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The puzzling origin and evolution of stellar populations in ω Centauri

A. Sollima[1], F. R. Ferraro[1], E. Pancino[2], and M. Bellazzini[2]

[1] Dipartimento di Astronomia – Università di Bologna, Via Ranzani 1, I-40127 Bologna, Italy, e-mail: antonio.sollima@oabo.inaf.it
[2] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy

Abstract. On the basis of large photometric and spectroscopic datasets, we investigated the general properties of the different sub-populations of ω Centauri in different regions of the color-magnitude diagram. In particular, we analysed the morphology, the structure and the chemical properties of the stellar populations of the system in various evolutionary stages. Such a large observational effort allowed us to constraint the different hypothesis on the origin and chemical evolution of this peculiar stellar system.

Key words. Galaxy: globular clusters : ω Cen – Stars: Population II – Stars: evolution

1. Introduction

The stellar system ω Centauri is the most massive and luminous globular cluster of the Milky Way and surely the most peculiar one in terms of structure, internal kinematics and chemical properties. The most astonishing peculiarity of this stellar system is the observed spread in its distribution of heavy elements (Norris et al. 1996). In particular, the metallicity distribution of its stars shows a multimodal behavior with a spread of ~ 1 *dex* i.e. an order of magnitude larger than those observed in Galactic globular clusters. For this reason, ω Cen could not be a "genuine" globular cluster but more likely the remnant of a dwarf galaxy which merged in the past with the Milky Way (Freeman 1993). In this framework, we started a key-project devoted to the study of the origin and evolution of the stellar populations contained in this stellar system (see Ferraro et al. 2003). This project is based on two main research channels: *i)* a multiwavelength photometric survey and *ii)* an extensive spectroscopic campaign performed using large samples of images and spectra collected with the current generation of imagers and spectrographs mounted at the European Southern Observatory (ESO) telescopes and onboard HST. This huge observational effort allowed us to study the properties of stars belonging to different stellar populations of this stellar systems along different evolutionary sequences.

2. Multiple stellar populations

The first result we obtained is based on the analysis of a mosaic of 9 images collected with FORS1@VLT in the BVI passbands (Sollima et al. 2005a). This dataset covers an area of $9' \times 9'$ around the cluster center. This anal-

