A Catalog of OB Stars from LAMOST Spectroscopic Survey

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Abstract

We present 22,901 OB spectra of 16,032 stars identified from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope data release 5 data set. A larger sample of OB candidates are first selected from the distributions in the spectral line indices’ space. Then, all 22,901 OB spectra are identified by manual inspection. Based on a subsample validation, we find that the completeness of the OB spectra reaches about 89 ± 22% for the stars with spectral types earlier than B7, while around 57 ± 16% B8–B9 stars are identified. The smaller completeness for late B stars will lead to the difficulty in discriminating them from A0–A1-type stars. The subclasses of the OB samples are determined using the software package MKCLASS. With a careful validation using 646 subsamples, we find that MKCLASS can give fairly reliable subtypes and luminosity classes for most of the OB stars. The uncertainty of the spectral subtype is around 1 subtype, and the uncertainty of the luminosity class is around 1 level. However, about 40% of the OB stars fail to be assigned to any class by MKCLASS, and a few spectra are significantly misclassified by MKCLASS. This is likely because the template spectra of MKCLASS are selected from nearby stars in the solar neighborhood, while the OB stars in this work are mostly located in the outer disk and may have lower metallicities. The rotation of the OB stars may also be responsible for the misclassifications. Moreover, we find that the spectral and luminosity classes of the OB stars located in the Galactic latitude larger than 20° are substantially different with those located in the latitude smaller than 20°, which may either be due to the observational selection effect or may hint a different origin of the high Galactic latitude OB stars.

Key words: catalogs – stars: early-type – stars: fundamental parameters – surveys

Supporting material: machine-readable table

1. Introduction

Massive stars (>8 $M_\odot$), historically classified as OB stars, are the main source of chemical enrichment and reionization of the universe, thus they play a major role in the evolution of their host galaxies. They can lead to various types of supernovae (SN), e.g., SN Ib, SN Ic, and SN II P (e.g., Pols 1997; Poelarends et al. 2008). They may also result in a rich diversity of gamma-ray burst (GRB) phenomena, including long GRBs and soft GRBs (e.g., Langer 2012). Through powerful stellar winds and SN explosions, massive stars can strongly influence the chemical and dynamical evolution of galaxies. They may also dominate the integrated ultraviolet (UV) radiation in high-redshift young galaxies.

Because of their enormous intrinsic brightness and short lives, massive OB stars (>8 $M_\odot$, referred as “normal” OB stars hereafter) were usually used as valuable probes of present-day elemental abundances (e.g., Gies & Lambert 1992; Kilian 1992; Venn 1995; Przybilla et al. 2013), especially for the blue supergiants, which are referred as an ideal tracer of extragalactic metallicity (see Kudritzki et al. 2008, 2012, 2014, 2016, and references therein). In addition, through studying the distances of about 30 OB stars in the solar vicinity, Morgan et al. (1952) first published the Milky Way spiral structure sketch. Recently, Xu et al. (2018) identified the distance from Gaia data release 2 (DR2) data (Gaia Collaboration et al. 2018) for about 6000 bright OB stars (Reed 2003) and mapped the nearby spiral arms with this samples. In addition, OB stars are also used as good tracers to explore the size of the Milky Way disk (Carraro et al. 2010, 2017; Carraro 2015), as they can be identified at large distances. Except for the “normal” OB stars, there are also some low-mass OB stars, such as hot subdwarfs, white dwarfs (WDs), blue horizontal-branch (BHB) stars, post-asymptotic giant branch (post-AGB) stars, etc.

Based on some stellar models, massive stars evolve through blue loops, i.e., from the main sequence to blue supergiant, to red supergiant, and then back to blue supergiant again (Schaller et al. 1992). Hence, blue supergiant is an important phase and can tightly constrain the evolution models of massive stars (Maeder et al. 2014). However, to date, we still have poor knowledge of massive stars in the blue supergiant evolution stage, especially how strong their stellar wind affects the evolution. As a consequence, the final destination of blue supergiants is unclear. For instance, if they have sufficient mass loss, they can evolve into a Wolf–Rayet star and finally become a WD, or explode as SN in the Wolf–Rayet stage, or explode directly as SN in the blue supergiant stage (Massey 2003; Crowther 2007; Smartt 2009). Furthermore, the variable stellar winds have also been identified in some blue supergiants from their variable Hα line profile, which made this issue more complicated (Aerts et al. 2010; Kraus et al. 2015; Hauke et al. 2016). In addition, the mass loss during the blue supergiant stage can play a similar role to supernova remnant in the feedback from the massive stars to the interstellar medium (ISM; Negueruela et al. 2010).

Binarity may also play an important role in the evolution of the massive stars (Langer et al. 2008; de Mink et al. 2009; Sana et al. 2013; Sana 2017). In general, massive stars have a high binary fraction (Mason et al. 2009) and most of them belong to...
short period systems (Sana & Evans 2011). Because of the expanding of the evolved primary massive stars, mass exchanging will occur in close binaries between the primaries and their companions, which may drastically alter the evolutionary track of a massive star (Podsiadlowski et al. 1992; Wellstein & Langer 1999; Claeys et al. 2011; Langer 2012).

Rotation is another important physical ingredient for massive stars, which may determine the fate of both single stars and binaries. Domiciano de Souza et al. (2003) pointed out that rotation deforms the star to an oblate shape, and extra mixing may be induced in the interior, which has been used to explain the observed surface abundance anomalies, such as nitrogen enrichment of several massive stars in the main-sequence phase (e.g., Heger & Langer 2000). However, the existence of the highly nitrogen-enriched with slow rotation and relatively non-enriched with fast rotation found in the Very Large Telescope (VLT)-Fibre Large Array Multi-Element Spectrograph (FLAMES) survey samples (see de Mink et al. 2009, and references therein) make the rotational mixing theory still debatable. These massive star samples with accurate abundance determinations and a wide range of rotational velocities were obtained from the VLT-FLAMES survey (Evans et al. 2005; Hunter et al. 2008).

