RAA 2015 Vol. **15** No. **10**, 1639–1646 doi: 10.1088/1674–4527/15/10/003
http://www.raa-journal.org *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

Discovery of high-velocity EHB stars in the globular cluster ω Centauri (NGC 5139)

Xin-Hua Gao[1], Shou-Kun Xu[1] and Li Chen[2]

[1] School of Information Science and Engineering, Changzhou University, Changzhou 213164, China; *xhgcczu@163.com*
[2] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China; *chenli@shao.ac.cn*

Received 2014 November 9; accepted 2015 March 22

Abstract We report the discovery of 45 high-velocity extreme horizontal branch (EHB) stars in the globular cluster Omega Centauri (NGC 5139). The tangential velocities of these EHB stars are determined to be in the range 93$\sim$313 km s^{-1}, with an average uncertainty of $\sim$27 km s^{-1}. The central escape velocity of the cluster is determined to be in the range 60$\sim$105 km s^{-1}. These EHB stars are significantly more concentrated toward the cluster core compared with other cluster members. The formation mechanisms of these EHB stars are discussed. Our conclusions can be summarized as follows: (1) A comparison of the tangential velocities of these EHB stars to the central escape velocity of the cluster shows that most if not all of these EHB stars are unbound to the cluster; (2) These EHB stars obtained high velocities in the central cluster region no longer than $\sim$1 Myr ago and may be subsequently ejected from the cluster in the next $\sim$1 Myr; (3) If the progenitors of these EHB stars were single stars, then they may have experienced a fast mass-loss process. If the progenitors were in close binaries, then they may have formed through disruptions by the intermediate-mass black hole in the cluster center.

Key words: Galaxy: globular clusters: individual: ω Cen (NGC 5139) — stars: Hertzsprung–Russell and C–M diagrams — stars: kinematics and dynamics — stars: binaries (including multiple): close

1 INTRODUCTION

Extreme horizontal branch (EHB) stars (also known as hot subdwarfs) play an important role in understanding stellar structure and evolution. It is widely accepted that EHB stars are composed of helium-burning cores and extremely thin hydrogen envelopes (Heber 1986, 2009; Saffer et al. 1994). Up to now, the formation mechanism of EHB stars has not been very clear, and various scenarios have been used to explain the formation of EHB stars (Mengel et al. 1976; Webbink 1984; Tutukov & Yungel'Son 1990; Lee 1994; Bressan et al. 1994; D'Cruz et al. 1996; Sweigart 1997; Yi et al. 1997; Han et al. 2002, 2003, 2007). In general, these scenarios can be divided into two types of models: a single star model and a binary star model. The binary star model proposed by Han et al. (2002, 2003, 2007) can explain major observational characteristics of field EHB stars.

The majority of field EHB stars are found to be in close binaries, which can be explained by the binary model of Han et al. (2002, 2003, 2007). However, a growing number of observations show that the binary fraction of EHB stars in globular clusters is significantly lower than that of field EHB stars (Allard et al. 1994; Aznar Cuadrado & Jeffery 2001; Maxted et al. 2001; Moni Bidin et al. 2006, 2008a,b, 2009, 2011; Moehler et al. 2011). This poses a serious challenge to the formation mechanism of EHB stars in globular clusters, which may reveal different formation mechanisms for cluster EHB stars (Han 2008). A binary fraction-age relation was proposed by Moni Bidin et al. (2008b), aiming to explain the difference between field and cluster EHB stars. Soon, Han (2008) confirmed the presence of a binary fraction-age relation based on their binary model (Han et al. 2002, 2003, 2007). The binary model of Han et al. predicted a much lower fraction of close EHB binaries in globular clusters (Han 2008). It is believed that close binaries may play an important role in the dense environment of globular clusters (Heggie 1975; Hut & Bahcall 1983), where star encounters could lead to the formation of high-velocity stars ((Lützgendorf et al. 2012). High-velocity stars have been found in several globular clusters based on radial velocity data (Gunn & Griffin 1979; Meylan et al. 1991; Lützgendorf et al. 2012). High-velocity EHB stars may also exist in some globular clusters, which could provide important clues about the formation mechanisms for cluster EHB stars. More specifically, high-velocity EHB stars may originate from the disruption of EHB binaries, which could explain the low fraction of EHB binaries observed in several globular clusters. If it is true, then field and cluster EHB stars may have the same formation mechanism.