Send offprint requests to: A. Sollima

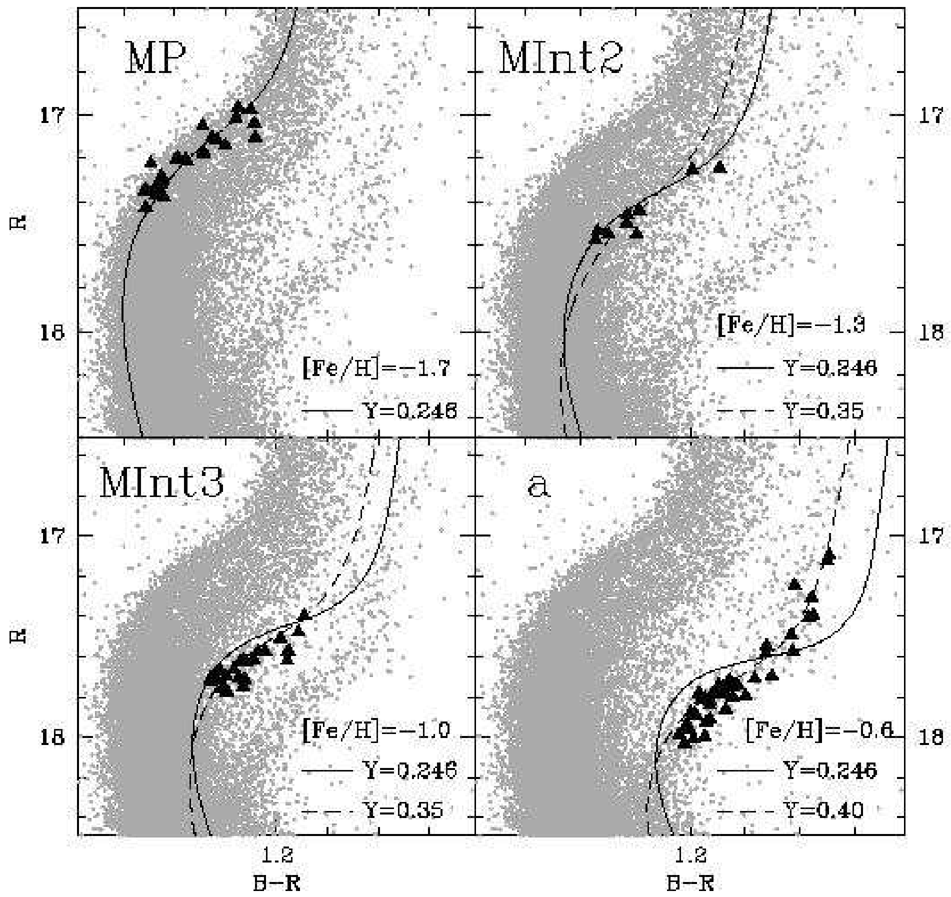

Fig. 1. Isochrone fitting of the four observed SGBs of ω Cen. The spectroscopic target stars belonging to different sub-populations are marked on the CMDs as triangles. Theoretical 16 Gyr old isochrones with appropriate metallicity and helium abundance are overplotted.

ysis allowed us to detect the presence in the color-magnitude diagram (CMD) of ω Cen of five distinct Red Giant Branches (RGBs) corresponding to as many stellar populations with different metallicities.

The same level of complexity has been evidenced in the Sub Giant Branch (SGB) region of the CMD thanks to deep BR ACS@HST observations of the central region of the cluster (Sollima et al. 2005b). In particular, the structure of the SGB of ω Cen is characterized by a number of distinct branches located at different magnitude levels.

The most surprising result concerns the bifurcation of the cluster Main Sequence (MS) discovered by Bedin et al. (2004). In particular, a narrow blue MS (bMS) running parallel to the red dominant cluster MS (rMS) has been evidenced. Spectroscopic studies performed on a sample of bMS stars (Piotto et al. 2005) indicated that these stars have a metallicity significantly higher ($[Fe/H] \sim -1.3$) than that measured in rMS stars ($[Fe/H] \sim -1.7$). This evidence is in contrast with canonical stellar evolution models that predict a redder location of the MS of more metal-rich populations. This evidence suggests that bMS stars could have a significant He overabundance ($\Delta Y \sim 0.15$; Norris 2004) with respect to the dominant cluster population. This last hypothesis poses serious problems regarding the mechanism of chemical enrichment of this stellar system.

3. Relative Ages

The first step we performed to study the chemical evolution of ω Cen has been to constraint the time-scale of its star-formation process. For this purpose, we observed the spectra of a sample of 256 SGB stars located in the CMD of ω Cen along different sub-populations with FLAMES@VLT (Sollima et al. 2006). We measured accurate metallicities for these stars which allowed to derive their relative ages by means of the comparison of their location in the CMD with suitable theoretical isochrones. Fig. 1 shows the isochrone fitting for the observed populations of ω Cen, assuming for each population different helium abundances ranging from the cosmological value Y=0.246 (Salaris et al. 2004) up to Y=0.4 . The main result of this analysis is that all the stellar populations of ω Cen are well represented by coeval isochrones. Interestingly, the assumption of a He enhancement for the metal-rich ($[Fe/H] > -1.3$) populations of ω Cen improve the fit of the overall SGB morphology, still maintaining the derived relative ages unchanged. Summarizing, the entire star formation process in ω Cen seems to be occurred in a short time-scale ($\Delta\ t < 1.5\ Gyr$), regardless of the adopted He abundances.