Alternative processes, such as mass transfer in binaries, may also play some role in the nitrogen enhancements of massive main-sequence stars proposed by Langer et al. (2008). In addition, rotation has been identified as an important factor to mass loss of massive stars for the evolution of both a single star and binary (Meynet & Maeder 2000, 2005; Heger & Langer 2000; Ekström et al. 2012; Langer 2012).

To obtain new spectral classifications of at least all Galactic O stars brighter than $B = 13$, the Galactic O-Star Spectroscopic Survey (GOSSS) has been carried out to get high-S/N blue–violet spectra with $R \sim 2500$ for about 1000+ O stars within a few kpc of the Sun (Maíz Apellániz et al. 2011). Sota et al. (2011, 2014) presented spectral classifications for a total of 448 stars, which is almost the largest catalog to date of the Galactic O stars with accurate spectral classification. In order to further study these O stars, such as their binarity, physical parameters, and so on, four other surveys (the Spectroscopic survey of Galactic O and WN stars (OWN), IACOB, the Northern Massive Dim Stars (NoMADS), and the Calar Alto Fiber-fed Echelle Binary Evolution Andalusian Northern Survey (CAFÉ-BEANS)) have also been carried out to obtain high-resolution optical spectroscopy of a subsample of Galactic O stars in parallel to GOSSS (Sota et al. 2014, and references therein). In addition, the Bright Star Catalog, also known as the Yale Bright Star Catalogue, contains 9106 stars and 4 nonstellar objects, of which all stars have $V \leq 6.5$ (Hoffleit & Warren 1991). This catalog contains 50 O stars and 1711 B stars, which can be seen by the naked eye. However, there is no survey project on the schedule that mainly focuses on Galactic B stars. Roman-Lopes et al. (2018) developed a near-infrared semi-empirical spectral classification method and successfully identified four new O stars, which were mistakenly classified as later B stars before, from the DR14 APO Galactic Evolution Experiment (APOGEE) spectra of 92 known OB stars.

While ionized helium (He II) lines appear in O stars, B stars are mainly identified from the optical neutral helium (He I) lines, which will essentially disappear in the spectra of A stars and O stars (Gray & Corbally 2009). Spectral analyses with large and homogeneous samples are very valuable for OB stars, because some new observational constraints can be outlined on their origin and evolutionary status. Furthermore, the distant and faint OB stars in the Milky Way are still rare. In this paper, we identify more Galactic OB stars from the DR5 of the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) survey, which contains around 8 million stellar spectra. Because of this survey mainly focus on the anti-center direction of the Milky Way, more distant and faint Galactic OB stars in the Galactic outer disk are identified in this work. Because their metallicities are lower than the ones in the solar neighborhood, these new OB stars may provide different evolution tracks and thus give new observational constraints.

The paper is organized as the following. In Section 2, we briefly introduce the basic data from LAMOST DR5, and the details of the method to search for OB stars are described in Section 3. In Section 4, the subclassification of the identified OB stars is conducted. In Section 5, we summarize the distribution of different subtypes of OB stars in line indices’ space and in spatial locations. Finally, a short conclusion is drawn in Section 5.

2. Data

2.1. The LAMOST Data

LAMOST, also called Guo Shou Jing telescope, is a 4 m reflective Schmidt telescope with 4000 fibers on a 20-square degree focal plane and a wavelength coverage of 370–900 nm (Cui et al. 2012; Luo et al. 2012; Zhao et al. 2012). The unique design of LAMOST enables it to take 4000 spectra in a single exposure to a dynamical range of magnitude from $r = 9$ to 18 mag at the resolution $R = 1800$ (Deng et al. 2012). The LAMOST survey has finally obtained more than 9 million low-resolution stellar spectra, 8 million of which are stellar spectra, after its 5 yr survey (DR5). Previous works have shown that LAMOST observations are biased more to the giant than the dwarf stars, since the limiting magnitude is relatively bright (Liu et al. 2014; Wan et al. 2015). With such a large amount of spectra, we are able to identify many interesting but relatively rare stellar objects, such as carbon stars (Ji et al. 2016; Li et al. 2018), Mira variables (Yao et al. 2017), or early-type emission line stars (Hou et al. 2016), etc.

2.2. Line Indices

According to Liu et al. (2015, 2017), the selection function of LAMOST survey does not strongly bias to any spectral type of star. This implies that LAMOST catalog should be composed of almost all types of stars. Liu et al. (2015) suggested to classify all types of normal stars from spectral line indices. Compared to the traditional approach to classify the spectral types, using line indices allows a semi-automatic classification. With multiple spectral line indices, various spectral types may transitionally change from one to another, which naturally reflect the variation of the astrophysical parameters, e.g., the effective temperature, surface gravity, and luminosity, from type to type.

The line index in terms of an equivalent width (EW) is defined by the following equation (Worthey 1994; Liu et al. 2015):

$$\text{EW} = \int \left(1 - \frac{F_\lambda}{F_c}\right) d\lambda,$$

(1)
where \( F_\lambda \) and \( F_C \) are the fluxes of spectral line and pseudo-continuum, respectively. \( F_C \) is estimated by linear interpolation of the fluxes located in the “shoulder” region on either side of the line bandpass. The unit of the line index under this definition is in Å. For the spectra with a signal-to-noise ratio (S/N) larger than 15, the typical uncertainty of the EWs of the atomic lines is smaller than 0.1 Å (Liu et al. 2015).

In light of Liu et al. (2015), we identify LAMOST-observed OB-type stars from the selection in line indices’ space. In general, as the hottest normal stars, OB-type stars show moderately weak Balmer lines with strong neutral or ionized He lines. The neutral metal lines, however, are very weak or even disappeared. We apply these features to discriminate OB-type stars from other cooler ones.

We recalculate the EW of spectral lines listed in Table 2 of Liu et al. (2015) for the LAMOST DR5 spectra. Moreover, we additionally calculate the EW of Ca II K line following the definition that the line bandpass is at (3924.7, 3942.7) Å and the two continua bands are at (3903, 3923) and (4000, 4020) Å following Beers et al. (1999) and the EW of He I (4471 Å), provided that the line bandpass is (4462, 4475) Å and the left and right continua are (4450, 4463) and (4485, 4495) Å, respectively. To obtain a stable measurement of Fe, we average over all nine Fe lines defined in Lick indices (Worthey 1994). That is, we denote \( \text{EW}_{\text{Fe}} \) as the mean value of lines 4383, 4531, 4668, 5015, 5270, 5335, 5406, 5709, and 5782 Å.

