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The blue hook: a keystone in understanding globular cluster evolution

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Abstract. The study of globular cluster evolution has many aspects yet to be fully understood. One of them is the coupling between the dynamical properties and the physical evolution of the stellar populations forming a single cluster. Here I will present a new model to explain both the anomalous extension and the large number of stars populating the blue hook locus in Omega Centauri. The key ingredients in this new explanation is the connection between the early dynamical properties of the second generation stars and their rotational velocity.

Key words. stars: Horizontal Branch; stars: low-mass; Globular Clusters: individual (ω Centauri)

1. Introduction

Globular Clusters (hereinafter GCs) are well known to host multiple populations of stars, whose components show variations in light elements and helium content. Indeed, a recent Hubble space telescope (HST) survey (Piotto et al. 2015), combining both optical and UV bands data, has highlighted the fact that almost all of the known GCs hosts two or even more stellar populations.

If we look at the Main Sequence (MS) or the Red Giant Branch (RGB) of these objects, the differences between the multiple populations in a GC are usually photometrically hidden, when studying the cluster in traditional optical bands. On the other hand, these same difference emerge strikingly in the morphology of the Horizontal Branch (HB), even in the traditional optical bands. Indeed, being the HB stars the direct result of the Helium flash at the tip of the RGB they are directly affected by the value of the evolving mass in the cluster which is strongly dependant on the mean chemistry of the population (most notably helium) and the age of the cluster (D'Antona et al. 2002).

Among the object currently categorized as GC, ω Centauri is the most complex example. Its dynamical and chemical properties led researchers to consider it the surviving nucleus of an ancient dwarf galaxy (see e.g. Gnedin et al. 2002; Bekki & Norris 2006; Bellazzini et al. 2008; Marconi et al. 2014). Nevertheless, its show signatures which resemble those of standard GCs. In fact, while the cluster stars can be subdivided into groups of different metallicity (Johnson & Pilachowski 2010; Marino et al. 2011; Villanova et al. 2014), inside each of these groups light elements abundances show variations as in mono–metallic clusters, making not trivial to understand the system evolution.

From the photometric point of view, ω Centauri shows one of the most complex colour-magnitude digram (CMD) known

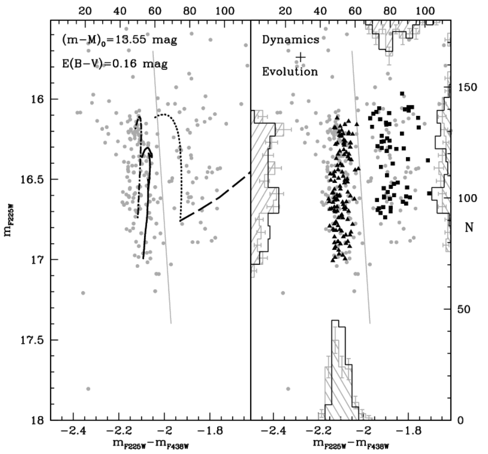

Fig. 1. tLeft panel: A magnified view of the BHK of ω Centauri in the F225W and F438W CMD. In the figure are also plotted some notable loci and models. The dashed line is the ZAHB locus corresponding to a mixture with Z = 0.005 and Y = 0.37. The dotted line is the last canonical HB model. The two models plotted as a solid and a dot-dashed lines are two LFM models. The lower track is a model obtained from the non rotating case, whereas the higher one is a fast rotating one. (see text for the details) *Right panel:* The results of the simulation obtained with this new model. In the figure the comparison of the simulation (black, filled triangles and squares) and the data is shown via the comparison of the histograms in the figure.

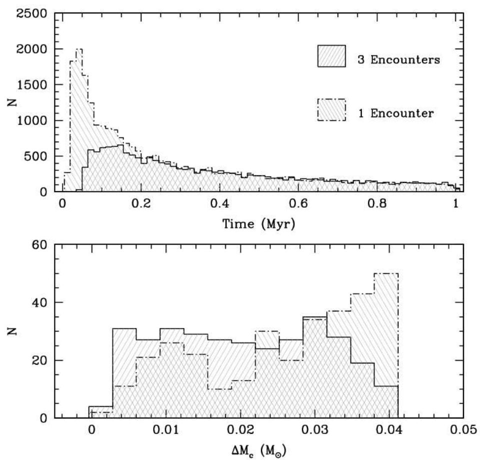

Fig. 2. Upper panel: Two histograms showing the frequency of the disk disruption events in the model. The solid line describe the case where we assume that three encounters are needed to destroy the disk whereas the dash-dotted line is for the case where just one encounter is enough. *Lower panel:* The histograms show the distribution of the core mass increase following the recipe describe in the model. As in the upper panel the solid line is for the three encounters case and the dot-dashed is for the single encounter one.

(Anderson & van der Marel 2010; Bellini et al. 2010). Its large variety of stellar populations shows itself through the presence of multiple MS and Sub-Giant Branches (SGB) that are quite evident even in the traditional optical bands. In addition, it shows a very extended HB which shows interesting feature along its entire length.

2. The blue hook of ω Centauri

Almost unique among the GCs, ω Centauri shows a very peculiar population of stars located at the end of the HB, forming the hook-like locus of its blue tail. This blue hook (hereinafter BHK) is a feature that few other GCs show; indeed other examples are found in the most massive ones: such as NGC2149 (Di Criscienzo et al. 2015), NGC2808 (Brown et al. 2001) and few others.

