SPINNING LIKE A BLUE STRAGGLER: THE POPULATION OF FAST ROTATING BLUE STRAGGLER STARS IN ω CENTAURI

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ABSTRACT

By using high-resolution spectra acquired with FLAMES-GIRAFFE at the ESO/VLT, we measured the radial and rotational velocities for 110 blue straggler stars (BSSs) in ω Centauri, the globular cluster-like stellar system harboring the largest known BSS population. According to their radial velocities, 109 BSSs are members of the system. The rotational velocity distribution is very broad, with the bulk of BSSs spinning at less than ∼40 km s⁻¹ (in agreement with the majority of such stars observed in other globular clusters) and a long tail reaching ∼200 km s⁻¹. About 40% of the sample has vₚ sin i > 40 km s⁻¹ and about 20% has vₚ sin i > 70 km s⁻¹. Such a large fraction is very similar to the percentage of fast rotating BSSs observed in M4. Thus, ω Centauri is the second stellar cluster, beyond M4, with a surprisingly high population of fast spinning BSSs. We found a hint of radial behavior for a fraction of fast rotating BSSs, with a mild peak within one core radius, and a possible rise in the external regions (beyond four core radii). This may suggest that recent formation episodes of mass transfer BSSs occurred preferentially in the outskirts of ω Centauri, or that braking mechanisms able to slow down these stars are least efficient in the lowest density environments.

Key words: blue stragglers – globular clusters: individual (NGC 5139) – techniques: spectroscopic

Online-only material: color figure, machine-readable table

1. INTRODUCTION

Blue straggler stars (BSSs) are now firmly established as an “anomalous” class of stars populating any stellar environment, ranging from open star clusters (Johnson & Sandage 1955; Mathieu & Geller 2009) to globular clusters (Sandage 1953; Ferraro et al. 1992, 2003; Piotto et al. 2004; Leigh et al. 2007), the Galactic field (Preston & Sneden 2000), and dwarf spheroidal galaxies (Momany et al. 2007; Mapelli et al. 2009).

In optical color–magnitude diagrams (CMDs), BSSs appear as objects brighter and bluer (hotter) than the normal turnoff (TO) stars, lying along an extension of the main sequence (MS). Their position in the CMD (Ferraro et al. 2006a; Lanzoni et al. 2007c), and direct spectroscopic and pulsation measurements (Shara et al. 1997; De Marco et al. 2005; Gilliland et al. 1998; Fiorentino et al. 2014), have shown that BSSs are more massive than normal TO stars. Two main scenarios have been proposed for their formation: direct stellar collisions (COL-BSSs; Hills & Day 1976) and mass transfer activity between binary companions (MT-BSSs; McCrea 1964), either due to stellar evolution or triggered by stellar interactions, possibly up to the complete coalescence of the two objects. The two mechanisms can possibly occur simultaneously in dense stellar systems, like globular clusters (GCs; Ferraro et al. 1993, 1997, 2009a; Dalessandro et al. 2013). Hence, these objects are not only tangible proof of the (mild or violent) interactions occurring between stars in GCs, but they also offer us the opportunity to investigate the internal dynamics of stellar systems (Ferraro et al. 2001; Mapelli et al. 2004, 2006; Lanzoni et al. 2007a, 2007b; Dalessandro et al. 2008a; Sabbi et al. 2004; Beccari et al. 2006). In this respect, one of the most recent exciting results has been obtained by Ferraro et al. (2012), who demonstrated that the BSS radial distribution can be used as a clock to measure the parent cluster dynamical age.

Despite their importance, many issues concerning BSS formation and properties are still open. In particular, one of the most challenging problems is the identification of observable features able to discriminate between the two formation channels. Negligible mixing between the inner cores and the outer envelopes is predicted for COL-BSSs (Lombardi et al. 1995) that should show normal C and O abundances. Conversely, MT-BSSs are expected to show C and O depletion on their surface (Sarna & De Greve 1996), because the material should come from the inner regions of the donor star where the CNO-cycle occurred. Indeed, this chemical signature has been observed in a sub-sample of BSSs in 47 Tuc (Ferraro et al. 2006a) and M30 (Lovisi et al. 2013a). Another interesting measurable BSS characteristic is the projected rotational velocity, vₚ sin i. Unfortunately, in this case, the theoretical interpretative scenario is significantly more complex since both MT- and COL-BSSs are expected to rotate fast (Sarna & De Greve 1996; Benz & Hills 1987), but braking mechanisms are suggested to occur and slow down the stars with timescales and efficiencies that are still unknown (Leonard & Livio 1995; Sills et al. 2005).

