New Oe Stars in LAMOST DR5

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Abstract

Stars of spectral type Oe are very rare. To date, only 13 Oe stars have been identified within our Galaxy. In this paper, we present six new Oe stars and four new B0e stars found in LAMOST DR5. Repeated spectral observations of the same Oe stars show some emission-line variability. The Hβ emission of TYC 4801-17-1 shows rapid V/R variation. Phase lags in the V/R ratio of TYC 4801-17-1 spectra are also seen. We found that the unusual O4.5 star RL 128 is an Oe star with variable Hα intensity and its Ca II triplet emission appears when Hα emission reaches maximum intensity. These newly identified early-type Oe and B0e stars significantly increase the known sample.

Key words: stars: early-type – stars: emission-line, Be – stars: massive

1. Introduction

The classic Oe spectral stellar type was defined by Conti & Leep (1974) as O-type spectra showing emission in the hydrogen lines, but without NIII λ4634-4640-4642 or He II λ4686 emission features. Some Oe stars additionally show emission in their He I lines. Stars of type Oe are often characterized by rapid rotation and double-peaked Balmer emission lines. Differences between the origins of P Cyg profile (from strong stellar winds, not a characteristic of Oe stars) and the double-peaked emission profile characteristic of the Oe spectral type was clearly noted in Figure 11 of Conti & Leep (1974).

Stars of type Oe are very rare (Negueruela et al. 2004). To date, there are only 13 Oe stars known in the Galaxy, reproduced here in Table 1. The Galactic O Star Spectroscopic Survey (GOSSS; Sota et al. 2011, 2014; Golden-Marx et al. 2016) confirms an Oe/O ratio of 0.03 ± 0.01. For comparison, Zorec & Briot (1997) present a mean Be/B ratio of at least 17%, while a B1e/B1 ratio is even as high as 34%. These statistics are consistent with Oe stars representing the hot end of the Be temperature distribution, with the mechanism, a rotating disk, being common to Be and Oe stars. The rarity of Oe stars can be attributed to the hot strong O star stellar winds blowing away the envelope around the star and in most cases preventing formation of a rotating disk, where characteristic (Oe and Be) double-peaked emission lines originate. However, Vink et al. (2009) suggested that Oe stars earlier than O9.5 have a different origin from classic Be stars.

Metallicity can affect the stellar wind, as stars with lower metallicity tend to have weaker winds. A stellar wind can take away angular momentum so that a more metal-poor star with less wind rotates more rapidly. Thus, a metal-poor star can form a rotating disk more easily, which can be retained even by the much hotter star. Golden-Marx et al. (2016) presented about 30 classical Oe stars in the Small Magellanic Cloud (SMC). The Oe/O frequency in the SMC is 0.26 ± 0.04, much higher than that in the Galaxy. There are also four known LMC Oe stars with types as hot as O6 and O7. One of them, star 77616, even shows double-peaked He II λ4686 emission (Golden-Marx et al. 2016).

Similar to classical Be stars, Oe stars often show significant emission-line variability: Rauw (2015) found that Hα, Hβ, and He I λ5876 of two original Oe stars, HD 45 314 and HD 60 848, showed strong variations. For HD 60 848, the variations of the equivalent widths of these lines are obviously asynchronous, while for HD 45 314, the emission lines are highly asymmetric and display strong line profile variations, and in 2013, these lines even changed from double-peaked to single-peaked. HD 120 678 also shows both complex light and spectral variations (Gamen et al. 2012). The origins of these variations are still unknown. A summary of long-term V/R (the ratio of violet peak strength to the red peak strength) variations can be found in Rivinius et al. (2013) and references therein.

Earlier stellar types have stronger stellar winds, so most Oe stars are later-O-type stars. The spectral classification of an O star is based on the ratio of the equivalent width of He II λ4542 to He I λ4471, where later O types have a small ratio. This standard, however, is not reliable for the Oe class. Frost & Conti (1976) noticed that He I λ4471 of HD 39 680 and HD 60 848 may suffer from emission infilling, which results in higher EW(He II λ4542)/EW(He I λ4471), thus mimicking earlier spectral types. All of the spectral types given in Table 1 are from the standard classification methodology—some may be cooler than their spectral type suggests.

Details of the formation of the rotating “decretion” (outwardly moving) disks in Oe (and Be) stars remain complex and puzzling (Struve 1931; Osaki 1986; Lee et al. 1991; Rivinius et al. 2001; Zorec et al. 2016, 2017). Undoubtedly, a larger Oe sample can help us to understand the nature of this type of emission-line star.

