The galaxy luminosity function in the LAMOST Complete Spectroscopic Survey of Pointing Area at the Southern Galactic Cap

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Abstract We present optical luminosity functions (LFs) of galaxies in the ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands, calculated using data in ~ $40 \deg^2$ sky area of the LAMOST Complete Spectroscopic Survey of Pointing Area (LaCoSSPAr) in the Southern Galactic Cap. Redshifts for galaxies brighter than r = 18.1 were obtained mainly with LAMOST. In each band, LFs derived using both parametric and non-parametric maximum likelihood methods agree well with each other. In the ${}^{0.1}r$ band, our fitting parameters of the Schechter function are $\phi_* = (1.65 \pm 0.36) \times 10^{-2} h^3 \,\mathrm{Mpc}^{-3}$, $M_* = -20.69 \pm 0.06$ mag and $\alpha = -1.12 \pm 0.08$, which agree with previous studies. Separate LFs are also derived for emission line galaxies and absorption line galaxies. The LFs of absorption line galaxies show a dip at ${}^{0.1}r \sim 18.5$ and can be fitted well by a double-Gaussian function, suggesting a bimodality in passive galaxies.

Key words: galaxies: luminosity function, mass function — galaxies: statistics — galaxies: distances and redshifts

1 INTRODUCTION

Luminosity is one of the most basic properties of galaxies. Studies of galaxy luminosity functions (LFs) have yielded direct statistical estimates for the space density of galaxies with respect to their luminosities, and provided important information about galaxy formation and evolution.

In recent years, many large spectroscopic surveys have been conducted to investigate the nearby universe. Among them, the Center for Astrophysics (CfA) Redshift Survey (Huchra et al. 1983), the Two-degree Field (2dF) Galaxy Redshift Survey (Lewis et al. 2002), the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Galaxy And Mass Assembly (GAMA) redshift survey (Driver et al. 2009; Baldry et al. 2010), and so on were all very successful, enabling us to gain a better understanding of the universe. Thanks to these surveys, many investigations of galaxy LFs have been undertaken, and they have provided important observational constraints on theories of galaxy formation and evolution.

Blanton et al. (2001) calculated the galaxy LFs in SDSS ugriz bands using SDSS commissioning data and discussed the dependence of luminosity on surface brightness, color and morphology. Blanton et al. (2003) fitted the LFs using two parameters, Q and P, to study effects of

luminosity and density evolution, respectively. Montero-Dorta & Prada (2009) calculated the LF with a sample selected from SDSS Data Release 6 (DR6, Adelman-McCarthy et al. 2008), and identified a remarkable excess at the bright end of the $^{0.1}u$ band LF. Loveday et al. (2012) focused on the evolution of LFs in a redshift range of 0.002 < z < 0.5 and pointed out different evolution features between blue galaxies and red galaxies based on the GAMA core data release (Driver et al. 2011).

At higher redshift (z > 0.5), Willmer et al. (2006) constructed B-band LFs of red and blue galaxies in different redshift slices from $z \sim 0.2$ to $z \sim 1.2$ based on the Deep Evolutionary Exploratory Probe 2 (DEEP2) redshift survey (Davis et al. 2003), and found a more significant luminosity evolution for blue galaxies while for red galaxies a more significant density evolution. Montero-Dorta et al. (2016) used the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) high redshift sample, and computed the high mass end of the SDSS $^{0.55}i$ band LFs of red sequence galaxies at redshift $z \sim 0.55$, suggesting that these red sequence galaxies formed at redshift z = 1.5 - 3. López-Sanjuan et al. (2017) examined the Bband LFs for star-forming and quiescent galaxies based on the Advanced, Large, Homogeneous Area, Medium-Band Redshift Astronomical (ALHAMBRA) survey (Moles et al. 2008), and provided a distinct understanding of the evolution of B-band LF and LF for different types of galaxies since $z \sim 1$.

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) is a Wang-Su reflecting Schmidt telescope (Wang et al. 1996; Su & Cui 2004; Cui et al. 2012; Zhao et al. 2012) located at Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). Thanks to its $\sim 20 \, \text{deg}^2$ field of view (FOV) and 4000 fibers, LAMOST can spectroscopically observe more than 3000 scientific targets simultaneously (nearly 5 times more than SDSS), making it efficient for obtaining spectra of celestial objects. LAMOST ExtraGAlactic Survey (LEGAS), an important part of LAMOST's scientific survey strategy, aims to cover \sim $8000\,{\rm deg^2}$ of the Northern Galactic Cap (NGC) and \sim 3500 deg^2 of the Southern Galactic Cap (SGC), and acquire hundreds of thousands of spectra targeting extragalactic objects with redshifts z < 0.3 in the next five years (Yang et al. 2018). When finishing its extragalactic survey, LAMOST will publish a catalog covering a large sky area (~ 11500 deg^2 in total) and containing millions of spectroscopic entries on galaxies.

