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The first symbiotic stars from the LAMOST survey

Jiao Li[1,2], Joanna Mikołajewska[3], Xue-Fei Chen[1], A-Li Luo[4], Alberto Rebassa-Mansergas[5], Yong-Hui Hou[6], Yue-Fei Wang[6], Yue Wu[4], Ming Yang[4], Yong Zhang[6] and Zhan-Wen Han[1]

[1] Key Laboratory for the Structure and Evolution of Celestial Objects, Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China; *lijiao@ynao.ac.cn; zhanwenhan@ynao.ac.cn*
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Nicolaus Copernicus Astronomical Centre, Bartycka 18, 00716 Warsaw, Poland
[4] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[5] Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
[6] Nanjing Institute of Astronomical Optics & Technology, National Astronomical Observatories, Chinese Academy of Sciences, Nanjing 210042, China

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Abstract Symbiotic stars are interacting binary systems with the longest orbital periods. They are typically formed by a white dwarf and a red giant that are embedded in a nebula. These objects are natural astrophysical laboratories for studying the evolution of binaries. Current estimates of the population of symbiotic stars in the Milky Way vary from 3000 up to 400 000. However, a current census has found less than 300. The Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST) survey can obtain hundreds of thousands of stellar spectra per year, providing a good opportunity to search for new symbiotic stars. We detect four such binaries among 4 147 802 spectra released by LAMOST, of which two are new identifications. The first is LAMOST J12280490–014825.7, considered to be an S-type halo symbiotic star. The second is LAMOST J202629.80+423652.0, a D-type symbiotic star.

Key words: binaries: symbiotic-stars — optical spectra — LAMOST

1 INTRODUCTION

Symbiotic stars are interacting binary systems with the longest orbital periods and a multicomponent structure. They are composed of an evolved cool giant and an accreting hot, luminous companion (usually a white dwarf, WD though some might have a neutron star or black hole) surrounded by a dense ionized symbiotic nebula. Therefore, symbiotic stars have composite spectra.

Depending on the nature of the cool giant, symbiotic stars are generally classified into three types: S-type (stellar), D-type (dusty) and D′-type. S-types contain normal giant stars with effective temperatures $T_{\rm eff} \sim 3000 - 4000$ K. They are the most numerous ($\sim 80\%$) and their orbital periods are of the order of a few years. D-types contain Mira-type variables and warm ($T \sim 1000$ K) dust shells. Their orbital periods are longer than 15 years (Mikołajewska 2003). D′-types contain F- or G-type cool giant stars surrounded by a dust shell with a temperature not higher than 500 K

(Allen 1984b). There are only 8 D′-types out of 188 symbiotic stars in the catalog published by Belczyński et al. (2000). The presence of both an evolved giant that suffers from heavy mass loss and a hot component producing copious amounts of ionizing photons results in a rich and luminous circumstellar environment. In particular, very different surroundings are expected, including both neutral and ionized regions, dust forming regions, accretion disks, interacting winds and jets, which make symbiotic stars a natural laboratory for studying binary interaction and evolution (Corradi et al. 2003 and references therein).

Symbiotic stars have been proposed as probable progenitors of type Ia supernovae (SNe Ia) (Hachisu et al. 1999; Chen et al. 2011), as rapid mass accretion from the cool giant component can cause the mass of the WD to reach the Chandrasekhar limit (Han & Podsiadlowski 2004; Wang & Han 2012). SNe Ia have been successfully used as cosmological distance indicators (Riess et al. 1998; Perlmutter et al. 1999), however, the exact nature of the progenitors of SNe Ia is still not clear. SN PTF 11kx, an SN Ia with a broad Hα line in its late spectrum, could have resulted from a symbiotic star (Dilday et al. 2012). Large numbers of symbiotic stars can help us to study the progenitors of SNe Ia. Hence, searching for new symbiotic stars is of extreme importance in the field of stellar evolution.