In this work, our aim is to detect probable high-velocity EHB stars in the globular cluster Omega Centauri using high-precision proper motions and photometric data.

The data and target selection are described in Section 2, and the kinematic analysis of the probable high-velocity EHB stars is presented in Section 3. In Section 4, we briefly discuss the possible origin of these high-velocity EHB stars.

2 DATA AND TARGET SELECTION

2.1 Data

We decided to analyze the EHB stars in this cluster using the proper motions and photometric data provided by van Leeuwen et al. (2000). This catalog contains 9847 stars with relative proper motions. The limiting magnitude is 16.0 mag for stars in the cluster center and 16.5 mag for stars in its outer parts. The precisions of these proper motions range from an average of 0.1 mas yr^{-1} for the brightest stars to an average of 0.65 mas yr^{-1} for the faintest ones. The precisions of proper motions are high enough that probable high-velocity EHB candidates can be isolated, since the lower precision of 0.65 mas yr^{-1} corresponds to $\sim$ 16 km s^{-1} at 5200 pc (Harris 1996). Among the identified stars, 9256 stars within $29.5'$ from the cluster center and with color-magnitude information have estimated membership probabilities and 7853 stars are probable cluster members.

2.2 Target Selection

A color-magnitude range ($0 \leq B - V \leq 0.4$ mag and $14.25 \leq V \leq 16.0$ mag) is used for isolating probable EHB candidates in the cluster, and 1950 EHB candidates are selected from the 9256 stars (Fig. 1). As shown in Figure 1, the probability of field star contamination in this color-magnitude range should be very low, and most of the 1950 EHB candidates should be cluster members. The total number of 1950 EHB candidates that have high membership probability is 1878, which also suggests a low contamination probability from field stars. To our knowledge, high-velocity EHB stars should have significantly higher velocities than those of common EHB stars. The central proper motion dispersion of the cluster is $\sim$ 1.2 mas yr^{-1} (van Leeuwen et al. 2000), and stars with total proper motion greater than 3.6 mas yr^{-1} ($\sim$89 km s^{-1} at 5200 pc) are considered as high-velocity EHB candidates.

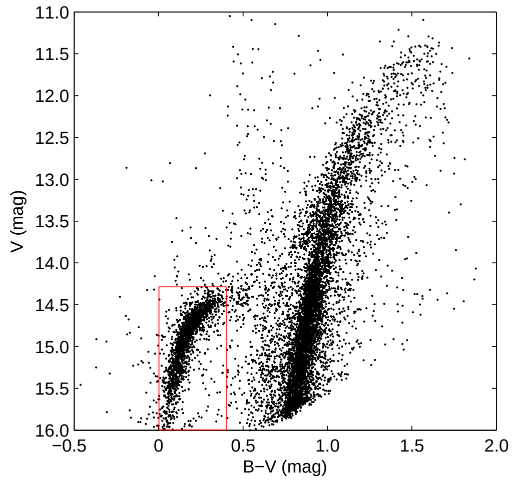

Fig. 1 The CMD of the 9256 stars. The red rectangle is used for isolating probable EHB candidates.

