 3 contains the star identification numbers in our catalogue and the corresponding ROA number from the survey of Woolley (1966); Col. 4 the star’s photographic B magnitude (Table 5 of Paper I); Col. 5 gives the number of repeat measurements; Cols. 6 and 7 the mean radial velocities $\langle v \rangle$ and their standard errors $\sigma_{\langle v \rangle}$. The calculated standard deviation from repeat measurements agrees reasonably well with the standard deviation found from the simulations, but it is on average 0.8 times the formal (standard) error provided by FXCOR. We return to this result in Sect. 2.6.

Stars with a large number of repeat measurements were always measured with the same fibers. We did similar Monte Carlo simulations to track down uncertainties and differences between the individual fibers using twilight spectra. Those differences are also well within the standard errors. The velocities of stars that were measured two or three times, but with different fibers and at different nights and even in different observing runs in general also agreed well within the standard errors.

There are ten stars which we observed in all three years. 72 stars overlap 1992–1993; 46 in 1993–1994; and 108 in 1992–1994. These measurements are in good agreement (the differences are smaller than the estimated uncertainties) except for a few probable misidentifications or binaries. Some misidentifications are probably due to pointing problems of some fibers and these measurements were not included. Some of the stars with a high number of repeat measurements ($n \geq 10$) are bright field stars.

The observations in 1993 were carried out with a setup that differed from that in 1992 and 1994 (see Sect. 2.1). The repeat measurements show that the best radial velocities from 1993 have errors as small as those from 1992 and 1994. However, the 1993 error distribution has a slightly more extended tail to larger values. Because many stars had repeat measurements in two years, we decided to treat the entire data set as one sample.

A physical source of velocity differences in the repeat measurements is the presence of binaries. Double stars or multiple stars will show a larger dispersion due to their orbital motion. From all probable cluster members (see Sect. 3.1) we have 303 stars measured more than once. Only about 4% of these have repeat measurements that differ significantly from the uncertainties indicated by the IRAF tasks ($\sigma_{\text{rep}} > 1.5 \times \sigma_{\text{iraf}}$). This is an indication that there is only a small fraction of binaries with short-periods in the cluster. Assuming that ω Cen has a period distribution similar to the one observed for nearby G dwarfs, Mayor et al. (1996) estimated the global binary frequency for binary systems with periods less than 10^4 days in ω Cen to be as low as 3–4%.

2.5. Comparison with other studies

Mayor et al. (1997) published radial velocities of 471 stars between $10''$ and $1342''$ from the cluster centre, obtained with CORAVEL. They found a mean radial velocity of the cluster of $\langle v_{mm} \rangle = 232.8 \pm 0.7 \text{ km s}^{-1}$. We have compared individual velocities of our sample (“*rr*”) with theirs (“*mm*”). We have 267 stars with ROA numbers in common. Figure 1a shows the velocities plotted against each other with their uncertainties. The velocities generally agree well, but there is a small systematic offset, which we ascribe to a zero-point error in our data. There are some outliers, notably two stars at $v_{mm} \approx 210 \text{ km s}^{-1}$ (LID 44065, 60065) which we assume are misidentifications (see below), and LID 35090 and 78035 where our measurements differ by nearly 220 km s^{-1} from the values reported by Mayor et al. We removed outliers by discarding all stars for which the measured velocities differ by more than four times the combined one-sigma error (“four-sigma clipping”). This leaves 250 stars. The weighted mean velocity offset between the two studies is $\langle v_{rr} - v_{mm} \rangle = -1.44 \pm 0.09 \text{ km s}^{-1}$.

Suntzeff & Kraft (1996) observed 199 members of ω Cen with $M_V \sim 1.25$ on the lower giant branch at radial distances between $8'$ and $23'$ (“faint sample”), and 144 members at $M_V \sim -1.3$ at radial distances between $3'$ and $22'$, to which they added another 17 observed by Seitzer (“bright sample”). They measured the velocities with ARGUS, but in the wavelength range $8200\text{--}8800 \text{ \AA}$ using the Ca II triplet. We