From the observational point of view, most of the BSSs appear to be slow rotators (with rotation velocities lower than 40 km s⁻¹) in all of the GCs studied so far by our group, namely, 47 Tuc (Ferraro et al. 2006a), NGC 6397 (Lovisi et al. 2010), M30 (Lovisi et al. 2013b), and NGC 6752 (Lovisi et al. 2013a). Even though the range of rotational velocities is larger than that spanned by normal MS stars in GCs (see, e.g., Lucatello & Gratton 2003), it is still compatible with that of the fastest rotating stars in “normal” evolutionary sequences in GCs, namely, horizontal branch stars redder than the Grundahl jump (Grundahl et al. 1999) with 8000 K < T_eff < 12,000 K (see Peterson et al. 1995; Behr et al. 2000a, 2000b). Nevertheless, some outliers have been found in 47 Tuc, M30, and NGC 6397.
(but not in NGC 6752): one BSS per cluster shows very high rotation, up to more than 90 km s\(^{-1}\). However, the most surprising result has been found for M4: out of the 20 BSSs investigated in this GC, Lovisi et al. (2010) identified 8 fast-rotating (FR) BSSs (with \(v_\times \sin i > 40\) km s\(^{-1}\)), corresponding to 40\% of the studied sample. Indeed, this is the largest percentage of FR BSSs ever found in any GC.

Here, we present the results obtained for a sample of BSSs in the stellar system \(\omega\) Centauri. All the evidence collected so far (Lee et al. 1999; Pancino et al. 2000; Ferraro et al. 2004; Norris & Da Costa 1995; Sollima et al. 2005; Origlia et al. 2003; Johnson & Pilachowski 2010) suggests that \(\omega\) Centauri is not a genuine GC, but possibly the remnant core of a tidally disrupted dwarf galaxy (see, e.g., Dinescu et al. 1999; Majewski et al. 2000; Bekki & Norris 2006). This stellar system hosts the richest BSS population observed so far in a GC, with more than 300 candidates (Ferraro et al. 2006b). Its normalized BSS radial distribution is flat, suggesting that the system is not dynamically relaxed, yet (Ferraro et al. 2012) note that a similar distribution has been found in only two other stellar systems: NGC 2419 (Dalessandro et al. 2008b) and Pal 14 (Beccari et al. 2011). This means that mass segregation did not yet have enough time to be effective and stellar interactions are very infrequent. For these reasons, the BSS population of \(\omega\) Centauri is thought to have mainly formed through MT activity in primordial binary systems (Ferraro et al. 2006b). This makes \(\omega\) Centauri the ideal stellar system for investigating the properties of MT-BSSs.

Recently, Simunovic & Puzia (2014, hereafter SP14) measured rotational velocities for 49 BSSs in \(\omega\) Centauri by using medium-resolution spectra (\(R \sim 10,000\)) taken with the Inamori Magellan Areal Camera and Spectrograph (IMACS) multimode facility at the Baade Megellan telescope. They found a quite large distribution of \(v_\times \sin i\), peaked around \(20–30\) km s\(^{-1}\) and reaching about \(170\) km s\(^{-1}\). One of the most intriguing results of their work is a hint that the FR BSSs are more centrally concentrated with respect to slower BSSs. Moreover, a trend between rotational velocity and color (and hence temperature) has been treated with respect to slower BSSs. Moreover, a trend between rotational velocity and color (and hence temperature) has been claimed. Based on these results, the authors suggested that the FR BSSs formed preferentially in the central regions and are also more massive than slow rotators.

As part of a systematic spectroscopic campaign aimed at studying the chemical and kinematical properties of BSSs in GCs (see previous results in Ferraro et al. 2006a; Lovisi et al. 2010, 2013a, 2013b), in this paper we present and discuss the rotation velocity distribution of 110 candidate BSSs in \(\omega\) Centauri.

The paper is organized as follows. Section 2 describes the observations, followed in Section 3 by the derivation of the atmospheric parameters. The measurements of radial and rotational velocities are discussed in Sections 4 and 5, respectively. Section 6 discusses the comparison between our results and those of SP14. Finally, Section 7 presents the discussion of the results and our conclusions.

2. OBSERVATIONS

The spectroscopic data set analyzed in this paper includes two samples of high-resolution spectra acquired with the multi-object spectrograph FLAMES-GIRAFFE (Pasquini et al. 2002)

\[3\] Note that only another GC-like stellar system with a similarly large metallicity spread has been found in the Galaxy: Terzan 5 in the Galactic Bulge (Ferraro et al. 2009b; Origlia et al. 2011, 2013).

\[4\] http://www.eso.org/sci/software/pipelines/
flat-fielding, wavelength calibration, and spectral extraction. For each grating, the wavelength contribution has been removed from each individual exposure by using a master-sky spectrum obtained as the median of all the sky spectra. Finally, for any given star the sky-subtracted spectra (corrected for radial velocity, RV; see Section 4) have been coadded together.