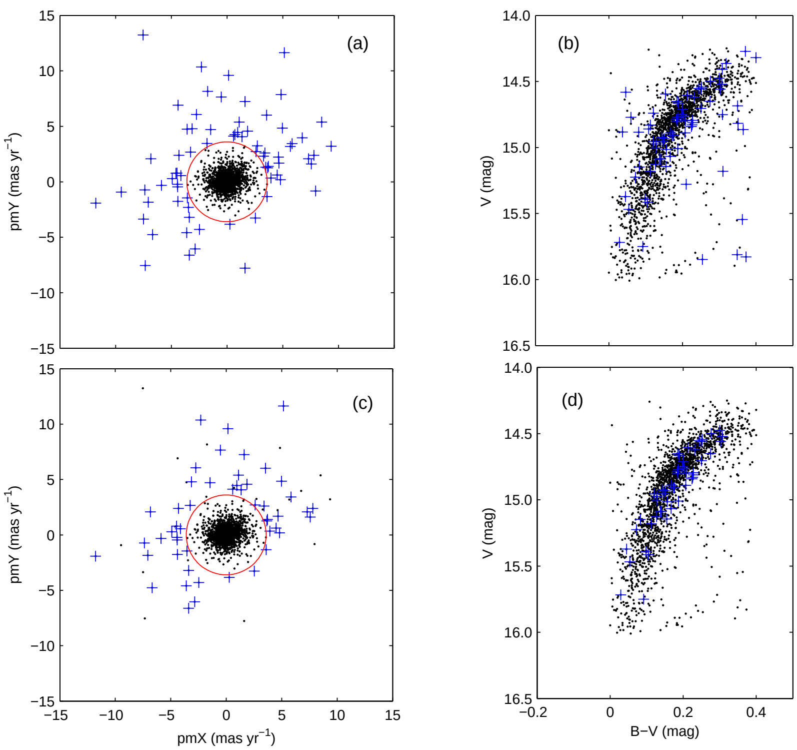

Fig. 2 (a): The proper motions of the 72 high-velocity EHB candidates (*blue pluses*) and other EHB candidates (*black dots*). The radius of the red circle is 3.6 mas yr^{-1} and the center of the red circle represents (0, 0) mas yr^{-1}; (b): The CMD of the 72 high-velocity EHB candidates (*blue pluses*) and other EHB candidates (*black dots*); (c): The proper motions of the 50 high-velocity EHB candidates (*blue pluses*) and other EHB candidates (*black dots*); (d): The CMD of the 50 high-velocity EHB candidates (*blue pluses*) and other EHB candidates (*black dots*).

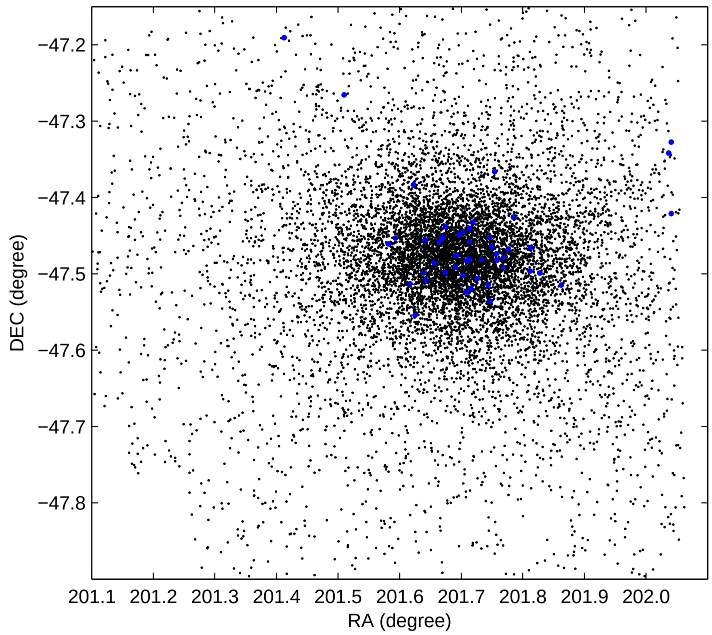

Fig. 3 The spatial distribution of the 50 high-velocity EHB candidates (*blue dots*) and other stars (*black dots*).

Figure 2 shows that 72 high-velocity EHB candidates meet this criterion. However, properties of the 72 high-velocity EHB candidates exhibited by the color-magnitude diagram (CMD) indicate the presence of a few field stars (Fig. 2(b)). After removing 22 probable field stars, 50 high-velocity EHB candidates are obtained for further analysis. As shown in Figure 2, properties of the CMD of the 50 high-velocity EHB candidates favor them being cluster members. More importantly, Figure 3 shows that almost all of the 50 high-velocity EHB candidates are centrally concentrated toward the cluster core. These high-velocity EHB candidates are likely cluster members.