This work is based on the LAMOST Complete Spectroscopic Survey of Pointing Area (LaCoSSPAr), an early project of LEGAS. LaCoSSPAr is a LAMOST key project aiming at observing all sources (galactic and extragalactic) with a magnitude limit of 14.0 < r < 18.1in two selected 20 deg^2 regions in SGC, where the faint magnitude limit is 0.1 mag deeper than LAMOST is designed to reach and 0.33 mag deeper than that of the SDSS legacy survey. This survey is designed to investigate the completeness and selection effects in the wider LEGAS survey (Yang et al. 2018). By using the spectra observed by LAMOST and cross-matching with data from other photometric surveys, the galaxy LFs can be investigated in specific bands. Our fields are located in the SGC, where the footprint covered by SDSS is small. Meanwhile, thanks to the high Galactic latitude, our galaxy sample suffers less from the effects of Galactic extinction.

In this paper, we use the galaxy redshift sample based on LaCoSSPAr, which is the most complete sample in LEGAS up to now, and combine with SDSS Petrosian magnitudes, to estimate the galaxy LFs in SDSS $^{0.1}g$, $^{0.1}r$, $^{0.1}i$ bands. Our sample has a fainter limiting magnitude than SDSS and our goal is to achieve a better understanding of the faint end of galaxy LFs. In Section 2, we give an introduction to LAMOST data and data reduction, and describe our sample selection and correction for the incompleteness. In Section 3, we introduce the methods used to estimate the galaxy LFs. In Section 4, we present the results of the LFs and discussion. A summary is provided in Section 5. Throughout this paper, we adopt a Friedmann-Robertson-Walker cosmological model with constants of $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \,\mathrm{km \, s^{-1} \, Mpc^{-1}}$.

2 SAMPLE

2.1 LaCoSSPAr, Data and Data Reduction

LaCoSSPAr surveys two $\sim 20 \text{ deg}^2$ regions in SGC with limiting magnitude of r = 18.1 mag. Originally, the plan was to select a high density region and a low density region to test possible environmental effects. The high density field (Field B: R.A.= 21.53° , Dec.= -2.20°) is chosen to cover a large Abell rich cluster (Abell et al. 1989) and the low density field (Field A: R.A.= 37.88° , Dec.= 3.44°) is selected in a blank region near Field B (as shown in fig. 1 in Yang et al. 2018). However, it was found later that Field A (low density field) actually contains 11 faint Abell and Zwicky clusters and therefore may not represent low density regions. The effects of the field selection will be discussed in Section 4. The input catalog for targets in the LaCoSSPAr survey was selected from Data Release 9 (DR9; Ahn et al. 2012) of the SDSS PhotoPrimary database, using the criteria of 14.0 < r < 18.1 and type = 'Galaxy'. Sources (936) were excluded when they are in the following special regions that are not observed by LAMOST: (1) in the fields of the five LAMOST guide CCDs, (2) within 10" from bright stars and (3) in dense regions. The final LaCoSSPAr target catalog contains 5623 sources, among which 5442 (96.8%) were observed successfully but 181 (3.2%) failed, mainly due to bad fibers.

The raw data of the successful observations were first reduced by the LAMOST 2D and 1D pipelines (Luo et al. 2012), which include bias subtraction, flat-fielding through twilight exposures, cosmic-ray removal, spectrum extraction, wavelength calibration, sky subtraction and exposure coaddition. However, for many spectra with relatively low signal to noise ratio (SNR), the pipeline does not work well. Low SNR makes it hard to recognize diagnostic lines. In addition, bad sky line subtraction often introduces fake lines that significantly affect the redshift measurement. Consequently, redshifts were obtained from the pipeline for only about a third of all the observed galaxies. To achieve a better redshift detection rate, additional data processing of the 1D spectrum was carried out using our own software (Yang et al. 2018). Briefly speaking, to improve the results of sky line subtraction, in the residual spectrum we replaced all > 3σ points around each skyline $(\pm 15 \text{ Å})$ by the values from continuum fitting. After this, we inspected each spectrum visually (by at least two individuals) and re-measured the redshifts by identifying emission lines and absorption lines. These new steps significantly improved the success rate of redshift detection (Bai et al. 2017). Redshifts of 3098 sources were detected, corresponding to a detection rate of 55%. They have a median redshift of $\bar{z} = 0.104$ and typical uncertainty of $\sigma_z/(1+z) < 0.001.$

2.2 Parent Sample and Redshift Completeness

The parent sample for the LF calculations is based on the LaCoSSPAr target catalog (see Sect. 2.1). Actually, many sources in that catalog are stars or fake targets that are mistakenly identified as galaxies by SDSS. To exclude them, we visually inspected the images of all sources with the SDSS navigator tool and discarded those showing obvious characteristics of a star, or which did not exhibit relevant features at all (fake sources). Furthermore, among the 3098 sources with LAMOST redshifts, 60 were found to be Galactic sources with z = 0 and were therefore dis-

carded. Finally, our parent sample contains 5531 galaxies, of which 3038 have redshifts from LAMOST. In addition, 457 galaxies in the sample have SDSS redshifts but no LAMOST redshifts. Altogether, 3495 galaxies in our sample have measured redshifts, corresponding to a redshift completeness of 63%. For galaxies brighter than the magnitude limit of the SDSS spectroscopic survey, r = 17.77 mag, the redshift completeness of the sample is 69% (2592/3749).