3. ATMOSPHERIC PARAMETERS AND SYNTHETIC SPECTRA

Atmospheric parameters (effective temperature and surface gravity) for our targets have been derived photometrically by orthogonally projecting the stellar position in the CMDs onto a set of theoretical isochrones with different ages (from 100 Myr to 5 Gyr) that are able to cover the entire extension of the BSS sequence in the CMD. In particular, we used isochrones from the Padova database (Bressan et al. 2012) with a metallicity of $Z = 0.0006$ and $\alpha$-enhanced chemical mixture (corresponding to $[\text{M/H}] \sim -1.5$ dex), and we assumed a distance modulus of $(m-M)_0 = 13.7$ mag and a color excess of $E(B-V) = 0.11$ mag (Ferraro et al. 2006b), suitable to best fit the old, metal-poor ([Fe/H] $\sim -1.5$ dex; see, e.g., Johnson & Pilachowski 2010) component of $\omega$ Centauri with a 13 Gyr isochrone. A microturbulent velocity of 0 km s$^{-1}$ is adopted for all of the targets because of the shallow convective (or fully radiative) envelopes expected for these stars (note that different assumptions for the microturbulent velocity have no impact on the determination of RVs and $v_\sin i$).

In order to measure RVs and $v_\sin i$ we made extensive use of synthetic spectra computed with the code SYNTHE (Sbordone et al. 2004; Kurucz 2005), adopting the last version of the Kurucz/Castelli linelist for atomic and molecular transitions. The line-blanketed model atmospheres have been computed with the code ATLAS9 (Castelli & Kurucz 2004) under the assumptions of Local Thermodynamic Equilibrium for all the species, one-dimensional, plane-parallel geometry, and without the inclusion of approximate overshooting in the flux computation. For each star, an ATLAS9 model atmosphere has been generated, adopting the appropriate stellar parameters of the target and assuming a metallicity $[\text{M/H}] = -1.5$ dex.

The synthetic spectra have been convolved with a Gaussian profile to reproduce the instrumental broadening of the different setups. The broadening for a given setup has been estimated by measuring the FWHM of bright, unsaturated lines in the reference Th-Ar calibration lamp (following the procedure adopted by Behr et al. 2000a). Finally, rotational velocities have been taken into account by convolving the synthetic spectra with a rotational profile (Kurucz 2005).

4. RADIAL VELOCITIES

RVs have been measured through the Fourier cross-correlation technique as implemented in the IRAF task fxcor (Tonry & Davis 1979). For each star, we used a synthetic spectrum computed with the appropriate stellar parameters. All of the templates have been computed by assuming $[\text{M/H}] = -1.5$ dex: note that the assumption of higher metallicities according to the broad metallicity distribution of $\omega$ Centauri is not a critical issue and does not affect the measure of RV.

For the targets observed with HR5A, RVs have been derived mainly from the Mg $\text{ii}$ triplet at 4480 Å (visible in almost all of the spectra observed with this grating) and other transitions when available. For the HR4, HR14A, and HR15N setups, we instead used the Balmer lines. RVs for the stars observed with the HR2 setup have been obtained from the photospheric Ca $\text{ii}$ K line. We made sure to exclude from the cross-correlation process the Ca $\text{ii}$ K interstellar line visible at $\sim -27$ km s$^{-1}$ (van Loon et al. 2009) that is associated with gas a few kiloparsecs distant along the line of sight of $\omega$ Centauri and which could produce a mismatch in the identification of the main peak of the cross-correlation function.

