A&A 637, A46 (2020)
https://doi.org/10.1051/0004-6361/202037500

Astronomy & Astrophysics

The proper motion of sub-populations in ω Centauri

N. Sanna[1], E. Pancino[1,2], A. Zocchi[3], F. R. Ferraro[4], and P. B. Stetson[5]

[1] INAF – Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
e-mail: `nicoletta.sanna@inaf.it`
[2] ASI Science Data Center, Via del Politecnico SNC, 00133 Rome, Italy
[3] European Space Research and Technology Centre (ESA/ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[4] Dipartimento di Fisica e Astronomia, Universitá degli Studi di Bologna, Via Gobetti 93/2, 40129 Bologna, Italy
[5] Herzberg Astronomy and Astrophysics, National Research Council, 5071 West Saanich Road, Victoria, British Columbia V9E 2E7, Canada

Received 14 January 2020 / Accepted 24 March 2020

ABSTRACT

The galactic globular cluster ω Centauri is the most massive of its kind, with a complex mix of multiple stellar populations and several kinematic and dynamical peculiarities. Different mean proper motions have been detected among the three main sub-populations, implying that the most metal-rich one is of accreted origin. This particular piece of evidence has been a matter of debate because the available data have either not been sufficiently precise or limited to a small region of the cluster to ultimately confirm or refute the result. Using astrometry from the second *Gaia* data release and recent high-quality, multi-band photometry, we are now in a position to resolve the controversy. We reproduced the original analysis using the *Gaia* data and found that the three populations have the same mean proper motion. Thus, there is no need to invoke an accreted origin for the most metal-rich sub-population.

Key words. globular clusters: individual: NGC 5139 – stars: kinematics and dynamics – proper motions

1. Introduction

Of all globular clusters (hereafter GCs) in the Milky Way, ω Centauri (ω Cen, NGC 5139) is the most massive ($3.24 \times 10^6\ M_\odot$, Zocchi et al. 2017) and the most complex in terms of its sub-populations. It is known to host from a minimum of three (Pancino et al. 2000; Ferraro et al. 2004) to at least 15 (Bellini et al. 2017) sub-populations. The complexity is observed in colour-magnitude diagrams (hereafter CMDs), where it appears most clearly in *Hubble* Space Telescope (HST) photometry (Bellini et al. 2017), which shows several co-existing main sequences. The cluster is even more complex from the point of view of its chemistry, with a large spread in metallicity (Norris et al. 1996; Pancino et al. 2002), extreme multiple populations (Gratton et al. 2011; Bastian & Lardo 2018), including strong enhancements in helium (Dupree & Avrett 2013), and s-process elements (D'Orazi et al. 2011).

The complexity of ω Centauri is reflected in its kinematics, but often with controversial results. In their study of 400 red giants, Norris et al. (1997) found that the metal-rich population is more centrally concentrated and kinematically cooler than the metal-poor population (see also Sollima et al. 2007; Bellini et al. 2009a). Moreover, the metal-poor stars show systemic rotation, while the metal-rich stars seem to be non-rotating. These results were confirmed by van de Ven et al. (2006) and Bellini et al. (2018), who used different sets of data to find differences in the radial distribution and rotation of the sub-populations, as well as possible differences in their anisotropy. However, based on their radial velocity investigations, Pancino et al. (2007) and van Loon et al. (2007) did not find any significant difference in the rotation or velocity spreads among the sub-populations. Another controversial topic that lingers is the possible presence of an intermediate-mass black hole, initially proposed by Noyola et al. (2008), but later put into doubt by, for example, van der Marel & Anderson (2010) or Zocchi et al. (2019), who studied the effect of several dynamical ingredients on reproducing the available data.

The recent second *Gaia* data release (hereafter DR2, Gaia Collaboration 2018a, 2016) provided data that could in principle settle some of the open issues, but unfortunately the central regions of ω Centauri are incomplete, as illustrated in Fig. 1. The incompleteness is caused by a combination of crowding effects, along with incomplete *Gaia* coverage due to the scanning law, and quality filtering of the catalogue prior to the release. The extremely strict membership selection performed by Gaia Collaboration (2018b) exacerbates the incompleteness, producing a large void in the central parts of the GC (Fig. 1, see also Fig. A.6 by Gaia Collaboration 2018b). The quality is expected to improve significantly with future *Gaia* releases (Pancino et al. 2017). It is not surprising, therefore, that no detailed analysis of the internal kinematics and dynamics of ω Cen, based on *Gaia* DR2 data, has yet appeared: so far, only studies on the systemic properties (Bianchini et al. 2018; Sollima et al. 2019) and on the tidal tails and stream (Myeong et al. 2018; Ibata et al. 2019) have been published. Baumgardt et al. (2019) derived a velocity dispersion profile for ω Cen with *Gaia* DR2 data, but no study of the kinematic differences among sub-populations in ω Cen has been published so far.

