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 λ4387, He I λ4471 and Mg II λ4481 absorption lines, as well as H β λ4861 and Hα λ6563 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 λ6563 and Hβ λ4861 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 ∼ 6% using SDSS-III/APOGEE (Eisenstein et al. 2011; Majewski 2012).

The Be Star Spectra database (BeSS¹) 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, 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 $\lambda$4387, He I $\lambda$4471 and Mg II $\lambda$4481 absorption lines, as well as those with Hβ $\lambda$4861 and Hα $\lambda$6563 emission lines.

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

$$EW_\lambda = \int 1 - \frac{f_l}{\bar{f}_c} \, d\lambda,$$

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.

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1 http://www.lamost.org/
Table 1 Empirical EW\(_\lambda\) of Known CBes in LAMOST

| Line     | EW\(_\lambda\) (Å) |
|----------|---------------------|
| He I \(\lambda\)4387 | 0.387 ± 0.185       |
| He I \(\lambda\)4471  | 0.663 ± 0.265       |
| Mg II \(\lambda\)4481 | 0.291 ± 0.141       |
| H\(\beta\) \(\lambda\)4861 | < 0.33             |
| H\(\alpha\) \(\lambda\)6563 | < 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 \(\lambda\)4387, He I \(\lambda\)4471 and Mg II \(\lambda\)4481 lines. In addition, the values of EW\(_\lambda\) should be less than 0.33 Å and 0.50 Å for the H\(\beta\) \(\lambda\)4861 and H\(\alpha\) \(\lambda\)6563 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 H\(\alpha\) emission line, very weak emission superposed on the H\(\beta\) absorption line, and the He I \(\lambda\)4387 and He I \(\lambda\)4471 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.
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 H\(\alpha\) variability of CBes so that we probably could not identify its H\(\alpha\) 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\(\arcsec\) 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 \(~15.8\) 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 \(~398\) 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).

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\(^3\) 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) | ∆J (mag) | H (mag) | ∆H (mag) | Ks (mag) | ∆Ks (mag) | Remark           |
|------|-----------|-------------------|---------|----------|---------|----------|----------|----------|-----------------|
| K01  | 558648    | J063259.37+045622.5 | 9.158   | 0.027    | 9.158   | 0.036    | 9.087    | 0.032    | detected        |
| K02  | 356675    | J033538.25+653518.1 | 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    | J053447.92+454619.6 | 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  | 580803    | 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  | 1556716   | J051427.40+324756.8 | 13.802  | 0.030    | 13.177  | 0.025    | 12.906   | 0.031    | poorly calibrated |

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

## Table 3 CB Candidates

| ID   | Designation 2MASS | J (mag) | ∆J (mag) | H (mag) | ∆H (mag) | Ks (mag) | ∆Ks (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+290282.1 | 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+524816.5 | 9.471   | 0.021    | 9.199   | 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*  |
| L10  | J064433.60+045757.7 | 9.669   | 0.023    | 9.532   | 0.021    | 9.264    | 0.019    | HD 263072, Em*  |
| L11  | J066556.23+525444.8 | 9.293   | 0.024    | 8.425   | 0.047    | 8.440    | 0.021    | detected        |

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 $\lambda$4387, He I $\lambda$4471 and Mg II $\lambda$4481 absorption lines, as well as H$\beta$ $\lambda$4861 and H$\alpha$ $\lambda$6563 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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