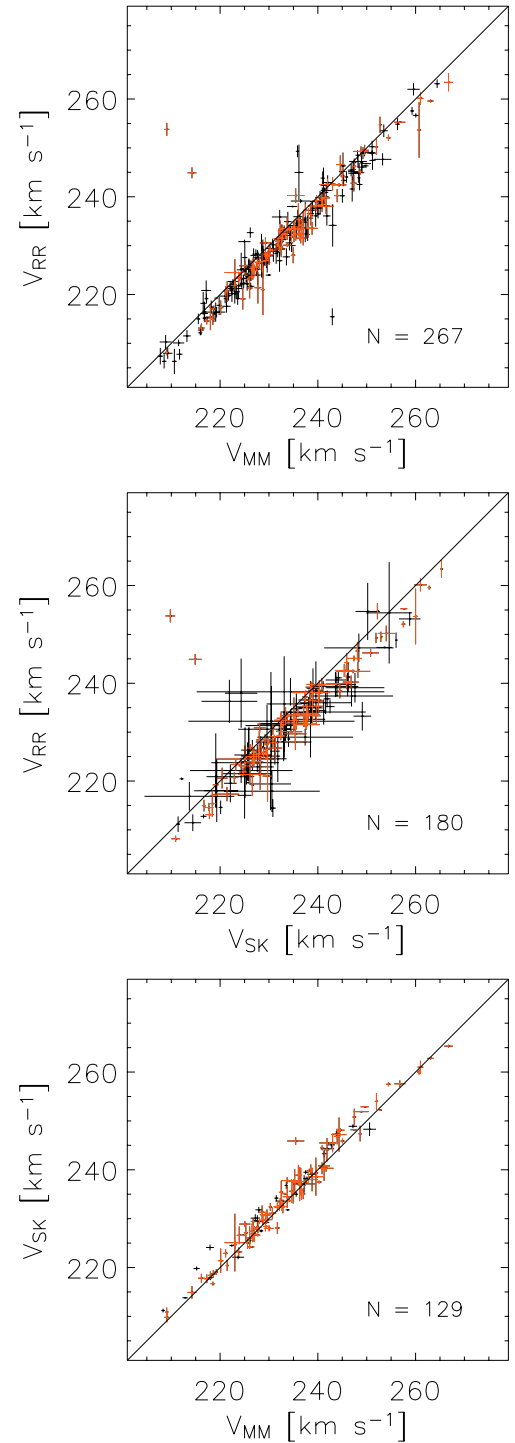


Fig. 1. Comparison of our radial velocity measurements (*rr*) with those of Mayor et al. (1997, *mm*) and of Suntzeff & Kraft (1996, *sk*). **a)** *rr* versus *mm*, **b)** *rr* versus *sk*, and **c)** *sk* versus *mm*, for stars in common. The red symbols identify the subset of 100 stars in common to all three studies.

have 180 stars in common with their total sample of 360 stars. Figure 1b shows the *rr* velocities versus the *sk* measurements. There is one star at about $v_{rr} \approx 220 \text{ km s}^{-1}$ which has been measured very precisely by both groups, but the measured velocities differ significantly (8 km s^{-1}). This large difference could be due to a chance combination of large errors, a binary, or is

Table 2. Comparison of three independent studies. Mean and dispersions of the pairwise differences in measured radial velocities for the 93 stars in common between the *rr*, *mm*, and *sk* samples, after four-sigma clipping to remove outliers.

	<i>rr</i> – <i>mm</i>	<i>rr</i> – <i>sk</i>	<i>sk</i> – <i>mm</i>
$\langle v \rangle$ (km s ⁻¹)	-1.50 ± 0.12	-2.09 ± 0.17	0.37 ± 0.10
σ (km s ⁻¹)	1.26 ± 0.09	1.68 ± 0.12	1.37 ± 0.07

Table 3. Median and external measurement errors for the three studies (*rr*, *sk* and *mm*) described in the main text. The second and third columns list the median standard error σ_{median} and the external error σ_{external} for the 93 stars in common to the three studies. The fourth column lists the median error for the total sample, and the fifth column the inferred external error (see main text). The units are km s⁻¹.

Study	93 overlap stars		Total sample	
	σ_{median}	σ_{external}	σ_{median}	σ_{external}
<i>rr</i>	1.43	1.13 ± 0.08	2.65	2.09 ± 0.15
<i>sk</i>	0.90	1.25 ± 0.08	1.60	2.22 ± 0.14
<i>mm</i>	0.56	0.56 ± 0.08	0.61	0.61 ± 0.09

a misidentification. The two outliers at $v_{sk} \approx 210$ km s⁻¹ are the same as those noted in Fig. 1a, confirming that they are misidentifications on our side. After four-sigma clipping we are left with 172 stars in common, which have a mean velocity offset of $\langle v_{rr} - v_{sk} \rangle = -2.02 \pm 0.15$ km s⁻¹.