There is, however, one dispute about a particularly controversial piece of evidence that can be settled with the present *Gaia* DR2 astrometry, even considering the limitations in the case of the central ω Cen regions. Combining the photometry by Pancino et al. (2000) with the proper motions

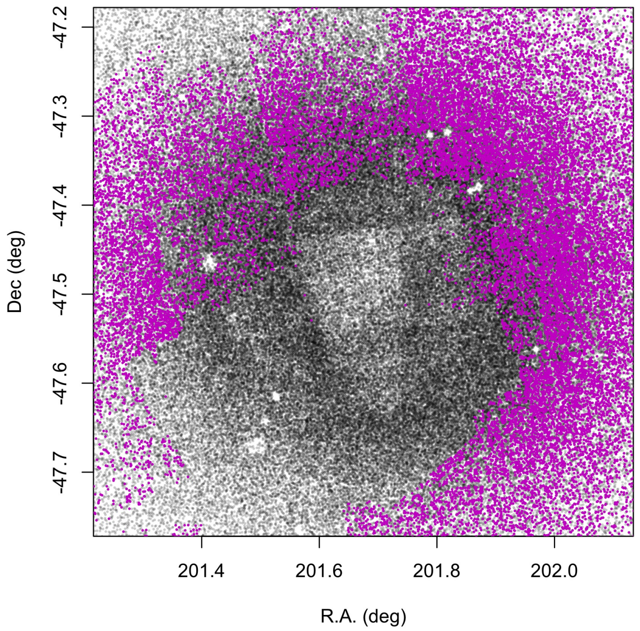

Fig. 1. Map of the central regions of ω Centauri in the *Gaia* DR2 catalogue. The holes caused by bright stars and the irregularly shaped incompleteness pattern in the central parts can be appreciated. The members by Gaia Collaboration (2018b) are marked as purple dots: their very strict selection leaves a void in the central parts.

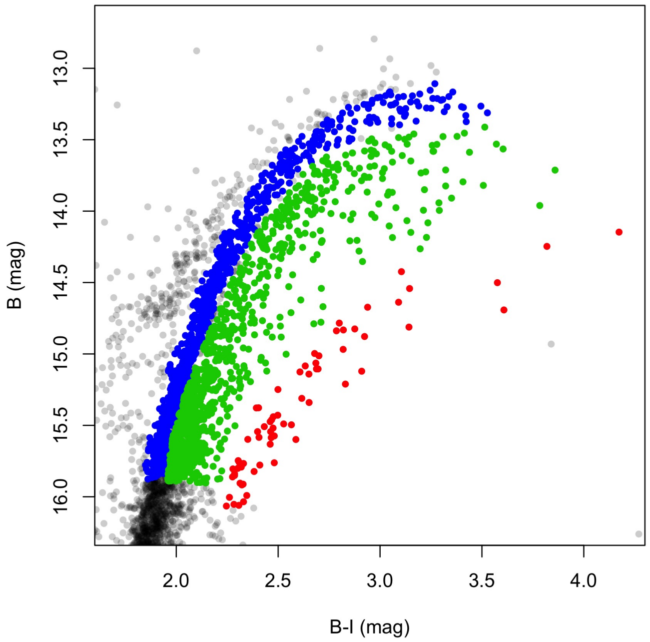

Fig. 2. Selection of the three sub-populations following criteria as similar as possible to those by Ferraro et al. (2002). The grey dots in the background represent the selected members of ω Centauri; blue dots represent the RGB-MP sample, following the nomenclature by Pancino et al. (2000) and Ferraro et al. (2002); green dots: the RGB-Mint sample; and red dots: the RGB-a sample.

by van Leeuwen et al. (2000), Ferraro et al. (2002) investigated the proper motions of three RGB sub-populations, which they labelled metal-poor (RGB-MP), metal-intermediate (RGB-MInt), and metal-rich or anomalous (RGB-a), concluding that the metal-rich sub-population should have an independent origin because its mean proper motion is not consistent with the bulk of the RGB stars. In other words, the RGB-a population would be an accreted system, not yet fully mixed, that was not originally part of the ω Cen main body; it may be, perhaps, a small GC of the original parent galaxy.