3. Identification of OB Stars

We first select the stellar spectra with an S/N larger than 15 in the \( g \) band from LAMOST DR5 and obtain 4,940,840 stellar spectra. It should be noted that some stars have been observed multiple times and contribute several spectra.

Second, we map the above stars in Ca II K versus \( \text{H}_{\gamma} \) plane (see Figure 1). We overlap the loci of the main-sequence and giant stars provided by Liu et al. (2015) and find that OB stars are mostly located at the area with smaller values of \( \text{H}_{\gamma} \) and Ca II K. Therefore, we empirically select the area surrounded by the red solid lines such that most of the stars following the loci of the OB types are included. Specifically, we select the stars satisfying the following criteria:

\[
\text{EW}_{\text{CaK}} < 2.5 - \frac{\text{EW}_{\text{H}\gamma}}{8} \tag{2}
\]

and

\[
-4.5 \leq \text{EW}_{\text{H}\gamma} \leq 14. \tag{3}
\]

After applying this cut, 151,902 OB candidates are selected.

Third, we further map the candidate samples in the Fe versus \( \text{H}_{\gamma} \) plane and remove the stars with strong Fe absorption features (see Figure 2). Although the figure indicates the location of the late-type stars, not many late-type stars are in the 151,902 samples after the previous cuts showing in Figure 1. The following empirical criteria is adopted

\[
\text{EW}_{\text{Fe}} < 1.5 \text{ if } \text{EW}_{\text{H}\gamma} < 6, \\
\text{EW}_{\text{Fe}} < -0.1(\text{EW}_{\text{H}\gamma} - 6) + 0.75 \text{ if } \text{EW}_{\text{H}\gamma} \geq 6. \tag{4}
\]

This cut can exclude most of the late-type stars, according to the stellar loci overlapped in the figure. We allow the cut in Fe slightly larger at \( \text{H}_{\gamma} < 6.0 \) to include most of the giant and supergiant stars since they may located in between the locus of the B-type main sequence and that of late-type stars. We finally obtain 122,504 OB candidates, in which 19,681 stars are with \( \text{H}_{\gamma} < 6 \) and 102,823 stars with \( \text{H}_{\gamma} \geq 6 \). The OB candidates with \( \text{H}_{\gamma} \geq 6 \) are substantially contaminated by A, F, and G stars, which have very weak or no He I absorption features.
The EWs of Ca II K, Hγ, Fe, and He I are noted to have negative values, which are due to the variation of the pseudo-continua affected by other absorption lines. These systematics are very difficult to remove since the nearby strong absorption lines make it impossible to find the real continua. Nevertheless, the systematic offsets would not affect the identification of the weak Ca II K, Fe, and Hγ features and strong He I (4471 Å) lines, not because of the absolute values of EWs, but the relative values play key role in the identification of OB stars.

In addition, using the above selection criteria, we may miss the stars without Ca II K, Hγ, or Fe measurements. This is mostly due to the spectra with bad fluxes in the relevant wavelength regions. To identify as many as OB stars, we add additional 2055 stars with incomplete measurements of any of the above lines to the OB star candidates.

We further inspect the spectra for totally 124,559 (122,504 + 2055) OB star candidates by eyes for confirmation. To judge whether the candidate spectra are real OB stars, we mainly used the following line features, such as the Hγ, Hδ, He I lines at 4026, 4387, 4471 Å, He II lines at 4200, 4541, 4686 Å, Mg II at 4481 Å Si III triplet at around 4552 Å, and N III triplet at 4634, 4640, 4642 Å, etc. The spectra without He I and He II line features are first removed. Then, the intensity of the Balmer lines are considered as the indicators of spectral type, because they are prominent and reach the maximum at A2. The ratios of the strengths of He I to He II lines are also used to distinguish O and B stars, because He II lines usually absent in the spectra of B stars and the intensities of He I tends to increase with decreasing temperature while He II decreases. The ratio He I 4471/Mg II 4481 Å is used to diagnose the contaminated stars, when it is less than 0 the star is removed. This procedure has been done at least twice by the same people and has been independently confirmed by other people to avoid severe bias of the judgment.

Finally, we identify 22,901 spectra of 16,032 OB stars from the 124,559 spectra of the candidate sample above via the visual inspection. The final OB sample includes 135 spectra of 91 O stars, 21,658 spectra of 15,087 B stars, 948 spectra of 727 hot subdwarfs (including sdO and sdB), and 160 spectra of 127 WDs. The summary of the numbers are listed in Table 1, and the catalog is listed in Table 3. Because in this work we are only concern with the “normal” OB stars, the hot subdwarfs and WDs selected in this work are not for purpose and thus are not guaranteed to be the complete samples.

![Figure 2. Distribution of 151,902 OB star candidates (the contours) in the Fe vs. Hγ plane. The symbols are same as in Figure 1. The red solid lines, which are based on Equations (4), are the line cuts used to further select OB star candidates.](image)

| Class | No. of Spectra | No. of Stars |
|-------|----------------|--------------|
| OB candidates⁴ | 124559 | ... |
| Normal O stars | 135 | 91 |
| Normal B stars | 21658 | 15087 |
| Normal OB stars⁵ | 21793 | 15178 |
| Hot subdwarfs | 948 | 727 |
| White dwarfs | 160 | 127 |
| Total OB stars⁶ | 22901 | 16032 |

**Notes.**

⁴ The candidates contains 122,504 spectra selected from spectral line indices and 2055 without line measurements.

⁵ This is the sum of normal O and B stars (the above two rows).

⁶ This is the total number of normal OB, hot subdwarfs, and white dwarfs (the sum of the above three rows).
We assign the spectral subtype by-eye inspection for these spectra according to the criteria listed in Table 2. We then map both the previously identified and missed spectra in the Ca II K versus Hγ and Fe versus Hγ planes in Figure 4. It shows that all the identified and missed OB stars comply with the selection criteria described by Equations (2)–(4). This means that the first cuts in the line indices’ space for OB stars are quite robust and essentially do not miss any OB stars.