Multiple RV measurements are available for 74 targets. We carefully verified that the values obtained from different gratings and in different epochs are consistent with each other. By excluding 17 BSSs that show hints of RV variations larger than the estimated uncertainties (which typically are smaller than 1 km s$^{-1}$), we find average differences that are always smaller than 1 km s$^{-1}$ between two different gratings, and smaller that 1–2 km s$^{-1}$ between two epochs. In particular, we found an average difference between data set 1 and data set 2 of $-0.3 \pm 0.6$ km s$^{-1}$ ($\sigma = 1.7$ km s$^{-1}$), thus guaranteeing a proper internal accuracy for our measurements. By cross-correlating the target list with the catalog of variable stars identified by Kaluzny et al. (2004) and Olech et al. (2005), we find 27 SX Phe, 6 W UMa, 2 detached eclipsing binaries, 1 candidate ellipsoidal variable, and 1 variable star with a period of $\sim 3.3$ days, but with no classification. Out of the 17 BSSs with hints of RV variations, 3 are classified as SX Phe and 3 as W UMa by Kaluzny et al. (2004) and Olech et al. (2005), while the remaining 11 do not show photometric variability. These findings demonstrate that our data set is not suitable for studies of RV variability and the search for binary systems. We therefore limit ourselves to indicate (when available) the variable type in Table 1, together with the identification name in the catalogs of Kaluzny et al. (2004) and Olech et al. (2005). For the targets with multiple measurements, we finally adopted the average value of RV, assuming as an uncertainty the dispersion of the mean normalized to the rms of the number of available measures.
Our sample includes 109 BSS members of the cluster, providing a mean RV of $233.2 \pm 1.4$ km s$^{-1}$ ($\sigma = 14.7$ km s$^{-1}$). Their coordinates, atmospheric parameters, and RVs are listed in Table 1. All but one of the observed targets have RVs between $\sim 191$ and $\sim 266$ km s$^{-1}$, in good agreement with the systemic RV of $\omega$ Centauri, peaked at [RV] = 233 km s$^{-1}$ (Sollima et al. 2009, but see also Mayor et al. 1997; Pancino et al. 2007; Monaco et al. 2010). Only one star belongs to the field: it has RV = 0.5 km s$^{-1}$, compatible with that observed (see Figure 7 in Sollima et al. 2009) and expected (see the Galactic model of Robin et al. 2003) for the thin and thick disc stars in the direction of $\omega$ Centauri.

5. ROTATIONAL VELOCITIES

Projected rotational velocities have been measured by performing a $\chi^2$ minimization between the observed spectra and a grid of synthetic spectra calculated with the atmospheric parameters of each program star and different values of $v_\text{sin} i$. Note that since abundance variations mainly affect the line core while rotation alters the entire line profile, a correct fit of the entire line profile also requires knowledge of the chemical abundances to properly reproduce the line depth. Thus, we used an iterative procedure to simultaneously measure abundance and $v_\text{sin} i$, and to provide a reliable fit of the entire line profile. Note that for all the stars, we assumed a global metallicity of [M/H] = $-1.0$ and $-0.5$ dex (according to the broad metallicity distribution of $\omega$ Centauri; see Johnson & Pilachowski 2010). We found variations of $v_\text{sin} i$ of about 0–1 km s$^{-1}$.

For stars in data set 1, we measured $v_\text{sin} i$ from several different spectral lines (typically 5–10, depending on the signal-to-noise ratio), in order to obtain independent measures. Then, the average value is assumed as a final measure. For stars in data set 2, RVs have been measured from the Ca ii K line. This feature is a robust diagnostic for BSS rotational velocities, because it is strong enough to be observable also in case of very high rotational velocity (meanwhile weaker features, such as those used for the spectra of data set 1, can be unobservable for $v_\text{sin} i > 100$ km s$^{-1}$). Moreover, its strength decreases when the surface temperature increases, making it easier to disentangle the contribution of the rotational velocity from the intrinsic line profile. However, among the coldest stars (where the intrinsic width of the Ca ii K line can make the measurement of the low $v_\text{sin} i$ more uncertain), other transitions are detectable and have been used to confirm the derived values of $v_\text{sin} i$. As discussed above, the interstellar Ca ii K line has been masked in order to not affect the fitting procedure of the photospheric line. Figure 3 shows examples of a few spectra in the Ca ii K line.
The average difference between data set 1 (von Zeipel 1924), usually expressed by a power law, rotating stars that are affected by the so-called gravity darkening with the star latitude. This is not totally true for very rapidly −line, shifted by about with low and high rotational velocities. The interstellar Ca

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than the poles (see also Espinosa Lara & Rieutord 2011). This effect should lead to an underestimate of such a difference (consistent with zero km s\(^{-1}\)) for the entire BSS sample, with the lower limits for the five BSSs also shown with arrows. The distribution turns out to be very broad, with a main peak at low velocities (5–20 km s\(^{-1}\)) and a long tail toward high \(v_\text{r} \sin i\) values (reaching \(\sim 200\) km s\(^{-1}\)). Note that such large values are unusual and unexpected for normal GC stars where the highest rotational velocities only reach values of \(\sim 40–50\) km s\(^{-1}\) and are observed among Horizontal Branch stars hotter than the instability strip and colder than the \textit{Grundahl Jump} (see, e.g., Behr et al. 2000a, 2000b; Lovisi et al. 2013b). Thus, BSSs populating the tail of the distribution certainly are the most FR stars observed in GCs. Instead, among the MS field stars, the rotational velocity is a function of the temperature (Cortés et al. 2009) with \(v_\text{r} \sin i\) values varying between \(\sim 10\) km s\(^{-1}\) for stars colder than \(\sim 9000\) K. Meanwhile, the \(v_\text{r} \sin i\) distribution covers a broad range, up to values larger than \(200\) km s\(^{-1}\) for hotter stars; note that the most rapidly rotating star discovered so far (namely, VFTS102 in 30 Doradus; Dufton et al. 2011) is an O-type star with a projected rotational velocity larger than \(\sim 500\) km s\(^{-1}\).

