Discovery of an accreted stellar system within the globular cluster ω Cen

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ABSTRACT

Recent wide-field photometric surveys (Lee et al.; Pancino et al.) have shown the existence of a previously unknown metal-rich ([Fe/H] ≃ −0.6) stellar population in the galactic globular cluster ω Centauri. The discovery of this new component, which comprises only a small percentage (≈ 5%) of the entire cluster population, has added a new piece to the already puzzling picture of the star formation and chemical evolution of this stellar system. In this Letter we show that stars belonging to the newly discovered metal-rich population have a coherent bulk motion with respect to the other cluster stars, thus demonstrating that they formed in an independent self-gravitating stellar system. This is the first clear-cut evidence that extreme metal-rich stars were part of a small stellar system (a satellite of ω Centauri?) that has been accreted by the main body of the cluster. In this case, we are witnessing an in vivo example of hierarchical merging on the sub-galactic scale.

Subject headings: globular clusters: individual (ω Cen)—stars: kinematics — stars: Population II

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1. Introduction

The giant globular cluster ω Centauri is the only Galactic globular that shows multiple stellar populations, with a very different heavy metal content. Large photometric (Lee et al. 1999; Hilker & Richtler 2000; Hughes & Wallerstein 2000; Pancino et al. 2000) and spectroscopic (Norris, Freeman & Mighell 1996; Smith et al. 2000) surveys have demonstrated the presence of a main population at [Fe/H] = −1.6 with a metal-rich tail extending up to [Fe/H] = −0.6. The detailed abundance patterns of tens of red giants spanning the entire metallicity range have been derived (see Norris & Da Costa 1995; Smith et al. 2000; Pancino et al. 2002a). The cluster also shows dynamical anomalies with respect to ordinary globulars, since it is partially substanined by rotation (Mayor et al. 1997; Merritt, Meylan & Mayor 1997). Moreover, while the metal-poor giants ([Ca/H] < −1.2) do rotate, the metal-rich ones do not show any sign of rotation (Norris et al. 1997, see below for further discussion).

Since its vicinity allows a very detailed study of its stellar content, this giant cluster represents a cornerstone in our understanding of the formation, the chemical enrichment and the dynamical evolution of stellar systems. However, in spite of the huge observational effort carried out so far, the global scenario for the formation and evolution of ω Cen still remains a mystery (see for instance Norris, Freeman & Mighell 1996; Smith et al. 2000, and discussions therein). To explain its peculiar properties and its heterogeneous mix of populations, different hypotheses have been suggested: (i) ω Cen is the relic of a larger galaxy partially disrupted by the tidal field of the Milky Way (Freeman 1993; Lee et al. 1999; Majewski et al. 2000); (ii) it is the result of the merging of two globulars (Searle 1977; Icke & Alcaino 1988; Makino et al. 1991). However, while some hints of a complex dynamical history have been found (Norris et al. 1997; Jurcsik 1998), none of the evidence presented so far is conclusive, and most important, the simple model of the merging of two ordinary globulars cannot fit the observed broad metallicity distribution (Norris, Freeman & Mighell 1996; Smith et al. 2000).

1.1. The sub-populations of ω Centauri

Recent wide-field photometric studies have added a new piece to this already complex jigsaw puzzle: an additional, well-defined Red Giant Branch (RGB) sequence has been discovered to the red side of the main RGB in the Color Magnitude Diagram (CMD; Lee et

1Based on WFI observations collected at La Silla, Chile, within the observing programmes 62.L-0354 and 64.L-0439.
The discovery of this anomalous branch (hereafter RGB-a) unveiled the existence of a further, previously unknown, metal rich sub-population in ω Centauri. In particular Pancino et al. (2000), taking advantage of the high accuracy and sensitivity of their \((B, B - I)\)-CMD, have identified three main sub-populations on the basis of their photometric properties: the main metal-poor component (MP; \([\text{Fe/H}] < -1.4\)); the metal-intermediate population (MInt; \(-1.4 \leq [\text{Fe/H}] < -0.8\)) and the anomalous population (RGB-a) which represents the extreme metal-rich end of the observed metallicity distribution.