Figure 5 shows the histograms of the spectral subtypes for the identified and missed OB stars. Based on this small subsample, the completeness of the identified OB stars earlier than B7 is better than 89 ± 22%, while the completeness of the OB stars later than B7 is larger than 57 ± 16%. Note that the missed OB stars are all later than B6. This is probably because the late B-type stars can quite difficult to discriminate from the early A-type stars because weak metal line features are sometimes not that clear.

We also noted that the completeness is under the selection function of LAMOST. LAMOST survey can only select a small fraction of targets to observe. Therefore, the completeness here means how many OB stars we identify from the LAMOST-observed spectra, which is different with the completeness with respect to the intrinsic OB population.

4. Subclassification

To better understand the selected OB stars, assigning a spectral subtype and luminosity class to each of them is critical. We apply MKCLASS, which is an automatic classification package developed by Gray & Corbally (2014), to classify the spectral subtype and luminosity class for the identified OB stars.

4.1. MKCLASS

MKCLASS is designed to classify blue–violet spectra in the MK spectral classification system (Keenan 1993). The direct comparison between the program star and the MK standard stars is carried out by the package during the classification process. The version 1.07 of MKCLASS⁴ is used to classify the 101,086 spectra of 80,447 objects over the entire Kepler field acquired through the LAMOST-Kepler project, which was designed to obtain high-quality, low-resolution spectra of a subsample, the completeness of the identified and missed spectra in the CaII K was 22%, while the completeness of the CaII K region was larger than 5.6 ± 16%. This means that the completeness is under the selection function of LAMOST.

Figures 3 and 4 show the distribution of He I (4471 Å) and Ca II (4226 Å) for 122,846 OB star candidates and 101,169 non-OB stars, respectively. Figure 3 shows the distribution of He I (4471 Å) for 122,846 OB star candidates and 101,159 non-OB stars. Bottom panel: histogram of the EW of He I for 122,846 OB star candidates (black), 21,690 identified normal OB stars (red), and 101,159 non-OB (blue) stars.

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Two MK standard star libraries (i.e., libr036 and libr18) are distributed with MKCLASS: one based on flux-calibrated spectra covered 3800–5600 Å and with a resolution of $R \sim 1100$, while the second one is based on rectified spectra covered 3800–4600 Å and with $R \sim 2200$. MKCLASS can determine the spectral type in terms of the MK system for a normal star and assess its performance of classification using “excellent,” “very good,” “good,” “fair,” and “poor” at the same time. The $\chi^2$ is computed between the program spectrum and the best matched spectrum of the standard star, which is the basis for performance assessment. Through applying successively greater amounts of noise to the spectrum of Kurtz (1984)’s solar flux atlas, Gray & Corbally (2014) investigated the impact of the S/N to the quality of MKCLASS outputs. They found that, for the solar spectrum with an S/N ≥ 20, MKCLASS could give the accurate spectral type G2 V.

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⁴ This can be obtained from http://www.appstate.edu/~grayro/mkclass/.
### Table 2
Criteria for Classifying OB Stars in the Temperature Dimension

| LumType | Criteria |
|---------|----------|
| O2-O3   | He I + II λ4026 < He II λ4200; weak N III 4634-40-42 emission* ↑; weak Si IV 4089-4116 emission ↑; median weak N IV 4058 emission ↑; weak N V 4604-20 ↓ |
|         | Weak He II 4686 | Weaker He II 4686 than class V | Weak He II 4686 emission |
| O4      | He I + II λ4026 < He II λ4200; weak N III 4634-40-42 emission ↑; weak Si IV 4089-4116 emission ↑; weak N V 4604-20 ↓ |
|         | Weak He II 4686 | Weaker He II 4686 than class V | Weak He II 4686 emission; N IV 4058 emission |
| O5      | He II λ4541 > He I λ4471; N III 4634-40-42 emission ↑ |
|         | He II λ4686 ≈ He II λ4541 |
|         | He II λ4686 < He II λ4541 |
|         | weak He II 4686 |
|         | weak Si IV 4116 emission |
|         | N III λ4634-40-42 ≈ He II λ4686 |
|         | He II 4686 emission |
|         | Si IV 4116 emission |
| O6      | He I λ4541 ≈ He I λ4471; N III 4634-40-42 emission ↑; weak Si IV 4089-4116 ↑ |
|         | median weak He II 4686 |
|         | He II λ4541 ≈ He I λ4471 |
|         | Wweak He II 4686 |
|         | He II λ4541 < He I λ4471 |
|         | He II 4686 emission; weak N III λ4097 |
| O7      | He I λ4471 ≈ He II λ4541; N III 4634-40-42 emission ↑; weak Si IV 4089-4116 ↑ |
|         | He II λ4686 > He I λ4471 |
|         | He II λ4686 ≈ He I λ4471 |
|         | Si IV 4686-4504 emission |
|         | He II 4686 emission |
| O8-O9   | He I λ4471 > He II λ4541; weak Si IV 4089 ↑ |
|         | C III λ4650 > He II λ4686 |
|         | Si IV λ4089 < C III λ4187 |
|         | C III λ4650 > He II λ4686 |
|         | Si IV λ4089 ≈ C III λ4187 |
|         | weak Si IV 4686-4504 emission |
|         | Si IV 4686-4504 emission |
|         | He II 4686 emission |
|         | N III λ4097 |
| B0      | Si IV 4552-68-75; weak He II 4200; O II 4070-76 ↑; Si IV 4089 ↑; He II 4686] |
|         | He II λ4686 > He I λ4711 |
|         | Si IV λ4089 > He I λ4121 |
|         | weak O II 4350 |
|         | He II λ4686 < He I λ4713 |
|         | O II 4350, N II 3995 |
|         | strong O II 4350, N III 4097, N II 3995 |
| B1      | Si IV 4552-68-75 ↑; N II 3995 ↑; O II 4070-76 ↑; Si IV 4089 ↑ |
|         | He II λ4552 ≈ Si III λ4568 |
|         | Si III λ4568 ≈ Si III λ4575 |
|         | Si III λ4552 < Si III λ4568 |
|         | Si III λ4568 < Si III λ4575 |
|         | Si III λ4552 > Si III λ4568 |
|         | Si III λ4568 > Si III λ4575 |
|         | strong O II 4350 |
| B2-B3   | Si I λ4128-30 < He I λ4121; He I λ4471 > Mg II λ4481; weak Si III 4552-68-75 ↑; C II 4267; O II 4070-76 ↑ |
|         | Weak He I 4121 |
|         | N II 3995 |
|         | Weak O II 4350, N II 3995 |
| B5      | He I λ4471 > Mg II λ4481; C II 4267; Si II 4128-30 |
|         | Si III λ4552-68-75 absent |
|         | Weak Si III 4552-68-75 |
|         | Weak Si III 4552-68-75 |
|         | Si I λ4128-30 < He I λ4121 |
|         | medium weak Si III 4552-68-75; N II 3995 |
| B7      | He I λ4471 > Mg II λ4481; C II 4267; weak Fe II 4233 |
|         | He I 4121 absent |
|         | Si I λ4128-30 ≈ He I λ4121 |
|         | Si I λ4128-30 < He I λ4121; weak N II 3995 |
| B8      | weak Fe II 4233; weak Si II 4128-30 ↑ |
|         | He I λ4471 < Mg II λ4481 |
|         | He I λ4471 < Mg II λ4481 |
|         | He I λ4471 ≈ Mg II λ4481 |
|         | Si I λ4128-30 > He I λ4444; C II 4267 |
| B9      | He I λ4471 < Mg II λ4481; weak Si II 4128-30 ↑; weak Fe II 4233 |
|         | Weak He I 4026 |
|         | Si II λ4128-30 ≈ He I λ4026 |
|         | Si II λ4128-30 > He I λ4026 |

