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SPECTROSCOPIC SEARCH FOR BINARIES AMONG EHB STARS IN GLOBULAR CLUSTERS *

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Abstract. We performed a spectroscopic search for binaries among hot horizontal branch stars in globular clusters. We present final results for a sample of 51 stars in NGC 6752 and preliminary results for the first 15 stars analyzed in M 80. The observed stars are distributed along all the HBs in the range $8000 \leq T_{\mathrm{eff}} \leq 32\,000$ K, and have been observed during four nights. Radial velocity variations were measured with the cross-correlation technique. We analyzed the statistical and systematic errors associated with the measurements in order to evaluate the statistical significance of the observed variations. No close binary system has been detected, neither among cooler stars nor among the sample of hot EHB stars (18 stars with $T_{\mathrm{eff}} \geq 22\,000$ K in NGC 6752). The data corrected for instrumental effects indicate that the radial velocity variations are always below the 3σ level of ~ 15 km s^{-1}. These results are in sharp contrast with those found for field hot subdwarfs, and open new questions about the formation of EHB stars in globular clusters and possibly of the field subdwarfs.

Key words: stars: horizontal branch – hot subdwarfs – binaries: spectroscopic – globular clusters: individual (NGC 6752, M 80)

1. INTRODUCTION

Although stellar evolution theory has successfully identified horizontal branch (HB) stars as post-core helium flash stars of low initial mass (Hoyle & Schwarzschild 1955; Faulkner 1966), we still lack a comprehensive understanding of their nature. There is a general agreement that the hottest HB stars (EHB) must have suffered a heavy mass-loss during their evolution, keeping only a thin envelope (~ 0.02 $M_{\odot}$), but their specific formation mechanism remains unclear. The bi-

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narity of EHB stars, as proposed by many authors (Mengel et al. 1976; Heber et al. 2002) can provide an explanation, since in a close binary system the mass-loss can be enhanced through a number of different binary evolution channels (Han et al. 2002). Binaries have been found to be very common among field subdwarf B-type stars (sdBs), considered to be the counterparts of the cluster EHB stars. Maxted et al. (2001) estimated that 69±9 % of sdB stars are close binaries with periods $P \leq 10$ days, and Han et al. (2003) by binary population synthesis techniques predicted a 76–89 % binary fraction. From the recent investigation of Morales-Rueda et al. (2003) it appears clear that close binaries with periods $P \leq 5$ days and semiamplitudes of the radial velocity variation $K \geq 50$ km s^{-1} are very common among sdBs. Nevertheless the binary scenarios, extensively investigated by Han et al. (2002), are not free from problems as shown by Lisker et al. (2005). Moreover a more recent survey of Napiwotzki et al. (2004) found a significantly lower binary fraction among the sdB sample (42 %), showing that we are still far from a full understanding of this kind of stars. With this contribution we investigate a sample of EHB stars in globular clusters, searching for evidence of the presence of close binaries among them.

2. OBSERVATIONS AND DATA REDUCTION

In the globular cluster NGC 6752 we selected 51 target stars from the photometric data of Momany et al. (2002). We chose to perform a more complete investigation distributing the sample along the entire HB, from cooler stars ($T_{\rm eff} \approx 8000$ K) to hot EHB stars ($T_{\rm eff} \geq 20\,000$ K), although our attention was focused toward the EHB sample among which we expected to find a high fraction of close binary systems. The targets were divided into three stellar fields for multiobject spectroscopy. The positions of the targets in the color-magnitude diagram of the cluster are shown in Figure 1. In Figure 2 we indicate their radial distribution with respect to the cluster center. The spectra were collected during four nights of observation (2002 June 12–15) at the VLT-UT4 telescope with the FORS2 spectrograph in MXU mode. During each night, up to two pairs of 1800 s exposures were obtained in each field with a grism 1400V+18 (0.5″ wide slits, 1.2 Å resolution), except in the third night in field A, where only one single exposure was acquired, and the first night in field C, where no observations were performed. In Table 1, the UT of the start of the pair of 1800 s exposures is shown.

Table 1. UT of the start of the exposures (hours and minutes).