Further identifying characteristics of Oe (and related Be) spectra to be kept in mind as we search the LAMOST DR5 sample for new members of the class that Porter & Rivinius (2003) summarized: (1) Classical Be stars are non-supergiant (i.e., luminosity class V to III) B stars with line emission in Balmer lines (and possibly other lines), The Be phenomenon is complex: not all B stars with emission lines are classical Be
Table 1
Previously Known Galactic Oe Stars

| Name                  | R.A. (degree) | Decl. (degree) | Spectral Type | References                  |
|-----------------------|--------------|----------------|---------------|-----------------------------|
| HD 24 534 (X Per)     | 58.846151    | 31.045837      | OBe           | Conti & Leep (1974)         |
|                       |              |                | B0 Ve         | Negueruela et al. (2004)    |
|                       |              |                | O9.5: npe     | Sota et al. (2011)          |
| HD 39 680             | 88.686377    | 3.854734       | O6 V:npe      | Walborn (1973)              |
|                       |              |                | O8.5 Ve       | Negueruela et al. (2004)    |
|                       |              |                | O6 V:npe var  | Sota et al. (2011)          |
| HD 45 314             | 96.815740    | 14.889224      | OBe           | Conti & Leep (1974)         |
|                       |              |                | B0 IVe        | Negueruela et al. (2004)    |
|                       |              |                | O9: npe       | Sota et al. (2011)          |
| HD 46 056             | 97.836912    | 4.834401       | O8 V(e)       | Frost & Conti (1976)        |
|                       |              |                | O8 Vn         | Sota et al. (2011)          |
| HD 60 848             | 114.273880   | 16.904252      | O8 V:pe       | Morgan et al. (1955)        |
|                       |              |                | O9.5 IVe      | Negueruela et al. (2004)    |
|                       |              |                | O8 V:pe       | Sota et al. (2011)          |
| HD 149 757 (ζ Oph)    | 249.289741   | −10.567090     | O9 V(e)       | Conti & Leep (1974)         |
|                       |              |                | O9.5 IV       | Negueruela et al. (2004)    |
|                       |              |                | O9.2 IIVm     | Sota et al. (2014)          |
| HD 155 806            | 258.830199   | −33.548421     | O7.5 IIIe     | Conti & Leep (1974)         |
|                       |              |                | O7.5 III((f)e) | Negueruela et al. (2004)    |
|                       |              |                | O7.5 V((f)z(e)) | Sota et al. (2014)          |
| HD 203 064(68 Cyg)    | 319.613257   | 43.945967      | O8 V(e)       | Conti & Leep (1974)         |
|                       |              |                | O7.5 III(n(f)) | Sota et al. (2011)          |
| HD 240 234            | 348.64358    | 59.83678       | O9.7 IIIe     | Negueruela et al. (2004)    |
| HD 17 520 B           | 42.810071    | 60.386118      | O9: Ve        | Sota et al. (2011)          |
| HD 93 190             | 161.081738   | −59.283011     | O9.7: V(n:e)  | Sota et al. (2014)          |
| HD 120 678            | 208.235085   | −62.720624     | O9.5 Ve       | Sota et al. (2014)          |
| V441 Pup              | 112.223241   | −26.108020     | O5: Ve        | Maíz Apellániz et al. (2016)|

Note. Bold values denote that the spectral type is O8 Vn in Sota et al. (2011).

Regarding O stars, there are several categories that include emission lines without being Oe stars. Indeed, Oe stars are a minority among O stars with emission lines. Sota et al. (2011, 2014) list the other types of O stars with emission lines: Ofc, Ofnp, O?p, early Of/WN, and O Iafpe. We also note that, as the resolution of the LAMOST spectrographs are typically $R \sim 1800$, when classifying Oe stars we should distinguish between observed/strict/uncorrected spectral types and those corrected for the infilling of He I 4471, something that can be done only with good-quality, high-resolution spectroscopy (see, e.g., the paragraph on V441 Pup in Maíz Apellániz et al. (2016)). In spite of these complexities, we believe uncovering more samples of the Oe phenomenon is important toward further progress in understanding their origins.

The paper is organized as follows. In Section 2, we introduce LAMOST and the selection method of the sample. New Oe and B0e stars found in LAMOST DR5 are presented in Sections 3 and 4, respectively. Finally, conclusions are given in Section 5.