In Figure 1, the magnitude distribution of galaxies in the parent sample is presented. For each galaxy, the Galactic extinction was corrected using the dust maps of Schlegel et al. (1998). The upper panels show histograms of magnitudes in qri bands for all visually-examined photometric galaxies. We utilize different colors to represent galaxies with redshifts from LaCoSSPAr (red), galaxies with redshifts from SDSS (orange) and galaxies having no redshifts (blue) in each bin. The lower panels give the fraction for different classes within each magnitude bin. The black dashed lines mark the magnitude limits of corresponding subsamples used in the calculation of individual LFs. Beyond these limits, the completeness (i.e., the ratio between galaxies with redshifts and galaxies identified photometrically) drops rapidly below 50%. Figure 1 demonstrates that the completeness of faint galaxies is better than that of bright galaxies. This counterintuitive result deserves some explanation. It appears that the success of redshift detection depends sensitively on how accurately the fiber position coincides with the target position. Because targets fainter than r = 16 were observed with longer integration times and more repeats (Yang et al. 2018), they are more resilient to the effect of bad fiber position, and therefore have better detection rates.

We checked the dependence of LaCoSSPAr redshift incompleteness on redshift itself by comparing with the SDSS spectroscopic sample. Given the magnitude limit of the SDSS spectroscopic main galaxy sample, in Figure 2 we plot the sky positions of all photometric galaxies (blue dots) and galaxies with SDSS redshifts (red dots), both brighter than r = 17.6, in our two fields. The Stripe 82 of SDSS Legacy Survey (Abazajian et al. 2009) overlaps with our survey, resulting in a higher SDSS redshift coverage between $-1.25^{\circ} < \text{Dec.} < 1.25^{\circ}$, as presented in Figure 2. To construct a complete comparison sample, we divided our two fields into many grid cells and calculated the ratio between galaxies having SDSS redshifts and photometric galaxies for each cell. In Figure 3, we display the completeness map of the SDSS survey in our two fields. The complete comparison sample (here after 'sample C')



Fig. 1 *Upper panels*: histograms of Petrosian magnitude in each band for all galaxies in the parent sample. Different colors represent galaxies with redshifts from LaCoSSPAr (*red*), galaxies having no LaCoSSPAr redshifts but having redshifts from SDSS (*orange*) and galaxies having no redshifts (*blue*). *Lower panels*: the fraction for different classes within each magnitude bin. The *black dashed lines* signify the upper magnitude limit of a subsample.



Fig. 2 Spatial distribution for photometric galaxies (*blue dots*) and galaxies having SDSS redshifts (*red dots*) with r < 17.6.



Fig. 3 The completeness map for the SDSS survey in our two fields. The color bar represents the ratio between galaxies having SDSS redshifts and photometric galaxies for each cell.

includes all galaxies located within cells that are 100% complete and with $-1.25^{\circ} < \text{Dec.} < 1.25^{\circ}$. It contains 120 galaxies.

A depiction of the redshift dependence on completeness is exhibited in Figure 4. In the upper panel, histograms of distributions of SDSS redshifts (blue bars) and LoCaSSPAr redshifts (orange bars) are plotted for sample C. The bin size has been adjusted to ensure roughly equal numbers of galaxies in each bin. The completeness and error are plotted in the lower panel. It appears that,



Fig. 4 Relationship between redshift completeness of LaCoSSPAr and galaxy redshift. *Upper panel:* the histograms of redshift distribution. The *blue bars* and *orange bars* represent counts of redshifts from the SDSS survey and LaCoSSPAr, respectively. We only include 100% complete cells within $-1.25^{\circ} < \text{Dec.} < 1.25^{\circ}$ in Fig. 3 to calculate the galaxy numbers. The bin sizes are set to ensure roughly equal numbers of galaxies for *blue bars* in each bin. *Lower panel: green dots* signify the ratio of number count of galaxies with LaCoSSPAr redshifts to number count of galaxies with SDSS redshifts in each bin in the upper panel.



Fig. 5 Upper panels: the histograms of Petrosian magnitude in the *r* band for galaxies in 'sample C' (*blue bars*) and galaxies only with redshifts from LaCoSSPAr in 'sample C' (*orange bars*). These galaxies are divided into z < 0.08 (*left panel*) and z > 0.08 (*right panel*). Lower panels: the ratio of counts in *orange bars* to counts in *blue bars*.

for galaxies with r < 17.6, the redshift completeness of LaCoSSPAr has two different levels for z < 0.08 and z > 0.08: ~ 0.4 for low redshift range and ~ 0.7 for high redshift range.