The approximate CMD locations of the three sub-populations defined above are shown in Figure 1. Stars belonging to the RGB-a are plotted as **small solid triangles**. Note that only a few stars belonging to this population were known before the discovery of the anomalous branch: in particular, only 6 RGB-a stars (marked as **large open triangles** in Figure 1) have previous metal abundance determinations (Evans 1983; Norris, Freeman & Mighell 1996) and only 8 have radial velocity determinations (Mayor et al. 1997).

Though the RGB-a population comprises only a small fraction (\(\sim 5\%\); Pancino et al. 2000) of the cluster’s stellar content, its origin and evolution is the new challenging question in the picture of ω Cen formation and evolution.

As part of a long-term project (Ferraro, Pancino & Bellazzini 2002) devoted to reconstruct the global evolutionary history of ω Centauri, we are building a comprehensive catalog combining all the relevant information available in the literature for stars in this cluster. Here we present the first results obtained by cross-correlating our wide field, multi-band photometric catalog (Pancino et al. 2000), comprising more than 220,000 stars, with the recently published proper motion study for \(\sim 10,000\) stars brighter than \(V \sim 16.0\) (van Leeuwen et al. 2000). The synthesis of these data-sets allows us to study for the first time the kinematical properties of the RGB-a stellar population.

## 2. Results

Figure 2 shows the proper motion distributions for the three different sub-populations defined above (see Figure 1): MP, MInt, and RGB-a (panels (a), (b) and (c), respectively). To exclude any effect due to uncertain measures we consider here only the stars with safe and accurate proper motions in the Van Leuwen’s catalog (i.e. quality flag < 4 and \(\epsilon_\mu < 0.5\) mas/yr). For sake of comparison, all the stars satisfying these selection criteria have also been plotted in each panel as **small dots**.

The most striking result is that the proper motion centroid of the RGB-a group is quite
different from that of the MP population. This means that the RGB-a stars have a coherent residual proper motion with respect to the dominant cluster population. The systematic residual turns out to be $\delta \mu_{RA} = +0.4$ and $\delta \mu_{DEC} = +0.7$ mas/yr, which corresponds to a total proper motion modulus of $|\delta \mu_{TOT}| = 0.8$ mas/yr, with respect to the centroid of the MP population. In order to exclude that the effect found above is due to any kind of systematic error (for example to spurious effects on the proper motion measures correlated to the color or the magnitude of the stars) we also considered the proper motion distribution of the Horizontal Branch (HB) stars, which have quite different colours and luminosities with respect to the giants: no systematic difference could be detected between the proper motion distributions of the HB and the RGB-MP groups. A two-dimensional generalization of the Kolmogorov-Smirnov test (KS; Fasano & Franceschini 1987), applied to the proper motion distributions of the HB and MP (see Table 1), suggest that the two samples are fully consistent, i.e., they are extracted from the same parent distribution. This test indicates that the systematic proper motion residual found for the RGB-a stars cannot be ascribed to any spurious colour/luminosity effect.

What is the statistical significance of the detected difference? Both mono-dimensional (Fig. 3a) and bidimensional KS tests (see Table 1) show that the probability that the proper motion distribution observed for the RGB-a stars is drawn from the same parent distribution of the MP population is lower than $10^{-13}$. We obtain the same answer by performing extensive Monte Carlo simulations: $10^6$ sub-samples of the same dimension of the RGB-a sample have been randomly extracted from the dominant (MP) proper motion distribution. For each extracted sample the total mean proper motion modulus $|\delta \mu_{TOT}|$ has been computed: in no case it turned out to be larger than or equal to that observed for the RGB-a stars. Moreover all of the extracted sub-samples have $|\delta \mu_{TOT}| \leq 0.4$, i.e., always much lower than what actually observed for the RGB-a (Figure 3, Panel (b)). These tests put the statistical significance of the result shown in Fig. 2 beyond any possible doubt: the RGB-a stars have a proper motion distribution that is not compatible with that of the bulk (MP) population of $\omega$ Cen.