This result has been debated since. Platais et al. (2003) suggested that it was an artefact caused by instrumental effects because the telescope used to obtain the proper motions by van Leeuwen et al. (2000) was moved from South Africa to Australia, so the optics and detectors were not the same in different epochs. Hughes et al. (2004) showed that a small colour term of 1 mas yr^{-1} in the proper motions was properly corrected by van Leeuwen et al. (2000) and it was in the opposite sense with respect to the RGB-a motion, thus the catalogue was reliable and the result solid. A deeper discussion of the problem can also be found in Bellini et al. (2009b), who presented a proper motion investigation using ground-based photometry and astrometry and found no proper motion difference among sub-populations. The authors suggested that an internal stellar proper motions investigation was required, but at that time a catalogue of sufficient quality was not available. More recently, Bellini et al. (2018) and Libralato et al. (2018) investigated the proper motions of small external regions of the main sequence (MS) sub-populations of the cluster using HST data and found that all the sub-populations – which do not correspond exactly to those defined by Ferraro et al. (2002) – share the same median proper motions within the uncertainties. Any difference they found was very small, much smaller than the $\simeq$0.8 mas yr^{-1} found by Ferraro et al. (2002). However, the HST astrometry was confined to small-area pointings in ω Cen.

Here, we profit from the updated multi-band photometry that was recently published by Stetson et al. (2019) and the exquisite proper motions available in *Gaia* DR2 to revisit the proper motion investigation of the three RGB sub-populations in ω Centauri. In particular, the *Gaia* DR2 astrometry has a much higher quality compared to any previous ground-based catalogue and covers the entire extent of the cluster, unlike previous HST astrometry, and therefore it is the only available astrometric catalogue that has the potential to finally settle this open controversy.

2. Data analysis and results

We based our analysis on the Johnson-Cousins *UBVRI* photometry by Stetson et al. (2019) and on the *Gaia* DR2 proper motions[1]. We also cross-matched the combined Stetson-*Gaia* catalogue with the original van Leeuwen et al. (2000) astrometry that was used by Ferraro et al. (2002)[2]. We examined some of the quality flags provided by *Gaia* DR2 for this sample, limiting our analysis to the red giant stars with $G < 17$ mag. We verified that the behaviour of the astrometric excess noise, goodness of fit, number of good observations used, and RUWE of the selected stars did not deviate from the typical collective behaviour of the sample; thus, we did not apply any specific selection. The initial catalogue of stars in common among the three sources contained 8613 stars.

We could not use the membership selection by Gaia Collaboration (2018b) because it is quite restrictive and it does not contain enough stars in the RGB-a population (see also Fig. 1). Therefore, we performed a less restrictive membership

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[1] The two catalogues were cross-matched with in-house software by P. B. Stetson.

[2] The cross-match was performed using the CataXcorr package, developed by P. Montegriffo at the INAF-Osservatorio di Bologna.

