FAST ROTATING BLUE STRAGGLERS IN THE GLOBULAR CLUSTER M4*

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ABSTRACT

We have used high-resolution spectra obtained with the spectrograph FLAMES at the European Southern Observatory Very Large Telescope to determine the kinematical properties and the abundance patterns of 20 blue straggler stars (BSSs) in the globular cluster (GC) M4. We found that ~40% of the measured BSSs are fast rotators (with rotational velocities >50 km s⁻¹). This is the largest frequency of rapidly rotating BSSs ever detected in a GC. In addition, at odds with what has been found in 47 Tucanae, no evidence of carbon and/or oxygen depletion has been revealed in the sample of 11 BSSs for which we were able to measure the abundances. This could be due to either low statistics, or a different BSS formation process acting in M4.

Key words: blue stragglers – globular clusters: individual (NGC 6121) – stars: abundances

1. INTRODUCTION

Blue straggler stars (BSSs) are brighter and bluer (hotter) than the main-sequence (MS) turnoff and they mimic a rejuvenated stellar population in globular clusters (GCs). From their position in the color–magnitude diagram (CMD) and from direct measurements (Shara et al. 1997; see also Ferraro et al. 1995), they are known to be more massive than the normal MS stars, thus indicating that some process able to increase the initial mass of single stars must be at work: BSSs could be generated by collision-induced stellar mergers (COL-BSSs; Hills & Day 1976), or they may form by the mass-transfer activity in a binary system (MT-BSSs; McCrea 1964), possibly up to the complete coalescence of the two companions. BSSs in different environments could have different origins (Fusi Pecci et al. 1992). In particular, BSSs in loose GCs might be produced from the coalescence of primordial binaries, whereas in high-density GCs BSSs might arise mostly from stellar collisions, particularly those involving binaries. Moreover, there is evidence that both mechanisms could act simultaneously within the same cluster (see the two distinct sequences of BSSs recently discovered in M30 by Ferraro et al. 2009), also depending on the different stellar densities at various distances from the cluster center. This is suggested by the bimodality of the BSS radial distribution detected in several GCs (see Ferraro & Lanzoni 2009 for a review). While theoretical predictions about the properties of BSSs generated by different formation channels are still uncertain and controversial, the search for chemical patterns onto the BSS surface seems to be the most promising route to discriminate between the two scenarios. In fact, hydrodynamic simulations (Lombardi et al. 1995; Sarna & De Greve 1996) suggest that very little mixing should occur between the inner cores and the outer envelopes of the colliding stars (hence COL-BSSs should not show any abundance anomaly), while depleted surface abundances of carbon (C) and oxygen (O) are expected for MT-BSSs, since the accreted material should come from the core region of a peeled parent star where nuclear processing has occurred. Indeed, this seems to be the case for the sub-sample of BSSs with significant CO depletion discovered in 47 Tucanae (47 Tuc) by Ferraro et al. (2006, hereafter F06).

In this framework, we are conducting an extensive survey of surface abundance patterns and kinematical properties of BSSs in a selected sample of GCs, by using the Very Large Telescope (VLT) of the European Southern Observatory (ESO). In this Letter, we report on new findings of this project concerning the GC M4.

2. OBSERVATIONS

The observations were performed at the ESO-VLT during three nights in 2008 June, using the multi-object facility FLAMES-GIRAFFE (Pasquini et al. 2002). The sample includes 20 BSSs, 53 subgiant branch stars (SGBs), and 38 red giant branch stars (RGBs). The spectroscopic target selection has been performed on a photometric catalog obtained by combining ACS@HST data for the central region (i.e., at radial distances r < 100") and WFI@ESO observations for the outer region. We have also taken into account the stellar proper motions for the wide-field sample (Anderson et al. 2006) and discarded all the stars having a source with a comparable or a brighter luminosity at a distance smaller than 3". The selected BSS sample represents ~70% of the entire population within 800" (≈11 core radii) from the cluster center (B. Lanzoni et al. 2010, in preparation), with ~50% of them being located at r < 100". The RGBs and SGBs have been selected from the WFI sample at 100" < r < 800".

Three different setups were used for the spectroscopic observations: HR15, HR18, and HR22, suitable to sample the He line, the O I triplet at λ ≈ 7774 Å, and the C I line at λ ≈ 9111 Å.
respectively. Exposure times amount to 1 hr for the HR15 setup and 2 hr each for the HR18 and HR22. Spectra have been pre-reduced using the standard GIRAFFE ESO pipeline. The accuracy of the wavelength calibration has been checked by measuring the position of a number of emission telluric lines (Osterbrock et al. 1996). Then, we subtracted the mean sky spectrum from each stellar spectrum. By combining the exposures, we finally obtained median spectra with signal-to-noise ratios ($S/N_s$) $\simeq$ 50–100 for the selected BSSs and SGBs, and $S/N \simeq$ 100–300 for the RGBs.