Notes.

- * This represents emission line, and others are absorption lines.
- † This means the lines strengthen with luminosity class from V to I.
4.2. Subclassification of OB Stars Using MKCLASS

Since the LAMOST spectra are not flux calibrated, we use the library libr18 for the classification. Before performing MKCLASS, we adjust the spectral calibration of the library spectra to make it consistent with the LAMOST spectra. The actual spectral resolution of the LAMOST spectra in blue wavelength is quantified using five strong arc lines at around 4046, 4358, 4678, 4800, 5090, and 5470 Å in the arc spectra (they are Hg and Cd lines since the blue arc lamp is an HgCd lamp, see Han et al. 2018). The median FWHM of these arc lines over ~4000 fibers (a few of dead fibers have been removed) is 2.78 ± 0.07 Å.

Therefore, we convolve the library lib18 to reduce the resolution from 1.8 to 2.8 Å so that its resolution is consistent with LAMOST spectra. We denote the new modified library as Figure 4. Left and right panels display the Ca II K vs. Hγ and Fe vs. Hγ distribution of the OB stars found in an arbitrarily selected 5000 spectra with an S/N > 15 and within Galactic latitude of 20°. The filled circles are OB stars identified with the previous approach, while the filled triangles are those failed to be identified. The colors code the spectral subtypes of these spectra according to the criteria of Table 2. The red lines in both panels stand for the same selection criteria used in Figures 1 and 2, respectively.

Figure 5. Black and red histograms show the distribution of spectral subtypes for the identified and missed OB stars, respectively, in the arbitrarily selected 5000 spectra. The two blue dots align with the right hand-side y-axis, which indicate the completeness of the selection criteria. The left blue dots indicate the completeness for the stars earlier than B7, while the right one indicates the completeness for the stars later than B7.

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### Table 3
OB Stars Identified in LAMOST DR5

| Obsid   | R.A.          | Decl.         | S/N          | Group ID | Group Size | SIMBAD       | MKCLASS     | Manual | Comments |
|---------|---------------|---------------|--------------|----------|------------|--------------|-------------|--------|----------|
| 250905055 | 0.059456      | 50.818608     | 82.53        |          |            | B9 II-III    | B           |        |          |
| 182612068 | 0.341024      | 50.132752     | 170.34       |          |            | B9hF0mK0 Eu  | B           |        |          |
| 250509157 | 0.527828      | 39.183206     | 127.71       |          | B9         | B            | B           |        |          |
| 269504062 | 1.370397      | 57.288634     | 366.68       | A2       | B9 V       | B            |            |        |          |
| 370703213 | 1.385054      | 46.492372     | 197.24       | B7 V     | B          |              |             |        |          |
| 364510227 | 2.630733      | 20.00764      | 256.31       | M9       | B2 II      | B            |             |        |          |
| 178304113 | 2.63467       | 40.198498     | 824.28       | B8       | A0 II      | B            |             |        |          |
| 266712010 | 5.554424      | 3.5839873     | 32.48        |          |            | sdOB         |             |        |          |
| 171114077 | 5.5625166     | 56.5166045    | 113.43       |          |            | B9.5 II-III  | B           |        |          |
| 171102035 | 5.614378      | 54.270211     | 331.61       |          |            | kA0hFzmG5    | B           |        |          |
| 468710180 | 6.949154      | 34.674069     | 85.52        | 2945     | 2          | sdOB         |             |        |          |
| 75091223  | 6.9491834     | 34.674052     | 21.14        | 2945     | 2          | sdOB         |             |        |          |
| 17108164  | 8.4675215     | 55.1001548    | 135.23       |          |            | B5 II        | B3 V        |        |          |
| 17159980  | 9.792189      | 56.815578     | 382.28       |          |            | B9 V         | B9.5 V      |        |          |
| 469316204 | 9.922347      | 58.743764     | 468.34       |          |            | ?            | B           |        |          |
| 55601164  | 10.44285      | 25.82604      | 213.21       | 935      | 5          | A3           | A9 mB9.5 V Lam Boo | B |
| 59401164  | 10.44285      | 25.82604      | 160.12       | 935      | 5          | A3           | A9 mB9 V Lam Boo | B |
| 157501164 | 10.442872     | 25.826017     | 553.11       | 935      | 5          | A3           | A9 mB7 V Lam Boo | B |
| 157601164 | 10.442872     | 25.826017     | 609.77       | 935      | 5          | A3           | A9 mB9 V Lam Boo | B |
| 194411065 | 10.442872     | 25.826017     | 909.16       | 935      | 5          | A3           | A9 a0 V Lam Boo | B |
| 353516249 | 15.840044     | 49.225157     | 27.18        | 2908     | 2          | WD           |             |        |          |
| 403216249 | 15.840044     | 49.225157     | 17.48        | 2908     | 2          | WD           |             |        |          |
| 368502216 | 18.444903     | 0.4746379     | 93.91        |          |            | DO           | WD          |        |          |
| 392201217 | 19.8885832    | 39.6548095    | 222.77       | 1976     | 3          | B5 II        | B5 II       |        |          |
| 392912106 | 19.8885832    | 39.6548095    | 200.05       | 1976     | 3          | B5 II        | B5 II       |        |          |
| 90810208  | 19.88863      | 39.654762     | 242.13       | 1976     | 3          | B5 II        | B5 II       |        |          |
| 380814123 | 26.899496     | 55.426933     | 346.78       |          |            | B1 V         | B2 V        |        |          |
| 380810029 | 27.958356     | 53.846751     | 416.5        |          |            | B2 IV-V      | B3 III      |        |          |
| 380812034 | 33.163063     | 56.548868     | 401.34       |          |            | B1 V         | B3 III      |        |          |
| 180305005 | 35.715096     | 41.479483     | 23.95        | 1948     | 2          | kB8hA1mA4    | O           |        |          |
| 180405005 | 35.715712     | 41.480129     | 31.34        | 1948     | 2          |                | O           |        |          |
| 15507059  | 35.7392       | 57.009        | 135.03       |          |            | Unclassifiable| B           |        |          |

