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Searching for classical Be stars in LAMOST DR1

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Abstract We report on searching for Classical B-type emission-line (CBe) stars in the first data release of the Large Sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST; also called the Guo Shou Jing Telescope). A total of 192 objects (including 12 previously known CBes) were identified as CBe candidates with prominent He I $\lambda 4387$, He I $\lambda 4471$ and Mg II $\lambda 4481$ absorption lines, as well as Hβ $\lambda 4861$ and Hα $\lambda 6563$ emission lines. These candidates significantly increase the currently known sample of CBes by about 8%. Most of the CBe candidates are distributed near the Galactic Anti-Center due to the observing strategy used for LAMOST. Only two CBes are in star clusters. These two CBes have ages of 15.8 and 398 Myr, respectively.

Key words: stars: emission-line — Be — stars: early-type — open clusters and associations: general

1 INTRODUCTION

Classical Be stars (CBes) are non-supergiant B-type stars characterized by the Balmer series, that mostly emit Hα $\lambda 6563$ and Hβ $\lambda 4861$ lines. Apart from their emission features, CBes have fast rotation with an equatorial speed reaching $70\% - 80\%$ of breakup velocity (Porter & Rivinius 2003). CBes exist not only in young or intermediate age star clusters but are also isolated in the field. In the past, astronomers concentrated on analysis of the properties of bright CBes with their individual observational data. Nowadays, large sky photometric surveys have made it possible to gain a more general and complete understanding of CBes. Zhang et al. (2005) analyzed the infrared color of 1185 CBe stars with 2MASS (Cutri et al. 2003) data. Raddi et al. (2015) present a catalog of 247 photometrically and spectroscopically confirmed CBes in the direction of the Perseus Arm of the Milky Way from IPHAS data (Drew et al. 2005). Furthermore, Chojnowski et al. (2015) discovered 128 new CBes and increased the total number of known CBes by $\sim 6\%$ using SDSS-III/APOGEE (Eisenstein et al. 2011; Majewski 2012).

The Be Star Spectra database (BeSS[1]) was created by Neiner et al. (2011), in order to collect all existing and future Be star spectra for statistical studies by the Be star community. The BeSS database currently has more than 2000 entries. The sample of CBes remains inhomogeneous because the wide-field spectroscopic observations are time consuming and often limited to bright stars.

[1] *http://basebe.obspm.fr*

Additionally, the sample of CBes is incomprehensive due to the insufficient information on ages or distances. With a large field of view and the highest current spectral acquisition rate, the Large Sky Area Multi-Object Spectroscopic Telescope (LAMOST) survey provides us an excellent opportunity to look for more CBes, thus enlarging the known sample size and giving researchers an opportunity to further study their general properties.

We report on using the LAMOST Data Release 1, hereafter LAMOST DR1, to search for CBes. We have developed an algorithm to identify CBes, and visually inspected their spectra for confirmation. In Section 2, we describe the acquisition of observations and methodology used for identifying Hα emission stars. In Section 3, we discuss the results and in Section 4 we give a summary of this study.

2 THE DATA AND SEARCHING METHODOLOGY

The major dataset utilized for this study was from LAMOST DR1. Additionally, the 2MASS point source catalog was also used to supplement the photometric analysis.

2.1 LAMOST DR1

LAMOST[2], also called the Guo Shou Jing Telescope, is a quasi-meridian reflecting Schmidt telescope located at Xinglong Observing Station in Hebei province, China. The telescope has an effective aperture of 3.6–4.9 m, and a field of view of about 5° in diameter. A total of 16 low-resolution spectrographs, 32 CCDs and 4000 fibers are mounted on the telescope. Each spectrograph has a spectral resolution of $R \sim 1800$ in wavelengths ranging from 3700 Å to 9000 Å (Cui et al. 2012; Zhao et al. 2012; Liu et al. 2015).

The LAMOST DR1 includes more than two million spectra with a limiting magnitude of $r \sim 18.5$ mag that are obtained from the pilot survey and first year general survey (Luo et al. 2012; Luo et al. 2015). The LAMOST DR1 also has stellar catalogs of about 1.2 million spectroscopically classified stars with their atmospheric parameters such as radial velocities, effective temperatures, surface gravities and metallicities. About a quarter of a million stars remain un-classified or not well-classified, which might be due to interstellar extinction in the short wavelength range resulting in a lack of good fittings. In order to identify a large sample of CBe candidates, we analyzed all spectra that had a signal-to-noise ratio (SNR) $\geq$ 10 from the LAMOST DR1.

