The Mg II absorption line systems in quasar spectra from the Large Sky Area Multi-Objet Fiber Spectroscopic Telescope

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Abstract Making use of the quasar spectra from the LAMOST, in the spectra data around Mg II emission lines, this paper has detected 217 Mg II NALs with \( \lambda_{2796} \gtrsim 3 \sigma_w \) and \( \lambda_{2803} \gtrsim 2 \sigma_w \) in a redshift range of \( 0.4554 \lesssim z_{\text{abs}} \lesssim 2.1110 \). For the quasars observed by both the LAMOST and SDSS, we find that 135 Mg II NALs were obviously observed in the LAMOST spectra, 347 Mg II NALs were obviously observed in the SDSS spectra, and 132 Mg II NALs were obviously observed in both the SDSS and LAMOST spectra. The missed Mg II NALs are likely ascribed to the low signal-to-noise ratios of corresponding spectra. Among the Mg II NALs obviously observed in the SDSS or LAMOST spectra, 8 Mg II NALs were significantly changed with \( \Delta \lambda_{2796} \gtrsim 3 \sigma_w \) in time intervals of \( \Delta \text{MJD}/(1 + z_{\text{em}}) = 359 - 2819 \) days.

Key words: line: identification C– quasars: absorption lines C– quasars: general

1 INTRODUCTION

Shortly after the discoveries of quasars (e.g., Bahcall & Salpeter 1965; Bahcall et al. 1966; Bahcall & Salpeter 1966), quasar absorption lines (QALs) were found in the UV-optical spectra of quasars. Nowadays, QALs are very common in the quasar spectra, and have been widely used to investigate the physical conditions associated with the quasar themselves or with the quasar intervening galaxies (the foreground galaxies far from the quasar systems). The strengths of the QALs are mainly determined by the column densities of the absorbing gas, therefore, the detections of QALs do not depend on the quasar emissions. In theory, QALs would be imprinted in the spectra of quasars so long as the continuum emissions from the central regions of quasars pass through foreground gas clouds with suitable column densities before they reach the observers. Therefore, QALs are an important probe of the universe, and a valuable tool to investigate the properties of quasars and galaxies.

The Mg II \( \lambda \lambda 2798,2803 \) resonance doublets are good tracers to reflect the properties of neutral gas and low ionization gas (e.g., Lanzetta & Bowen 1990; Hamann 1997; Rao & Turnshek 2000), since they have strong oscillator strengths. In addition, the long rest wavelengths of the Mg II absorption doublet allow ground-based telescopes to track them with \( z < 0.2 \). Therefore, Mg II QALs are commonly detected in UV-optical spectra of quasars. The Mg II QALs have been found that they are likely related with foreground galaxies (e.g., Bergeron 1986; Bergeron & Boissé 1991; Lundgren et al. 2009; Chen et al. 2010; Kacprzak et al. 2010; Farina et al. 2014), or with quasar systems themselves (e.g.; Vanden Berk et al. 2008; Shen & Ménard 2012; Chen et al. 2018a). The Mg II QALs formed within foreground galaxies are often called as intervening QALs, which generally have absorption line redshifts much less than the emission line redshifts \( z_{\text{abs}} \ll z_{\text{em}} \), and the ones formed within quasar system themselves are often called as associated QALs, which generally have \( z_{\text{abs}} \approx z_{\text{em}} \). The associated Mg II QALs have potential to reveal the information on quasar’s outflows/inflows, host galaxies, environments, circumgalactic medium, and so on (e.g., Bowen et al. 2006; Shen & Ménard 2012; Farina et al. 2014; Chen 2017; Chen et al. 2018a). The intervening Mg II QALs have potential to reveal the information on galactic disks, outflows/inflows, dwarf galaxies (e.g., Le Brun et al. 1993; Charlton & Churchill 1996; Mo &
In the last two decades, the number of quasar spectra is huge increased after the advance of large spectroscopic surveys of the Sloan Digital Sky Survey (SDSS, York et al. 2000). The SDSS gathered quasar spectra in wavelength range of $\lambda \approx 3600 - 10000$ Å (Abazajian et al. 2009; Alam et al. 2015) at a resolution of $R \approx 2000$. Using the quasar spectra of the SDSS, many groups have compiled large samples of Mg II QALs (e.g., Nestor et al. 2005; Lundgren et al. 2009; Quider et al. 2011; Seyffert et al. 2013; Zhu & Ménard 2013; Chen et al. 2015, 2018a). The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) is located at Xinglong Observatory, China, which is a reflecting Schmidt telescope with effective aperture of 4 m and equipped with 4000 fibers (e.g., Cui et al. 2012; Zhao et al. 2012). The LAMOST quasar survey is carried out under the LAMOST ExtraGalactic Survey since the regular survey in September 2012 (LEGAS; Zhao et al. 2012), which gathered quasar spectra in wavelength range of $\lambda \approx 3800 \sim 9100$ Å at a resolution $R \approx 1800$. Both the coverage wavelength and resolution of the LAMOST quasar spectra are similar to those of the SDSS. The SDSS quasar spectra have been widely used to search for Mg II QALs, however, no one survey of QALs is carried out in the LAMOST quasar spectra up to this day. In this paper, we utilize the LAMOST quasar spectra to systematically search for associated Mg II QALs.