Figure 1c shows the comparison of the *sk* and *mm* velocities. These data set have 129 stars in common. Four-sigma clipping reduces this to 117, with mean offset $\langle v_{sk} - v_{mm} \rangle = 0.41 \pm 0.08$ km s⁻¹.

Finally, we have two stars in common with Tyson & Rich (1991), namely ROA 55 ($v_{rr} = 221.7 \pm 0.9$ km s⁻¹, $v_{tr} = 220.4 \pm 0.2$ km s⁻¹) and ROA 70 ($v_{rr} = 227.7 \pm 2.7$ km s⁻¹, $v_{tr} = 213.9 \pm 4.4$ km s⁻¹). Both stars were observed multiple times by Mayor et al. (1997) with an accuracy of better than 1 km s⁻¹, and are without a doubt variable: 39 measurements of ROA 55 give $v_{mm} = 226.3 \pm 4.0$ km s⁻¹ and 23 measurements of ROA 70 give $v_{mm} = 229.9 \pm 4.3$ km s⁻¹.

2.6. External error estimate

There are 100 stars in common between all three studies (*rr*, *mm* and *sk*). Removing outliers by means of four-sigma clipping leaves 93, which cover the full range of velocities seen in ω Cen (Fig. 1). Table 2 lists the mean and the dispersions of the pairwise differences, as well as the dispersion in these values, for these 93 stars, calculated with the expressions summarized in Appendix B. As expected, the differences are fully consistent with the systematic offsets between the three studies derived in Sect. 2.5 for the larger samples of pairwise overlaps.

The dispersions listed in Table 2 allow us to estimate the true external sigmas for each of the three studies. Since $\sigma_{v_1-v_2}^2 = \sigma_{v_1}^2 + \sigma_{v_2}^2$ etc., we can solve for the true σ_{v_i} ($i = 1, 2, 3$) given the three $\sigma_{v_i-v_j}^2$'s. The results are listed in the third column of Table 3, and can be compared with the median of the reported individual errors for these 93 stars in each of the three studies.

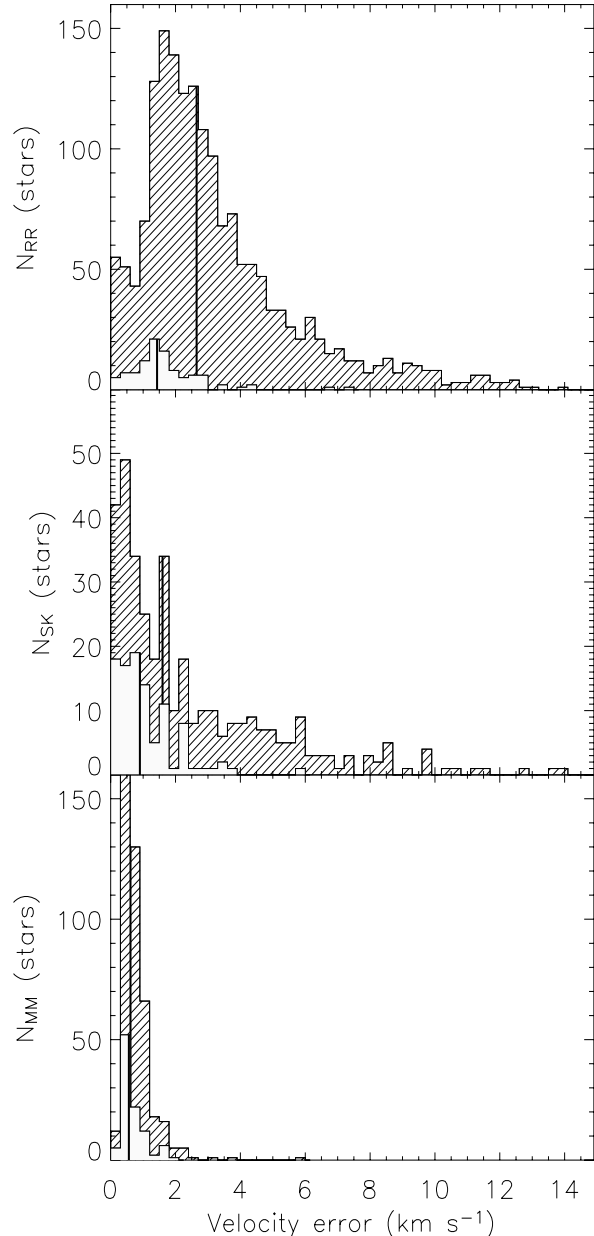


Fig. 2. Histograms of errors in the radial velocities reported for the *rr*, *sk* and *mm* samples (*top*, *middle* and *bottom panel*). The light-shaded areas are the similar histograms for the 93 stars in common between the three studies. The solid vertical lines indicate the median value of each of the distributions.