3. ANALYSIS AND RESULTS

The procedure adopted to derive the radial and rotational velocities, and the $[O/Fe]$, $[C/Fe]$, and $[Fe/H]$ abundance ratios for the observed sample is summarized below. Table 1 lists the values obtained for the BSSs together with the adopted temperatures and gravities.

**Radial velocities.** Radial velocities ($V_{\text{rad}}$) were measured using the IRAF task *fxcor* that performs the Fourier cross-correlation between the target spectra and a template of known radial shift, following the prescriptions by Tonry & Davis (1979). As a template for the samples of BSSs, SGBs, and RGBs, we used the corresponding spectra with the highest $S/N$, for which we computed $V_{\text{rad}}$ by measuring the wavelength position of a few tens of metallic lines. Radial velocity values obtained from the three different setups are consistent with each other within the uncertainties which are of the order of 0.5 km s$^{-1}$ for the SGB stars and most of the BSSs (see Table 1) and 0.15 km s$^{-1}$ for the RGBs. For the fast rotating stars (see below), $V_{\text{rad}}$ has been estimated from the centroid of the $H\alpha$ line, which is almost unaffected by rotation.

Figure 1 shows the derived $V_{\text{rad}}$ distribution for the giants (RGBs+SGBs) and the BSSs. The mean radial velocity of the total sample is $\langle V_{\text{rad}} \rangle = 71.28 \pm 0.50$ km s$^{-1}$, with a dispersion $\sigma = 5.26$ km s$^{-1}$. The distribution for the giant stars is peaked at nearly the same value, $\langle V_{\text{rad}} \rangle = 71.25 \pm 0.43 (\sigma = 4.08)$ km s$^{-1}$, which we adopt as the systemic velocity of M4. This is in good agreement with previous determinations (Peterson et al. 1995; Harris 1996; Marino et al. 2008; Sommariva et al. 2009; Lane et al. 2010). The average of the BSS radial velocity distribution is also similar, $\langle V_{\text{rad}} \rangle = 71.40 \pm 2.01$ km s$^{-1}$, but the dispersion is larger ($\sigma = 9$ km s$^{-1}$) due to the discordant values measured for five of these stars (see Table 1).

**Rotational velocities.** To derive the stellar rotational velocities we have used the method described by Lucatello & Gratton (2003). In particular, we have computed the Doppler broadening
While this value has been strictly measured for a few SGB stars only, the impact of such an assumption on the derived rotational velocities and chemical abundances is negligible.

**Chemical abundances.** As the reference population needed to identify possible anomalies in the BSS surface abundances, we have considered the SGBs, since episodes of mixing and dredge-up may have modified the primordial abundance patterns in the RGBs. Chemical abundances have been derived from the equivalent width measurements by using the WIDTH9 code (Kurucz 1993a; Sbordone et al. 2004). Gravities have been determined (within 0.2 dex) by comparing the target position in the CMD with a grid of evolutionary tracks extracted from the BaSTI Library (Pietrinferni et al. 2006). This also yielded to a mass distribution for the observed BSSs, which peaks at $\sim 1M_\odot$ with the most massive object being at $\sim 1.3M_\odot$. Abundance errors have been computed by taking into account the uncertainties on the atmospheric parameters and those on the equivalent width measurements. For each star they typically are of the order of 0.1–0.2 dex.

The iron content for the SGBs and BSSs has been derived from the equivalent widths of about 10 and 2–7 Fe i lines, respectively. For the SGBs the resulting average iron abundance is [Fe/H] = $-1.10 \pm 0.01$, with a dispersion $\sigma = 0.07$ about the mean, in good agreement with previous values (ranging between $-1.20$ and $-1.07$; Harris 1996; Ivans et al. 1999; Marino et al. 2008; Carretta et al. 2009). Because of the significant deformation of the spectral line profiles, no iron abundance has been derived for the eight fast rotators. Moreover, technical failures in the spectrograph fiber positioning prevented us to measure it for two additional objects (see Table 1). The iron abundance obtained for the remaining 10 BSSs has a mean value of $-1.27$ and a dispersion $\sigma = 0.10$, consistent, within the errors, with the values derived for the SGBs.