2. Introduction to LAMOST and the Selection Method of the Sample

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; also called Guoshoujing Telescope;
Figure 1. Blue spectra of Oe stars.
Wang et al. 1996; Su & Cui 2004; Cui et al. 2012) is a special reflecting Schmidt telescope with a 5° field of view and effective aperture of 3.6–4.9 m. It accommodates 4000 fibers on its focal plane and can obtain nearly 4000 spectra during one exposure. Its wavelength coverage is 3650–9000 Å with \( R \sim 1800. \) Each of the 16 spectrographs records images of 250 fibers on two 4 K \( \times 4 \) K CCDs. As of the end of 2017 July, more than 9 million spectra have been obtained.³

³ See http://dr5.lamost.org/.

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**Figure 2.** Hα emission of selected Oe stars. The red line is the central wavelength of Hα.
We select candidate O-type stars in LAMOST DR5 by using the O-type spectral star criteria given by Maíz Apellániz et al. (2016), then the Oe candidates stars are further selected by eye. We checked all 2D and 1D LAMOST spectra of individual exposures of Oe stars and rejected bad pixels or pixels contaminated by cosmic rays or poorly subtracted sky lines. All candidate Oe stars were previously cataloged as being of early type (usually late O or early B), though some of the previous observations date back decades. Some, but not all, had emission noted, but none of our Oe (B0e) identified objects had previously been classified of the Oe (B0e) type.

We note that the wavelengths in LAMOST spectra are all in vacuum, but to be coherent with the literature, lines are still named by their air wavelengths. The spectral classification methodology and luminosity criterion used in this paper are from Sota et al. (2011, 2014) and Maíz Apellániz et al. (2016).

3. New Oe Stars in LAMOST DR5

Details of spectra of the six stars that we newly identify from LAMOST spectra as meriting the Oe spectral class are given here.

Figure 3. The z-band spectra of selected Oe stars. The amplitudes of the emission lines are suppressed for readability. Ca II triplets are indicated by the blue dashed lines.
is a dwarf. The broad He lines indicate it is a rapid rotator. Thus, we assign it a spectral type of O9.5 Vn.

In Figure 1, the most outstanding difference between these three spectra is the variation of the single-peaked [O III] λλ 5007 emission, while its neighbor, double-peaked He I λ 5016, remains unchanged. The double-peaked Hα and Hβ emission lines can be seen in Figures 2 and 1, respectively, with V/Rs ascending from MJD57795 to MJD57797. Its double-peaked Paschen series emissions are shown in Figure 3. The V/Rs of Hα and Hβ are obviously greater than 1, while the V/Rs of Paschen lines are all around 1. The N1 λ8680/3/6 emissions are obvious, while N1 λ8629, λ8712, and λ8719 emissions are weak. The double-peaked O I λ8446 emission can be inferred from V/R < 1 of Pa18 and the weak red component of O I λ8446 emission, while the V/R > 1 of Pa13 indicates weak Ca II triplet emission.

Long-term V/R variations of Be stars have been well known since McLaughlin (1961) with a mean period of about 7 years. TYC 4801-17-1 clearly shows rapid V/R variations over three consecutive days. The dramatically ascending V/Rs of Hα and Hβ from MJD57795 to MJD57797 imply that TYC 4801-17-1 may have the rapidest V/R variation in known Oe class to date.

The V/R phase lag is defined as different V/Rs between different emission lines in a spectrum. Wisniewski et al. (2007) reported V/R phase lags between Hα with V < R and other emission lines with V > R in ζ Tau. They supposed that there
is a one-armed density wave with a significantly different average azimuthal morphology in the circumstellar disk, such that the different emission lines formed in different radii show different V/R phases, which is confirmed by Steff et al. (2009) and explained by a global disk oscillation model (Carciofi et al. 2009). Chojnowski et al. (2015) also presented the phase lags of Be stars in APOGEE spectra. TYC 4801-17-1 shows obvious V/R phase lags as have been mentioned above. Specifically, the V/R ∼ 1 at Paschen series and HeI λ5016, while the V/R > 1 at Hα and Hβ.

**HD 255 055:** In SIMBAD, it was assigned O (Wackerling 1970), O9.0Vp(e?) (Cruz-Gonzalez et al. 1974), O9Vp (Morgan et al. 1955; Hiltner 1956), or O9V:pe (Kohoutek & Wehmeyer 1999). There are five spectra in LAMOST DR5. Only two spectra with Hβ at maximum and minimum phases, respectively, are shown in Figure 1. The star is a typical O9.5 star based on the ratios of HeII λ4542/HeI λ4388 and HeII λ4200/HeI λ4144 from the spectrum of MJD56968. The HeII λ4686/HeI λ4713 indicates luminosity class III. Thus, we assign it a spectral type of O9.5 III.