Looking at the CMDs of ω Centauri described in Anderson & van der Marel (2010) and in the more recent ones in Bellini et al. (2010, 2013) we can see that the BHK hosts almost the 30% of the total HB stars, and similar percentages have been observed in the other GC that host a BHK (e.g. 2419 Di Criscienzo et al. 2015). The peculiarities of this group of stars do not end with their shape and number. From this point of view the case of ω Centauri is unique for its relatively close distance has allowed a spectroscopic analysis of those faint stars to be conducted. The results of those observations describe features that are difficult to describe with canonical HB evolution. Latour et al. (2014) showed that the observed temperatures of these stars are sensibly higher than the ones located in the blue HB of ω Centauri.

As a further complication the two sides of this locus show different temperatures as well, with the blue part showing higher temperatures than the red one. Latour et al. (2014) also observed that the surface chemistry of this stars is also peculiar. Indeed the observations showed that the blue side of the BHK hosts stars both carbon and helium rich while the stars populating the red part are not.

The features observed in the BHK of ω Centauri strongly suggest that the phenomenon of the late helium flash mixing (LFM) is responsible for the production of these stars (Brown et al. 2001, 2010). Indeed, the stars originating from such a process will be helium and carbon rich, hotter and slightly fainter than his non mixed counterparts. Miller Bertolami et al. (2008) showed that in the metallicity range observed in GCs the occurrence of the LFM is a very rare phenomenon (with a possible range of mass $\leq 0.01 M_{\odot}$), thus a companion mechanism is needed to be able to populate the observed locus in such large numbers. Moreover, a single LFM of second generation star (i.e. helium rich) is not able to completely reproduce the entire length of the observed BHK, as shown in Fig. 1. Thus, a dedicated scenario, compatible with the current formation theories for the multiple populations in GCs, which is also able to enhance the occurrence of LFM, has to be constructed.

Indeed a number of different scenarios have been proposed to describe the feature. Cassisi et al. (2009) suggested that the BHK stars originated from both the first generation and the helium enhanced populations; Lei et al. (2015) on the other hand suggested that these stars live in binary systems and that the enhanced wind favoured the occurrence of the LFM; D'Antona et al. (2010) suggested instead that the BHK originated from deep mixing occurred during the star ascent of the RGB, thus not involving the LFM. All these scenarios have some problems in the description of the observed feature (Tailo et al. 2015). A new kind of model for these kind of stars is thus required.

2.1. A dynamical model for the Blue Hook

Here we suggest that the stars populating the BHK are the progeny of those stars that have undergone the LFM process after having acquired high rotational velocity in their early pre-main sequence (PMS) phases. PMS stars (T Tauri like object) are fast rotators that quickly lose their angular momentum via the magnetic coupling with their accretion disk (Armitage & Clarke 1996). If the connection with the disk is severed during these early stages by the dynamical interaction occurring in the formation environment, the star will be able to maintain its rotational velocity. Stars originating from this process have higher core mass than the standard, non rotational, ones, resulting in a brighter model, thus providing a way to cover the observed magnitude range (Tailo et al. 2015).

Our starting point in building this scenario is an N-body model of the cluster. We are following the orbits of 50'000 particles distributed according a King's profile, with a concentration (c) of 1.7, meant to represent the denser environment where the second generation stars formed. The two histograms in the upper panel in Fig. 2 tracks the frequency of the disk disruption events in the assumption that one or three encounters are required to interrupt the magnetic braking. In the following paragraphs we will assume that the number of interaction required to break the disk is three. If we combine this result with the T Tauri inertia momentum evolution and a relation connecting the rotational velocity with the core mass increase (Tailo et al. 2015) we obtain the distribution of core mass increase described in the lower panel of Fig. 2. In order to compare the different position of a non rotational LFM model with a rotational one, we over plot the model corresponding to an increase of $0.04 M_{\odot}$ in the left panel of Fig. 1. It is clear how a model with this core mass enhancement is able to reproduce the entire length of the observed locus.

The right panel of Fig. 1 represents the results of a stellar population synthesis realized using this dynamical model as a base. Globally the simulation has been realized following the classical recipes described in D'Antona et al. (2002). The mass loss needed to reach the BHK region is 0.19 $M_{\odot}$, 0.04 $M_{\odot}$ higher than the one needed to describe the red part of the HB (Tailo et al. 2016). The blue part of the BHK in Fig. 1 has been realized using the rotational LFM models (triangles) while the red side of the BHK, slow rotating, has been obtained from standard HB models. The four histograms in the panel compare the colour and magnitude distribution of the stars in the data (shaded grey) and in the simulation (black). The agreement between the simulation and the data is remarkably good.

3. Conclusion

We have described a new kind of model for the BHK stars in ω Centauri. This new model involve coupling of the early dynamical evolution with the physical evolution of LFM models. The agreement reached between the simulations and the data is remarkably good. It is worth noting that the possible enhanced rotation rate necessary to this model to work may also implies an enhanced mass loss during the ascent of the RGB. The necessity of enhanced mass loss to describe the complete HB of various GC, found also in NGC2419 (Di Criscienzo et al. 2015) and in Fornax dSph galaxy GCs (D'Antona et al. 2013), may be another signature of a strong connection between the early dynamical history of the second generation stars and their physical evolution.

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