The outline of this paper is as follows. Section 2 describes the quasar sample and spectral analysis, Section 3 is for the results and discussions, and Section 4 is a brief summary.

2 QUASAR SAMPLE AND SPECTRAL ANALYSIS

The LAMOST carried out a pilot survey in 2011 October, and began regular surveys from September 2012 until 2017 June (e.g., Wu et al. 2010a,b; Luo et al. 2012, 2015). Utilizing the Data Release 1 — 5 of quasar catalogs from the LAMOST, Ai et al. (2016), Dong et al. (2018) and Yao et al. (2019) have compiled 43 109 quasars through checked the LAMOST spectra. In this paper, we make use of the LAMOST spectra of these 43 109 quasars to search for Mg II QALs around Mg II emission lines.

This paper mainly aims to search for associated Mg II QALs with line width less than a few hundreds $\text{km s}^{-1}$ (NALs, narrow absorption lines) in the spectral data around Mg II emission lines. Therefore, combining the coverage wavelength of the LAMOST spectra, we first reduce the parent sample of the LAMOST quasars with $3600/2800 < (1 + z_{\text{em}}) < 9300/2800$. In term of the statistical results of Chen & Pan (2017), most of the associated Mg II QALs are located within a velocity range of $v_r < 2000 \text{ km s}^{-1}$. Some outflow Mg II NALs might have been accelerated to high velocities by quasar radiations. We conservatively search for Mg II NALs in a wide velocity range, namely, from the blue wings $v_r = 10 \ 000 \text{ km s}^{-1}$ until the red wings of Mg II emission lines (e.g., Chen et al. 2018a). This wide velocity range should contain the vast majority of outflow Mg II NALs with high velocity, although a few of outflow Mg II NALs with $v_r > 10 \ 000 \text{ km s}^{-1}$ will be outside our survey of QALs. In addition, we also constrain the quasars with median $S/N > 3 \text{ pixel}^{-1}$ in surveyed spectral region (e.g., Chen et al. 2018a). Based on these two limits, the parent sample of the LAMOST quasars is reduced from 43 109 quasars to 12 317 quasars. Figure 1 shows the emission line redshifts of the 12 317 quasars with black solid-line.

We adopt the methods utilized by Chen et al. (2015) and Chen et al. (2018a) to search for Mg II NALs. The main processes are described as follows.