Figure 4 shows the distribution of \(v_\text{r} \sin i\) for the entire BSS sample, with lower limits for the five BSSs also shown with arrows. The distribution turns out to be very broad, with a main peak at low velocities (5–20 km s\(^{-1}\)) and a long tail toward high \(v_\text{r} \sin i\) values (reaching \(\sim 200\) km s\(^{-1}\)). Note that such large values are unusual and unexpected for normal GC stars where the highest rotational velocities only reach values of \(\sim 40–50\) km s\(^{-1}\) and are observed among Horizontal Branch stars hotter than the instability strip and colder than the Grundahl Jump (see, e.g., Behr et al. 2000a, 2000b; Lovisi et al. 2013b). Thus, BSSs populating the tail of the distribution certainly are the most FR stars observed in GCs. Instead, among the MS field stars, the rotational velocity is a function of the temperature (Cortés et al. 2009) with \(v_\text{r} \sin i\) values varying between \(\sim 10\) km s\(^{-1}\) for stars colder than \(\sim 9000\) K. Meanwhile, the \(v_\text{r} \sin i\) distribution covers a broad range, up to values larger than \(200\) km s\(^{-1}\) for hotter stars; note that the most rapidly rotating star discovered so far (namely, VFTS102 in 30 Doradus; Dufton et al. 2011) is an O-type star with a projected rotational velocity larger than \(\sim 500\) km s\(^{-1}\).

As quoted above, 17 stars have been found in common between the two data sets. A comparison of the two independent data sets 1 and 2 turns out to be quite small, \(\Delta v_\text{r} = (v_\text{r} \sin i)_1 - (v_\text{r} \sin i)_2 = -0.6 \pm 1.7\) km s\(^{-1}\) (1σ ∼ 6.7 km s\(^{-1}\)). Such a difference (consistent with zero km s\(^{-1}\)) guarantees that there is no systematic effect present in our analysis and its small rms uncertainty can be adopted as an estimate of the internal accuracy of our measurements. For stars for which two measurements of \(v_\text{r} \sin i\) are available, we assumed the mean rotational velocity. For two stars in common between the two data sets for which only lower limits are derived from the spectra of data set 1, we assumed the value obtained from data set 2. Finally, five stars available only in data set 1 show featureless spectra for the HR5 grating, and hence only lower limits can be derived by comparison between the observed and synthetic spectra. Finally, the external accuracy of our measures is demonstrated by the good agreement with the independent results of SP14 for 13 targets in common between the two data sets (see Section 6), and by the values we obtained for a sample of 24 sub-giant branch stars observed during the same runs discussed here (they are all consistent with zero km s\(^{-1}\), in agreement with the typical rotational velocity of stars in this evolutionary phase).

It is important to specify that the values of \(v_\text{r} \sin i\) are derived by assuming that the stellar atmospheric parameters do not vary with the star latitude. This is not totally true for very rapidly rotating stars that are affected by the so-called gravity darkening (von Zeipel 1924), usually expressed by a power law, \(T_{\text{eff}} \propto g_{\text{eff}}^\beta\) (with \(\beta < 0.25\)), implying that the equatorial regions are cooler than the poles (see also Espinosa Lara & Rieutord 2011). This effect should lead to an underestimate of \(\sim 10\%–20\%\) of \(v_\text{r} \sin i\) for stars with relevant rotation (>200 km s\(^{-1}\)), such as O- and B-type stars (see Towsend et al. 2004 and Ramirez-Águdelo et al. 2013). Our results do not include corrections for gravity darkening; however, this effect should only marginally affect the observed BSSs (since most of them rotate much more slowly than the OB-type stars), and thus would not modify our conclusions on the \(v_\text{r} \sin i\) distribution.

Uncertainties in the fitting procedure of each individual line have been estimated by resorting to Monte Carlo simulations, creating for some targets (representative in terms of atmospheric parameters and spectral quality) a sample of 1000 synthetic spectra with added Poisson noise and repeating the analysis. The typical uncertainties for slow-rotating stars range from \(\sim 3\) km s\(^{-1}\) up to \(\sim 5\) km s\(^{-1}\) according to the signal-to-noise ratio. For FR stars the uncertainties can reach \(\sim 20\) km s\(^{-1}\), in particular, for BSSs with \(v_\text{r} \sin i\) larger than \(\sim 150\) km s\(^{-1}\). For those stars for which \(v_\text{r} \sin i\) has been derived from different lines, we assumed as the internal uncertainty the dispersion of the mean (weighted on the Monte Carlo uncertainties of each individual line) normalized to the square root of the number of lines. For the stars for which only one line has been used (as the majority of the targets of data set 2), the Monte Carlo uncertainty has been adopted.