In Figure 5, we divided the 120 galaxies in 'sample C' into a z > 0.08 subsample and a z < 0.08 subsample. Galaxies in the high redshift subsample all manifest r > 16.0 mag, so they have higher completeness. In the low redshift subsample, galaxies cover a large magnitude range from 14.4 mag to 17.6 mag. Among them, bright galaxies have lower completeness while faint galaxies still have relatively higher completeness. It appears that the difference between redshift incompleteness in the two redshift ranges is caused by the different incompletenesses between bright and faint galaxies, as illustrated in Figure 1.

2.3 Samples for LFs in Different Bands

Samples for LFs in different bands were constructed by applying corresponding redshift limits and apparent magnitude limits to the parent sample. The lower magnitude limits were set to be 14.0 mag in all bands. The upper magnitude limit in the r band was defined to be the same as that of LaCoSSPAr, r < 18.1 mag. In other bands, we chose the upper limit at the magnitude where the redshift completeness falls rapidly (Fig. 1). For the redshift limits, we select the upper redshift limits where 98 percent of galaxies are included in the sample to avoid large noise in determination of the normalization at high redshift. The lower redshift limits are the same as those in Blanton et al. (2001),



Fig. 6 Upper panels: the LFs of LaCoSSPAr in SDSS ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands. The black dots are the SWML LFs with error bars and black lines are the results of best Schechter function fit by using the STY method. The red thick lines trace the LFs of Blanton et al. (2003) along with their corresponding error regions, and thin red lines are the best-fitting Schechter functions. Both of these line types are drawn under the assumption of simple evolution. LFs of Field A and Field B are also plotted as squares and triangles, respectively. In the ${}^{0.1}r$ -band panel, we overplot the dotted line shown in fig. 15 in Blanton et al. (2003), which represents the best-fit Schechter function based on a sample of ~10 000 galaxies, not accounting for the effect of evolution. Lower panels: histograms of the number of galaxies in each bin for SDSS ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands, from left to right respectively.



Fig.7 The color-magnitude diagram for the *r*-band subsample described in Sect. 2.3. *Red* and *blue colored dots* are used to distinguish absorption line galaxies from emission line galaxies. The *black contour lines* signify the *r*-band subsample and a *black dashed separation line* marks the rest-frame bimodality of galaxies (Zehavi et al. 2011).

which can reduce the effect of galaxy peculiar velocities when calculating galaxy luminosity distance.

The lower and upper limits of redshift and magnitude along with the number of galaxies for the samples are listed in Table 1. In this work, we did not include the u, z bands because of their relatively large photometric uncertainties.

 Table 1 Magnitude and redshift limits and galaxy counts of samples for LFs in different bands.

Band	Magnitude limit	Redshift limit	No. of Galaxies
g	14.0 < m < 18.7	0.016 < z < 0.23	2718
r	14.0 < m < 18.1	0.016 < z < 0.27	3412
i	14.0 < m < 17.6	0.016 < z < 0.275	3235

3 LUMINOSITY FUNCTIONS

We employed the KCORRECT v4_3 (Blanton & Roweis 2007) code to estimate the K-corrections for SDSS magnitudes. To compare with LFs in previous works based on SDSS data, we adopted 'blueshift = 0.1' when executing this code, and obtained absolute magnitudes in z = 0.1 blueshifted bandpasses.

In LF calculations, we exploited two methods based on the maximum likelihood approach. One is the parametric maximum likelihood method introduced by Sandage et al. (1979), the so called STY method. This is based on the probability for a galaxy at redshift z_i and absolute magnitude M_i to be included in a magnitude-limited sample

$$p_{i} = \frac{\phi(M_{i})}{\int_{\max[M_{\max}(z_{i}),M_{1}]}^{\min[M_{\max}(z_{i}),M_{2}]} \phi(M) dM} , \qquad (1)$$

where $M_{\min}(z_i)$ and $M_{\max}(z_i)$ are the minimum and maximum absolute magnitudes a galaxy at redshift z_i can have to be included in the sample respectively, and M_1 and M_2 are the absolute magnitude limits of the sample. To correct for incompleteness, the following correction factor Fac_n(mag_{bin}) is defined for every galaxy in each bin,

$$Fac_n(mag_{bin}) = \frac{1}{Fraction_{red}(mag_{bin}) + Fraction_{orange}(mag_{bin})}.$$
 (2)

Here Fraction_{red} and Fraction_{orange} correspond to red bars and orange bars presented in Figure 1 respectively. We assume that the incompleteness depends only on the apparent magnitude. A Schechter function (Schechter 1976) for $\phi(M)$ is adopted when maximizing the log-likelihood function $\ln \mathcal{L}$,

$$\phi(M) = 0.4 \ln(10) \phi_* 10^{-0.4(M-M_*)(\alpha+1)} \\ \times \exp(-10^{-0.4(M-M_*)}) , \qquad (3)$$

$$\ln \mathcal{L} = \sum_{i}^{N_{\text{gal}}} \operatorname{Fac}_{i} \ln p_{i} .$$
(4)

The other method, the Stepwise Maximum Likelihood Method (SWML), is a non-parametric method described by Efstathiou et al. (1988). This method does not depend on any assumption about the particular form of an LF. The sample is divided into $N_{\rm bin}$ bins according to the absolute magnitude, and the LF can be calculated as

$$\phi(M) = \phi_i, M_i - \Delta/2 < M < M_i + \Delta/2,$$

 $i = 1, 2, ..., N_{\text{bin}},$
(5)

where ϕ_i is the value of the LF in each bin, which can be derived iteratively by maximizing a log-likelihood function similar to that in Equation (4).