Norris et al. (1997) found evidence that, while the most metal-poor stars in their sample ([Ca/H] $< -1.2$) rotate, the most metal-rich ones instead show no sign of rotation. Is there a connection between this effect in the radial velocities and what we find here in the proper motion distribution? First of all, it must be noted that the metal-rich sample in Norris et al. (1997) is mostly a subsample of our MInt population, and it contains only a handful of stars belonging to the RGB-a, so the two effects regard two different groups of stars. To prove this point, we plot the metal-rich sample of Norris et al. in Panel (d) of Figure 2: the difference between their distribution and that of the RGB-a population (Panel (c) of Figure 2) can be clearly appreciated. Moreover, both the bidimensional KS tests (Table 1) and the
boot-strap Montecarlo simulations like those described above demonstrate that the proper motion distribution of the RGB-a cannot be extracted from the same parent population of the MInt, nor from the same parent distribution of the metal-rich sample of Norris et al., at the highest level of confidence ($P < 10^{-5}$). Thus we conclude that the RGB-a group shows a proper motion distribution which is significantly different from that of any other sub-population in ω Cen.

On the other hand, the membership of the RGB-a stars to the ω Cen system is proven by the radial velocities. Table 2 lists the mean radial velocities for each sub-sample defined in Section 1.1. Though radial velocities have been measured only for ten RGB-a stars, their mean velocity turns out to be fully consistent with that measured for the other sub-populations. This proves that all the considered sub-populations are locked in the same gravitational potential.

Assuming a distance of 5360 pc for the cluster (Thompson et al. 2001), the absolute differential proper motion of the RGB-a population corresponds to a total mean tangential velocity of $V_t \simeq 19.8$ km s$^{-1}$ with respect to the main system, in excellent agreement with the velocity dispersion measured in the core of ω Centauri (Mayor et al. 1997; van Leeuwen et al. 2000). By combining this estimate with the difference in the radial velocity between the RGB-a and MP stars ($\Delta V_r = 1.4$ km s$^{-1}$ – see Table 2), we obtain a total mean velocity $V_{tot} \sim 20$, still significantly lower than the half-mass escape velocity for ω Cen ($V_{esc} = 44$ km s$^{-1}$), as recently estimated by Gnedin et al. (2002). The observed bulk motion of the RGB-a stars is fully consistent with being driven by the potential well of the whole cluster. We can thus conclude that the RGB-a population is a coherently moving group of stars, gravitationally bound to the ω Cen system.

Although a detailed discussion of the MInt properties is beyond the scope of this paper, it is worth mentioning that also the MInt population shows a different proper motion distribution with respect to the MP population. Although the effect is smaller than the one shown by the RGB-a population (see Figure 2), the tests in Table 1 and Figure 3 prove that the difference is still significant. Moreover, since this sub-population basically coincides with the metal-rich group of Norris et al. (1997) (see Table 1), we can confirm that the global kinematical properties of the MInt stars are distinct from those of the main population of ω Cen.
Table 1. Bidimensional KS test for the proper motion distributions.

| Sub-Populations         | $D$         | $P$            |
|-------------------------|-------------|----------------|
| RGB-a vs MP             | 0.567       | $1.6 \times 10^{-14}$ |
| RGB-a vs N97            | 0.455       | $3.0 \times 10^{-6}$ |
| MP vs HB                | 0.003       | 0.46           |
| MInt vs Norris et al. (1997) | 0.13       | 0.33           |
| MInt vs MP              | 0.264       | $6.5 \times 10^{-11}$ |
| MInt vs RGB-a           | 0.396       | $5 \times 10^{-6}$ |

Note. — Bidimensional KS test for the proper motion distributions of the sub-populations discussed. $D$ is the maximum difference in the cumulative distribution, $P$ is the probability that the two populations are drawn from the same parent distribution.