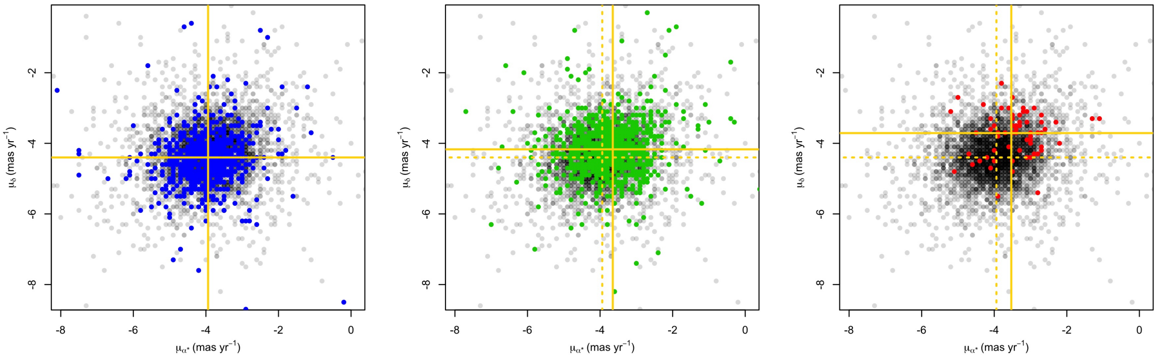

Fig. 3. Proper motion vector diagram of the selected members of ω Centauri (grey dots in all panels) using the astrometry by van Leeuwen et al. (2000). Each panel represents one RGB sub-population with the same colours as in Fig. 2. The solid yellow lines are the mean motion of each sub-population according to Ferraro et al. (2002), while the RGB-MP mean motion is reported as a dotted yellow line in the *middle* and *right panels*. The RGB-Mint and RGB-a populations are clearly offset from the RGB-MP one, as was found by Ferraro et al. (2002).

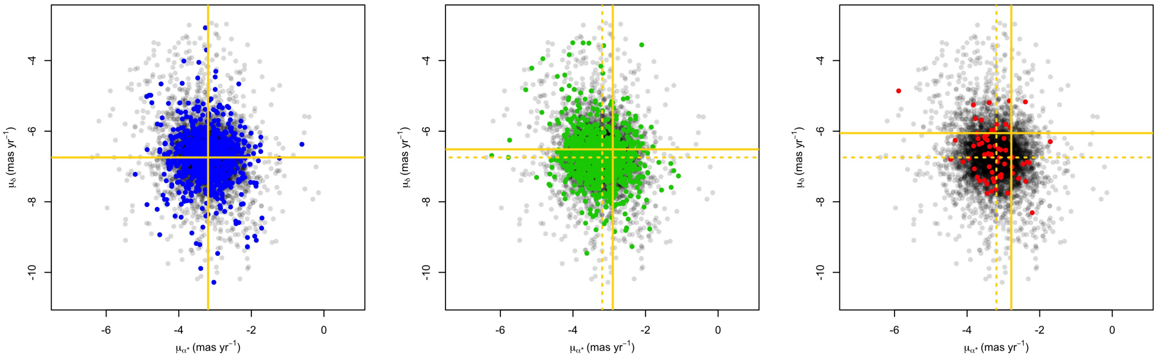

Fig. 4. Same as Fig. 3, but using the *Gaia* DR2 motions from Gaia Collaboration (2018b). The yellow lines now correspond to the centroid of the motion by Gaia Collaboration (2018b), but the offsets of the RGB-Mint and RGB-a from the RGB-MP are the same as in Fig. 3. It is evident that the three populations have compatible mean proper motions.

Table 1. Comparison of (weighted) mean proper motions for the sub-population samples, among different literature sources, where F02 stands for Ferraro et al. (2002), V00 for van Leeuwen et al. (2000), and G18 for Gaia Collaboration (2018b).

Population	μ_{α^*} (mas yr^{-1})	μ_δ (mas yr^{-1})	Reference
RGB-MP	–4.00 ± 0.02	–4.44 ± 0.02	Here, using V00
RGB-Mint	–3.76 ± 0.03	–4.20 ± 0.02	
RGB-a	–3.44 ± 0.08	–3.78 ± 0.08	
RGB-MP	–3.94	–4.40	F02, using V00
RGB-Mint	–3.65	–4.27	
RGB-a	–3.53	–3.71	
RGB-MP	–3.21 ± 0.02	–6.73 ± 0.02	Here, using G18
RGB-Mint	–3.27 ± 0.02	–6.74 ± 0.02	
RGB-a	–3.28 ± 0.07	–6.64 ± 0.07	

selection, with the goal of cleaning the catalogue from obvious non-members, by retaining all stars within a 5D ellipsoid defined as follows:

$$\frac{(\alpha-\alpha_0)^2}{r^2}+\frac{(\delta-\delta_0)^2}{r^2}+\frac{(\mu_{\alpha^*}-\bar{\mu}_{\alpha^*})^2}{(3\sigma_{\mu_{\alpha^*}})^2}+\frac{(\mu_\delta-\bar{\mu}_\delta)^2}{(3\sigma_{\mu_\delta})^2}+\frac{(\varpi-\bar{\varpi})^2}{(5\sigma_\varpi)^2}<1,$$