For both methods, we used the minimum variance estimator (Davis & Huchra 1982) to independently calculate the normalization constant \bar{n} of each LF. \bar{n} represents the number density of galaxies, and it can be expressed as

$$\phi(M) = \bar{n}\phi^*(M) , \qquad (6)$$

where $\phi^*(M)$ is the unit-normalized LF. We did not carry out the correction for cosmic evolutionary effects because it may introduce significant uncertainties due to our relatively small sample size and large number of parameters involved in the calculation (Blanton et al. 2003).

In the calculation of errors for the STY LFs, we implemented the jackknife re-sampling method which has been incorporated in many previous works (Blanton et al. 2003; Loveday et al. 2012). We divided our total region into eight sub-regions of approximately equal area, each time omitting one region in the calculation, and retrieved a set of parameters $x^k = \{\alpha, M_*, \bar{n}\}$. The statistical variance of the fitting parameter $x^k = \{\alpha, M_*, \bar{n}\}$ can be written as

$$\operatorname{var}(x^{k}) = \frac{N-1}{N} \sum_{n=1}^{N} (x_{n}^{k} - \bar{x}^{k})^{2} , \qquad (7)$$

where N = 8 is the number of jackknife regions and \bar{x}^k is the mean of the parameter x_n^k fitted while excluding region *i*. It should be pointed out that, for large samples covering widely separated sky areas (e.g., Blanton et al. 2003), the jackknife method can include uncertainties due to largescale structure across the survey, namely the cosmic variance. However, due to the relatively small area of our survey, this does not apply to our results. Therefore, while the uncertainties of parameters (α , M_*) in our work may be underestimated, the cosmic variance is added to the error of \bar{n} . It is estimated according to Peebles (1980); Somerville et al. (2004); Xu et al. (2012)

$$\sigma_{cv}^2 = J_2(\gamma) \times (r_0/r_{\text{sample}})^{\gamma} , \qquad (8)$$

where $r_0 = 5.59 \ h^{-1} \text{ Mpc}$ and $\gamma = 1.84$ (Zehavi et al. 2005) are parameters in the two point correlation function, r_{sample} represents the radius of sample volume and J_2 is

$$J_2(\gamma) = \frac{72}{(3-\gamma) \times (4-\gamma) \times (6-\gamma) \times 2^{\gamma}} .$$
(9)

In the ${}^{0.1}r$ band, the cosmic variance contributes $\sim 63.3\%$ of the error in \bar{n} .

For SWML LFs, the errors of ϕ_i were calculated using inversion of the information matrix as described in Efstathiou et al. (1988).

In every band, we also calculated the luminosity density using parameters of the corresponding STY LF

$$j = \int_0^\infty dL L\phi(L) = \phi_* L_* \Gamma(\alpha + 2) . \qquad (10)$$

4 RESULTS AND DISCUSSION

4.1 LFs and Luminosity Densities

As depicted in Figure 6, our LFs obtained using the parametric STY method and the nonparametric SWML method agree well in all three bands. In every band, our LF extends approximately $\sim 1 \text{ mag}$ toward the fainter end compared to that of Blanton et al. (2003), because the LAMOST redshift survey is deeper than SDSS. The marginally significant discrepancy with the results of Blanton et al. (2003) is mainly due to the cosmic evolution correction carried out by them but omitted in this work (see Sect. 4.1). Indeed, when compared to their ${}^{0.1}r$ LF without evolution correction (green dotted line in the middle panel of Fig. 6), the discrepancy is reduced remarkably: the difference is $< 1\sigma$ for any Schechter function parameter except for M_* (2.5 σ , Table 2). Another reason for the differences between LFs of Blanton et al. (2003) and ours could be due to the cosmic variance. Both Field A and Field B from which our sample was selected are affected by clusters (see Sect. 2.1). In Figure 6, the LFs derived using subsamples of sources in the two fields are overplotted separately. The difference between results from the two fields is mainly in the faint end. In the bright end of $^{0.1}r$ LFs, the result of the complete sample and that of the subsamples in the two fields are all slightly higher than the non-evolution LF of Blanton et al. (2003). Nevertheless, as shown in Table 2, the difference between values of our $^{0.1}r$ band density parameter \bar{n} and that of the non-evolution model of Blanton et al. (2003) is only 7%, significantly less than 1σ . In this work, we used 0.4 for the width of the absolute magnitude bin for the SWML estimates to ensure that there is an adequate number of galaxies in each bin. From the lower panels in Figure 6, it can be seen that in the $^{0.1}r$ band ~ 10 galaxies are in the faintest bin. This to some extent makes our errors bars corresponding to SWML estimates seem comparable to Blanton et al. (2003)'s results (Fig. 6), though our sample size is much smaller.