Current estimates for the Galactic population of symbiotic stars vary considerably from 3000 (Allen 1984b) and 30 000 (Kenyon et al. 1993) to 3×10^5–4×10^5 (Magrini et al. 2003). However, there are less than 300 Galactic symbiotic stars known (Belczyński et al. 2000; Miszalski et al. 2013; Miszalski & Mikołajewska 2014; Rodríguez-Flores et al. 2014). This incompleteness is due to the lack of deep all-sky surveys at wavelengths where symbiotic stars can be efficiently selected against other stellar sources (Belczyński et al. 2000; Miszalski & Mikołajewska 2014; Mikołajewska et al. 2014). Most of the known symbiotic stars have been discovered by large Hα surveys, e.g. the INT Photometric Hα Survey and the AAO/UKST SuperCOSMOS Hα Survey, and then confirmed by deep spectroscopy and long-term I-band light curves of the corresponding candidates. The Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST) survey can obtain hundreds of thousands of stellar spectra per year, providing a good opportunity to find new symbiotic stars. To contribute to progress in this field with a large spectroscopic survey, we devise a selection method to find symbiotic stars from data released by LAMOST (including DR1, DR2 and DR3). As a result, we detect four symbiotic star spectra, of which two are new identifications and the other two have been previously identified by Downes & Keyes (1988).

The structure of the paper is as follows. Section 2 briefly introduces the LAMOST survey and our method to select symbiotic stars. Section 3 describes the four symbiotic stars we identify. Section 4 is the discussion. We conclude in Section 5.

2 SPECTROSCOPIC OBSERVATIONS AND TARGET SELECTION

2.1 The LAMOST Survey

LAMOST is a 4.0 m quasi-meridian reflecting Schmidt telescope located at Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences, characterized by both a large field of view and large aperture. The telescope is equipped with 16 low-resolution spectrographs, 32 CCDs and 4000 fibers. Each spectrograph is fed with the light from 250 fibers and approximately covers a wavelength range of $3700 - 9100$ Å with a resolution of about 1800. With the capability of its large field of view and acquiring a large number of targets, the LAMOST telescope is dedicated to the spectral survey of celestial objects in the whole northern sky (Cui et al. 2012; Zhao et al. 2012; Liu et al. 2015).

The current data from LAMOST contain data release 1 (DR1), data release 2 (DR2) and data release 3 (DR3). The number of spectra in DR1, DR2 and DR3 are 2 204 860, 1 443 843 and 499 099, respectively (see Table 1). The spectra are classified as stars, galaxies, quasars and unknowns (mainly due to the poor quality of their spectra). DR1 includes both 1 487 200 spectra obtained during the

Table 1 Characteristics of Data from LAMOST

Data	Total	Star	Galaxy	QSO	Unknown
DR1	2 204 860	1 944 406	12 082	5017	243 355
DR2	1 443 843	1 240 792	23 967	4251	174 833
DR3	499 099	437 299	5 229	574	55 997

Notes: The number of spectra which are classified as stars, galaxies, QSOs and unknowns by the LAMOST pipeline. DR1 includes both 1 487 200 spectra obtained during the first year of the general survey, and 717 660 spectra which were observed during the pilot survey. For more details see the website *http://dr.lamost.org/ucenter/mytoken*.

first year of the general survey and 717 660 spectra which were observed during the pilot survey (Luo et al. 2012). Due to the lack of a network of photometric standard stars, the flux calibration is relative. The LAMOST spectra are unambiguously identified by a plate identifier, a spectrograph identifier and a fiber identifier (Song et al. 2012; Ren et al. 2014).

Based on LAMOST data, lots of works have been done. For example, Ren et al. (2014) identified 119 WD-main sequence binaries, Zheng et al. (2014) reported a hypervelocity star with a heliocentric radial velocity of about 620 km s^{-1}, and Zhong et al. (2014) discovered 28 candidate high-velocity stars at heliocentric distances of less than 3 kpc. For more details see the website *http://www.lamost.org/public/publication?locale=en*.