2.2 The Search Algorithm

The major indicator of a B-type star is the set of hydrogen Balmer absorption lines in conjunction with some neutral helium (He I) absorption lines or an ionized magnesium (Mg II) absorption line. CBes in particular feature hydrogen emission lines mostly at Hα and Hβ, but fade through the rest of the Balmer series. Therefore, we focus on searching for stars with prominent He I $\lambda4387$, He I $\lambda4471$ and Mg II $\lambda4481$ absorption lines, as well as those with Hβ $\lambda4861$ and Hα $\lambda6563$ emission lines.

To quantify these line indexes, we calculated the equivalent width (EW$_\lambda$) of each line by the following equation

$$\mathrm{EW}_\lambda = \int 1 - f_l/\bar{f}_c \, d\lambda \,, \tag{1}$$

where f_l is the flux of each line and $\bar{f}_c$ is the average of the local pseudo-continuum estimated within the 140 Å width of each line. The integration range covered a width of 10 Å. The empirical values of EW$_\lambda$ for lines from known CBes were observed by LAMOST. These values are estimated and summarized in Table 1. The CBe candidates are required to have similar EW$_\lambda$ values as known CBes

[2] *http://www.lamost.org/*

Table 1 Empirical EW_λ of Known CBes in LAMOST

Line	EW_λ (Å)
He I $\lambda4387$	0.387 ± 0.185
He I $\lambda4471$	0.663 ± 0.265
Mg II $\lambda4481$	0.291 ± 0.141
Hβ $\lambda4861$	< 0.33
Hα $\lambda6563$	< 0.50

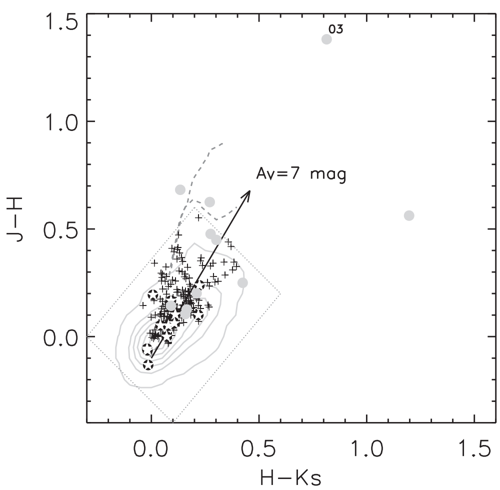

Fig. 1 The 2MASS color-color diagram. The black dashed lines show the giant (*upper*) and dwarf (*lower*) loci (Bessell & Brett 1988) converted to the 2MASS system. The arrow represents the reddening direction (Rieke et al. 1985) for typical Galactic interstellar extinction (radial velocity = 3.1). The gray contours delineate the known distribution of CBes, and the dotted-box is defined as the Be region that includes most CBes. The black crosses are CBe candidates. The known CBes are denoted with white stars and grey filled circles for identified and unidentified, respectively.

at He I $\lambda4387$, He I $\lambda4471$ and Mg II $\lambda4481$ lines. In addition, the values of EW_λ should be less than 0.33 Å and 0.50 Å for the Hβ $\lambda4861$ and Hα $\lambda6563$ lines, respectively.

To rule out contamination by B[e] or Herbig Ae/Be stars, the CBe candidates are also required to have similar colors as known CBes. We define a "Be region" with a $J-H$ versus $H-K_s$ color-color diagram. The Be region could cover most Be stars that are collected from the literatures (Zhang et al. 2005). As shown in Figure 1, gray contours represent over 1000 known CBes. Assuming that most CBes have similar infrared colors, we could thus select CBe candidates inside the gray-dotted region in the color-color diagram. From LAMOST DR1, we finally identified 192 CBe candidates. Among these candidates, 180 are newly discovered CBe candidates and 12 are previously known CBes.

Figure 2 shows the spectrum of one of the CBe candidates, L002, with the Hα emission line, very weak emission superposed on the Hβ absorption line, and the He I $\lambda4387$ and He I $\lambda4471$ absorption lines.

3 RESULTS AND DISCUSSION

Although there are more than 2000 CBes that have been presented by previous studies (Neiner et al. 2011; Zhang et al. 2005; Raddi et al. 2015), only 23 CBes were cross-matched with LAMOST DR1.