Table 2 lists our best-fitting parameters, luminosity densities, number densities and their 1σ uncertainties in ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands. For comparison, we also tabulate the parameters of the ${}^{0.1}r$ band non-evolution LF of Blanton et al. (2003). The uncertainties of best fitting parameters in our work are larger than those in Blanton et al. (2003), because small sample sizes selected from small sky areas are used in this work. Our ${}^{0.1}r$ band luminosity density agrees very well with that of Blanton et al. (2003) based on the non-evolution LF. Our luminosity densities are also consistent with the luminosity density evolution trend displayed in figure 20 of Loveday et al. (2012).

4.2 Dependence of LFs on Spectral Type

Depending on whether there are obvious emission lines in their spectra, Yang et al. (2018) divided galaxies observed in the LaCoSSPAr survey into emission line galaxies and absorption line galaxies. The absorption line galaxy sample comprises 1375 typical passive galaxies. Figure 7 presents the color-magnitude diagram of $M_{0.1r}$ vs. $^{0.1}(g - r)_0$ for the *r*-band subsample described in Section 2.3. Here $^{0.1}(g - r)_0$ is the rest-frame color for *g* and *r* bands that are blueshifted by 0.1. Red dots represent the absorption line galaxies and blue dots the emission line galaxies. A contour diagram and a separation line are also overplotted in Figure 7. The color-magnitude separation line (black dashed) is taken from Zehavi et al. (2011)

$$^{0.1}(g-r)_0 = 0.21 - 0.03 \times M_{0.1r}$$
 (11)

In Figure 8, SWML LFs of SDSS $^{0.1}g$, $^{0.1}r$, $^{0.1}i$ bands for emission line galaxies (blue dots), absorption line galaxies (red dots) and red galaxies (those located above the separation line in Fig. 7, red open circles) are plotted, and are compared to the LFs of the total sample. The absorption line galaxies exhibit higher number densities than emission line galaxies at the luminous end (Mag_{0.1}, or Mag_{0.1}; > 21.5 mag) in $^{0.1}r$ and $^{0.1}i$ bands. In each band, the LF of emission line galaxies appears to have a Schechter function profile with a steeper faint end slope than that of the total sample. For absorption line galaxies (and red galaxies), the LFs display an obvious dip at $M - 5 \log_{10} h \sim -18.5$ mag in all three bands. A standard Schechter function cannot provide a good fit to the LF of absorption line galaxies over the entire magnitude range.

Similar results have been found in many previous works on LFs of passive galaxies in different photometric bands and different redshift ranges (Madgwick et al. 2002; Wolf et al. 2003; Blanton et al. 2005; Salimbeni et al. 2008; Loveday et al. 2012; López-Sanjuan et al. 2017). Madgwick et al. (2002) investigated galaxy LFs for the 2dF survey in the M_{b_j} band for different spectral types. They divided their galaxies into four spectral types by introducing a new parameter η , which identifies the average emission and absorption line strength in the galaxy restframe spectrum. Their LF for 'Type 1' galaxies (absorption line galaxies) shows an obvious dip at $M_{b_j} - 5 \log_{10} h \sim$ -16 mag.

For comparison, in Figure 8 we overplot the LFs of red (red dotted lines) and blue galaxies (blue dotted lines) by Loveday et al. (2012) in three bands, and by Montero-Dorta & Prada (2009) in the $^{0.1}r$ band (red and blue dashed lines). The LFs of blue galaxies in Loveday et al. (2012) are in general lower than those of our emission line galaxies. A possible cause for this, besides the difference in definitions of blue galaxies and emission line galaxies, could be

This work $\phi_* (10^{-2} h^3 \,\mathrm{Mpc}^{-3})$ $M_* - 5\log_{10}h$ $\bar{n} (10^{-2} h^3 \,\mathrm{Mpc}^{-3})$ Band $j + 2.5 \log_{10} h \text{ (mag in Mpc}^3)$ α $^{0.1}g$ 2.93 ± 0.54 -19.49 ± 0.05 -0.91 ± 0.08 -15.61 ± 0.22 2.70 ± 0.50 0.1r 1.65 ± 0.36 -20.69 ± 0.06 -1.12 ± 0.08 -16.32 ± 0.27 1.52 ± 0.33 $^{0.1}i$ -16.47 ± 0.24 1.22 ± 0.24 -21.15 ± 0.06 -1.14 ± 0.06 1.13 ± 0.22 Blanton et al.(2003) (no evolution) $\phi_* (10^{-2} h^3 \,\mathrm{Mpc}^{-3})$ $M_* - 5\log_{10}h$ $\bar{n} (10^{-2} h^3 \,\mathrm{Mpc}^{-3})$ Band $j+2.5\log_{10}h~({\rm mag~in}\,{\rm Mpc}^3)$ α 0.1r1.77-20.54-1.15-16.281.63

Table 2 Three parameters ϕ_* , M_* , α of the Schechter function fits, luminosity densities and number densities in ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands from this work and Blanton et al. (2003).