1. The pseudo-continuum fits. We invoke a cubic spline plus multi-Gaussian functions to fit the underlying continuum and emission lines of quasar spectra, where the multi-Gaussian functions mainly account for the broad absorption features and/or the emission lines. The fitting results are often called as pseudo-continuum. In our experience, the narrow Mg II emission line is difficulty distinguished from the broad one for most of the quasar spectra (e.g. Chen et al. 2019b), except for some quasars hosting strong narrow Mg II emission components. During the processes of the the pseudo-continuum fits and the Mg II NAL

$$\beta \equiv \frac{v_r}{c} = \frac{(1+z_{\text{em}})^2-(1+z_{\text{obs}})^2}{(1+z_{\text{em}})^2+(1+z_{\text{obs}})^2},$$

where the $c$ is the speed of light.
The Mg II NALs in the LAMOST quasar spectra

surveys (next step), we visually inspect the fitting results one by one. For the bad fits, we will fit these spectra again by adjusting the original parameters of the Gaussian functions used to describe the emission/absorption lines.

The spectra are normalized by the pseudo-continuum fits, including the flux and flux uncertainties. The Mg II NALs are searched in the normalized spectra. This paper is mainly focuses on the narrow absorption lines, which usually have line widths less than a few hundreds km s\(^{-1}\). Therefore, we disregard the broad absorption lines (BALs), which often show continual absorption features with widths > 2000 km s\(^{-1}\) at depths <10% under the pseudo-continuum fit (e.g., Weymann et al. 1979). As two examples, Figure 2 displays the spectra of quasar J125058.11+570921.7 and J112654.96+163136.3, which are over plotted with the pseudo-continuum fits.

2. The Mg II NAL surveys. Absorption lines are surveyed in normalized spectra. The surveys are controlled by the separations of Mg II doublets, which are varied with redshifts. Each Mg II doublet candidate is fitted with two Gaussian functions. The fitting results are visually inspected. As examples, Figure 2 also displays the fitting results of three Mg II NALs with \(z_{\text{abs}} = 0.9188, 1.4187, \text{and } 1.4729\).

3. Absorption line redshifts and equivalent widths. We estimate the redshifts of Mg II NALs with the Gaussian function fitting center of the Mg II \(\lambda 2796\). The equivalent widths \((W)\) of absorption lines are determined by the integrations of Gaussian function fitting profiles. The errors of equivalent widths \((\sigma_w)\) are contributed from the uncertainties in the flux \((\sigma_{\text{flux}})\) and the placements of the pseudo-continuum fits \((\sigma_{\text{cont}})\), namely, \(\sigma_w^2 = \sigma_{\text{flux}}^2 + \sigma_{\text{cont}}^2\). The \(\sigma_{\text{flux}}\) is estimated via

\[
(1+z_{\text{abs}})\sigma_{\text{flux}} = \sqrt{\sum_{i=1}^{N} P^2(\lambda_i - \lambda_0) \frac{\sigma_{\text{flux},i}^2}{\mathcal{I}_{\text{flux},i}} \Delta \lambda_i},
\]

where \(P(\lambda_i - \lambda_0)\) is line profile centered at \(\lambda_0\), \(\mathcal{I}_{\text{flux},i}\) is spectra flux, \(\sigma_{\text{flux},i}\) is spectra flux uncertainty, and the summation is over \(3\sigma\) line widths. The \(\sigma_{\text{cont}}\) is related to the placement of the pseudo-continuum fit and the line width of absorption line near the pseudo-continuum fit \((\lambda_{\text{max}} - \lambda_{\text{min}})\), namely, \(\sigma_{\text{cont}} \propto (\lambda_{\text{max}} - \lambda_{\text{min}})\sigma_{\text{pf}}\) (e.g.; Misawa et al. 2014; Chen et al. 2015). Accounting for the signal-to-noise ratio \((S/N)\) of absorption line, we estimate the \(\sigma_{\text{cont}}\) by

\[
\sigma_{\text{cont}} = A(\lambda_{\text{max}} - \lambda_{\text{min}}) \frac{\Delta \lambda_i}{S/N},
\]

where the calibration parameter \(A\) is estimated by fitting the pseudo-continuum multiple times around the absorption line, and the \(S/N\) is estimated with the methods used by Qin et al. (2013). See Qin et al. (2013) for the detailed calculation of the \(S/N\) of absorption line.