Oxygen and carbon abundances have been computed from the equivalent widths of the O i triplet and the C i lines, respectively, and the derived values have then been corrected for non-local thermodynamic equilibrium effects. For O abundances these corrections were derived by interpolating the grid by Gratton et al. (1999); for C abundances we adopted the empirical relation obtained by interpolating the values listed by Tomkin et al. (1992). The resulting average abundances for the SGB sample are [C/Fe] = $-0.16 \pm 0.02$ ($\sigma = 0.17$) and [O/Fe] = $0.29 \pm 0.02$ ($\sigma = 0.17$). No measurements have been possible for the very fast rotating BSSs and for a few other objects (see Table 1). Hence, we were able to measure both the C and O abundances only for 11 BSSs out of 20 observed. Figure 3 shows the results obtained in the [C/Fe]–[O/Fe] plane. The values measured for the 11 BSSs are in agreement with those of the SGBs, with no evidence of depletion either in carbon or in oxygen. We finally note that also in the three cases for which only the oxygen or the carbon abundance has been measured (see Table 1), the values obtained are in agreement with those of the SGBs.

4. DISCUSSION

Before discussing in details the main findings of the present work it is necessary to verify whether some of the investigated stars do not belong to the cluster. In particular, five BSSs have been found to display anomalous $V_{\text{rad}}$, which may cast some doubts about their membership. However, BSSs 42424 and 64677 have measured proper motions well in agreement with the expectations for stars in the cluster. In particular, five BSSs have been found to display anomalous $V_{\text{rad}}$, which may cast some doubts about their membership. However, BSSs 42424 and 64677 have measured proper motions well in agreement with the expected value of $0.0 \text{ km s}^{-1}$, with the highest value being $13.4 \pm 3.4 \text{ km s}^{-1}$ for an SGB. The rotational index distribution for the BSSs (see Table 1) is quite different, with eight stars (40% of the total) being fast rotators, i.e., rotating at more than $50 \text{ km s}^{-1}$ (while normal F-G type stars typically spin at less than $30 \text{ km s}^{-1}$; Cortés et al. 2009). Interestingly, three (out of five) BSSs with anomalous $V_{\text{rad}}$ are also fast rotators.

The derived values for BSSs may be affected by systematic uncertainties, since these stars could be underluminous for their masses (van den Berg et al. 2001; Sandquist et al. 2003; Mathieu & Geller 2009). While we do not have direct spectroscopic indicators for gravity, uncertainties of 0.2 dex translate in abundances variations smaller than 0.1 dex.
those of the cluster members (Anderson et al. 2006). All the other objects have measured rotational velocities significantly larger than expected for normal stars of the same spectral type, thus making unlikely that they belong to the field. We have also used the Besançon Galactic model (Robin et al. 2003) to derive the radial velocity and metallicity distributions of the Galactic field stars in the direction of M4 within the same magnitude and color intervals shared by our BSS sample. The $V_{\text{rad}}$ distribution is peaked at $-14.6$ km s$^{-1}$ and has a dispersion $\sigma = 50.7$ km s$^{-1}$. As a consequence, the probability that the BSSs with anomalous radial velocity belong to the field is always smaller than 1.7%. The theoretical metallicity distribution of field stars is peaked at $[\text{Fe/H}] = -0.17 \pm 0.02$ ($\sigma = 0.45$). The iron abundance measured in two of the five BSSs with anomalous radial velocity ($[\text{Fe/H}] = -1.35$ for BSS 42424 and $-1.23$ for BSS 64677) is clearly largely inconsistent with the field value and concordant, within the errors, with that of M4 stars. Based on these considerations, we therefore conclude that all the BSSs with anomalous $V_{\text{rad}}$ are indeed members of M4. We note that if the discrepancies were caused by the orbital motion in binary systems, under realistic assumptions about the total mass, the orbits would be reasonable for a GC, with separations ranging from a few to 10–20 AU. These BSSs do not show any evidence of photometric variability (Kaluzny et al. 1997), and variations of $V_{\text{rad}}$ with full amplitudes exceeding 3 km s$^{-1}$ on a time interval of 72 hr are excluded by our observations for BSSs 42424 and 64677 (no such information is available for the fast rotators). However, these results do not disprove that they are in binary systems. For instance, they are still consistent with what is expected for $\sim 90\%$ of binaries characterized by an eccentricity–period distribution similar to that recently observed by Mathieu & Geller (2009) and populating the tail of the velocity distribution in M4 (R. D. Mathieu & A. M. Geller 2010, private communication). Indeed, further observations are urged to search for clear-cut signatures of binarity.