This reveals that the CORAVEL errors are estimated accurately, but that there are discrepancies for the ARGUS velocities. The errors reported by *sk* appear to be 0.7 times the external error, while the external errors in our own study appear to be 0.8 times the formal errors provided by FXCOR. This is not unexpected, as FXCOR is known to overestimate the errors (see Sect. 2.3).

Figure 2 shows the histograms of the reported errors in the radial velocity measurements for all three studies, not only for the total samples, but also for the 93 stars in common to all three studies. All error distributions are skewed, with particularly significant tails towards large errors for the ARGUS

velocities. The median errors σ_{median} listed in Table 3 are indicated by vertical solid lines. The 93 overlap stars are all brighter than B -magnitude of 14, and as a result their errors are systematically smaller. This suggests that the average true external errors for the complete samples are larger than estimated from just the 93 overlap stars. We estimate these errors by simply multiplying the median error with the same correction factor as found for the 93 stars. The results are listed in the fifth column of Table 3, and show that our ARGUS data for the Mgb wavelength region are of the same accuracy as the ARGUS measurements by Suntzeff & Kraft (1996) around the Ca II triplet, and are about a factor two less accurate than the CORAVEL data of Mayor et al. (1997).

The fibers we used for our observations are relatively large (Sect. 2.1), and might sometimes contain a contribution of a neighbouring star, or of unresolved background light. This could cause the derived radial velocities to be biased towards the mean cluster velocity, which would also bias the derived velocity dispersion. This systematic effect is expected to be stronger in the crowded center, and for fainter stars.

Our sample of 1966 stars contains 1634 stars without any neighbour disturbing the stellar image (class 0 stars of Paper I). None of the remaining 182+150 class 1 and 2 stars, the images of which are at most mildly disturbed, overlap with the sk or mm samples, so no external error estimate is possible for this subset of our sample. We have computed the mean velocity and intrinsic velocity dispersion for each of these two classes, and find no difference with the similar results for the class 0 subsample. Furthermore, plots of the differences $v_{rr} - v_{mm}$ and $v_{rr} - v_{sk}$ versus magnitude and versus distance to the centre show no evidence for any systematic trends. This is particularly relevant for the comparison with the sk sample, which consists of a “bright” and a “faint” subset, together covering nearly the entire magnitude range of our sample. Finally, we also checked whether the intrinsic dispersion for the entire set depends on magnitude in different radial bins. We experimented with the size and location of the radial and magnitude bins, but other than the expected decline of velocity dispersion with radius (see Paper III), found no evidence for a dependence on magnitude. We conclude that effects of crowding by neighbours and of unresolved background light can be ignored safely, and that our external error estimate is valid for the entire sample.

Figure 3 shows the median standard error of our measurements, as provided by FXCOR, plotted versus photographic B -magnitude (Paper I), in bins of 0.5 mag. The number of stars per bin is indicated also. The measurement for LID 60087 with $B = 11.08$ (see Table 1) is not included. Our external estimate suggests that the real errors are smaller by a factor 0.8, so we also show the same curve multiplied by this factor. The resulting median errors are below 1.5 km s^{-1} for stars brighter than $B = 14$, increase to 2.5 km s^{-1} at $B = 16$, and continue to increase for the modest number of fainter stars.

Table 4 presents our results. Column 1 gives the Leiden identification number of the star (LID; Paper I). Column 2 gives the mean heliocentric radial velocity $\langle v \rangle$ and Col. 3 lists our best estimate of the standard error $\sigma_{\langle v \rangle}$ (0.8 times the standard error provided by FXCOR). Column 4 gives the number of individual ARGUS measurements for each star. The associated coordinates