where $r = 30'$ (the maximum extension allowed for a uniform coverage in the ground-based photometry); (α_0, δ_0) are the central coordinates of ω Centauri by Stetson et al. (2019); ($\bar{\mu}_{\alpha^*}$, $\bar{\mu}_\delta$, $\bar{\varpi}$) are the systemic motion and parallax measurements by Gaia Collaboration (2018b)[3]; ($\sigma_{\mu_{\alpha^*}}$, σ_{μ_δ}, σ_ϖ) represent the median absolute deviation (MAD) of the proper motion and parallax distributions of members, refined after a few iterations, and set to (1.09, 1.29) mas yr^{-1} and 0.69 mas, respectively. Following the selection, the sample was made up of 5113 stars. The typical (median) uncertainties on the individual stars are in the range of 0.08–0.12 mas yr^{-1} in the case of μ_{α^*} and 0.12–0.17 mas yr^{-1} in the case of μ_δ. We note that the errors are larger for the bright stars ($G \lesssim 13$ mag) than for the faint ones, owing to the fact that *Gaia* is not designed to target bright stars.

We manually selected the three RGB sub-population samples following the criteria by Ferraro et al. (2002) as closely as possible, as shown in Fig. 2. In particular, we used the same limiting magnitudes for the selection of the populations labelled by Pancino et al. (2000) and Ferraro et al. (2002) as RGB-MP and RGB-MInt, while for the so-called RGB-a population we selected slightly fainter stars ($B \lesssim 16.1$ mag) thanks to the clearer separation from the bulk of the RGB population. As a first sanity check, adopting our selections, we reproduced the original result by Ferraro et al. (2002) using the van Leeuwen et al. (2000) astrometry to make sure that our selection of the three sub-populations was comparable with theirs. The result is shown in Fig. 3, where we do indeed observe that the populations labelled by Pancino et al. (2000) and Ferraro et al. (2002) as RGB-MInt and RGB-a have a different mean proper motion compared to the RGB-MP population. In particular, as shown in Table 1, our results are fully compatible with the offsets found

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[3] As customary, $\mu_{\alpha^*} = \mu_\alpha \cos\delta$ (see, e.g. Lindegren et al. 2016).