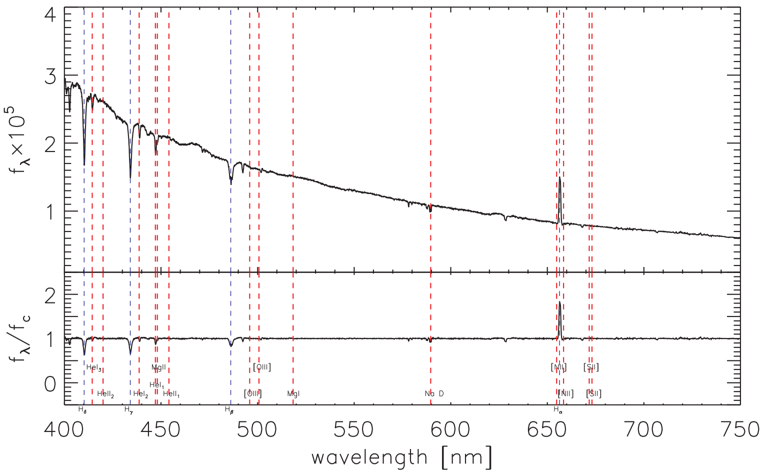

Fig. 2 A spectrum of one newly found CBe L002 in LAMOST DR1. The flux in the upper panel is relative flux. Blue dashed lines indicate the Balmer series, and red dashed lines represent some major lines. The lower panel shows normalized spectra with respect to the pseudo-continuum.

Among these observed CBes, 12 cases were re-identified. Some CBes were not re-identified due to low SNR (five stars) or poor calibration (four stars). Another un-identified known CBe K03, also called GSC 02342–00359, was a young stellar object and classified as an F0-G4 star in NGC 1333 with large reddening as seen in Figure 1 (Liu et al. 1980). The reason may be related to the Hα variability of CBes so that we probably could not identify its Hα emission line at a certain epoch (Rivinius et al. 2013). There was only one known CBe K10 that was not re-identified because of its weak Mg II absorption. Therefore, excluding the spectra with poor calibration and low SNR, the detection rate of CBes is about 85%. The known CBes are listed with their 2MASS magnitudes in Table 2 and some bright ($J < 9$ mag) CBes with matching radii larger than $5''$ are listed below star K13.

The new CBe sample increases the current sample size by about 8%. The CBe candidates are listed with their corresponding 2MASS magnitudes in Table 3 and the associated SIMBAD[3] objects are given in the last column. Although some of these candidates have been identified as emission line stars by Kohoutek & Wehmeyer (1997)[4], the spectral types were not yet confirmed until the LAMOST observations. The spatial distribution of CBe candidates from LAMOST DR1 is shown in Figure 3. Most CBe candidates were found along the Galactic plane, which is similar to results of previous studies. CBe candidates are more concentrated toward the Galactic Anti-Center because of the observing strategy that was used.

The distance and age of CBes can be determined if they are members of star clusters. Using the method of membership identification presented by Yu et al. (2015) that is based on photometric isochrones, spatial distributions and proper motions, we found that only two CBes are members of open clusters. CBe L032 is a member of open cluster Kronberger 18 with an age of $\sim$15.8 Myr and a distance of 2700 pc (Kharchenko et al. 2013). Also, CBe L056 is a member of open cluster FSR 1025 with an age of $\sim$398 Myr and a distance of 2095 pc (Kharchenko et al. 2013). The upper limit on the age of CBes can thus be extended to 398 Myr which is older than what was found from previous studies by McSwain & Gies (2005).

[3] *http://simbad.u-strasbg.fr/simbad/*
[4] *http://www.hs.uni-hamburg.de/DE/Ins/Per/Kohoutek/index.html*