Table 3 Least squares fitting parameters of double-Gaussian function to LFs of absorption line galaxies in each band.

Band	$\phi_{1,G} \ (10^{-2} \ h^3 { m Mpc}^{-3})$	$M_{1,G} - 5\log_{10}h$	$\sigma_{1,G}^2$	$\phi_{2,G} \ (10^{-2} \ h^3 { m Mpc}^{-3})$	$M_{2,G} - 5\log_{10}h$	$\sigma_{2,G}^2$	χ^2_{ν}
$^{0.1}g$	0.40	-18.95	1.36	0.40	-15.63	3.66	0.66
$^{0.1}r$	0.34	-20.04	1.53	0.23	-16.50	4.40	0.93
$^{0.1}i$	0.30	-20.35	1.66	0.18	-16.96	4.40	1.07

Table 4 Least squares fitting parameters of double-power-law Schechter function to LFs of absorption line galaxies in each band.

Band	$M_{*,S} - 5 \log_{10} h$	$\alpha_{1,S}$	$\alpha_{2,S}$	$\phi_{1,S}$	$\phi_{2,S}$	χ^2_{ν}
				$(10^{-5} h^3 \mathrm{Mpc}^{-3})$	$(10^{-2} h^3 \mathrm{Mpc}^{-3})$	
$^{0.1}g$	-19.48	-1.90	-0.53	9.05	0.79	0.80
0.1r	-20.68	-2.03	-0.52	1.91	0.66	1.31
$^{0.1}i$	-21.16	-2.57	-0.64	0.08	0.53	1.67

the cosmic evolutionary effect because our galaxies have a higher median redshift ($\bar{z} = 0.104$) than theirs (all with z < 0.1) and we did not apply any evolutionary correction. For red galaxies, Loveday et al. (2012) fitted the LFs with double-power-law Schechter functions, in the form

$$\phi(M) = 0.4 \times \ln(10) \exp[-10^{-0.4(M-M_{*,S})}] \\ \times \phi_{1,S} 10^{-0.4(M-M_{*,S})(\alpha_{1,S}+1)} \\ + \phi_{2,S} 10^{-0.4(M-M_{*,S})(\alpha_{2,S}+1)}.$$
(12)

They show poor agreements with our results for both absorption line galaxies and red galaxies. Montero-Dorta & Prada (2009) used the Schechter function to fit their LFs for red and blue galaxies. Their $^{0.1}r$ band LF of blue galaxies shows a much better agreement with ours than Loveday et al. (2012), but the LF of red galaxies is significantly different from ours.

We found that a double-Gaussian function, as defined in what follows, can provide significantly better fits to the LFs of absorption line galaxies and red galaxies

$$\phi = \phi_{1,G} \exp\left(-\frac{(M - M_{1,G})^2}{2\sigma_{1,G}^2}\right) + \phi_{2,G} \exp\left(-\frac{(M - M_{2,G})^2}{2\sigma_{2,G}^2}\right).$$
(13)

In Figure 9 and Tables 3–4 we compare results of double-Gaussian fittings and double-power-law Schechter function fittings. For absorption line galaxies, the former not only provides a much better fit to the dip at $M_{0.1r} - 5 \log_{10} h \sim -18.5$ mag, but also results in smaller reduced- χ^2 's in all three bands than the latter. While the double-power-law Schechter function has one characteristic absolute magnitude $(M_{*,S})$, the double-Gaussian function has two characteristic absolute magnitudes $M_{1,G}$ and $M_{2,G}$. This may hint at a bimodality in the population of absorption line galaxies, with the two sub-populations having distinctively different characteristic luminosities (masses): the more massive sub-population has the luminosity of L^* galaxies, while galaxies in the less massive sub-population are ~ 3.5 mag (i.e., $\sim 25 \times$) fainter.