Only the Balmer series lines show emission with variation, as shown in Figure 1. Its Hβ emission line is saturated in the spectrum of MJD56968 and is not given in Figure 2. The weak emission in the Paschen lines Pa11 and Pa12 can be seen in the spectrum of MJD56968 in Figure 3, while other Paschen lines are infilled.

It is also cataloged as a Kepler K2 star (EPIC 202060093), showing photometric variation at a low frequency without any cause given (Buysschaert et al. 2015).

**V KM Cas:** It was classified as O9.5V((f)) by Gonzalez & Gonzalez (1956) and Massey et al. (1995). There are two spectra in LAMOST DR5. In Figure 1, the ratios of HeII λ4542/HeI λ4388 and HeII λ4200/HeI λ4144 are around 1, which indicate its spectral type is O9, while its high ratio of HeII λ4686/HeI λ4713 indicates it should be a dwarf. The broad He lines indicate it is also rapid rotator. However, there is no sign of NIII λ4634/40/41 emission. Thus, we assign it a spectral type of O9 Vn. In SIMBAD, it is an eruptive variable star, which implies that our spectra might miss the high phase of NIII λ4634/40/41 emission. Its Hα emission line shows variation between two epochs, as shown in Figure 2.

**LS II +23 14:** It was assigned a spectral type B0Vn by Reed (2003). The spectrum in Figure 1 indicates a spectral type of O9.7 from the ratio of HeII λ4542/Si III λ4552, while the intensities of Si IV λ4089 and λ4116 lines indicate its luminosity is III. The broad HeI lines imply it is also a rapid rotator. Thus, it is an O9.7 IIIn star. Its Hα in Figure 2 shows that it is an Oe shell star.

**RL 128 = ALS 19 265:** The unusual properties of this star were noted by Chromey (1979). It is very faint (V = 15.11) and very far from the Sun (65 kpc) and was classified as O7. Recently, Maíz Apellániz et al. (2016) assigned it a spectral type of O4.5V((c))z, based on their high-quality spectrum.

**Figure 5.** Blue spectra of B0e stars.
4. New B0e Stars in LAMOST DR5

We find four new B0e stars in LAMOST DR5. The blue spectra of these B0e stars are shown in Figure 5, while their Hα lines are shown in Figure 6.

2MSS J03354517+5141074: We cannot find any information about this star in SIMBAD. In Figure 5, its Balmer series until Hα all show emissions in their centers. Moreover, Hβ emission is asymmetric. Besides, its He i λ5016 as well as λ5876, λ6678, λ7065, and λ7281 lines also show emissions. Its weak He II λ4542 indicates it is a B0 star, and its strong Si IV λ1089 and λ1416 lines indicate its luminosity is III. Though suffering from infillings, its He I lines are all very broad; thus, we assign it a spectral type of B0 III.

BD+62 441: There are two spectra of different epochs for this star in LAMOST DR5, which are overplotted in Figure 5 with the black spectrum from MJD57382 and the red spectrum from MJD57707. It was assigned B2III (Rydstrom 1978), B0 (Heckmann & Dieckvoss 1975), or B0I (Voroshilov et al. 1985). The weak Si IV λ4089 and λ4116 lines indicate it is a B0 V star. Its Hβ of MJD57707 is more emissive than that of MJD57382, though Hβ infilling is weak in either epoch.

HD 265 134: It was assigned B0 by Nesterov et al. (1995) or O9.5III by Biaiacchi et al. (1982). In Figure 5, its weak He II λ4542 indicates it is a B0 star. The broad He I lines indicate it is a rapid rotator. Considering that the shallow Si IV λ4089 and λ4116 are formed from the rotational broadening of intrinsically narrow deep lines, we assign it a spectral type of B0 III. Its Hα shown in Figure 6 indicates it is a Be shell star. No infilling is seen in Hβ, and the “e” suffix is based on Hα only.

BD+51 921: There are three spectra from different epochs for this star in LAMOST DR5. Two of them are overplotted in Figure 5, with the black spectrum from MJD57798 and the red spectrum from MJD57058. It was assigned B0II by Hiltner (1956), but in Figure 5, the similar intensity of Si IV λ4116 to that of He I λ4121 indicates its luminosity class is III; thus, it is a B0 III star. The variation of the Hα profile between three epochs is obvious, as shown in Figure 6. No infilling is seen in Hβ, and the “e” suffix is based on Hα only.