Table 2. Mean Radial velocities for the three sub-populations in $\omega$ Cen

| Sub-Pop | $V_{rad}$ | $\sigma_V$ | N  |
|---------|-----------|------------|----|
| MP      | 234.2     | 14.5       | 186|
| MInt    | 231.1     | 13.0       | 76 |
| RGB-a   | 235.6     | 9.8        | 10 |

Note. — Radial velocities are from Mayor et al (1997), for RGB-a stars a few additional stars have been observed by Pancino et al. (2002a).
3. Discussion

By cross-correlating the photometric catalog by Pancino et al. (2000) and the proper motion catalog by van Leeuwen et al. (2000), we have shown that (i) the proper motion distribution of the RGB-a population is not compatible with the one of the dominant (MP) population; (ii) the proper motion distribution of the RGB-a is significantly different also from the MInt population (which includes the metal-rich group by Norris et al. 1997), (iii) the radial velocity ensures us that the coherent moving RGB-a group is gravitationally tied to the main body of ω Cen.

This strongly suggest that the RGB-a sub-population had an (at least partially) independent origin with respect to the bulk of the cluster population (i.e., MP and/or Mint stars). This conclusion is also supported by other observational results. For example, Pancino et al. (2000) showed that the spatial distribution of the RGB-a stars is elongated perpendicularly to the major axis of the dominant MP population of ω Centauri. Furthermore, both high-resolution optical (Pancino et al. 2002a) and medium-resolution IR (Origlia et al. 2002) spectroscopic analyses have shown that RGB-a stars are less α-enhanced than the other sub-populations in ω Cen. This fact suggests that the interstellar medium from which they formed could have been polluted by SNIa ejecta, as opposed to all the other cluster stars (see, e.g. Cunha et al. 2002, and references therein). In addition, it is worth noticing that all of the six RGB-a stars studied before (large empty triangles in Figure 1) exhibit strong BaII lines (Evans 1983) and in general very high abundances of post-iron peak elements (Evans 1983; Vanture, Wallerstein & Suntzeff 2002). These elements are thought to be produced mainly by intermediate-low mass asymptotic giant branch stars (Busso, Gallino & Wasserburg 1999).

On the other hand, many authors (see e.g. Norris & Da Costa 1995; Smith et al. 2000, and references therein) showed that the s-process elements overabundance seems to increase continuously with [Fe/H], at least for stars belonging to the RGB-MP and MInt populations, since only few data are available for the RGB-a population. For example, according the abundance analysis by Vanture, Wallerstein & Suntzeff (2002), ROA300 (an RGB-a member) shows a substantially higher abundance of s-process elements with respect to star ROA201 (which is conversely an MInt member). If this kind of discontinuous behaviour is confirmed, it will further support the hypothesis that the RGB-a population had a very different evolutionary and chemical history with respect to the other stars of ω Centauri.

In the simplest conceivable scenario, the RGB-a stars originated as an independent stellar system, now trapped and disrupting in the potential well of ω Centauri. Since the chance of capturing a completely independent object orbiting in the halo of the Galaxy is highly unlikely, it is reasonable to presume that the accreted system was a former satellite of
ω Centauri. This fact would be in agreement with the hypothesis that ω Centauri is in fact the relic of a larger galaxy, partially disrupted by the Galactic tidal field (as suggested by Freeman 1993; Lee et al. 1999; Dinescu, Girard & van Altena 1999; Majewski et al. 2000). If this is the case, we are witnessing the process of hierarchical merging, simultaneously occurring on two very different scales: the ω Centauri system is merging into the Milky Way and the RGB-a system is merging into ω Centauri. High resolution Cold Dark Matter (CDM) models (Moore et al. 1998) predict that hierarchical clustering processes do occur down to the dwarf-galaxy scale ($M \sim 10^7 M_\odot$) even at the present day. Apparently, we have found an in vivo example, suggesting that hierarchical merging occurs also on sub-galactic scales ($M \sim 10^{4-5} M_\odot$).