Notes.

a The signal to noise at the g band.
b The ID number of the star that was observed many times.
c The number of exposures for the same star.
d The spectral/luminosity type identified by eye in this work.
e The “peculiar” spectra identified by eye.

(This table is available in its entirety in machine-readable form.)

**Figure 6.** Distribution of stars in the spectral subtype vs. luminosity class plane according to the results from MKCLASS with quality evaluation better than “good” and including “good.” The number of stars that fell in each small bin is drawn in different gray levels and is also marked as text in the figure. The rows between two luminosity types are those MKCLASS assigns to both types. For instance, the row between II and III are those II–III given by MKCLASS.
Then, we submit the 21,793 normalized spectra of our identified normal OB stars (subdwarfs and WDs are excluded) to MKCLASS. The output results are listed in Table 3. The eighth column is the MK spectral type identified by MKCLASS in the standard format, i.e., the spectral subtype at the first place, followed by the luminosity class.

Figure 6 shows the distribution of stars in the spectral subtype versus luminosity class plane according to MKCLASS with quality evaluation better than “good” and including “good.” It shows that most of the OB stars are distributed between B3 and A1 in their spectral type. Only 123 are classified as O-type stars. Five hundred twenty four stars are even classified as F-type stars. While most of the OB-type stars are in luminosity class V (main sequence), two substantial giant/supergiant branches are displayed in the figure: one is located at around B4–B5 and the other is at around B8–A0. If we focus on the overdensities of the distribution, two substantial overdensities can be seen at B4 V with 1100 samples and B9 II–III with 591 stars, respectively. The branches and overdensities reflect the combination of the intrinsic distribution of the OB stars in the spectral and luminosity types and the observational selection effect.

According to the online documentation, the libr18 spectral library only contains stars up to spectral type O9. This means that MKCLASS would not be able to identify any star earlier than O9. Figure 7 shows the histograms of the results identified by the MKCLASS for 135 spectra of 91 O stars identified in the by-eye analysis (see Table 3). As can be seen, except results with labels “?” or “??,” most of O stars identified via visual analysis are identified as type O9 by MKCLASS.

**4.3. Quality Flags from MKCLASS**

Among the results of subclassification, 209 spectra are rated as “excellent” with the median S/N = 427 at the g band, 8109 as “verygood” with S/N = 166, 3279 as “good” with S/N = 50, 762 as “fair” with S/N = 96, and 1 as “poor” with S/N = 19. Gray et al. (2016) pointed out that spectral types with “fair” are uncertain and those with “poor” are unreliable. These two quality categories are usually assigned to the spectra with substantial defects or a low S/N.

Figure 8 shows the correlation between the quality flags from MKCLASS and S/N of the spectra. It shows that the “excellent” results are only for the spectra with an S/N larger than 200. Most of the spectra with an S/N larger than 100 obtain the quality level of “verygood.” Most of the stars with an S/N lower than 100 are assigned with “good” and “fair.” Note that there are also 273 stars with an S/N larger than 200
assigned with “good” and “fair.” This is mostly because (1) a few spectra have overestimated the S/N and (2) MKCLASS may significantly misclassify the subtypes for a few stars.

The top panel of Figure 9 shows the distribution of the spectral types of the OB stars obtained from MKCLASS. While not many spectra are qualified as “excellent,” we show that the majority are the stars with quality of “verygood,” covering from type O9 to A1. A trend is that the distribution of the spectral types shows two peaks at B4 and B9, respectively. The two peaks are likely due to the two overdensities located at B4 V and B9 II–III, respectively, displayed in Figure 6. There are 1205 OB spectra misclassified as F-type stars with a quality level of “good” and “fair.” We analyze some of the sample of these spectra in Section 4.4.

The bottom panel shows the distribution of the luminosity class from MKCLASS. As expected, most of the stars are main-sequence (V) stars. The quality flags “fair” only appear in luminosity classes I and V.

### 4.4. Issues of the MKCLASS Results

Some of the OB spectra are not correctly classified by MKCLASS.

MKCLASS assigns question marks to 4922 spectra. According to Gray et al. (2016), this is likely because some fluxes in the spectra are negative. However, when we investigate the spectra in detail, we find many of them are normal B-type stars. Figure 10 shows some of a sample of spectra classified by MKCLASS with labeled with question marks (see the first to third spectra). From this figure, we can see that this issue is mainly due to the spectra with emission lines (first spectrum), lower signal to noise (second), or strong helium lines (third).