Table 2 23 Known CBes Found in LAMOST DR1

ID	DR1 index	Designation 2MASS	J (mag)	ΔJ (mag)	H (mag)	ΔH (mag)	K_s (mag)	ΔK_s (mag)	Remark
K01	558648	J063259.37+045622.5	9.158	0.027	9.158	0.036	9.087	0.032	detected
K02	356675	J035358.25+465351.8	9.287	0.022	9.049	0.028	8.826	0.023	detected
K03	1542080	J032910.40+312159.2	9.368	0.030	7.987	0.031	7.173	0.023	variant
K04	555829	J063337.49+044847.0	9.395	0.024	8.946	0.023	8.644	0.023	poorly calibrated
K05	567874	J052314.90+374253.6	9.644	0.020	9.582	0.015	9.475	0.015	detected
K06	500325	J051502.46+364155.0	9.971	0.020	9.828	0.019	9.737	0.018	low SNR
K07	436313	J035447.92+445619.6	10.318	0.022	10.218	0.030	10.000	0.023	detected
K08	1752150	J055554.66+284706.3	10.966	0.036	10.914	0.033	10.872	0.027	detected
K09	589106	J063129.76+045449.1	11.449	0.024	10.887	0.025	9.690	0.021	low SNR
K10	588035	J063241.74+045338.4	11.927	0.021	11.822	0.025	11.664	0.024	missed
K11	1745288	J060559.66+280247.7	12.023	0.021	11.341	0.020	11.208	0.018	poorly calibrated
K12	510383	J044927.22+450443.8	12.284	0.020	12.083	0.021	11.873	0.018	low SNR
K13	1556719	J051427.40+324756.8	13.802	0.030	13.177	0.025	12.906	0.031	poorly calibrated
K14	1718553	J051214.46+411300.8	6.373	0.024	5.896	0.033	5.621	0.016	poorly calibrated
K15	587291	J063354.40+043935.2	6.996	0.020	6.945	0.040	6.866	0.023	detected
K16	1768331	J070534.82+142831.7	7.156	0.020	7.220	0.024	7.238	0.024	detected
K17	589139	J063259.01+054756.6	7.640	0.023	7.390	0.049	6.966	0.020	low SNR
K18	638021	J151811.89+313849.2	7.907	0.020	7.713	0.031	7.706	0.016	detected
K19	1749404	J054853.75+290801.7	7.959	0.024	8.015	0.047	8.035	0.029	detected
K20	1496502	J075704.21+025655.6	8.020	0.034	7.917	0.061	7.806	0.024	detected
K21	1620649	J062404.17+252508.1	8.042	0.024	7.916	0.016	7.752	0.018	low SNR
K22	321794	J044440.68+503202.1	8.123	0.020	7.956	0.023	7.865	0.020	detected
K23	447292	J065513.76+052554.4	8.293	0.024	8.425	0.047	8.440	0.021	detected

Notes: K14–K23 are matched from the 2MASS point source catalog with radii larger than 5″.

Table 3 CBe Candidates

ID	Designation	J (mag)	ΔJ (mag)	H (mag)	ΔH (mag)	K_s (mag)	ΔK_s (mag)	SIMBAD
L001	J043131.26+475750.7	9.062	0.027	8.721	0.015	8.435	0.019	EM* MWC 474, Em*
L002	J043953.63+540146.1	9.102	0.021	8.867	0.015	8.598	0.014	BD+47 1000, Em*
L003	J062753.84+003329.1	9.145	0.029	9.010	0.023	8.814	0.021	HD 291668
L004	J054520.88+290928.1	9.164	0.022	9.165	0.021	9.150	0.017	HD 247042
L005	J052948.83+373100.0	9.176	0.024	9.098	0.032	9.018	0.022	BD+37 1207, Em*
L006	J050543.34+353110.7	9.181	0.023	9.068	0.031	8.861	0.023	HD 280498, Em*
L007	J063131.81+053051.7	9.416	0.023	9.285	0.022	9.057	0.021	HD 258983, Em*
L008	J044324.22+542816.5	9.471	0.021	9.119	0.015	8.891	0.021	TYC 3737-1292-1
L009	J054538.09+185753.7	9.508	0.021	9.500	0.024	9.484	0.022	HD 247221, Em*
L010	J064433.60+045757.7	9.669	0.023	9.532	0.021	9.264	0.019	HD 263072, Em*
...	...	...	...	...	...	...	...	...
L032[1]	J065029.43+063621.0	10.453	0.026	10.404	0.023	10.328	0.023	TYC 160-841-1
...	...	...	...	...	...	...	...	...
L056[2]	J051841.29+374030.0	10.975	0.019	10.966	0.028	10.946	0.026	HD 280870, Em*
...	...	...	...	...	...	...	...	...
L171	J053549.34+271917.2	14.988	0.036	14.574	0.049	14.451	0.063	new
L172	J003135.88+434905.3	15.252	0.044	15.185	0.087	15.111	0.123	V* HQ And, Nova
L173	J065742.53+175352.4	15.302	0.067	15.158	0.114	15.197	0.140	new
L174	J004339.36+411008.6	15.616	0.072	15.395	0.107	15.343	0.166	[HIB95] 29-13
L175	J003720.64+401637.6	15.745	0.068	15.486	0.126	15.374	0.196	new
L176	J004510.03+413657.6	15.766	0.070	15.636	0.122	15.562	0.177	new
L177	J052416.11+331819.9	15.803	0.073	15.363	0.103	15.006	0.140	new
L178	J004623.13+413847.4	15.829	0.064	15.697	0.128	15.602	0.170	LGGS J004623.14+413847.5
L179	J052432.28+332654.3	15.916	0.086	15.364	0.085	15.145	0.170	new
L180	J013420.91+303039.6	15.989	0.066	15.887	0.147	15.847	0.209	LGGS J013420.95+303039.9

Notes: [1] a member of the open cluster FSR 1025; [2] a member of the open cluster Kronberger 18.