Without a detailed knowledge of the structural parameters for the RGB-a system, no quantitative conclusion can be made concerning the timescales involved in the accretion of the RGB-a by ω Cen. However, as an approximate criterium, we can assume that an accreted self-gravitating stellar system can resist the tidal field stress of the main accreting system if its density is larger than the average density of the host system at its orbital radius (Oh, Lin & Aarseth 1995; Burkert 1997). From the data at our disposal (Pancino et al. 2000; Ferraro, Pancino & Bellazzini 2002; Pancino et al. 2002b), we can roughly estimate that the RGB-a population has a central density comparable to that of the MP population and a core radius significantly smaller ($r_c^{RGB-a} \sim 0.5r_c^{MP}$) than that of the main MP population. Then, according to equation 18 by Gehrhard (2000), the RGB-a system is expected to dissolve under the tidal strain of ω Cen if its orbital radius is lower than $\sim 1r_c^{MP}$, i.e. the “dangerous” zone for the accreted RGB-a should be limited to the core of ω Cen.

The observational facts collected so far (Norris et al. 1997; Jurcsik 1998; Lee et al. 1999; Pancino et al. 2000; Ferraro, Pancino & Bellazzini 2002) point towards a multiple merging and/or accretion event in the past history of ω Cen. However unlikely this may appear, we have no other way to explain the structural and kinematical properties of the various cluster sub-populations. We may note that, as a typical galaxy evolves by accreting smaller systems (i.e., the Sagittarius Dwarf Spheroidal for the Milky Way), the past history of this giant cluster (or dwarf galaxy?) was probably characterized by multiple accreting/merging episodes. Some signatures of these remote events are still observable in the relic of the disrupting sub-systems. The exact connection between the different accreted stellar components (MInt and RGB-a), still remains to be fully understood. A complete radial velocity study of the more metal rich components in ω Cen will shed more light on this point.

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Fig. 1.— Approximate locations of the three RGB sub-populations (defined in the text) in the CMD, RGB-a stars are plotted as small solid triangles. The six RGB-a stars which have been identified and studied before the discovery of the anomalous branch are highlighted by large empty triangles.
Fig. 2.— Proper motion plane ($\mu_{RA}, \mu_{Dec}$) for stars in $\omega$ Cen. All stars in the Van Leween’s catalog with accurate proper motion measures have been plotted (small dots). Only stars with accurate measures ($\sigma_\mu < 0.5$ mas/yr) and quality flag $< 4$ have been considered. The solid circle deliniates the region where stars with a membership probability larger than 99% lie. In the first three panels stars belonging to the three RGB sub-populations defined in the text (see Figure 1) are marked with filled dots: the MP, the MInt and RGB-a populations in (a), (b) and (c), respectively. The dashed circle in panel (c) highlighted the center of symmetry for the RGB-a population. The proper motion distribution for the “metal-rich” sub-sample ($[Ca/H] < 1.2$) discussed by Norris et al (1997) is shown in panel (d), for comparison. As can be seen, the Norris et al sample is fully consistent with the MInt population and does not show the coherent residual proper motion signature detected in the RGB-a stars. The proper motion of the centroid for each population is reported in each panel. In addition, it is interesting to note that the three sub-populations show a similar dispersion ($\sigma_\mu \sim 0.6$ mas/yr).
Fig. 3.— Panel (a): Cumulative distribution ($\phi$) in the proper motion plane (see Figure 1), for the three sub-population (MP: heavy solid line; MInt dotted line; RGB-a dashed line). The X-axis variable ($d$) is the geometric distance of each star to the MP proper motion centroid ($\mu_{RA} = -3.94, \mu_{DEC} = -4.40$) in units of mas/yr). Only stars with accurate proper motion measurements (see the caption of Figure 1) and lying within the circle shown in panel (a) of Figure 1 have been considered. Panel (b): distribution of $|\delta\mu_{TOT}|$ for one million of “RGB-a-equivalent” subsamples randomly extracted from the MP population. Note that the observed value lies at more than 10$\sigma$ from the mean of the simulated samples.