2.2 Optical Spectra of Symbiotic Stars

Optical spectra of known symbiotic stars have been cataloged by Allen (1984b) and Munari & Zwitter (2002). These spectra are characterized by the presence of absorption features typical of late-type giant stars (spectral type K or M). These include, among others, CaI, FeI, H_2O, CO and TiO lines. Strong nebular Balmer line emission, as well as HeI, HeII and the [OIII], [NeIII], [NV] and [FeVII] forbidden lines can also be seen. Additionally, more than 50% of symbiotic stars show broad emission features at $\lambda 6830$ Å and an emission feature that is similar but a factor of ~ 4 weaker at $\lambda 7088$ Å, which only exists in symbiotic stars. The $\lambda 6830$ Å band profile has a typical width of about 20 Å and it often ranks among the 10 most intense lines in the optical region of symbiotic stars (which may reach 5% of the intensity of Hα). The $\lambda\lambda 6830$ and $\lambda\lambda 7088$ lines are due to Raman scattering of the OVI resonance doublet $\lambda\lambda 1032$, $\lambda\lambda 1038$ by the neutral hydrogen in the atmosphere of the cool giant and the inner parts of its stellar wind (Schmid 1989).

In S-type stars (e.g. V2416 Sgr in Fig. 1, top panel), the continuum has obvious absorption features originating from the red giant. Although the Balmer, HeI and HeII lines are strong, the forbidden lines such as [OIII] and [NeIII] are weak and even fade away. The Balmer decrement is generally steeper than $\mathrm{H}\alpha/\mathrm{H}\beta \sim 2.8$ (case B) (Kogure & Leung 2007).

In D-type stars (e.g. V336 Car in Fig. 1, bottom panel), the Balmer lines are strong and the forbidden lines are well developed in a wide range of excitation from [OI] up to [FeVII] and [NeV]. The Balmer decrement is also steeper than in the nebular case. The wide range of ionization levels in D-types reflects the fact that their nebulae are ionization-bounded whereas in at least some S-types the nebulae are density-bounded.

The emission lines of D′-type stars (see Fig. 6; note that this is one of our four identified LAMOST symbiotic binaries) are similar to those of D-types. The most conspicuous property of D′-type stars is the presence of a G- or F-type giant instead of a cooler star (Mürset & Schmid 1999).

According to the above described features, we use the following criteria to classify an object as a symbiotic star (Mikolajewska et al. 1997; Mikołajewska et al. 2014; Belczyński et al. 2000):

(a) Presence of the absorption features of a late-type giant: TiO, H_2O, CO, CN and VO absorption bands, as well as CaI, CaII, FeI and NaI lines.
(b) Presence of strong HI and HeI emission lines and presence of emission lines from ions such as HeII, [OIII], [NV] and [FeVII] with an equivalent width exceeding 1 Å.
(c) Presence of the $\lambda\lambda6830$ emission line, even if the cool giant features are not obvious.

2.3 Selection Method

Based on the spectral properties of symbiotic stars and features of LAMOST data, we devise a selection method to find symbiotic stars. This follows a three-step procedure.

(i) In order to directly compare the spectra, we first normalize the flux into the range [0,1] following

$$F_{\rm n} = \frac{F_\lambda - F_{\rm min}}{F_{\rm max} - F_{\rm min}}, \tag{1}$$

where $F_{\rm max}$ and $F_{\rm min}$ are the maximum and minimum fluxes of each spectrum, respectively.
(ii) Unlike the vast majority of spectra observed by LAMOST, symbiotic stars display Balmer emission lines, especially the Hα and the Hβ lines. We therefore select symbiotic stars by analyzing the intensity of the Hα and Hβ lines, i.e. $I(\mathrm{H}\alpha)$ and $I(\mathrm{H}\beta)$. These intensities are obtained from the following equation,

$$I(\lambda_0) = \int_{\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda} (F_{\rm n} - F_{\rm c})\, d\lambda, \tag{2}$$

where $F_{\rm c}$ is the continuum fitted by the Global Continuum Fit method of Lee et al. (2008) (the [OIII]$\lambda4340, \lambda4959$ and $\lambda5007$ lines are removed when we fit the continuum). The $\Delta\lambda$ for Hα and Hβ are set to 50 and 10 Å, respectively. As the fluxes have been normalized, the intensity of the lines does not have truly physical significance.