5. Conclusions

In this paper, we present six new Oe stars found in LAMOST DR5 data, increasing the numbers of known Oe stars by nearly 50%. We also list four new B0e stars found in LAMOST DR5. TYC 4801-17-1 shows rapid V/R variations at Hβ and a V/R phase lag. Moreover, we find the unusual O4.5 star RL 128 is also an Oe star with variable Hα intensity—rare Ca II triplet emission appears at the maximum phase of Hα emission.

All new Oe and B0e stars with their relevant spectral information from LAMOST DR5 are listed in Tables 2 and 3, respectively. The parallaxes and their errors are from Gaia DR2.4

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4 See https://gea.esac.esa.int/archive/.
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Table 2

| Star Name | MJD   | Plate ID  | Spectralgraph ID | Fiber ID | R.A. (degree) | Decl. (degree) | Parallax (mas) | Spectral Type |
|-----------|-------|-----------|------------------|----------|---------------|---------------|----------------|---------------|
| EM* GGR 149 | 56393 | Crab_HIP115990_2 | 09            | 080      | 353.810657    | 60.006443     | 0.3166 ± 0.0249 | O9.7 IVne     |
|           | 57353 | Crab_HIP115990_2 | 09            | 080      |               |               |                |               |
|           | 57707 | Crab_HIP115990_2 | 09            | 080      |               |               |                |               |
| TYC 4801-17-1 | 57795 | NGC230101   | 08            | 106      | 103.183433    | –0.187982     | –0.8209 ± 0.2103 | O9.5 Vne     |
|           | 57796 | NGC230101   | 08            | 106      |               |               |                |               |
|           | 57797 | NGC230101   | 08            | 106      |               |               |                |               |
| HD 255 055 | 56968 | NGC2168_3   | 06            | 210      | 94.923531     | 23.288947     | 0.5274 ± 0.0466 | O9.5 IIIe    |
|           | 57391 | KP061029N225952V01 | 13         | 040      |               |               |                |               |
|           | 57439 | KP062257N223048V01 | 15         | 232      |               |               |                |               |
|           | 57442 | kp2_00_6_1  | 04            | 102      |               |               |                |               |
|           | 57707 | kp2_00_6_1  | 04            | 102      |               |               |                |               |
|           | 57707 | kp2_00_6_2  | 04            | 102      |               |               |                |               |
| V* KM Cas | 57382 | NGC1027_3   | 10            | 248      | 37.376939     | 61.495598     | 0.4063 ± 0.0320 | O9 Vne       |
|           | 57707 | NGC1027_3   | 10            | 248      |               |               |                |               |
| LS II +23 14 | 57884 | HD3385291   | 07            | 231      | 295.051998    | 23.627886     | 0.2725 ± 0.0347 | O9.7 IIIe    |
| RL 128    | 55862 | B6212       | 02            | 247      | 96.249448     | 26.822039     | 0.1575 ± 0.0538 | O4.5 Ve      |
|           | 55874 | GAC_097N28,B1 | 02          | 247      |               |               |                |               |
|           | 56232 | GAC097N26B1 | 03            | 198      |               |               |                |               |
|           | 56639 | GAC097N26B1 | 03            | 198      |               |               |                |               |

Table 3

| Star Name | MJD   | Plate ID  | Spectralgraph ID | Fiber ID | R.A. (degree) | Decl. (degree) | Parallax (mas) | Spectral Type |
|-----------|-------|-----------|------------------|----------|---------------|---------------|----------------|---------------|
| 2MASS J03354517+5141074 | 57407 | HD034854N505024V02 | 14        | 107      | 53.938267     | 51.685386     | 0.2851 ± 0.0314 | B0 Vne     |
| BD+62 441 | 57382 | NGC1027_3 | 15            | 023      | 40.448588     | 62.657267     | 0.3550 ± 0.0368 | B0 Ve       |
|           | 57707 | NGC1027_3 | 15            | 023      |               |               |                |               |
| HD 265 134 | 55967 | GAC_100N13_V4 | 13          | 220      | 102.891369    | 13.617259     | 0.1517 ± 0.0833 | B0 IIIe    |
| BD+51 921 | 57058 | NGC1545_3  | 12            | 249      | 66.362744     | 52.043780     | 0.1416 ± 0.0358 | B0 IIIe    |
|           | 57326 | HD042432N505042V01 | 15         | 137      |               |               |                |               |
|           | 57798 | HD042432N505042V02 | 15         | 137      |               |               |                |               |

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