Figure 4 provides the rotational velocities of 47 BSSs in omega Centauri measured using IMACS@Magellan spectra (\(R \sim 10,000\)). In their work, the derivation of \(v_\text{r} \sin i\) is based on the penalized pixel fitting of the Gauss-Hermite expansion of the line profile adopting as templates 12 spectra of stars with spectral type similar to that of the target BSSs, acquired with the ELODIE

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### 6. COMPARISON WITH SP14

SP14 provide the rotational velocities of 47 BSSs in omega Centauri measured using IMACS@Magellan spectra (\(R \sim 10,000\)). In their work, the derivation of \(v_\text{r} \sin i\) is based on the penalized pixel fitting of the Gauss-Hermite expansion of the line profile adopting as templates 12 spectra of stars with spectral type similar to that of the target BSSs, acquired with the ELODIE
Figure 5. Behavior of the projected rotational velocity as a function of the effective temperature. Arrows indicate $v_{\text{rot}} \sin i$ lower limits.

Figure 6. Difference between the rotational velocities measured in this work and those of SP14, as a function of our $v_{\text{rot}} \sin i$ for the 14 BSSs in common between the two samples. Errorbars are calculated as the sum in quadrature of the individual uncertainties. Note that the large errorbar of the BSS #111709 is due to the large uncertainty quoted by SP14 ($\sim 60$ km s$^{-1}$). The inset shows the rotational velocity differences as a function of the stellar effective temperature.

The residuals show a quite well-defined trend with large differences (up to $\sim 35$ km s$^{-1}$) for low rotational velocities ($v_{\text{rot}} \sin i < 20$–$30$ km s$^{-1}$) and a substantial agreement at large velocities. This suggests that the differences between the two works are essentially due to the relative low resolution of IMACS (which is about half the FLAMES one). As expected, in fact, at lower resolution it is more difficult to correctly measure small $v_{\text{rot}} \sin i$ because the line profile is dominated by the instrumental broadening.

We investigated in detail the origin of the large difference in the rotational velocity of star #111709 measured in the two studies: $v_{\text{rot}} \sin i = 165$ km s$^{-1}$ in SP14 and $v_{\text{rot}} \sin i = 29$ km s$^{-1}$ in our work. In Figure 7, we show a portion of the spectrum of this star around the Mg II line at 4481 Å with overimposed synthetic spectra calculated with the rotational velocity derived in our analysis (thin solid line) and in SP14 (dashed black line). The comparison clearly demonstrates that the observed profile of the Mg II line cannot be reproduced with the large value of $v_{\text{rot}} \sin i$ quoted by SP14. We attribute such a discrepancy to the different lines used to measure the rotation velocity.

In fact, in the spectral ranges investigated by SP14 and at the relatively low spectral resolution of IMACS, metallic transitions very sensitive to rotation become weak or even disappear in hot stars like BSS #111709 ($T_{\text{eff}} = 10,250$ K), and the only measurable lines are those of the Balmer series. In general, these lines are only marginally sensitive to rotation and suffer from several effects not easily modeled or well constrained. In fact, the detailed inspection of a grid of synthetic spectra computed with fixed atmospheric parameters and different values of $v_{\text{rot}} \sin i$ reveals that the core of the line is the only region of the Balmer profile sensitive to rotation. As an example, in Figure 8, we compare synthetic spectra around the $H_{\gamma}$ and $H_{\beta}$ Balmer lines, calculated by assuming the same atmospheric parameters ($T_{\text{eff}} = 10,000$ K, $\log g = 4.5$) and by varying only the rotational velocity. As is apparent, an increase of $v_{\text{rot}} \sin i$ from
0 km s\(^{-1}\) up to 200 km s\(^{-1}\) produces no effects on the FWHM and the wings of the lines (which are instead very sensitive to \(T_{\text{eff}}/\log g\) variations, as discussed by Fuhrmann et al. 1993). The variations of the core depth are relatively small with respect to the assumed changes of \(v_{\sin i}\), and only a few pixels of the entire line profile can therefore be used. On the other hand, small variations of the atmospheric parameters lead to large variations of the entire line profile. Moreover, since the core of the Balmer lines forms in the most external layers of the photosphere, it can suffer from several effects that are not easy to take into account and that could vary from star to star (e.g., departures from the Local Thermodynamical Equilibrium, stellar winds, chromospheric activity, and convective granulation). All these effects prevent the use of the Balmer lines as solid indicators of rotational activity, and only for a small subset did they also use the spectral regions around the \(H\gamma\) and \(H\beta\) (as is clearly visible in Figure 8).