In the LAMOST spectra of 12 317 quasars used to searched for Mg II NALs, we detect 217 Mg II NALs with \(W_{\lambda 2796}^r \geq 3\sigma_w\) and \(W_{\lambda 2803}^r \geq 2\sigma_w\), whose parameters are listed in Table 1. Among these 12 317 quasars, 6427 quasars have been spectroscopically observed by the SDSS. In the same surveyed spectra regions, for the 6427 quasars observed by both the LAMOST and SDSS, Chen et al. (2015) detected 347 Mg II NALs with \(W_{\lambda 2796}^r \geq 3\sigma_w\) and \(W_{\lambda 2803}^r \geq 2\sigma_w\) from the SDSS spectra, while this paper only detects 135 Mg II NALs with \(W_{\lambda 2796}^r \geq 3\sigma_w\) and \(W_{\lambda 2803}^r \geq 2\sigma_w\) from the LAMOST spectra. Among the 135 Mg II NALs imprinted in the LAMOST spectra and with \(W_{\lambda 2796}^r \geq 3\sigma_w\) and \(W_{\lambda 2803}^r \geq 2\sigma_w\), 132 Mg II NALs were imprinted in the SDSS spectra (Chen et al. 2015) as well, but the rest 3 Mg II NALs were missed by Chen et al. (2015). Among the 347 Mg II NALs imprinted in the
has shown that the detection rate compares the distributions of the \( S/N \) of quasar spectra and the equivalent widths of Mg II NALs. It is clearly seen that the \( S/N \) of the LAMOST spectra (median \( S/N = 14.3 \)) are slightly smaller than those of the SDSS spectra (median \( S/N = 16.7 \)). The Kolmogorov-Smirnov (KS) tests suggest that the \( S/N \) of the SDSS spectra are obviously different from those of the LAMOST spectra, while the equivalent widths of Mg II NALs measured from the SDSS spectra are similar to those measured from the LAMOST spectra. In addition, the right panel of Figure 4 clearly indicates that the weak Mg II NALs are difficultly detected in the spectra with low \( S/N \). For example, no Mg II NALs with \( W_r^{\lambda 2796} < 0.7 \) Å was detected in the spectra with \( S/N < 7 \).

Figure 5 also compares the distributions of the \( S/N \) of quasar spectra and the equivalent widths of Mg II NALs, where the Mg II NALs are only detected in the SDSS spectra. It is clearly seen that the \( S/N \) of the LAMOST spectra (median \( S/N = 6.4 \)) are much smaller than those of the SDSS spectra (median \( S/N = 18.9 \)). Although the KS-test suggests that the distribution of equivalent width measured from the SDSS spectra is different from that measured from the LAMOST spectra, the median \( W_r^{\lambda 2796} \) measured from the LAMOST spectra (0.92 Å) is consistent with that measured from the SDSS spectra (0.93 Å). In addition, in term of the equivalent widths measured respectively from the LAMOST and SDSS spectra, 83.7% of the Mg II NALs are consistent within 1σ error, and 97.6% of the Mg II NALs are consistent within 2σ error. Therefore, the low \( S/N \) of the LAMOST spectra would be the main reason why some Mg II NALs detected in the SDSS spectra were missed from the LAMOST spectra (see also Figure 3).

### 3 RESULTS AND DISCUSSIONS

Section 2 has shown that the detection rate of Mg II NALs is obviously lower in the LAMOST spectra than that in the SDSS spectra. This would be mainly ascribed to the lower \( S/N \) of the LAMOST spectra relative to the SDSS spectra. Of course, the evolution of Mg II NALs might also play a role to the low detection rate of Mg II NALs in the LAMOST spectra. Figure 3 shows the detection rates of Mg II NALs as a function of \( S/N \) of the LAMOST spectra, which clearly implies that the detection rate of weak Mg II NALs is obviously dependent on the \( S/N \) of spectra. For example, detection rates of Mg II NALs with \( W_r^{\lambda 2796} > 0.2 \) Å (or \( W_r^{\lambda 2796} > 0.5 \) Å) are increased rapidly with \( S/N \) when \( S/N < 12 \).