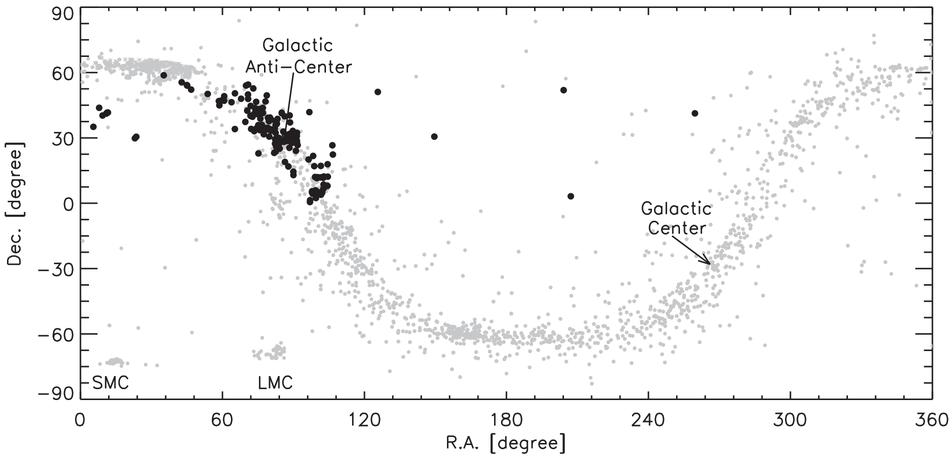

Fig. 3 The spatial distribution of CBes. The small gray dots are known CBes from Zhang et al. (2005), Neiner et al. (2011) and Raddi et al. (2015). The large dots are the CBe candidates from LAMOST DR1. The Galactic Center/Anti-Center and Magellanic Clouds are marked.

4 SUMMARY

We describe a search for CBes using LAMOST DR1. A total of 192 (with 12 previously known CBes) objects were identified as CBes with prominent He I $\lambda4387$, He I $\lambda4471$ and Mg II $\lambda4481$ absorption lines, as well as Hβ $\lambda4861$ and Hα $\lambda6563$ emission lines. These candidates significantly increase the current sample size of CBes by about 8%. Most of the CBe candidates we found are distributed around the Galactic Anti-Center due to the observing strategy used for LAMOST. Only two CBe candidates, L032 and L056, were found to be members of open star clusters. These stars have ages of 15.8 and 398 Myr, respectively.

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References

Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Chojnowski, S. D., Whelan, D. G., Wisniewski, J. P., et al. 2015, AJ, 149, 7
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA (Research in Astronomy and Astrophysics), 12, 1197
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, 2246, 0
Drew, J. E., Greimel, R., Irwin, M. J., et al. 2005, MNRAS, 362, 753
Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, AJ, 142, 72

Kharchenko, N. V., Piskunov, A. E., Schilbach, E., Röser, S., & Scholz, R.-D. 2013, A&A, 558, A53
Kohoutek, L., & Wehmeyer, R. 1997, Astronomische Abhandlungen der Hamburger Sternwarte, 11
Liu, C.-P., Zhang, C.-S., & Kimura, H. 1980, Acta Astronomica Sinica, 21, 354
Liu, X. W., Zhao, G., & Hou, J. L. 2015, RAA (Research in Astronomy and Astrophysics), 15, 1089
Luo, A.-L., Zhang, H.-T., Zhao, Y.-H., et al. 2012, RAA (Research in Astronomy and Astrophysics), 12, 1243
Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2015, RAA (Research in Astronomy and Astrophysics), 15, 1095
Majewski, S. R. 2012, in American Astronomical Society Meeting Abstracts, 219, 205.06
McSwain, M. V., & Gies, D. R. 2005, ApJS, 161, 118
Neiner, C., de Batz, B., Cochard, F., et al. 2011, AJ, 142, 149
Porter, J. M., & Rivinius, T. 2003, PASP, 115, 1153
Raddi, R., Drew, J. E., Steeghs, D., et al. 2015, MNRAS, 446, 274
Rieke, G. H., Cutri, R. M., Black, J. H., et al. 1985, ApJ, 290, 116
Rivinius, T., Carciofi, A. C., & Martayan, C. 2013, A&A Rev., 21, 69
Yu, P. C., Lin, C. C., Chen, W. P., et al. 2015, AJ, 149, 43
Zhang, P., Chen, P. S., & Yang, H. T. 2005, New Astron., 10, 325
Zhao, G., Zhao, Y.-H., Chu, Y.-Q., Jing, Y.-P., & Deng, L.-C. 2012, RAA (Research in Astronomy and Astrophysics), 12, 723