At the temperature and gravity of BSS #111709, the Balmer lines show very large wings, and metallic feature sensitive to rotations could hardly be measured, especially at moderate spectral resolution. This is the most likely explanation for the large discrepancy found between the value of \(v_{\sin i}\) estimated by SP14 (from the Balmer lines) and the one we obtained from some metallic lines. Because of their lower effective temperatures, such a problem is significantly mitigated for the remaining stars held in common between the two studies (see the inset in Figure 6). We note that for the vast majority of the targets in \(\omega\) Centauri, SP14 measured the rotational velocity from the spectral region around the \(H\gamma\) and \(H\beta\) Balmer lines, and only for a small subset did they also use the spectral regions around the Mg \(\text{II}\) line at 4481 Å and the Mg \(b\) triplet at \(\sim 5180\) Å. Thus, the rotational velocity of the hottest stars could be biased if only Balmer lines were used in the analysis. However, given the general agreement between the two samples (Figure 6), in the next section we also discuss the two data sets together (for the stars held in common, we adopted our FLAMES values because of the higher spectral resolution).

7. DISCUSSION AND CONCLUSIONS

In this work, we presented the rotational velocities of 109 BSSs in \(\omega\) Centauri. This is the largest homogeneous characterization of the rotational properties of the BSS population ever performed in a single stellar system. As shown in Figure 4, the distribution of rotational velocities is peaked at low values (10–30 km s\(^{-1}\)) with a long tail toward larger values. Indeed, the fraction of BSSs populating the tail is considerable. By assuming \(v_{\sin i} = 40\) km s\(^{-1}\) as a reasonable threshold between slow and fast rotators (see also Lovisi et al. 2010), it turns out that 44 BSSs (out of the 109 observed) are FRs. This corresponds to \(\sim\)40\% of the studied sample. Adding the BSSs analyzed in SP14 and not held in common with the FLAMES data set, we obtain a total of 142 BSSs. The rotational velocity distribution of the combined sample is shown in the upper panel of Figure 9. The overall shape corresponds well to that in Figure 4, and the fraction of BSSs spinning faster than 40 km s\(^{-1}\) remains unchanged (59 BSSs are FRs, corresponding to \(\sim\)40\% of the entire sample). However, the distribution of \(v_{\sin i}\) shown in Figure 9 suggests that a higher velocity boundary for separating FRs may be more appropriate. Consistently with SP14, we thus assumed 70 km s\(^{-1}\) as a threshold value, finding that 28 out 142 BSS (20\%) can be labeled as fast spinning BSSs. This is in agreement with the fraction obtained by considering our FLAMES sample alone, and with that quoted by SP14 for their data set. Interestingly enough, the fraction of FR BSSs in M4 (Lovisi et al. 2010; see the lower panel of Figure 9 for a direct comparison) is very similar to that of \(\omega\) Centauri, independent of the adopted boundary (\(\sim\)40\% with \(v_{\sin i} = 40\) km s\(^{-1}\), and \(\sim\)30\% with 70 km s\(^{-1}\)), even though the total size of the sample is considerably smaller (including only 20 stars). Totally different results are obtained for the other GCs investigated so far, namely, 47 Tuc, NGC 6397, M30, and NGC 6752.
Figure 9. Upper panel: rotational velocity distribution for the combined sample of BSSs in ω Centauri (109 stars studied in this work with FLAMES spectroscopy and 33 targets from SP14). Lower panel: rotational velocity distribution for the 20 BSSs studied by Lovisi et al. (2010) in M4. Gray histograms refer to upper limits.

(Ferraro et al. 2006a; Lovisi et al. 2012, 2013a, 2013b, respectively), where the bulk of BSSs have $v \sin i < 30$–40 km s$^{-1}$ and only one star per cluster (if any) has high rotational velocity (larger than $\sim 80$–100 km s$^{-1}$). Thus, besides M4, ω Centauri is the second cluster with a significant fraction of FR BSSs.

Interesting insights can also be drawn from the BSS spatial distribution. SP14 found that the FR-BSSs (with $v \sin i > 70$ km s$^{-1}$) in ω Centauri are more segregated toward the center with respect to the slowly rotating objects. While the targets in their sample cover only the inner $\sim 8'$, the combined data set extends out to $\sim 13'$, corresponding to $\sim 4.8r_c$ (the adopted cluster center and core radius are from Ferraro et al. 2006b: $\alpha_{J2000} = 13^h 26^m 46.5$, $\delta_{J2000} = -47^\circ 28' 41''.1$, $r_c = 2'.55$).