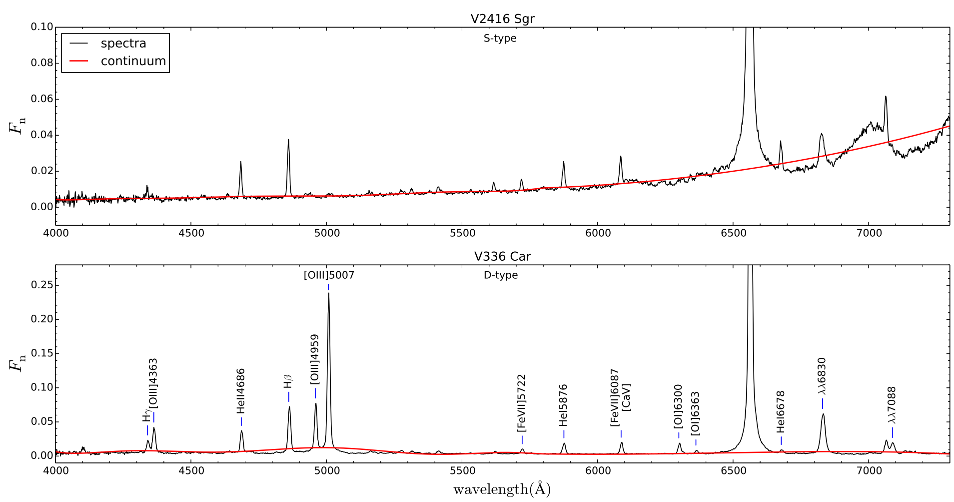

Fig. 1 V2416 Sgr (*top panel*) and V336 Car (*bottom panel*), an S-type and a D-type symbiotic star, respectively (Allen 1984a). The black and red lines are the spectra (*continuum plus lines*) and continua of the objects, respectively. We have normalized the flux into the range [0, 1] following Eq. (2).

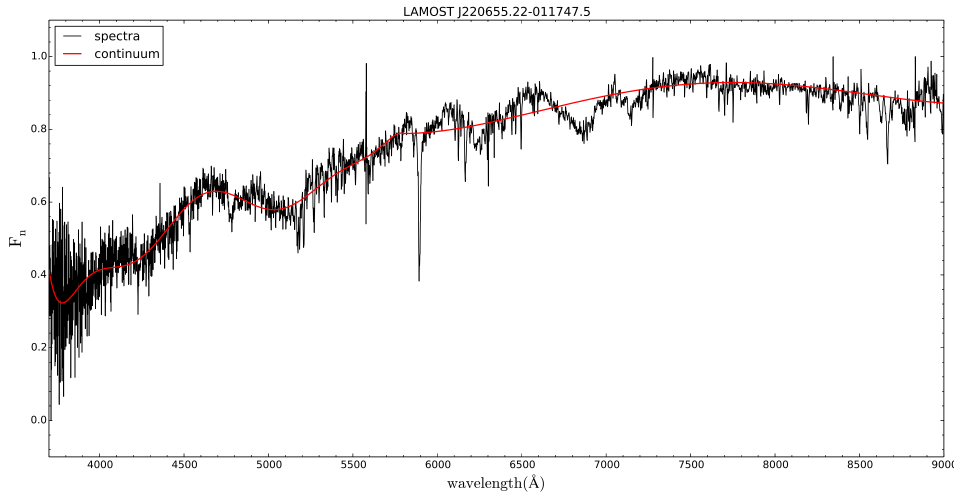

Fig. 2 LAMOST J220655.22–011747.5 shows an M0 type spectrum. The black line traces the spectrum of the object. The red line is the continuum fitted by the Global Continuum Fit method of Lee et al. (2008).

Table 2 Spectra Identified by Our Routine as Symbiotic Binaries

Data	Total	Star	M-type	Step(ii)	Step(iii)	Symbiotic star
DR1	2 204 860	1 944 406	67 282	44 983	4758	1
DR2	1 443 843	1 240 792	54 888	64 691	7631	2
DR3	499 099	437 299	18 054	15 408	2377	1

Notes: (1) Total means the number of spectra we processed from each data release for LAMOST. (2) The columns Star and M-type list the number of stars and M type spectra, respectively. (3) The columns Step(ii) and Step(iii) have the number of spectra processed by step(ii) and step(iii) in Sect. 2.3 respectively. The column Symbiotic star gives the number of symbiotic stars found in each data release.