The fact that none of the 14 BSSs for which we measured C and/or O abundances show signatures of depletion is quite intriguing. Of the 42 BSSs investigated in 47Tuc, F06 found that 6 (14\%) are C-depleted, with 3 of them also displaying O depletion. Accordingly, in M4 we could have expected 1–2 BSSs with depleted carbon abundance, and 0–1 BSS with both C and O depletion. Hence, the resulting non-detection may just be an effect of low statistics and is still consistent with the expectations. Alternatively, the lack of chemical anomalies in M4 BSSs might point to a different formation process: while at least six BSSs (the CO-depleted ones) in 47Tuc display surface abundances consistent with the MT formation channel, all the (investigated) BSSs in M4 may derive from stellar collisions, for which no chemical anomalies are expected. Finally, it is also possible that the CO depletion is a transient phenomenon (F06) and (at least part of) the BSSs in M4 are indeed MT-BSSs which already evolved back to normal chemical abundances.

The most intriguing result of this study is the discovery that a large fraction (40\%) of the investigated BSSs in M4 are fast rotators, with rotational velocities ranging from $\sim 50$ km s$^{-1}$ up to more than 150 km s$^{-1}$. We emphasize that this is the largest population of fast rotating BSSs ever found in a cluster. Approximately 30\% of the BSSs spinning faster (at 20–50 km s$^{-1}$) than MS stars of the same color have been recently found in the old open cluster NGC188 (Mathieu & Geller 2009), while BSSs in younger open clusters are found to rotate slower than expected for their spectral type (e.g., Shetrone & Sandquist 2000; Schönberner et al. 2001). For GCs only scarce and sparse data have been collected to date. The most studied case is that of 47Tuc, where 3 (7\%) BSSs out of the 45 measured objects (Shara et al. 1997; De Marco et al. 2005; F06) have rotational velocities larger than 50 km s$^{-1}$, up to $\sim 155$ km s$^{-1}$. The object studied by Shara et al. (1997) is the second brightest BSS in 47Tuc, and all the others are located at the low-luminosity end of the BSS region in the CMD. In addition, they span almost the entire range of surface temperatures and distances from the cluster center. For comparison, apart from being more numerous, the fast rotating BSSs in M4 are also found at all luminosities, temperatures, and radial distances (see Figure 4). There is a weak indication that the rapid rotating BSSs in M4 tend to be more centrally segregated than normal BSSs, even if the small number of stars in our sample prevents a statistically robust result (following a Kolmogorov–Smirnov test, the probability that the two distributions are extracted from the same parent population is $\sim 44\%$). The fastest rotating BSS in M4 (BSS 2000121, with $I_{\text{rot}} \sim 150–200$ km s$^{-1}$) corresponds to star V53 of Kaluzny et al. (1997), which is classified as a W UMa contact
binary. Interestingly, even in the F0e sample of 47Tuc the fastest BSS (spinning at \( \sim 100 \text{ km s}^{-1} \)) is a W UMa binary. These two stars also occupy a very similar position in the CMD, at the high-temperature and low-luminosity side of the BSS region.

Unfortunately, from the theoretical point of view, rotational velocities cannot be easily interpreted in terms of BSS formation processes. In fact, fast rotation is expected for MT-BSSs because of angular momentum transfer, but some braking mechanisms may then intervene with efficiencies and timescales that are still unknown. The predictions about rotational velocity of COL-BSS are controversial (Benz & Hills 1987; Leonard & Livio 1995; Sills et al. 2005). In particular, the latter models show that angular momentum losses through disk locking are able to decrease the BSS rotational velocity from values as high as \( \sim 100 \text{ km s}^{-1} \) down to \( 20 \text{ km s}^{-1} \). Hence, the fast rotating BSSs observed in M4 could be generated either through mass transfer activity or through stellar collisions, on condition that no significant braking has (still) occurred.

Three of the BSSs (namely 52702, 53809, and 1000214) of the five with anomalous \( V_{\text{rot}} \) are also fast rotators. Such a high rotation is difficult to account for by synchronization or mass transfer effects in binary systems, since the orbital separation would not be small enough. A fascinating alternative is that such anomalies in the radial and rotational velocities are due to three- and four-body interactions that occurred in the cluster core: these could have originated fast spinning BSSs and kicked them out to the external regions at high speed (apart from star 1000214, the other two are located well beyond the cluster core radius). Interestingly enough, the dynamical history of the cluster could support such a scenario. In fact, although its stellar density profile is well reproduced by a King model, recent Monte Carlo simulations (Heggie & Giersz 2008) suggest that M4 could be a post-core collapse cluster, its core being sustained by the “binary burning” activity. The fast rotating and high-velocity BSSs could be the signature of such an activity.

While bringing a wealth of information, the results obtained to date for 47Tuc and M4 are still too scarce to provide a clear overall picture. Collecting additional data on rotational velocities and chemical abundances for a significant number of BSSs in a sample of GCs with different structural parameters is indeed a crucial requirement for finally understanding the formation mechanisms of these puzzling stars and their link with the cluster dynamical history.

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