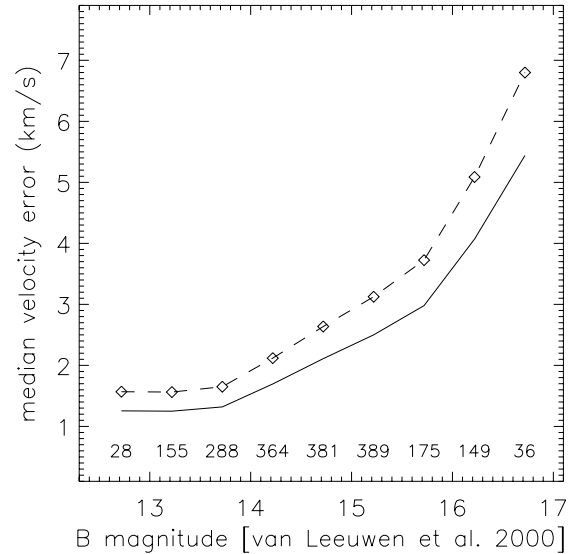


Fig. 3. Median error in our radial velocity measurements as a function of photographic B -magnitude, in 0.5 mag bins. The numbers below the diamonds indicate the number of measurements in each bin. The dashed line connects the median error derived from the standard errors provided by FXCOR. Our external error analysis demonstrates that these standard errors are overestimated, and need to be multiplied by a factor 0.8. The solid line shows the corrected median errors, which correspond to the individual errors reported in Table 4.

Table 4. Summary of results, extract only. LID: Leiden identification number from Paper I; mean measured heliocentric radial velocity $\langle v \rangle$ and the standard error $\sigma_{\langle v \rangle}$, in km s^{-1} ; n : number of individual measurements (see text for details).

LID	$\langle v \rangle$ km s^{-1}	$\sigma_{\langle v \rangle}$ km s^{-1}	n
00009	208.0	1.2	1
00012	242.2	3.3	1
00014	219.6	6.0	1
01010	26.6	5.7	1
01015	235.2	2.0	1

α and δ , and the B magnitude and $B - V$ colour, can be found in Table 5 of Paper I. As discussed in Sect. 2.5, the reported measurements for LID 35090, 44065, 60065, and 78035 are suspect.

3. Results

We briefly discuss membership and distribution over the cluster for our sample of stars, present a colour-magnitude diagram, and describe the mean velocity and velocity dispersion field. We use these as input for the determination of the dynamical distance to ω Cen in Paper III.

3.1. Membership determination

Figure 4 shows a histogram of all 1966 mean radial velocities. Because of the large radial velocity of the cluster ($232.8 \pm 0.7 \text{ km s}^{-1}$, Mayor et al. 1997) there is a clear distinction

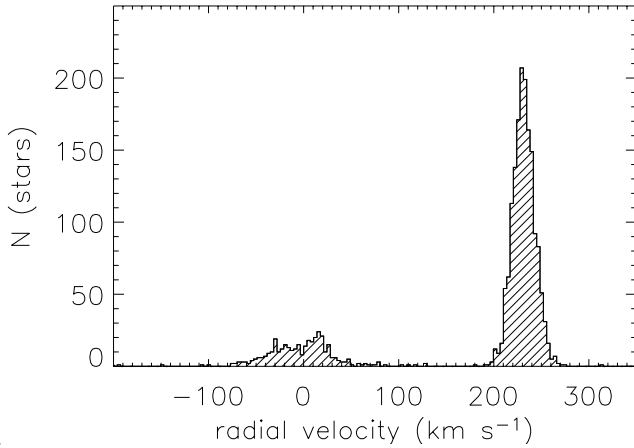


Fig. 4. Histogram of the 1966 measured radial velocities in the direction of ω Centauri. The distribution centred around radial velocity zero corresponds to the field stars, and the strongly peaked distribution centered near 232 km s^{-1} is the cluster.

between cluster members and field stars. Our sample contains 1589 stars with a velocity between 160 and 300 km s^{-1} . Paper I reports proper motion measurements for all of these, and notes that 36 have a low probability of being a member based on the proper motions alone. The separation between cluster and field is sufficiently clean in radial velocity to consider all 1589 stars secure members.

Figure 5 shows the positions for the 1589 radial velocity members with proper motion measurements. Since the cluster centre does not coincide with the centre of the plate material from which the proper motions were derived, we have full azimuthal coverage only up to $15'$ from the cluster centre. Stars with a radial velocity measurement are fairly evenly spread over the cluster, except for a stronger concentration of measurements in a ring at about $4'$, which is due to observational constraints. The furthest member based on radial velocity measurements is star 95 002 (no ROA number available) with a radial velocity of 209.1 km s^{-1} , at a distance of $37'.7$ ($0.8 r_t$) from the cluster centre.