3 KINEMATICS OF THE HIGH-VELOCITY EHB STARS

The following equations can be used to calculate the tangential velocities of the 50 high-velocity EHB candidates:

$$\mu = \sqrt{(pmX)^2 + (pmY)^2}, \tag{1}$$

$$V_{\rm t} = 4.74 \cdot \mu \cdot D, \tag{2}$$

where (pmX, pmY) are relative proper motion (unit: arcsec yr^{-1}), μ is total proper motion, $V_{\rm t}$ is tangential velocity (unit: km s^{-1}) and D is cluster distance (unit: pc). By adopting $D = 5200$ pc (Harris 1996), the tangential velocities of these high-velocity EHB candidates are determined to be in the range 93$\sim$313 km s^{-1}, with an average uncertainty of $\sim$27 km s^{-1}. Whether or not these high-velocity EHB candidates are unbound depends on their local escape velocities in the cluster. The local escape velocities at different distances from the cluster center can be estimated based on

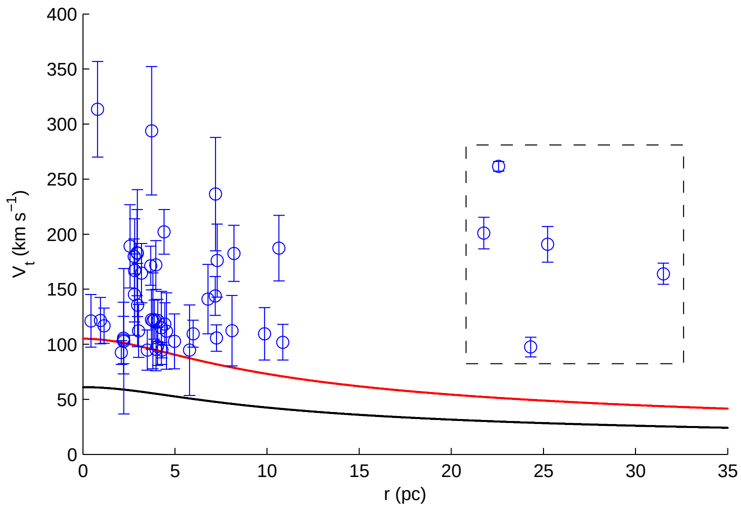

Fig. 4 The tangential velocities and local escape velocities of the 50 high-velocity EHB candidates. The red and black lines indicate the local escape velocities based on the lower and upper limits of the total mass M, respectively. The five stars in the rectangle are likely to be foreground stars.

the Plummer model (Plummer 1911):

$$\Phi(r) = \frac{-GM}{\sqrt{r^2 + a^2}}\,, \tag{3}$$

$$V_{\rm esc}(r) = \sqrt{-2\Phi(r)}\,, \tag{4}$$

$$R_{\rm c} = 0.65a\,, \tag{5}$$

where $\Phi(r)$ is the gravitational potential at distance r from the cluster center, G is the gravitational constant, M is the total mass of the cluster, a is a constant, $V_{\rm esc}(r)$ is the local escape velocity at r, and $R_{\rm c}$ is the core radius of the cluster. The total mass of the cluster has been estimated to be in the range 2.4∼7.1×10^6 $M_\odot$ (Meylan & Mayor 1986; Mandushev et al. 1991; Richer et al. 1991; Miocchi 2010, D'Souza & Rix 2013). By adopting a core radius of $2.4'$ and distance 5200 pc (Harris 1996), we have $R_{\rm c} \sim 3.6$ pc. The central escape velocity of the cluster is estimated to be in the range $60 \sim 105$ km s^{-1} owing to the uncertainty in total mass M. The central escape velocities (the maximum escape velocity in the cluster) estimated by Gnedin et al. (2002) (∼60 km s^{-1}) and McLaughlin & van der Marel (2005) (∼55 km s^{-1}) are quite consistent with our lower limit (∼60 km s^{-1}).

Figure 4 shows the tangential velocities and projected distances of these high-velocity EHB candidates, where the local escape velocities at different distances from the cluster center are also shown. It should be noted that the true distances from the cluster center of these high-velocity EHB candidates should be larger than the projected distances. So, the comparison of the tangential velocities with the local escape velocities in Figure 4 indicates that most if not all of these high-velocity EHB candidates seem to be unbound to the cluster.