Meanwhile, MKCLASS assigns “Unclassifiable” for 89 spectra. Gray et al. (2016) thought that these are because of the negative fluxes in the cores of strong lines (e.g., Ca II K), which are introduced by the excessive background subtraction. We investigate these spectra and find that many of them look normal (see the fourth spectrum in Figure 10). The fourth
The spectrum seems have stronger He I lines than the template spectrum. Moreover, MKCLASS cannot converge to a single type but provides discrepant classifications with different criteria for 4422 spectra. In these cases, MKCLASS outputs flags like "kB8hA9mK0 Eu," which means that the K-line determined spectral type is B8, the hydrogen-line determined type is A9, and the metallic-line classified type is K0 (e.g., see the fifth spectrum in Figure 10). In the mean time, the star may show strong Eu lines, which should not be true for early-type stars. This kind of results are because MKCLASS determines separate temperature types using the CaII K line, the hydrogen lines, and the general metallic lines from the spectra. When these determinations are not consistent, MKCLASS tends to give a long and complicated special type. There is no quality evaluations given for this kind of classifications.

4.5. Assess Performance of the MKCLASS

We access the performance of MKCLASS in two ways. First, we use the OB stars with multiple observations to check the consistency of the MKCLASS. For each observed spectra, we have one MKCLASS classification. For the OB stars with multiple observations, we can compare whether MKCLASS assigns consistent classes for same stars based on different epoch spectra. Figure 12 shows the distribution of the standard deviations of the spectral and luminosity types of the repeatedly observed OB stars. We can see that, for most of the stars with multiple observations, the MKCLASS can give consistent spectral and luminosity types with dispersions of about 1 subtype and 0.5 luminosity level, respectively.

Second, we arbitrarily select 1000 OB stars to independently classify them by eye. When we do the manual inspection, we do not know the results of classification from MKCLASS. In other word, this test is a blind test. Based on Gray & Corbally (2009) and considering the low-resolution characteristics of the LAMOST spectra, we select a set of the most prominent features to discriminate the spectral and luminosity types.

For O-type stars, the prominent features include HeI and He II lines at 4026, 4200, 4541, and 4686 Å, which are a group of NIII lines located at 4634–4640–4642 Å. HeII 4200, 4541, and HeI/II 4026 reach their maximum at O5. They are weakened when the luminosity type changes from dwarf to giant. They become very weak or even become emission lines in the spectra of supergiants. The N III lines strengthen from O2 to O4 and then weaken when the spectral type changes to O7. Meanwhile, these lines also become stronger in giant stars (Walborn & Fitzpatrick 1990; Lennon 1997; Gray & Corbally 2009; Sota et al. 2011).

For B-type stars, the line ratio between He I 4471 and Mg II 4481 Å is the well-known indicator of the spectral type. Luminosity types of B-type stars are usually discriminated by looking at the ionized metal lines, e.g., Si II 4128–4130, Si III 4552–4568–4575, C II 4267, N II 3995 Å, etc.

More detailed criteria for discrimination of the spectral subtype and luminosity class are listed in Table 2. In this table, the first row of each spectral subtype gives the general features.
Figure 13. Panels from top to bottom show the sequence of the manually classified luminosity classes, i.e., V, III, and I, respectively. The sequence of manually classified spectral subtypes for sample spectra are displayed in each panel. The corresponding spectral subtypes, luminosity classes, and the \textit{obsid} (the ID of a spectrum in the LAMOST catalog) are marked under the corresponding spectra. Important line features are marked in the plots.
of the subtype. The second row of each subtype provides the criteria of the luminosity classification.

Based on all these criteria, we obtain the spectral subtypes and luminosity classes of all the arbitrarily selected OB stars. Compared to MKCLASS results, 646 of the 1000 spectra are assigned meaningful subclasses (not “?” or “Unclassifiable”) with quality flags of at least “good” by MKCLASS. We then assess the performance of MKCLASS only using these 646 “good” or better spectra.

To validate the manual classification, we select the representative spectra and sort them in the sequence of the manually classified luminosity classes in Figure 13. The sequence of manually classified spectral subtypes for sample spectra are displayed in each panel.

In the top panel, in which the sequence of spectral subtypes for main-sequence stars are displayed, the features that indicate the change of the spectral subtypes are clearly seen. For instance, He I 4471 are first strengthened and then weakened from B1 V (top) to B9 V (bottom). The most insensitive, He I 4471, displays at B3 V, while Mg II gradually strengthens when the spectral types become later. The other He I lines show a trend similar to 4471 Å line. In the mean time, the Balmer lines become stronger from top to bottom.

The bottom panel shows the sequence of spectral subtypes for supergiants. Essentially, the metal lines, such as Si III, Si IV, O II, and C II, are stronger in supergiant, while Balmer lines are shallower.

The variance of the spectral line features along either the sequence of spectral subtypes or luminosity classes are consistent with Gray & Corbally (2009). This confirms that the manual inspection and classification of the subsamples of the OB stars are reliable.

We compare the spectral subtypes and luminosity subtypes between the manual classification results and those from MKCLASS. Figure 14 shows the histograms of the difference (manual class–MKCLASS) of the spectral subtypes (top panel) and luminosity classes (bottom panel). For convenience, the numbers are used to represent the spectral subtype and luminosity subtype, which are 0.1-0.9 for O1-O9, 1.0-1.9 for B0-B9, and I-5 for I-V, respectively.

We find that, in the top panel, the mean value of the difference (blue dashed line) is at around +0.025, implying that the manually classified spectral subtype is consistent with the results from MKCLASS. Moreover, the 15% and 85% percentiles in the differences show that the dispersion between the two methods is less than 1 subtype. This confirms that, statistically, MKCLASS can obtain quite reliable results for most of the OB-type stars.

The difference of luminosity classes shown in the bottom panel seems more scattered than the spectral subtype, although the mean value of the difference of the luminosity class is also located at around zero. This is reasonable because the features sensitive to luminosity are mostly weak and are not easily well investigated in low-resolution spectra. The 15% and 85% percentiles show that the dispersion between the two methods is about one level of the luminosity class.