It is important to emphasize that fitting the continuum of M-type or later type spectra is subject to systematic uncertainties in the range $\lambda 5500 - 7500$ Å, as shown in Figure 2. In order to efficiently select symbiotic stars, it becomes important to set proper values for the intensity of the Hα and Hβ lines. In our work, they were set to $I(\mathrm{H}\alpha) > 0.5$ and $I(\mathrm{H}\beta) > 0.2$ respectively, which efficiently exclude spectra displaying the Balmer series in absorption or in faint emission (such as the spectrum shown in Fig. 2).

(iii) The Balmer series and other emission lines in symbiotic stars are very prominent, hence the continuum is generally flat in the optical spectrum (see Fig. 1). We therefore average the normalized continuum F_{n} in the $4000 - 7300$ Å wavelength range and exclude all spectra with an average above 0.4.

After performing the above steps over the entire LAMOST spectroscopic database, we select 4758, 7631 and 2377 spectra in DR1, DR2 and DR3, respectively, as symbiotic star candidates (see Table 2). Visual inspection of the spectra revealed that most of these are planetary nebulae and B(e) stars. Finally, we find four symbiotic stars, two of which have been cataloged in the past and the other two are new identifications (see Table 3).

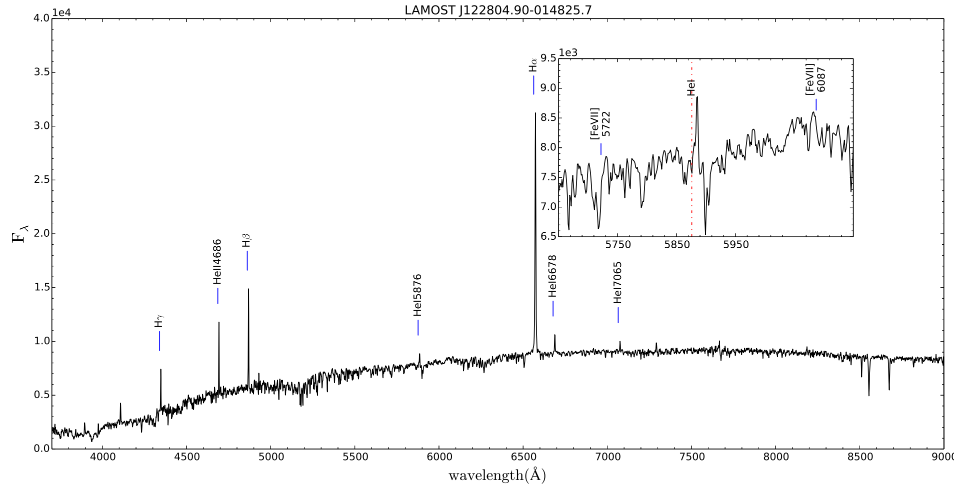

Fig. 3 LAMOST J122804.90–014825.7 is a new S-type symbiotic star, with a radial velocity $v_{\rm r} \sim (374 \pm 2)$ km s^{-1}. The vertical dashed line in the inset shows the wavelength of HeI $\lambda5876$. The faint [FeVII] lines have the same velocity shift. F_λ is relative flux.

Table 3 Symbiotic Stars Observed by LAMOST

Desig (LAMOST J)	Date MJD	IR type	u	g	r	i	z	Cool spectra	DR	Name
122804.90–014825.7	56592	S	15.88	15.46	12.18	11.67	11.92	K3	DR2	—
194957.58+461520.5	56592	S	12.54	—	—	—	—	M2	DR2	StHA 169
202629.80+423652.0	56946	D	15.05	14.07	13.49	—	—	Mira	DR3	—
214144.88+024354.4	56204	D′	10.94	10.33	10.01	11.39	10.56	G5	DR1	StHA 190

Notes: Basic properties of the symbiotic stars, which are ordered by right ascension from epoch J2000.0. The first and the third symbiotic stars are new discoveries, and the others were identified by Downes & Keyes (1988).

3 SYMBIOTIC STARS OBSERVED BY LAMOST

Figures 3–6 show the LAMOST spectra of the four symbiotic stars we have identified.