Section 2 has shown that there are 132 Mg II NALs with \( W_r^{\lambda 2796} \geq 3\sigma_w \) and \( W_r^{\lambda 2803} \geq 2\sigma_w \), which were detected from both the SDSS and LAMOST spectra. For these 132 Mg II NALs, Figure 4 compares the distributions of the \( S/N \) of quasar spectra and the equivalent widths of Mg II NALs. It is clearly seen that the \( S/N \) of the LAMOST spectra (median \( S/N = 14.3 \)) are slightly smaller than those of the SDSS spectra (median \( S/N = 16.7 \)). The Kolmogorov-Smirnov (KS) tests suggest that the \( S/N \) of the SDSS spectra are obviously different from those of the LAMOST spectra, while the equivalent widths of Mg II NALs measured from the SDSS spectra are similar to those measured from the LAMOST spectra. In addition, the right panel of Figure 4 clearly indicates that the weak Mg II NALs are difficultly detected in the spectra with low \( S/N \). For example, no Mg II NALs with \( W_r^{\lambda 2796} < 0.7 \) Å was detected in the spectra with \( S/N < 7 \).

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#### 3.1 Velocities and equivalent widths of Mg II NALs

Velocity offsets of absorbers are a convenient tool to distinguish the associated absorbers from the intervening ones. The Mg II NALs with \( v_r < 2000 \) km s\(^{-1} \) are often considered as associated absorption systems, while the Mg II NALs with \( v_r > 2000 \) km s\(^{-1} \) would be mainly dominated by the intervening absorption systems (e.g., Chen & Pan 2017). We search for Mg II NALs in the LAMOST spectra data with \( v_r \leq 10000 \) km s\(^{-1} \). This wide surveyed region results in the sample of Mg II NALs detected from the LAMOST spectra, which contains not only associated Mg II NALs but also a significant number of intervening Mg II NALs. The black line of Figure 6 displays the velocities of the 217 Mg II NALs detected from the LAMOST spectra and with \( W_r^{\lambda 2796} \geq 3\sigma_w \) and \( W_r^{\lambda 2803} \geq 2\sigma_w \), which is similar to the results discovered from the much
Table 1  Catalog of Mg II absorption line systems

<table>
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<tr>
<th>OBSID</th>
<th>LAMOST name</th>
<th>spectra name</th>
<th>$z_{\text{EM}}$</th>
<th>$z_{\text{abs}}$</th>
<th>$W_{\lambda 2796}^{\text{LAMOST}}$</th>
<th>$W_{\lambda 2803}^{\text{LAMOST}}$</th>
<th>$v_{r}$</th>
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Fig. 4  Comparisons of the S/N of quasar spectra and equivalent widths of Mg II NALs, where the Mg II NALs were detected from both the LAMOST and SDSS spectra. Right panel clearly shows that the weak Mg II NALs are mainly detected in the spectra with high S/N.

Fig. 5  Comparisons of the S/N of quasar spectra and equivalent widths of Mg II NALs, where the Mg II NALs were only detected from the SDSS spectra.

larger samples of Mg II NALs (e.g., Nestor et al. 2008; Wild et al. 2008; Chen et al. 2015, 2018a). The significant excess around $u \approx 0$ would be mainly contributed from the absorptions formed within the media surrounding quasars, such as quasar’s host galaxies, clusters, outflows with low velocities, and so on.

Figure 7 shows the absorption strengths of the 217 Mg II NALs detected by this paper. Both the distributions of the absorption strength (the left panel of Figure 7) and the absorption strength ratios $DR = W_{\lambda 2796}^{\text{LAMOST}} / W_{\lambda 2803}^{\text{LAMOST}}$ (the right panel of Figure 7) are similar to previous results (e.g., Quider et al. 2011; Chen et al. 2015, 2018a). There are $\sim 97\%$ of Mg II NALs with $W_{\lambda 2796}^{\text{LAMOST}} \geq 0.5$ Å, and $\sim 74\%$...
of Mg II NALs with $W_r^{\lambda 2796} \geq 1$ Å. There are about 97% of the Mg II NALs, whose absorption strength ratios are in a range of $1 - \sigma_{DR} \leq DR \leq 2 + \sigma_{DR}$, where 1 and 2 are the completely saturated and unsaturated absorption (Strömgren 1948), respectively.