3.2. Colour–magnitude diagram

Figure 6 shows the colour–magnitude diagram for all stars from our sample of 1966 for which Paper I gives a B -magnitude and $B - V$ colour. The colour-excess $E(B - V)$ towards ω Cen has been established as 0.11 mag (Lub 2002). Most cluster members are found on the giant branch, which is quite broad, and extends redwards, most likely as the result of the presence of multiple stellar populations in the cluster (e.g., Norris & Da Costa 1995; Pancino 2002). The “anomalous giant branch” (Lee et al. 1999; Pancino et al. 2000; Ferraro et al. 2004) corresponds to the detached giant branch passing through $B = 15$ and $B - V = 1.2$, containing about two dozen stars. Their mean radial velocity and velocity dispersion are consistent with the values for the entire cluster. The few bright members with $B < 13$ bluewards of the giant branch, reminiscent of Fehrenbach’s star HD 116745 (LID 16018; see Fehrenbach & Duflot 1962), are possibly post-AGB stars. The non-members

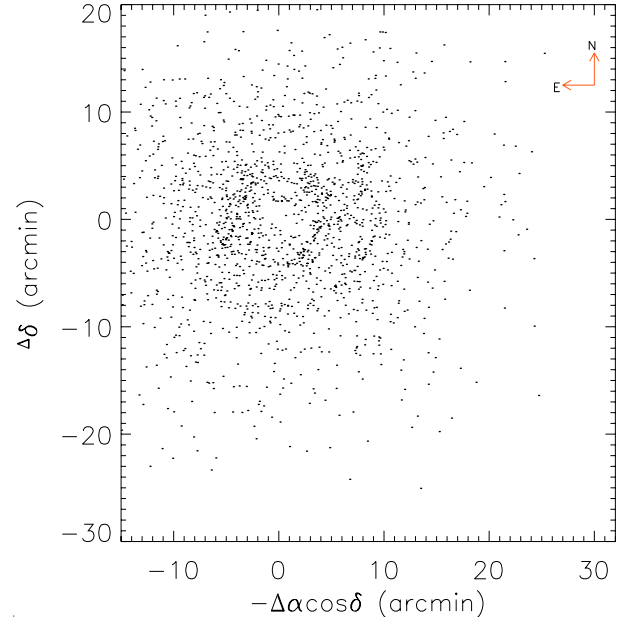


Fig. 5. Positions of 1589 possible radial velocity members which have proper motions (Paper I), relative to the centre of ω Centauri.

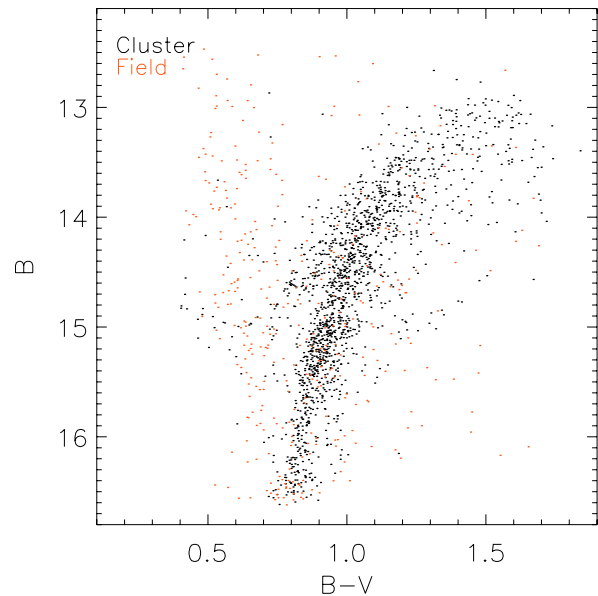


Fig. 6. Colour–magnitude diagram for the subset of 1966 stars for which Paper I reports a B -magnitude and $B - V$ colour. Of these, 1589 have a heliocentric radial velocity in the range between 160 and 300 km s^{-1} , and are considered secure members of ω Cen. These are indicated by the black dots. The remaining 504 stars (red dots) are field stars.

are distributed more homogeneously over the diagram, as expected. The near-vertical band with $B - V \sim 0.55$ consists of main-sequence stars over a significant range of distances.

3.3. Rotation and velocity dispersion

An indication of internal rotation of ω Cen based on proper motion measurements was found by Dickens & Woolley (1967). They saw evidence for solid body rotation in the centre of

the cluster and showed that the apparent ellipticity of ω Cen ($\varepsilon = 1 - b/a$) increases from approximately zero in the centre to a maximum of 0.25 at $10'$, and decreases slowly and regularly to almost zero at the tidal radius of the cluster. Dickens & Woolley (1967) suggested that the rotation axis should be approximately North-South in the plane of the sky. These conclusions were confirmed by Geyer et al. (1983). Rotation was observed as well by Harding (1965) based on radial velocities of 13 stars in the cluster, and was later confirmed by the CORAVEL study (Meylan et al. 1995; Merritt et al. 1997).