4. The Helium problem

As outlined above, the assumption of a He gradient among the different populations of ω Cen helps to explain most of the puzzling observational evidences gathered in the past (i.e. bMS, Extreme Horizontal Branch stars (EHB), SGB morphology, etc.). In order to investigate the spatial properties of bMS stars we collected a set of deep BR images with FORS1@VLT covering a wide area from 6' to 26' from the cluster center (Sollima et al. 2007). We calculated the ratio of bMS to rMS stars at different distances from the cluster center up to about an half of the cluster tidal radius. We found that bMS stars are more concentrated of a factor of two in the inner 12' with respect to rMS stars. This evidence indicates that the chemical mechanism that produced the possibly He-enriched stars worked more efficiently in the innermost region of the cluster.

In this context, another important result concerns the RR Lyrae population of ω Cen. Indeed, if all the metal-rich populations of ω Cen have a significant He overabundance, they would not produce a sizable number of RR Lyrae variables. In fact, He-rich stars would reach larger effective temperatures ($T_{\rm eff}> 20,000K$) than He-normal stars during their He-burning stage, failing to penetrate into the instability strip. This is a consequence of the faster evolution induced by the increase of the He abundance that leads He-rich stars to reach the tip of the RGB with lower envelope masses. To investigate this issue, we obtained a set of high-resolution spectra for a sample of 74 RR Lyrae stars of ω Cen with FLAMES@VLT. We revealed the presence of a significant group of sub-luminous metal-intermediate ($[Fe/H] \sim -1.2$) RR Lyrae whose location in the CMD is not compatible with any He overabundance. This result complicates the puzzle since suggest the presence of two different populations in ω Cen with similar metallicities ($[Fe/H] \sim -1.3$) but very different He abundances: *i)* a population of He-enriched stars which produces the bMS and the significant population of EHB stars and *ii)* a population which has the cosmological He abundance and produces the observed population of sub-luminous RR Lyrae.

5. Conclusions

Thanks to the large photometric and spectroscopic datasets collected in the last five years we derived the chemical properties of the dif-