Note that from Figure 14 there are 28 and 52 stars that show larger than a 3σ difference in the spectral and luminosity type between the manual approach and MKCLASS. We double checked these spectra and find that mostly MKCLASS has mistakenly assigned the subclass. Figure 15 shows some samples. The first spectrum misclassified as “B3 V” in MKCLASS is actually a “B8 III-type star according to its weaker He I lines, its similar strength between He I 4471 and Mg II 4481 Å, and its visibly weak Si II 4128-30 lines. The second spectrum, which is obviously a “B3 V” star according to their relatively stronger He I 4471 than Mg II 4481 Å, is misclassified as “F4 V” by MKCLASS. MKCLASS assigns a type of “B5 Ib-II” to the third spectrum, which is actually a “B9 Ib-type star with its weaker He I 4471 and strong middle Mg II 4481 Å. The fourth spectrum should be a “B3 II”-type star with its weaker Balmer lines and weak O II 4070/4076 Å, which is misclassified as “B1 V.” MKCLASS assigns “B4 Ib-II” to the fifth spectrum, which should be “B1 V” based on its visible Si IV 4089 and the absence of C II 4267.

Nevertheless, statistically, MKCLASS performs pretty well for most of the OB-type stars. Misclassifications in a small fraction of samples may be due to the lack of the template OB-type spectra in MKCLASS. Indeed, the template spectra are mostly from the stars near the Sun, while the LAMOST OB samples distribute in a wide range of Galactocentric radii in the Galactic outer disk. As a consequence, the LAMOST OB stars have, in general, a lower metallicity than the template, providing a radial metallicity gradient (Dafān & Cunha 2004). Therefore, given the same spectral subtype (which is a proxy of
effective temperature) and luminosity class (a proxy of surface gravity), the corresponding weak metal lines for the observed samples are not necessarily the same as the template spectra. Finally, relatively larger rotation of the early-type stars may be another reason to distort the classification.

5. Discussion and Conclusions

5.1. Distribution in Line Indices’ Space

Figure 16 shows the distributions of the identified OB stars in \( \text{He}\,\text{I} (4471\,\text{Å}) \) versus \( \text{H}\,\gamma (4340\,\text{Å}) \) plane (filled circles). The colorful stars indicate the median positions of the spectral subtypes coded with colors for the luminosity class V stars. The triangles indicate the locus of the luminosity class III stars with the color-coded spectral subtypes.

Figure 16. Distribution of the OB-type stars in \( \text{He}\,\text{I} (4471\,\text{Å}) \) vs. \( \text{H}\,\gamma (4340\,\text{Å}) \) plane (filled circles). The colorful stars indicate the median positions of the spectral subtypes coded with colors for the luminosity class V stars. The triangles indicate the locus of the luminosity class III stars with the color-coded spectral subtypes.

Figure 17. Distributions of OB stars in Galactic latitude. The black line indicates the distribution of all OB stars, while the red triangles, green crosses, and blue filled circles display the distributions for the IV/V-, III-, and I/II-type stars. The y-axis is in logarithmic scale.

Figure 17. Distributions of OB stars in Galactic latitude. The black line indicates the distribution of all OB stars, while the red triangles, green crosses, and blue filled circles display the distributions for the IV/V-, III-, and I/II-type stars. The y-axis is in logarithmic scale.

Figure 15. Sample spectra that have substantially inconsistent classifications between manual inspection and MKCLASS. The best-fit spectra from the MKCLASS library are also provided by red dashed lines for comparison.

Figure 15. Sample spectra that have substantially inconsistent classifications between manual inspection and MKCLASS. The best-fit spectra from the MKCLASS library are also provided by red dashed lines for comparison.
should be found. Figure 18 shows that the distributions of the OB stars in Galactic latitude larger than 20° are substantially different, which may either be due to the observational selection effect or may hint a different origin of the high Galactic latitude OB stars. The stars located in high Galactic latitude are mostly concentrated between B3 and A0, while the stars located at low Galactic latitude show more spectral types earlier than B3 and also a substantial O9–B0 branch.

A few channels can explain the high Galactic latitude OB stars. First, some of them are scattered massive stars that originally formed in the disk (Martin 2004). Second, some of them may be formed in situ (Keenan et al. 1986). Third, some are evolved stars, such as BHB stars or post-AGB stars (Tobin 1987). To better distinguish the nature of them, a medium or high spectral resolution observation is required.

### 5.2. Spatial Distribution

Figure 17 shows the distribution of all 21,793 OB spectra in Galactic latitude. While most of them are located in the low Galactic latitudes as expected, 886 of them located at high Galactic latitude (>20° or <−20°), in which few massive stars should be found. Figure 18 shows that the distributions of the OB stars in Galactic latitude larger than 20° (left panel) and smaller than 20° (right panel) are substantially different, which may either be due to the observational selection effect or may hint a different origin of the high Galactic latitude OB stars. The stars located in high Galactic latitude are mostly concentrated between B3 and A0, while the stars located at low Galactic latitude show more spectral types earlier than B3 and also a substantial O9–B0 branch.

The spatial distribution in Galactic coordinates shows that most of the OB stars are located at low Galactic latitude. The spectral classes for the high Galactic latitude OB stars are substantially different than those located in the low Galactic latitude, which may either be due to the observational selection effect or may hint a different origin of the high Galactic latitude OB stars. These high Galactic latitude OB stars are particularly interesting in the sense that their origin is not clear. According to previous studies, some of these stars are likely runaway stars scattered from the disk population, and a few of them should be low-mass evolved BHB or post-AGB stars. It is worth following up with high spectral resolution observations for these samples in the future.

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Software: MKCLASS (Gray & Corbally 2014).

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### References

Aerts, C., Lefever, K., Baglin, A., et al. 2010, A&A, 513, L11  
Beers, T. C., Rossi, S., Norris, J. E., Ryan, S. G., & Sheilds, T. 1999, AJ, 117, 981  
Carraro, G. 2015, BAAA, 57, 138  
Carraro, G., Sales Silva, J. V., Moni Bidin, C., & Vazquez, R. A. 2017, AJ, 153, 99  
Carraro, G., Vázquez, R. A., Costa, E., Perren, G., & Moitinho, A. 2010, ApJ, 718, 683  
Claey, J. S. W., de Mink, S. E., Pols, O. R., Eldridge, J. J., & Baes, M. 2011, A&A, 528, A131