As shown in Figures 4 and 5, five of the 50 high-velocity EHB candidates are very likely to be foreground stars due to their distinctly larger projected distances (>5.5 $R_{\rm c}$) and smaller uncertainties in tangential velocities. We conclude that the total number of high-velocity EHB stars in this globular cluster is 45, which are all, except for five, concentrated inside 2 $R_{\rm c}$.

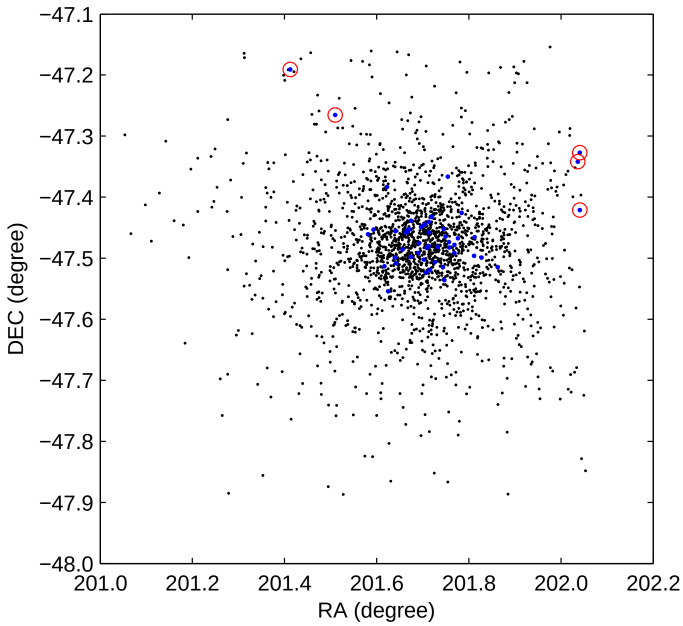

Fig. 5 The spatial distribution of the 50 high-velocity EHB candidates (*blue dots*) and other EHB candidates (Fig. 1). The five stars marked with red circles are likely to be foreground stars (which correspond to those indicated in Fig. 4).

4 CONCLUSIONS AND DISCUSSION

We identify 45 high-velocity EHB stars in the globular cluster Omega Centauri. They are all very likely to be cluster members due to properties of their CMD and spatial distribution. Most of the 45 high-velocity EHB stars seem to be unbound due to their high tangential velocities. By adopting the distance $D = 5200$ pc (Harris 1996), the concentration parameter $c = 1.31$ (Harris 1996) and the core radius $R_{\rm c} = 2.4'$ (Harris 1996), the tidal radius $R_{\rm tid}$ of the cluster is found to be $\sim$74 pc. For a high-velocity EHB star with spatial velocity $V = 100$ km s^{-1}, the dynamical crossing timescale ($R_{\rm tid}/V$) is $\sim$1 Myr. Such a short timescale means that these high-velocity EHB stars obtained their present velocities no longer than $\sim$1 Myr ago. These high-velocity EHB stars may be subsequently ejected from the cluster in the next $\sim$1 Myr. We conclude that some high-velocity EHB stars in the Galactic halo may have originated in some globular clusters. Recently, several high-velocity EHB stars in the Galactic halo were discovered (Tillich et al. 2011).

These high-velocity EHB stars are of particular interest because most of them are located in the dense core ($< 2R_{\rm c}$) of the cluster. However, because the masses of these high-velocity EHB stars are only $\sim$0.5 $M_\odot$ (Heber 1986, 2009; Saffer et al. 1994), they should not show higher central concentration than other cluster members. These high-velocity EHB stars may have experienced fast mass-loss if their progenitors were single stars. Close encounters between single stars and binaries may play an important role in the core of globular clusters since the star densities, and hence the encounter rates, are much higher in the core than in other regions (Heggie 1975; Hut & Bahcall 1983; Meylan & Heggie 1997). Close encounters in the cluster core could lead to the formation of high-velocity stars (Lützgendorf et al. 2012). Observations have shown that the binary fraction in globular clusters may be very low (Albrow et al. 2001; Sollima et al. 2007; Davis et al. 2008; Dalessandro et al. 2011), which could indicate a high efficiency of binary disruption in globular clusters (Hut et al. 1992; Ivanova et al. 2005). Numerical experiments have shown that close binaries (also known as hard binaries) cannot be disrupted through close encounters, but close binaries tend to become more hard through all types of encounters (Heggie 1975). Because of two-body relaxation, massive close binaries tend to sink into the cluster center due to energy equipartition. The existence of an intermediate-mass black hole in the center of this cluster has been put forward as a way to explain observational trends (Noyola et al. 2008, 2010; van der Marel & Anderson 2010; Miocchi 2010), and tidal breakup of binary stars by the central black hole may lead to the formation of high-velocity stars (Hills 1988, 1991; Yu & Tremaine 2003). The presence of these high-velocity EHB stars in the cluster core may indicate a possible link to close binaries in the cluster core.