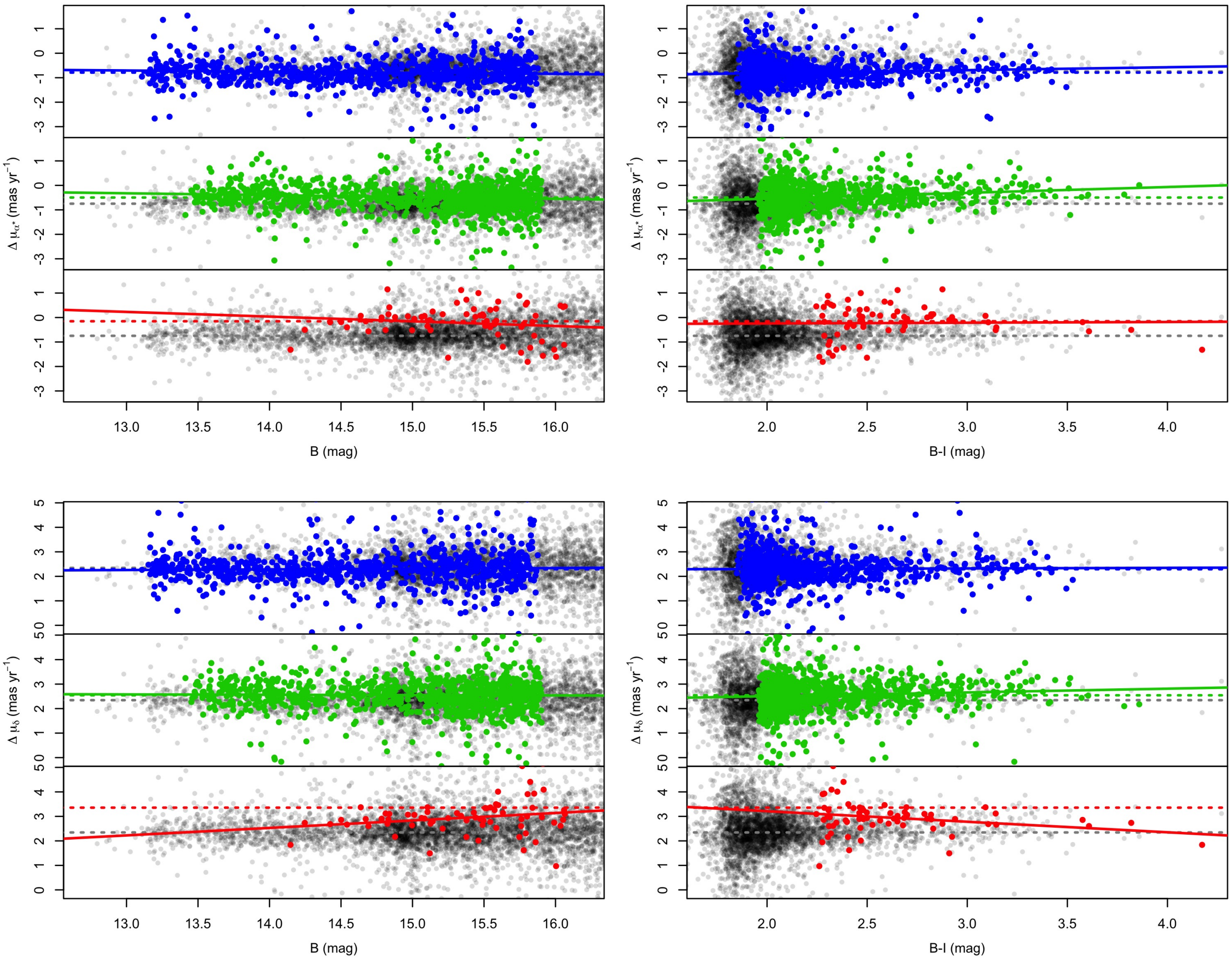

Fig. 5. Difference of the proper motion in RA (*top panels*) and Dec (*bottom panels*) by van Leeuwen et al. (2000) and Gaia Collaboration (2018b) as a function of magnitude (*left panels*) and of colour (*right panels*). Stars are coloured as in the previous figures. The average difference between the two catalogues are plotted as grey dotted lines, the ones for each sub-population are plotted as dotted lines of the respective colours, and the linear fits for each sub-population are shown as solid lines of the respective colours. None of the slopes are statistically significant, even the few that appear large are driven by single data points and a small sample size (see Sect. 2 and Table 2).

by Ferraro et al. (2002). We then repeated the same experiment with the *Gaia* DR2 proper motions, as illustrated in Fig. 4 and with the results reported in Table 1, but in this case all three populations appear clearly compatible with the same mean proper motion and with the Gaia Collaboration (2018b) systemic value for the cluster. We note here that the systemic motion of ω Cen derived by van Leeuwen et al. (2000) and by Gaia Collaboration (2018b) are quite different from each other, especially as far as μ_δ is concerned. Both estimates are quite different from the one by Dinescu et al. (1999) as well.

As a final check, we plot the star-by-star differences of the van Leeuwen et al. (2000) and Gaia Collaboration (2018b) proper motions as a function of magnitude and colour (Fig. 5). We checked for the presence of significant slopes using four indicators: the p-values of the angular coefficient of linear fits, the Spearman rank coefficient ρ, the Pearson correlation coefficient r, and the Kendall rank coefficient τ (Table 2). We found no significant slopes in any of the samples against colour or magnitude, contradicting the finding by Platais et al. (2003) but confirming the findings by Pancino (2003) and Hughes et al. (2004) in this respect. Even the apparent slopes visible in some of the panels of Fig. 5 are not significant and driven by single data points and sample sizes. As can be seen in Table 2, the errors on the angular coefficents m and intercepts q of the fits are very large. Besides the p-value of the linear fit, all three correlation tests have also large p-values (generally well above $\simeq 0.05$) and the correlation coefficients ρ, r, and, τ are always much closer to zero than to ± 1.

In past studies, the absence of a significant residual slope of the proper motion as a function of colour and magnitude was taken as proof that no spurious effect was present in the van Leeuwen et al. (2000) catalogue. However, from Fig. 5, it is evident that this condition was necessary but not sufficient; even if no slope is present in the data, each sub-population clearly drifts away from the mean motion of the cluster in one catalogue but not in the other. We can also see from Fig. 5 that the offsets found in Fig. 3 and Table 1 are entirely compatible with the differences between the proper motion measurements in the two catalogues, suggesting a spurious measurement effect in the van Leeuwen et al. (2000) catalogue.