The distribution of $v \sin i$ as a function of the distance from the cluster center is shown in Figure 10 for our sample (gray circles) and for the additional targets from SP14 (empty squares). The ratio between the number of FRs and the total number of BSSs ($N_{FR}/N_{BSS}$), measured in concentric annuli with radii equal to 1, 2, 3, 4, and 5 $r_c$, is plotted in Figure 11. Our measurements alone (solid circles), as well as the combined sample (empty triangles), show a trend with the distance from center. In agreement with the findings of SP14, the fraction of FRs is larger in the central regions than at $\sim 3r_c$ ($N_{FR}/N_{BSS} = 0.24$ and 0.11, respectively, for the combined sample). A larger fraction is found in the most external regions, beyond $4r_c$, where the fraction of fast spinning BSSs reaches 45% of the total. Because of the small number statistics of the sample (in particular for the outermost regions), the uncertainty in each single bin is large. In order to assess the statistical significance of this possible behavior, we performed a Kolmogorov–Smirnov test between the radial distributions of the populations of fast- and slow-rotating BSSs, yielding a $\sim 20\%$ probability that the two samples are extracted from the same parent distribution. Even if this test provides a statistical significance smaller than $2\sigma$, a different radial distribution for FR and slow-rotating BSSs cannot be totally ruled out. Also, we checked this result against changing the coordinates of the cluster center according to the values quoted in the literature by Anderson & van der Marel (2010), van Leeuwen et al. (2000),

6 We note that the distances quoted in SP14 have been calculated by neglecting the term cos(Dec). By taking this term into account and computing the correct distances, we find that all of their targets are located within $3r_c$ (instead of $\sim 4.6r_c$) from the center, and all of the FR-BSSs but two (i.e., 7 out of 9) are positioned within $1r_c$ (instead of $2r_c$).
and Noyola et al. (2008), finding no variations in the observed behavior. On the other hand, no similar trend is observed for M4, the other GC with a large population of FR BSSs. However, the size of the sample is very limited in that case, and therefore we cannot exclude that the fraction of fast rotating BSSs in M4 also has a bimodal radial trend with a significant rise outward. Based on the flat BSS radial distribution observed in ω Centauri, Ferraro et al. (2006b) suggested that the vast majority of these stars (if not all) has a non-collisional origin and probably formed through MT in binary systems. On the other hand, theoretical models predict high rotational velocities for MT-BSSs, at least at the moment of their formation (Sarna & De Greve 1996; Lombardi et al. 1995). The occurrence of subsequent processes, such as magnetic braking or disk locking, might then slow down the stars. Thus, it is reasonable to conclude that the high rotational velocity observed in the FR BSSs of ω Centauri is observational confirmation that significant transfer of angular momentum occurs during the MT-BSS formation process. Additional support comes from the fact that all of the 6 W Uma stars in our sample are FR BSSs (with $v_r \sin i > 90 \text{ km s}^{-1}$). These variables are compact binary systems that experience an active phase of MT, and their evolution is thought to lead to the total coalescence of the two components, eventually forming a BSS (Vilhu 1982). Note that W Uma stars with high rotational velocities have also been found in 47 Tuc (Ferraro et al. 2006a), M4 (Lovisi et al. 2010), and M30 (Lovisi et al. 2013a). Only two W UMa stars with slow rotational velocities have been observed (in 47 Tuc; see Ferraro et al. 2006a), and both show evidence of CO-depletion on their surfaces, which is interpreted as the chemical signature of the MT process. This might suggest that these stars have been captured when they are still accelerating toward very high rotational velocities: enough CO-depleted material was already transferred onto the secondary to be detectable in its atmosphere and the star rotational velocity is not yet too high to prevent the spectroscopic measurement of chemical abundances. Under the assumption that most of the BSSs in ω Centauri are generated by MT, the discovered FRs could either be recently formed BSSs (for which the braking mechanisms have not had enough time yet to be effective), or, for some unknown reason, they could have been able to preserve their initial high rotation longer. Indeed, no significant distinction between fast and slow rotating BSSs pointing toward a different formation epoch has been observed in the CMD. On the other hand, the detailed efficiencies and timescales of the braking mechanisms are still not known and therefore firm conclusions are hard to be drawn here. However, the observed radial distribution of fast and slow rotating BSSs, with a possible central peak and a significant outward rise of the fraction of fast spinning BSSs, seems to suggest that environment can play a role in this game. In particular, it could indicate either that recently formed MT-BSSs prevail in the outskirts of ω Centauri, or that braking processes are less efficient in the lowest density regions of the system. The slight increase observed within $1 R_{\odot}$ may suggest that stellar interactions can contribute to the transfer of angular momentum and accelerating BSSs (see also Lovisi et al. 2010 and SP14). So far, such a distribution has been detected only in ω Centauri and further determinations of rotational velocities for large samples of BSSs in other clusters are needed to provide a solid answer about the ubiquity of this phenomenon.

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