We have computed a smooth representation of the mean velocity $\langle v \rangle$ and of the velocity dispersion σ of the measurements (cf. Merritt et al. 1997). This was done by adaptive kernel smoothing. For each star, we created a bin containing its 200 nearest neighbors, and computed the mean velocity $\langle v \rangle$ and velocity dispersion σ for the bin, using a maximum likelihood method with a Gaussian kernel centred on the star to correct for the individual measurement errors (see Paper III). This procedure correlates the values at different points, but it produces smooth maps of $\langle v \rangle$ and σ which bring out the main features of the line-of-sight kinematics of ω Cen. They are shown in Fig. 7. The mean velocity field is very regular, and peaks at about 6 km s^{-1} at $8'$, beyond which it decreases. The contours of constant velocity dispersion are elongated, and range from 15 km s^{-1} in the centre to 8 km s^{-1} at $10'$. The decline continues to the edge of the field, where we measure about 6 km s^{-1} at $25'$.

We emphasize that the kinematic maps shown in Fig. 7 have *not* been corrected for the perspective rotation caused by the significant space motion of the cluster and the relatively large field over which we have kinematic measurements. We do this in Paper III, and show there that the resulting maps remain smooth, but that the position angles of the zero velocity curve and the orientation of the elongated contours of constant velocity dispersion change significantly.

4. Conclusions

We have presented radial velocities obtained with ARGUS for 2134 stars in the field of the globular cluster ω Centauri brighter than photographic B -magnitude 16.5. We have shown that the standard errors provided by the data reduction pipeline need to be multiplied by 0.8. The externally-estimated median errors are below 2 km s^{-1} for the stars brighter than B -magnitude of 15, which constitute the bulk of the sample. Based on these measurements, we conclude that 1589 stars are members of ω Centauri. The velocities provide clear evidence for rotation with an amplitude of about 6 km s^{-1} . The velocity dispersion is 15 km s^{-1} in the inner few arcmin, and decreases monotonically to about 6 km s^{-1} at a radius of about $25'$. We use these velocities in a companion paper (Paper III) to correct the proper motions from Paper I for the remaining overall (solid-body) rotation, and then model the internal dynamics of ω Cen, and determine its distance.

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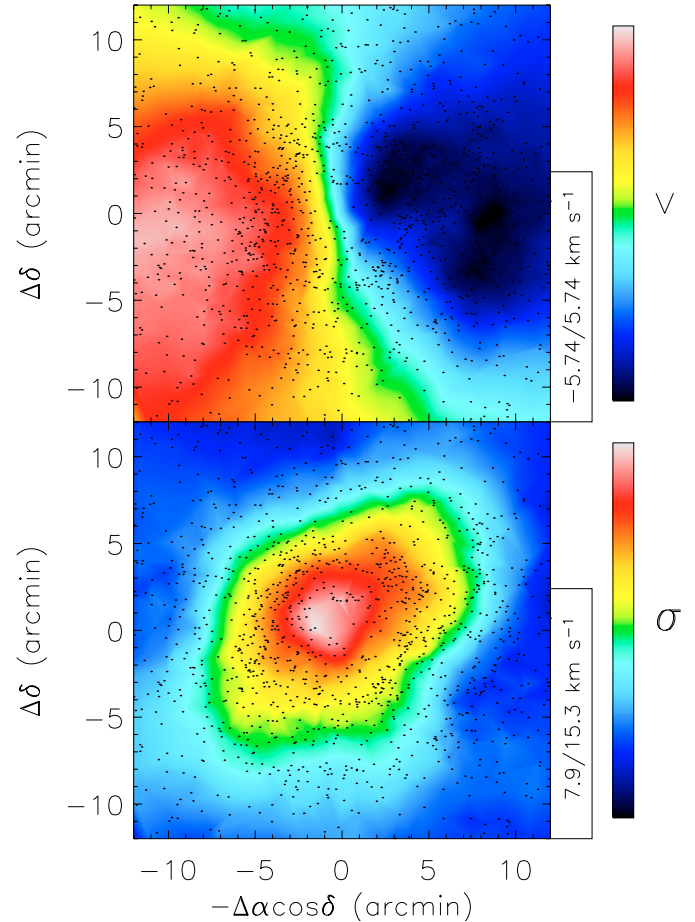


Fig. 7. Kinematics of ω Cen, based on adaptive smoothing of the individual measurements, as described in the text. **a)** Mean radial velocity field after subtraction of the systemic velocity, **b)** radial velocity dispersion. The dots indicate the positions of the individual measurements. The observed velocities have not been corrected for the perspective rotation caused by the space motion of the cluster, and these maps should therefore be interpreted with caution (Paper III).