We found that Pfahl (2005) has analyzed the binary disruption process by including a black hole with mass $10^2 \sim 10^4\ M_\odot$ in a globular cluster environment, and the total disruption rate for an intermediate mass black hole ($10^3\ M_\odot$) is only 0.1$\sim$1 Myr^{-1}. Pfahl (2005) also found that the disruption process can readily lead to the formation of high-velocity stars ($>$100 km s^{-1}), which can easily escape from their host cluster. It should be noted that the total disruption rate (0.1$\sim$1 Myr^{-1}) derived by Pfahl (2005) is for all binaries in globular clusters, so the disruption rate for EHB binaries is even much lower. If our 45 high-velocity EHB stars originated from binaries, then the disruption rate by an intermediate mass black hole in the cluster center should at least be 45 Myr^{-1}. Indeed, the disruption rate near an intermediate mass black hole may be highly uncertain (Hopman 2009). Hopman (2009) found a much higher disruption rate of 10 Myr^{-1} based on a very different relaxation time from that of Pfahl (2005). So, binary disruption by an intermediate mass black hole cannot be completely excluded for our 45 high-velocity EHB stars, since the disruption rate of binaries near an intermediate mass black hole is highly uncertain. Miller & Hamilton (2002) suggested that $10^3\ M_\odot$ black holes may be common in the centers of dense globular clusters. These high-velocity EHB stars may be dynamical signatures for the presence of an intermediate mass black hole in Omega Centauri. The results of simulations (Lützgendorf et al. 2012) show that the average ejection velocities caused by close encounters may be lower than 100 km s^{-1}, which cannot explain the high velocities (93$\sim$313 km s^{-1}) of these high-velocity EHB stars.

Acknowledgements This research was supported by the National Natural Science Foundation of China (NSFC, Grant No. 11403004) and the School Foundation of Changzhou University (ZMF 1002121). C.L. would like to acknowledge support by the 973 Program (2014CB845702), the Strategic Priority Research Program The Emergence of Cosmological Structures of the Chinese Academy of Sciences (CAS; grant XDB09010100) and by the NSFC (No. 11373054). The authors are grateful for the insightful comments of an anonymous referee, which greatly improved the article. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France.

References

Albrow, M. D., Gilliland, R. L., Brown, T. M., et al. 2001, ApJ, 559, 1060
Allard, F., Wesemael, F., Fontaine, G., Bergeron, P., & Lamontagne, R. 1994, AJ, 107, 1565
Aznar Cuadrado, R., & Jeffery, C. S. 2001, A&A, 368, 994
Bressan, A., Chiosi, C., & Fagotto, F. 1994, ApJS, 94, 63
Dalessandro, E., Lanzoni, B., Beccari, G., et al. 2011, ApJ, 743, 11
Davis, D. S., Richer, H. B., Anderson, J., et al. 2008, AJ, 135, 2155
D'Cruz, N. L., Dorman, B., Rood, R. T., & O'Connell, R. W. 1996, ApJ, 466, 359
D'Souza, R., & Rix, H.-W. 2013, MNRAS, 429, 1887
Gnedin, O. Y., Zhao, H., Pringle, J. E., et al. 2002, ApJ, 568, L23
Gunn, J. E., & Griffin, R. F. 1979, AJ, 84, 752
Han, Z. 2008, A&A, 484, L31

Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R., & Ivanova, N. 2002, MNRAS, 336, 449
Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, MNRAS, 341, 669
Han, Z., Podsiadlowski, P., & Lynas-Gray, A. E. 2007, MNRAS, 380, 1098
Harris, W. E. 1996, AJ, 112, 1487
Heber, U. 1986, A&A, 155, 33
Heber, U. 2009, ARA&A, 47, 211
Heggie, D. C. 1975, MNRAS, 173, 729
Hills, J. G. 1988, Nature, 331, 687
Hills, J. G. 1991, AJ, 102, 704
Hopman, C. 2009, ApJ, 700, 1933
Hut, P., & Bahcall, J. N. 1983, ApJ, 268, 319
Hut, P., McMillan, S., & Romani, R. W. 1992, ApJ, 389, 527
Ivanova, N., Belczynski, K., Fregeau, J. M., & Rasio, F. A. 2005, MNRAS, 358, 572
Lee, Y.-W. 1994, ApJ, 430, L113
Lützgendorf, N., Gualandris, A., Kissler-Patig, M., et al. 2012, A&A, 543, A82
Mandushev, G., Staneva, A., & Spasova, N. 1991, A&A, 252, 94
Maxted, P. f. L., Heber, U., Marsh, T. R., & North, R. C. 2001, MNRAS, 326, 1391
McLaughlin, D. E., & van der Marel, R. P. 2005, ApJS, 161, 304
Mengel, J. G., Norris, J., & Gross, P. G. 1976, ApJ, 204, 488
Meylan, G., & Mayor, M. 1986, A&A, 166, 122
Meylan, G., Dubath, P., & Mayor, M. 1991, ApJ, 383, 587
Meylan, G., & Heggie, D. C. 1997, A&A Rev., 8, 1
Miller, M. C., & Hamilton, D. P. 2002, MNRAS, 330, 232
Miocchi, P. 2010, A&A, 514, A52
Moehler, S., Dreizler, S., Lanz, T., et al. 2011, A&A, 526, A136
Moni Bidin, C., Catelan, M., Villanova, S., et al. 2008a, in Astronomical Society of the Pacific Conference Series, 392, Hot Subdwarf Stars and Related Objects, eds. U. Heber, C. S. Jeffery, & R. Napiwotzki, 27
Moni Bidin, C., Catelan, M., & Altmann, M. 2008b, A&A, 480, L1
Moni Bidin, C., Moehler, S., Piotto, G., Momany, Y., & Recio-Blanco, A. 2009, A&A, 498, 737
Moni Bidin, C., Moehler, S., Piotto, G., et al. 2006, A&A, 451, 499
Moni Bidin, C., Villanova, S., Piotto, G., & Momany, Y. 2011, A&A, 528, A127
Noyola, E., Gebhardt, K., & Bergmann, M. 2008, ApJ, 676, 1008
Noyola, E., Gebhardt, K., Kissler-Patig, M., et al. 2010, ApJ, 719, L60
Pfahl, E. 2005, ApJ, 626, 849
Plummer, H. C. 1911, MNRAS, 71, 460
Richer, H. B., Fahlman, G. G., Buonanno, R., et al. 1991, ApJ, 381, 147
Saffer, R. A., Bergeron, P., Koester, D., & Liebert, J. 1994, ApJ, 432, 351
Sollima, A., Beccari, G., Ferraro, F. R., Fusi Pecci, F., & Sarajedini, A. 2007, MNRAS, 380, 781
Sweigart, A. V. 1997, ApJ, 474, L23
Tillich, A., Heber, U., Geier, S., et al. 2011, A&A, 527, A137
Tutukov, A. V., & Yungel'Son, L. R. 1990, AZh, 67, 109
van der Marel, R. P., & Anderson, J. 2010, ApJ, 710, 1063
van Leeuwen, F., Le Poole, R. S., Reijns, R. A., Freeman, K. C., & de Zeeuw, P. T. 2000, A&A, 360, 472
Webbink, R. F. 1984, ApJ, 277, 355
Yi, S., Demarque, P., & Oemler, Jr., A. 1997, ApJ, 486, 201
Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129