Peng et al. (2010, 2012) argued that passive galaxies are mainly formed through two distinct processes of "mass quenching" and "environment quenching." The massive central galaxies (characterized as L^* galaxies) are presumably quenched by the first process, and low mass satellite galaxies are quenched by the second process. Is the "bimodality" of the absorption line galaxies consistent with this theory? To answer this question, we carried out the following test: Firstly we cross-matched our sample of absorption line galaxies with the SDSS-



Fig. 8 SWML estimates of LFs for emission line galaxies (*blue dots and error bars*) and absorption line galaxies (*red dots and error bars*) in ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands in our work. The *red unfilled circles* are the SWML estimates of LFs for red galaxies corresponding to galaxies located above the separation line in Fig. 7. The *black dots, error bars* and *black solid lines* are the same as LFs presented in Fig. 6. The *dashed lines* plotted in ${}^{0.1}r$ band are the best fitting Schechter function of LFs for blue galaxies (*blue dashed line*) and red galaxies (*red dashed line*) estimated by Montero-Dorta & Prada (2009). The *dotted lines* in each band signify the LFs for blue (*blue dotted lines*) and red (*red dotted lines*) galaxies at low redshift (z < 0.1) from fig. 13 of Loveday et al. (2012), which are all fitted with the double-power-law Schechter function.



Fig. 9 Double-Gaussian function (*black solid lines*) and double-power-law Schechter function (*green dashed lines*) fits to LFs of absorption line galaxies in ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands. The *red dots* are SWML estimates of absorption line galaxies displayed in Fig. 8. *Red dotted lines* represent the LFs for red galaxies at low redshift (z < 0.1) from fig. 13 of Loveday et al. (2012).

DR7 based NYU Value-Added Galaxy Catalog (NYU-VAGC) that Yang et al. (2007) used for group identifications, and then checked the matches for memberships in Yang's groups. After excluding galaxies associated with one-galaxy groups (i.e., single galaxies) and with groups having no halo mass estimates (uncertain groups), we found 83 absorption line galaxies (70 bright galaxies with $M_{0.1r} - 5 \log_{10} h < -18.5, 13$ faint galaxies with $M_{0.1r} -$ $5 \log_{10} h > -18.5$) belonging to 30 groups. Among the 70 bright galaxies ("more massive galaxies"), 26 (37%) are the brightest or most massive galaxies in their groups, and another 7 (10%) are the second brightest galaxies in groups with three or more members, suggesting that $\sim 50\%$ of these galaxies are the master galaxies in groups. On the other hand, none of the faint galaxies is the brightest or most massive galaxy in any group to which they belong. Actually, 8 out of the 13 faint absorption line galaxies belong to a single rich group (group-ID 280, with 34 identified members), and indeed they appear to be the "satellite" galaxies in the group, which all have an M_r rank after the 20th. Our results seem to agree with the hypotheses that the bright and massive absorption line galaxies tend to be master galaxies in groups, while most faint and less massive absorption line galaxies are satellites, consistent with the theory of Peng et al. (2010, 2012). It is worth noting that, because of the poor coverage of the SDSS spectroscopic survey in our fields (Fig. 3), only a small fraction of the absorption line galaxies have matches in the NYU-VAGC catalog. Also, the number of faint galaxies (83) is much less than that of bright galaxies (1292) in the absorption line galaxy sample since the volume associated with the former is much smaller than that of the latter.

5 SUMMARY

LAMOST is one of the most powerful telescopes in terms of accessing the spectra of celestial objects. As a key project associated with LAMOST, LaCoSSPAr, provides the most complete dataset of LEGAS up to now. In this work, we analyzed the redshift incompleteness in the LaCoSSPAr survey quantitatively, and obtained the first measurements of the galaxy LFs in the ${}^{0.1}g$, ${}^{0.1}r$, ${}^{0.1}i$ bands using LAMOST spectroscopic data.

We employed both parametric (STY) and nonparametric (SWML) maximum likelihood methods to construct LFs, and found good agreements between the results. Our LFs are comparable to previous works using SDSS data. Thanks to the deeper magnitude limit of LAMOST, compared to results based on SDSS data, we were able to extend the faint end of the LFs by ~ 1 mag. Our luminosity densities are consistent with the luminosity density evolution obtained by Loveday et al. (2012).

We divided our sample into emission line galaxies and absorption line galaxies, and derived their LFs separately. Our results show that, in every band, the SWML estimate of emission line galaxy LFs has a Schechter function profile with a steeper faint end slope than that of the total sample. The LFs of absorption line galaxies exhibit an obvious dip near $\sim 18.5 \,\mathrm{mag}$ in all three bands, and cannot be fitted by Schechter functions. On the other hand, double-Gaussian functions, with two characteristic absolute magnitudes $M_{1,G}$ and $M_{2,G}$, provide excellent fits to them. This may hint at a bimodality in the population of absorption line galaxies (representing passive galaxies), with the two sub-populations having distinctively different characteristic luminosities (masses): the more massive sub-population has the luminosity of L^* galaxies, while galaxies in the less massive sub-population are $\sim 3.5 \,\mathrm{mag}$ (i.e., $\sim 25 \times$) fainter. Investigations using the group catalog of Yang et al. (2007) indicate that the former tend to be the master galaxies in groups while most of the latter are satellites.

This work is based on a small size galaxy sample within a $\sim 40 \text{ deg}^2$ survey area, which leads to large statistical uncertainties in LF estimates. In the future, we can expect a sample covering a large area when LAMOST finishes its LEGAS survey which can give us better-constrained and unbiased estimates for LFs.

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