3.1 LAMOST J122804.90–014825.7

The presence of strong HeII $\lambda4686$ emission implies the presence of a hot component in the object (Fig. 3). The spectrum indicates a radial velocity of $v_{\rm r} \sim (374 \pm 2)$ km s^{-1}. We can see faint [FeVII] emission lines with the same Doppler shift as the inset of Figure 3. The spectrum also displays Mg$\lambda5176$ and CaII triplet absorption lines. It is classified as K3 type by the LAMOST pipeline, which indicates it is the cool giant component of a symbiotic star, so we identify it as an S-type system.

Based on the g, r and i magnitudes, the V magnitude is $m_{\rm V} \sim 13.5$ mag[1], and we assume a typical absolute magnitude for the K3 type cool giant to be $M_{\rm V} \sim 0.1$ mag. The spectroscopic distance in this case would be about 5 kpc. The Galactic coordinates are $l = 291.0062$, $b = 60.5226$, so the vertical distance between this object and the Galactic disk is about 4.3 kpc. It seems to be a halo symbiotic star.

[1] *http://classic.sdss.org/dr4/algorithms/sdssUBVRITransform.html*

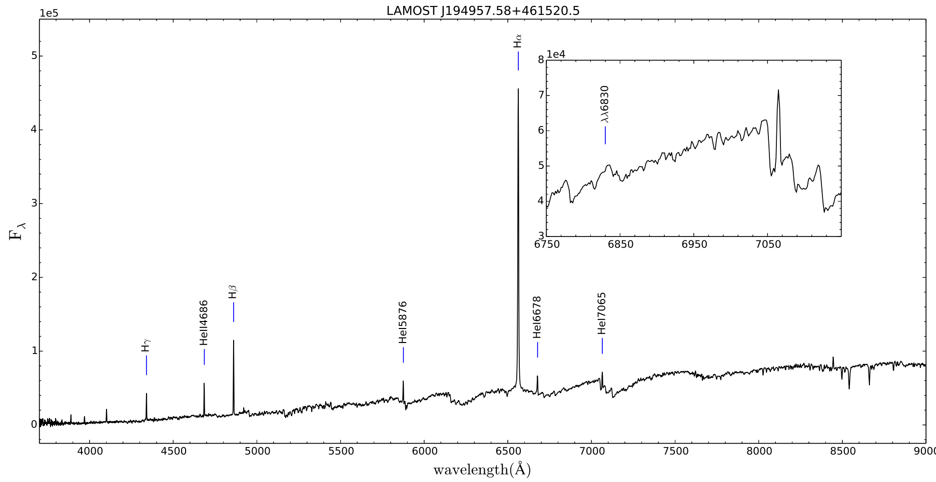

Fig. 4 LAMOST J1194957.58+461520.5 is an S-type symbiotic star, which was observed by Downes & Keyes (1988), and is listed as StHA 169 in the Belczyński et al. (2000) catalog of symbiotic stars. F_λ is relative flux.

3.2 LAMOST J194957.58+461520.5

The spectrum of J194957.58+461520.5 acquired by LAMOST is very similar to the one presented by Downes & Keyes (1988) in the range $4000 - 7300$ Å. LAMOST J194957.58+461520.5 is included in the Belczyński et al. (2000) catalog of symbiotic stars as StHA 169. The spectrum shows a strong and broad Hα emission line. The other Balmer lines, as well as HeI and HeII $\lambda4686$ lines, are also clearly present. At the same time there is a faint feature at $\lambda\lambda6830$, as shown in Figure 4. The spectrum displays obvious TiO absorption bands and CaII triplet absorption lines, and the star is classified as M2 by the LAMOST pipeline. It is an S-type symbiotic star.