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Appendix A: Additional measurements

We observed an additional 339 stars not discussed in the main text. These consist of (i) 87 stars with $B - V < 0.4$; and (ii) 252 stars without colour information².

The first group contains many stars whose colours put them on the horizontal branch of ω Cen. About half of the velocities provided by FXCOR turned out to lie in the range covered by members of ω Cen, while the others all appeared to lie in a small interval near 20 km s^{-1} , which resulted in an anomalous peak in the field star histogram of Fig. 4. As a result, we suspect that many, if not all, of these horizontal-branch stars are in fact cluster members, and that FXCOR provided an erroneous value for their radial velocity. For this reason, we do not trust the

² The number of stars with ARGUS radial velocity measurements quoted in Paper I did not distinguish between our main sample of 1966, and the 339 discussed here.

Table A.1. Summary of results, extract only. LID: Leiden identification number from Paper I; α and δ are right ascension and declination in decimal degrees; mean measured heliocentric radial velocity $\langle v \rangle$ and the standard error $\sigma_{\langle v \rangle}$ (0.8 times the standard error provided by FXCOR), in km s^{-1} ; n : number of individual measurements; B : photographic magnitude in mag.

LID	α	δ	$\langle v \rangle$	$\sigma_{\langle v \rangle}$	n	B
00002	200.90579	-47.15459	-15.6	5.2	1	14.65
00004	201.03029	-47.15715	-42.6	4.0	1	15.56
00020	202.16182	-47.70901	-51.5	1.9	1	13.20
01002	200.95038	-47.16522	5.4	2.0	1	15.76
01004	201.11462	-47.16870	-74.1	3.3	1	16.34
01005	201.12079	-47.16557	51.3	2.8	1	15.46

values of the horizontal-branch “members” either, and decided to remove all stars with $B - V < 0.4$ from our main sample. We list these stars and their positions in Table A.1, together with our nominal measured $\langle v \rangle$, the standard error $\sigma_{\langle v \rangle}$ (0.8 times the standard error provided by FXCOR, see Sect. 2.6), the number of measurements, and the photographic B magnitude.

Most of the stars without colour information were in the initial preliminary proper motion catalog, but not in the final proper motion catalog (see Sect. 2.2) which formed the basis of Table 5 in Paper I. The bulk of the stars is expected to have $B - V \geq 0.4$, and the resulting measurements should be reliable. As we do not know for certain which of these stars are blue, and hence unreliable, we decided to exclude the entire set from the analysis in the main paper. They are all listed in Table A.1.

Appendix B: Mean and dispersion

Given a sample of N radial velocities v_i ($i = 1, \dots, N$) with corresponding measurement errors σ_i , we calculate the mean $\langle v \rangle$ of this sample as

$$\langle v \rangle = \frac{1}{S} \sum_{i=1}^N w_i v_i, \quad (\text{B.1})$$

and the dispersion s as

$$s^2 = \frac{1}{b^2(N)} \frac{1}{S} \sum_{i=1}^N w_i (v_i - \langle v \rangle)^2, \quad (\text{B.2})$$

with weights $w_i = 1/\sigma_i^2$ and $S = \sum_{i=1}^N w_i$. The factor

$$N b^2(N) = \frac{2\Gamma^2\left(\frac{N}{2}\right)}{\Gamma^2\left(\frac{N-1}{2}\right)} \approx N - \frac{3}{2}, \quad (\text{B.3})$$

with $\Gamma(z)$ the gamma function, makes s an unbiased estimator of the dispersion³. Assuming that the velocities are Gaussian distributed, the uncertainties $\sigma_{\langle v \rangle}$ of the mean, and σ_s of the dispersion, are given by

$$\sigma_{\langle v \rangle} = \frac{1}{\sqrt{S}} \quad (\text{B.4})$$

³ If $N b^2(N)$ is replaced by $N - 1$, we obtain the well-known unbiased estimator of the variance.

and

$$\sigma_s^2 = \sigma_{\langle v \rangle}^2 \left[\frac{N-1}{N b^2(N)} - 1 \right] \approx \frac{N \sigma_{\langle v \rangle}^2}{2N-3}. \quad (\text{B.5})$$

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