3. Conclusions

Our main result is that when using *Gaia* DR2 data, the three sub-populations have compatible mean motions with each other and with the Gaia Collaboration (2018b) systemic motion of ω Cen. Previous astrometric catalogues, most notably those by Bellini et al. (2009b, 2018), have provided the same result.

Table 2. Linear fits and correlation coefficients for the sub-populations (see Fig. 5).

Population	x	y	m	q	p	r	ρ	τ
RGB-MP	B	μ_{α^*}	-0.10 ± 0.54	-0.046 ± 0.037	0.21	–0.044	–0.005	–0.005
	B	μ_δ	1.91 ± 0.59	0.027 ± 0.040	0.51	0.023	0.021	0.013
	B-I	μ_{α^*}	-1.05 ± 0.19	0.119 ± 0.086	0.17	0.048	–0.001	0.001
	B-I	μ_δ	2.25 ± 0.21	0.024 ± 0.094	0.80	0.009	–0.008	–0.006
RGB-MInt	B	μ_{α^*}	0.67 ± 0.83	-0.076 ± 0.055	0.17	–0.044	–0.101	–0.070
	B	μ_δ	2.77 ± 0.62	-0.015 ± 0.041	0.72	–0.012	–0.062	–0.042
	B-I	μ_{α^*}	-1.02 ± 0.27	0.238 ± 0.117	0.04	0.066	0.184	0.124
	B-I	μ_δ	2.20 ± 0.20	0.153 ± 0.087	0.08	0.057	0.150	0.101
RGB-a	B	μ_{α^*}	2.72 ± 3.89	-0.192 ± 0.253	0.45	–0.093	–0.048	–0.023
	B	μ_δ	-1.74 ± 2.69	0.305 ± 0.175	0.09	0.212	0.212	0.159
	B-I	μ_{α^*}	-0.30 ± 0.85	0.031 ± 0.321	0.92	0.012	0.029	0.006
	B-I	μ_δ	4.07 ± 0.58	-0.431 ± 0.219	0.05	–0.237	–0.185	–0.143

Notes. For each population, a linear fit of y (the proper motion component) as a function of x (magnitude or colour) is performed. The angular coefficent m and the intercept q of each fit are listed, along with the statistical significance of the fit p. The correlation coefficients by Pearson (r), Spearman (ρ), and Kendall (τ) are also reported (see text for a discussion).

However, Bellini et al. (2009b) could count on astrometric errors of the order of a few mas yr^{-1}, that is, a few times larger than the putative proper motion offsets among sub-populations, similarly to van Leeuwen et al. (2000), while the HST astrometric catalog by Bellini et al. (2018) had sub-mas uncertainties, comparable to those in the *Gaia* DR2 catalogue but, of course, limited to a very small area. Thus, *Gaia* DR2 is the only presently available catalogue with sufficient quality and area coverage to settle the controversy.

The conclusion that can be drawn from the available literature body and the present analysis is that, indeed, as was suggested by Platais et al. (2003), the van Leeuwen et al. (2000) catalogue contained spurious instrumental effects, although they were not so immediately evident as a simple colour or magnitude trend. Indeed, a colour trend of about 1 mas yr^{-1} was found and removed from the van Leeuwen et al. (2000) catalogue, as pointed out by Hughes et al. (2004), but this was not sufficient to correct the problem. This implies that it is not necessary to assume that the RGB-a population was an external system which was then accreted by the main body of ω Cen. We expect that the next *Gaia* releases will include a treatment of crowding effects (Pancino et al. 2017) and will rely on more high-quality data in the central parts. Combined perhaps with HST astrometry, *Gaia* data do have the potential to help us decipher the complex kinematic structure and evolution of ω Cen and its sub-populations.

Acknowledgements. We thank the referee for the useful suggestions. NS and EP acknowledge the financial support to this research by INAF, through the Mainstream Grant 1.05.01.86.22 assigned to the project "Chemo-dynamics of globular clusters: the *Gaia* revolution" (P.I. E. Pancino). AZ acknowledges support through a ESA Research Fellowship. This work has used data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. All figures and the statistical analysis were done with the R programming language (R Core Team 2017; Dowle & Srinivasan 2017) and Rstudio (`https://www.rstudio.com/`).

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