Field	Night			
	12	13	14	15
A	8:43	2:44 3:56	9:34	7:47
B	5:55 6:59	5:08	8:33	8:58
C	–	8:04	6:39 7:33	6:36

Due to different positions of the slits on the mask, the spectra covered slightly different spectral ranges, but in each spectrum the Hβ line was always present, except for star 14 in field C, that has been excluded from our analysis.

The data reduction has been performed with standard MIDAS procedures, as described in detail in Moehler et al. (2004) and Moni Bidin et al. (2005). During the same observing run similar data were acquired also for 32 HB stars in M 80.

3. MEASUREMENTS

Radial velocity (RV) variations have been measured with the cross-correlation (CC) technique (Tonry & Davis 1979) with the *fxcor* IRAF task. Before coadding the single 1800 s exposures in pairs we performed a CC between them in order to verify that no significant RV variation had occurred. For every star each spectrum has been cross-correlated with all the others, performing 10 CCs for each star in fields A and B, and 6 in field C, covering different temporal intervals from one hour to 3.1 days.

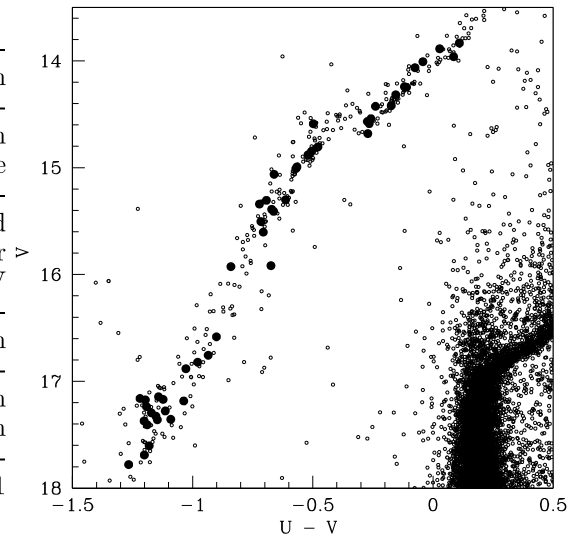

Fig. 1. Positions of the observed stars in the color-magnitude diagram of NGC 6752. Data from Momany et al. (2002).

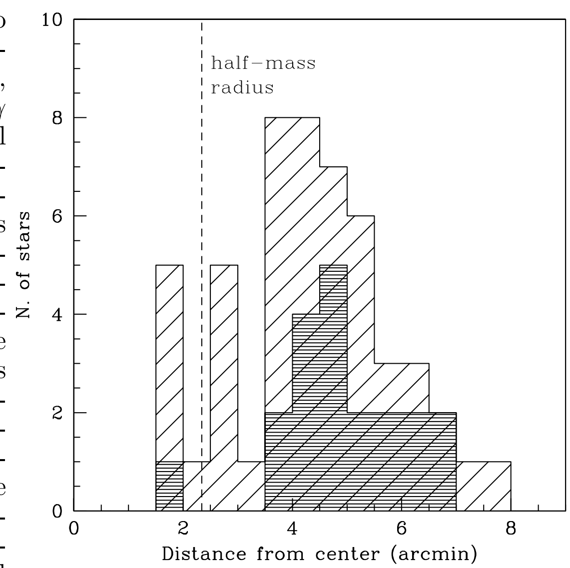

Fig. 2. Radial distribution of the observed stars. The dark shaded area indicates hot stars ($T_{\rm eff}$ $\geq$ 20 000 K). The half-mass radius from Harris (1996) is also indicated.

Our analysis was focused on the Hβ line, cross-correlating the 4830–4890 Å spectral range. Nevertheless, all the measurements have been repeated also at other wavelengths, cross-correlating the entire spectra, with and without Hβ and Hγ when present in the spectral range. In each CC the position of the center of the cross-correlation function (CCF) has been determined with a Gaussian fit (for example, see Recio-Blanco et al. 2004 for a description of the procedure). In the measurements of hot stars it has been often impossible to cross-correlate the entire spectra without the Hβ line, and we selected spectral intervals with the strongest He lines instead, in order to minimize the noise included in the CC procedure and obtain a CCF with a clear peak. We also applied a Fourier filter of various shapes (Brault & White 1971) to the noisy spectra, obtaining always better CCFs but substantially unchanged results.