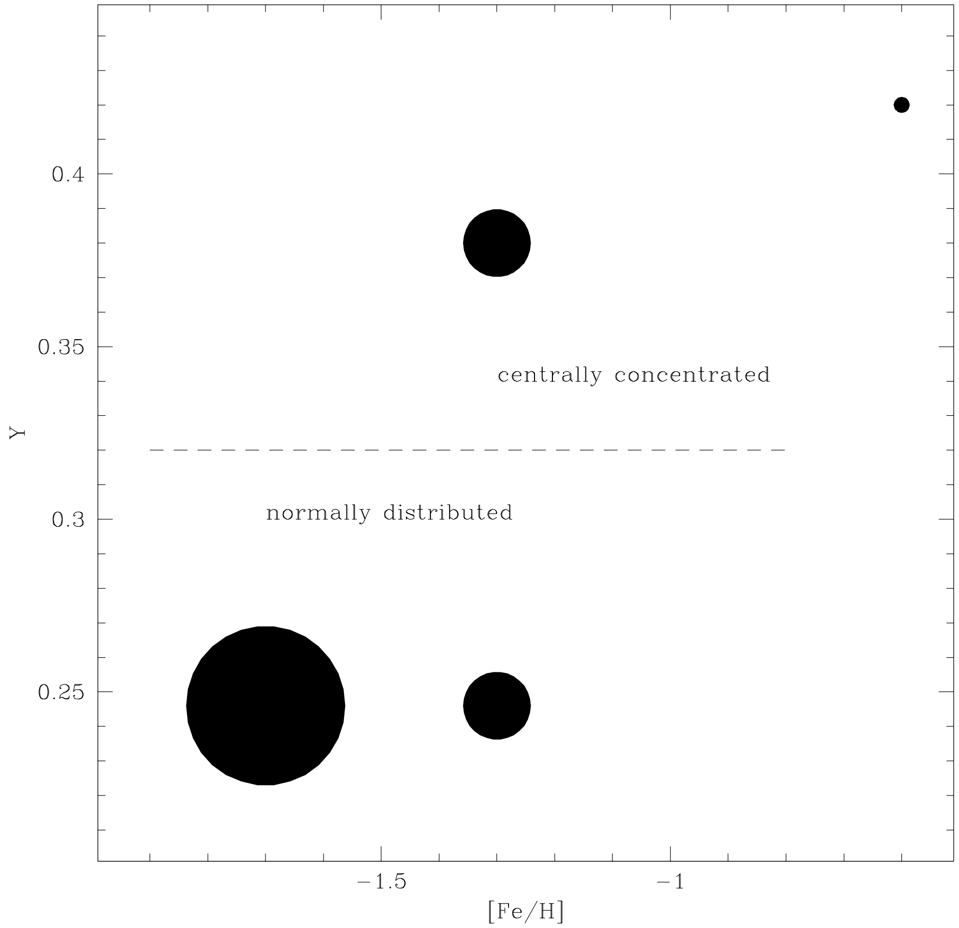

Fig. 2. Iron ([Fe/H]) versus helium (Y) abundance plot for the different stellar populations of ω Cen. The dimension of the dots indicate the size of the population.

ferent stellar population present in the giant stellar system ω Cen and posed firm constraints to its star formation time-scale.

Summarizing, the entire population mix of ω Cen is composed by:

- a main metal-poor population ($[Fe/H] \sim -1.7$) with a cosmological He abundance and which comprise $\sim$ 50% of the entire cluster population;
- a metal-intermediate population ($[Fe/H] \sim -1.3$) with a cosmological He abundance which produces the observed population of sub-luminous RR Lyrae;
- a metal-intermediate population ($[Fe/H] \sim -1.3$) with a significant He overabundance ($\Delta Y \sim 0.15$) which produces the bMS. This population contains $\sim$ 30% of the cluster stars and is more centrally concentrated than the other cluster populations;
- a metal-rich population ($[Fe/H] \sim -0.6$) which contains $\sim$ 5% of the cluster stellar content. Weak evidences (mainly based on

its SGB morphology) suggest that it could have a large He abundance ($Y > 0.4$). Also this population has been found to be more concentrated toward the innermost region of the cluster than the dominant cluster population (Pancino et al. 2003).

In Fig. 2 the four populations of ω Cen described above are represented in a [Fe/H] vs Y plane. As can be noted, the chemical evolution of ω Cen appears to be bifurcated in this plane. In particular we can distinguish: *i)* a branch that follows the canonical chemical evolution, forming metal-enriched populations without modifying the He abundance and *ii)* a branch characterized by a steep gradient in He abundance as a function of the metallicity ($\Delta Y/\Delta Z >> 100$). The most important result in this regard is that this behavior has a strong dependence on the radial distance from the cluster center. This evidence indicates that the chemical evolution of ω Cen proceeded in a inhomogeneous way, favoring the formation of He-rich populations mainly in the central part of the system.

In the last three years a number of hypotheses have been put forward to explain the large He overabundance proposed for the bMS (Norris 2004; Piotto et al. 2005; Maeder & Meynet 2006; Bekki & Norris 2006; Chuzhoy 2006; Tsujimoto et al. 2007; Choi & Yi 2007). However, none of them is able to explain all the observational evidences gathered in the past. Note however that large uncertainties are still involved in the interpretation of the chemical evolution of ω Cen mainly due to: *i)* uncertainties in the stellar yields (in particular for AGB stars) and *ii)* the lack of a rigorous treatment of the inhomogeneous chemical evolution. This last task is complicated by the interaction between ω Cen and the Milky Way. In fact, if we accept the hypothesis that ω Cen is the relic of a dwarf galaxy partially disrupted by the tidal field of the Milky Way, then most of its initial mass (and almost all of its gas content) have been stripped during the last Gyrs of its evolution (Tsuchiya et al. 2003).

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