3.3 LAMOST J20262980+4236520

The spectrum of this object is shown in Figure 5. The Balmer and [OIII] lines are clearly present. Weak [NII] $\lambda6548$, $\lambda6584$ lines on both sides of the Hα line can also be seen, however, the HeI and HeII lines are very weak. There is an obvious $\lambda\lambda6830$ line ($I\left(\lambda\lambda6830\right)/I\left(\mathrm{H}\alpha\right) \sim 7.6\%$) and a $\lambda\lambda7088$ line. The flat continuum and the intensity ratios $I\left([\mathrm{OIII}]\lambda5007\right)/I\left(\mathrm{H}\beta\right) \sim 0.89$ and $I\left([\mathrm{OIII}]\lambda4363\right)/I\left(\mathrm{H}\gamma\right) \sim 4.29$ (Gutierrez-Moreno & Moreno 1995; Mikołajewska et al. 2014; Rodríguez-Flores et al. 2014) suggest that LAMOST J20262980+4236520 is a D-type symbiotic star, so its cool giant is a variable. The signal to noise ratio is relatively low at the iz bands where the spectrum is also affected by systematic uncertainties due to sky subtraction.

3.4 LAMOST J214144.88+024354.4

LAMOST J214144.88+024354.4 is a D′-type symbiotic star. It is listed as StHA190 in the catalog by Belczyński et al. (2000). The spectrum, shown in Figure 6, is nearly identical to the one presented by Downes & Keyes (1988) in the wavelength range $4000 - 7300$ Å. The spectrum is classified as G5 type by the LAMOST pipeline, which is consistent with the D′-type nature of this symbiotic binary. A high-resolution optical spectrum of StHA 190 was analyzed by Smith et al. (2001), who identified it as a giant with temperature $T_{\rm eff} = 5300 \pm 150$ K and metallicity $[\mathrm{Fe/H}] \sim 0$ based on

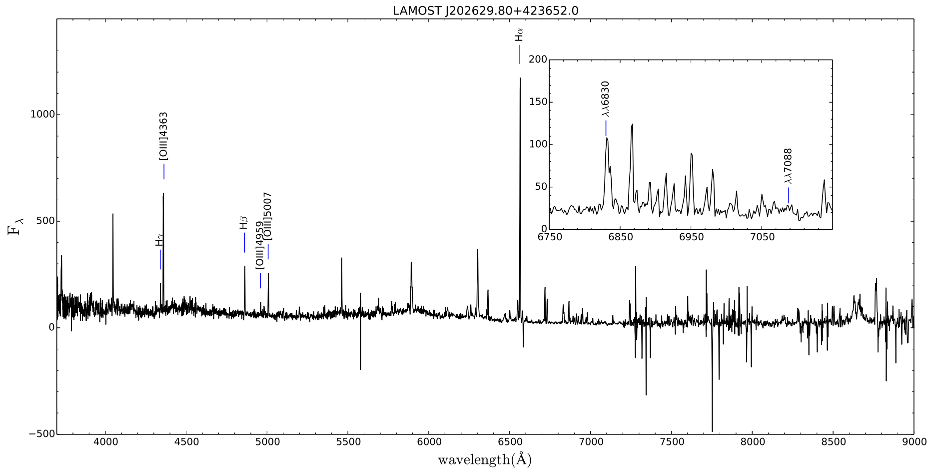

Fig. 5 LAMOST J20262980+4236520 is a new D-type symbiotic star. The red part of the spectrum is affected by systematic uncertainties due to sky subtraction. F_λ is relative flux.

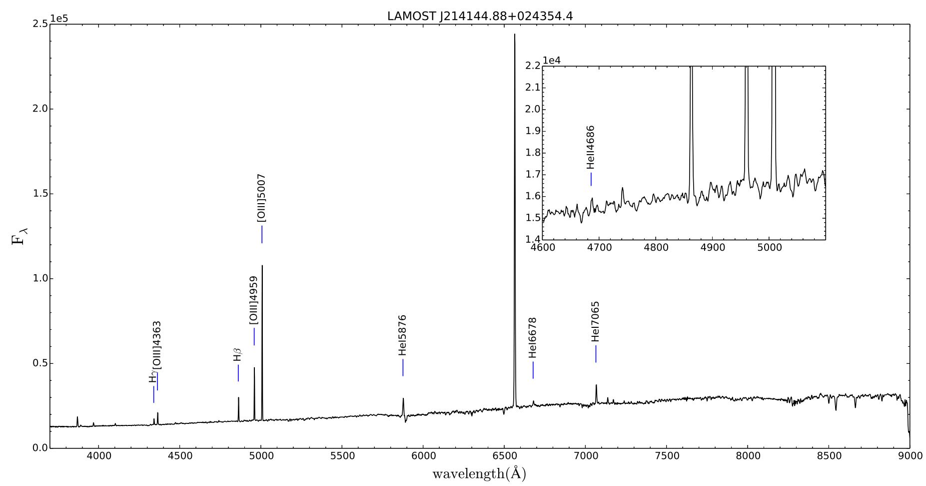

Fig. 6 LAMOST J214144.88+024354.4 is a D′-type symbiotic star, included in the Belczyński et al. (2000) list as StHA 190. F_λ is relative flux.