The [OI] 5577 Å sky line has been used as zero-point in order to correct the spectral shifts due to differences between lamp and star spectra.

We have been forced to correct the data for a systematic effect due to different positions of stars inside the slits in different nights. The effect was up to 10–12 $\mathrm{km\,s^{-1}}$. On the slit images (without grism), acquired just before each pair of exposures, we measured the position of the stars with respect to the center of the slit with a Gaussian fit of the stellar profile parallel to the dispersion direction. Then we translated the displacements between the frames to $\mathrm{km\,s^{-1}}$ with the instrumental relation 1 pixel = 38.2 $\mathrm{km\,s^{-1}}$ and applied them as corrections to the RV variations. A trend with Y position was evident, but with a certain scatter due to random errors, and we opted to derive the final corrections from the values obtained from the least-square solution of this relation, in order to avoid to introduce additional noise to the results.

This procedure gave corrections very similar to the RV variations measured, indicating both that the removal of the systematic effect had been successful and that the RV variations observed were due only to it.

We measured absolute RVs in order to check the cluster membership of our targets, by means of CCs with the template star HD 188112, a binary sdB star with known ephemeris (Heber et al. 2003). These RVs have undergone similar correction procedures as described before. The errors (1σ) of these measures are 6–10 $\mathrm{km\,s^{-1}}$. All the stars show an absolute RV in agreement with that of the cluster (–27.9 $\mathrm{km\,s^{-1}}$, Harris 1996) within 2σ and can be considered RV cluster members.

4. ERROR ANALYSIS

The detection of binary systems in our survey is strongly dependent on a proper estimate of the error budget. We performed an accurate analysis of all the sources of errors and estimated their values (σ). Finally, all the error sources have been combined in quadrature. The resulting errors are about 3–5 km s^{-1}, with the exception of some measurements for hotter stars, where the low S/N sometimes increased the total error up to 7.5 km s^{-1}. In Table 2 we summarize the contribution of each error source and the corresponding ranges (1σ). The CC error is evaluated directly from the CC theory (Tonry & Davis 1979).

Table 2. Estimates of errors.

Error	Range of values (km s^{-1})
$\sigma_{\rm CC}$	0.5-2 (Hβ) 1-5 (weak lines)
$\sigma_{\rm wlc}$	1.4-1.6
$\sigma_{\rm sky}$	1.5
$\sigma_{\rm disp}$	0.7-1.4
$\sigma_{\rm fit+ext}$	0.7-1.5 (cooler stars) 2.1-3.5 (hotter stars)

The wavelength calibration (wlc) error has been measured on the lamp images calibrated with the coefficients obtained in the wlc procedure, analyzing the position of nine bright lamp lines.

The errors introduced by the corrections for the sky line position, $\sigma_{\rm sky}$, and for the displacement of the star inside the slits, $\sigma_{\rm disp}$, have been estimated from the dispersion of the corrections around the least-square solution when plotted against the Y positions.

We identified two additional sources of errors: the choice of the "best fit" of CCF peak and the extraction of the spectra. In fact a different extraction can

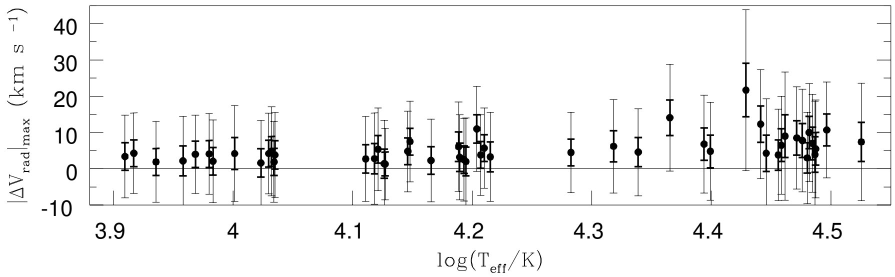

Fig. 3. Maxima of RV variations (in absolute value) measured in Hβ as a function of the temperature of the stars. The thick error bar indicates the 1σ interval, the thin one – 3σ.

cause a slightly different line profile; the CC procedure is sensitive enough to reveal it. In measurements on hot stars these have been identified as the main source of error. We evaluated them together extracting all the spectra a second time in a different manner and performing new measures in Hβ with different fits and, finally, measuring the dispersion $\sigma_{\text{fit+ext}}$ of the differences between these new data and the previous ones. This error was strongly dependent on the S/N of the spectra. Then we divided the targets into two groups (stars cooler and hotter than $\sim 20\,000$ K).

5. RESULTS

5.1. Results from Hβ

In Figure 3 we summarize the results obtained from measurements in the Hβ wavelength range, where we obtained the most reliable data. All the RV variations are small, lower than 15 km s^{-1}, except for one star, and are never greater than the estimated 3σ interval. They are only slightly higher for hotter stars, but with larger errors due to decreasing S/N in the spectra. We therefore conclude that *none of the observed RV variations can be considered statistically significant*.

Star 15 in field A exhibited higher RV variations in the third night, and the higher datum plotted in the figure (21.7 km s^{-1}) refers to these measurements. We consider this result interesting but particularly dubious, because it was obtained in the only not-summed spectrum (a single 1800 s exposure, as mentioned before), where all the stars tended to show higher RV variations due to the increased noise, and a comparable variation is never seen in any of the other observing nights.

5.2. Results from other lines

The results from CCs involving the entire spectral range did not provide additional information, because they always repeated the results already obtained with Hβ. This is due to the sensitivity of CC technique to the stronger line, and the extreme difference in strength between Balmer and others lines in our spectra.

The results obtained with Hγ, when present in the spectra, always confirm the ones obtained in Hβ wavelength range. The differences are always lower than 10 km s^{-1}, with just a handful of exceptions in agreement with a Gaussian distribution given the evaluated σ value.

None of the variations measured with weak lines ever exceeds the evaluated

3σ value, confirming the previous conclusions. The measurements with weak metallic lines have given very good results for cooler stars, mainly in the range $11\,500 \leq T_{\rm eff} \leq 18\,000$ K due to the presence of many lines induced by radiative levitation of heavy elements (Glaspey et al. 1989; Behr 2003). In these cases the differences between the measured variations and the ones in Hβ are really small, always below 4 km s^{-1}. For hotter stars the low S/N and the lack of lines complicated the measurements, and the results are less reliable. Occasionally the difference reaches 30 km s^{-1}, but always in the sense of limiting the highest RV variations measured in Hβ and never emphasizing them. In fact, the stars, that show the highest variations in Figure 3, do not show great variation in these measurements.

5.3. Detection probability

In order to better understand our results, we calculated the probability of detecting a binary in our observations as a function of the period P. We assumed circular orbits and a mass of 0.5 $M_\odot$ for each component, in order to relate the semiamplitude of the RV variation to the period. These assumptions are representative of typical binary systems observed among field sdBs. We repeated the calculations assuming a companion of 0.1 $M_\odot$. Systems with a low-mass companion are a minority among field sdBs, but their presence is well established. Our survey is not sensitive enough for this kind of systems, except for the shortest periods, and from our results we cannot draw interesting conclusions about them. The probabilities are shown in Figure 4 (the solid line for a 0.5 $M_\odot$ companion and the dotted line – for 0.1 $M_\odot$).

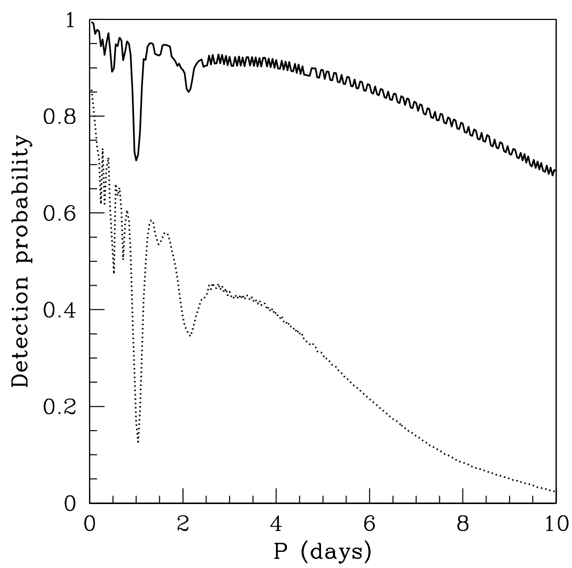

Fig. 4. Probability of detecting a binary in our observations.