fitting the spectrum with model atmospheres. The spectral type reported here is consistent with these results.

4 DISCUSSION

We use 4 147 802 LAMOST spectra to find symbiotic stars, of which 3 622 479 are classified as stars by the LAMOST pipeline (see Table 2). Since about 1% of the stars are red giants in our solar neighborhood[2], a rough estimate of the number of red giant stars in these spectra is around 30 000.

[2] *http://pages.uoregon.edu/jimbrau/astr122/Notes/Chapter17.html*

Table 4 Symbiotic Stars in the Footprint of LAMOST DR1

Name	RA	Dec	J	r
EG And	00 44 37.1	+40 40 45.7	3.65	6.6
BD Cam	03 42 09.3	+63 13 00.15	1.31	4.5
UV Aur	05 21 48.8	+32 30 43.1	4.03	8.3
TX CVn	12 44 42.0	+36 45 50.6	7.47	8.7
T CrB	15 59 30.1	+25 55 12.6	5.70	2.1
AG Dra	16 01 40.5	+66 48 09.5	7.15	9.2
Draco C-1	17 19 57.6	+57 50 04.9	14.38	16.7
StHA 190	21 41 44.8	+02 43 54.4	8.71	10.0
AG Peg	21 51 01.9	+12 37 29.4	5.00	5.8

Notes: These symbiotic stars are in the area defined by the footprint of LAMOST DR1. RA and Dec are the celestial coordinates.

Magrini et al. (2003) proposed that the number of symbiotic stars can be taken to be 0.5% of the total number of red giants. Therefore there should be more than 100 symbiotic stars that can be identified. However, we should note that the estimated number of Galactic symbiotic stars from Magrini et al. (2003) is 1–2 orders of magnitude higher than that given by others as shown in Section 1. So, the real number of symbiotic stars among the LAMOST stellar spectra may be less than 100. As a first step, we only identified four symbiotic binaries, far below what we expected. By comparing the coordinates between the known symbiotic stars listed in the catalog published by Belczyński et al. (2000) and the footprint of LAMOST DR1, there should be nine identifiable symbiotic stars in the area of the footprint (see Table 4). According to the plate design of LAMOST, for brighter stars ($r \leq 14$ mag), only those with $9 \leq J \leq 12.5$ mag from the 2MASS catalogs are chosen as potential targets (Luo et al. 2015). This immediately rules out eight of the nine symbiotic stars. For fainter stars ($r > 14$ mag), there are five criteria used to select potential targets (Yuan et al. 2015), which might exclude the symbiotic star Draco C-1. StHA 190 has not been excluded, probably because its J-band magnitude is very close to the target selection criteria of brighter stars. In future work, we will apply the selection method to data released by the Sloan Digital Sky Survey (SDSS) to find more symbiotic stars and check the efficiency of our method.

5 CONCLUSIONS

We have found four symbiotic stars among 4 147 802 spectra released by LAMOST DR1, DR2 and DR3. The objects LAMOST J194957.58+461520.5 and LAMOST J214144.88+024354.4 are listed in the Belczyński et al. (2000) catalog of symbiotic stars as StHA 169 and StHA 190, respectively, and they can be identified by our method. The LAMOST spectra of these two objects are nearly identical to those provided by Downes & Keyes (1988). LAMOST J12280490–014825.7 is a new symbiotic star and is considered to be a halo S-type with a radial velocity of $v_{\rm r} \sim (374 \pm 2)$ km s^{-1}. LAMOST J20262980+4236520 is also a new symbiotic star classified as D-type. As LAMOST continues to operate, more symbiotic star spectra will be obtained.

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