5.4. Results for M 80

Since this is a work in progress we are still unable to show a plot similar to Figure 3 for the stars observed in M 80. Nevertheless we can point out that the preliminary analysis of the first 15 stars in this cluster gives the results similar to what obtained in NGC 6752. The variations are small, the highest values being around 20 km s^{-1}. Only two RV variations exceed 15 km s^{-1}, similarly to what was observed in NGC 6752. It must be emphasized that the results on M 80 are going to be less significant than in the case of NGC 6752 both because the stars are much fainter and the errors are larger, and because strong wind from north during the observing run prevented us from observing this cluster in the first two nights, so that the detection probability is reduced. We evaluated a loss of sensitivity of about 20–25 % for periods up to 5 days (compared to that in NGC 6752), which, for longer periods, drops rapidly to very low values.

6. CONCLUSIONS

The results shown in Figure 3 indicate that there is no close binary system in our sample, neither among cooler stars, nor among EHB targets. All the RV variations are within the estimated errors and are significantly lower than what expected. In the compilation of Morales-Rueda et al. (2003) for all field binary sdB stars with known periods, the RV semi-amplitudes are always greater than 30 km s^{-1}. These binary systems would be easily detectable in our survey. If the binary fraction of EHB stars in NGC 6752 were 69 %, as found by Maxted et al. (2001) in the field, we would expect that 13±2 of our 18 stars with $T_{\rm eff} \geq 22\,000$ K should be binaries. According to the period distribution found by Morales-Rueda et al. (2003) 80 % of them should have $P \leq 5$ days, and thus 9±2 binary systems should have been detected in our sample. The absence of evidence of their presence is in sharp contrast with these previous results, and can indicate a significant difference between sdB stars in and outside globular clusters.

In conclusion, most of the EHB stars in NGC 6752, and possibly in M 80, are not close binaries. These results pose a number of problems. First of all, we are forced to conclude that the dominant mechanism for the formation of these stars in globular clusters does not involve the interactions within a close binary system. Although the high close binary fraction among field sdBs indicates that binary interactions can play an important role, our results on the EHB stars in NGC 6752 indicate that there must be other mechanisms at work.

It is possible that in GCs there are different formation channels of EHB stars with respect to the main ones in the field. For example, dynamical evolution of GCs could remove the primordial binaries able to produce sdB stars, at least in the inner part of the cluster. This is an interesting possibility, which has already been proposed also to explain why the frequency of blue stragglers (BSs) in GCs is significantly smaller than the frequency of field BSs (Piotto et al. 2004), and the anticorrelation between the frequency of BSs in GC cores and the GC total mass (Davies et al. 2004). At the same time, the GC environment can favor different formation mechanisms for the EHB stars, like close encounters and collisions among stars (at least in the cluster cores), or even more complex scenarios like the ones proposed to explain the anomalous double main sequence population in Omega Centauri (Bedin et al. 2004 and Piotto et al. 2005) and in NGC 2808 (D'Antona et al. 2005). Apparently, in these two clusters, a second generation of stars could have formed from material polluted by SNe and/or intermediate mass AGB star ejecta. These stars have an enhanced He content and could explain the presence of the EHB in both clusters.

An extended survey of the presence of close binaries among cluster EHB stars, from the inner core to the outskirts of NGC 6752, and of the presence of binaries with low companions or with longer (100 days or so) periods in NGC 6752 and other clusters with EHBs, is absolutely needed in order to test the hypothesis of the environment effects on the main production channels of these stars.

We note also that Peterson et al. (2002) reported a high fraction of binaries among the same type of stars in the same cluster, but Peterson (priv. comm.) also pointed out that their sample is mainly located in the outer regions of the cluster.

In concluding this brief discussion, we note that Napiwotzki et al. (2004) suggested that the low binary fraction among field sdBs found in their survey could be due to contamination of the sample by halo and thick disk stars, absent in Maxted et al. (2001) sample since it included only bright (thin disk) stars. On average, our cluster EHB stars are expected to be older and possibly more metal-poor than the Napiwotzki et al. sample, and apparently, the fraction of binaries among them is even smaller than among thick disk-halo sdBs, suggesting a possible dependence on ages or metallicities or on a combination of these parameters.

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