3.2 The Mg II NALs with multi-epoch observations

Among the 12 317 quasars used to search for Mg II NALs in this paper, 6427 quasars were previously observed by the SDSS. Figure 8 shows the time intervals of the quasars between the LAMOST and SDSS observations. There are 5049 quasars that were repeatedly observed by the LAMOST within a time interval $\Delta MJD/(1 + z_{em}) > 1$ year. Some Mg II NALs are likely changed in this large time intervals. For the 6427 quasars observed by both the LAMOST and SDSS, we find that there are 347 Mg II NALs imprinted in the SDSS spectra, of which 132 Mg II NALs were also obviously observed in the LAMOST spectra ($W_r^{\lambda 2796} \geq 3\sigma_w$ and $W_r^{\lambda 2803} \geq 2\sigma_w$). For the rest of 347 – 132 = 215 Mg II NALs that were obviously observed in the SDSS spectra but not detected by this paper, we have also measured their absorption strengths or upper limits of absorption strengths. We compute the changes of Mg II NALs between the LAMOST and SDSS observations with $\Delta W_r = W_r^{\text{LAMOST}} - W_r^{\text{SDSS}}$, where the $W_r^{\text{LAMOST}}$ and $W_r^{\text{SDSS}}$ are for the absorption strengths measured from the spectra of the LAMOST and SDSS, respectively. Figure 9 shows the changes of the Mg II NALs between the LAMOST and SDSS observations. We find that there are 8 Mg II NALs with $|\Delta W_r^{\lambda 2796}| \geq 3\sigma_w$ (called as variable Mg II NALs), which were changed in timescales of $\Delta MJD/(1 + z_{em}) = 359 - 2819$ days. The time intervals and velocity offsets of the variable Mg II NALs are shown with red line in Figures 8 and 6, respectively. The spectra of the variable Mg II NALs are displayed in Figure 10.

The associated Mg II NALs are located within the vicinities of quasar center regions. Under the model of photoionization equilibrium, the gas column densities of associated Mg II NALs can be changed by the variations in quasar emissions (e.g., Narayanan et al. 2004; Chen et al. 2018b, 2019a, and references therein). On the other hand, the bulk of movements of Mg II absorbing clouds relative to quasar sightlines can give rise to changes in the efficient coverage fractions of Mg II absorbing clouds to quasar center regions, and thus can also result in changes in the total column densities of Mg II NALs and produce variable Mg II NALs. The changes in quasar emissions cannot play a role in changing the gas column densities of intervening Mg II NALs, since they are far away from quasar systems. In addition, in a timescale of a few years, the bulk of movements of absorbing clouds is difficult to obviously change the total column densities of intervening Mg II NALs, since the intervening Mg II NALs usually have low densities and much large sizes. Therefore, most of the variable Mg II NALs are often expected to be physically associated with quasar systems.

Assuming the bulk of movements of Mg II absorbing clouds relative to quasar sightlines result in variable Mg II NALs. Assume also that the variable Mg II absorbers are located around the Mg II broad emission line region (BELR). The maximum speed ($v_{max}$) of the variable Mg II absorber across the quasar sightline can be in the order of the rotational speed, which obeys the Kepler’s law. That is, $v_{max} \approx \sqrt{GM_{BH}/R_{\text{BELR}}}$. We directly take the values of black hole mass ($M_{BH}$) and continuum luminosities at 3000 Å ($L_{3000}$) from Yao et al. (2019). Using the radius-luminosity relation (Panda et al. 2019), we derive the $R_{\text{BELR}}$ from the $L_{3000}$, and thus estimate the maximum speeds of the variable Mg II absorbers across the quasar sightline with $v_{max} = \sqrt{GM_{BH}/R_{\text{BELR}}}$. The derived $R_{\text{BELR}}$ and $v_{max}$ are provided in Table 2, respectively. For a optical thick and geometric thin accretion disc, the UV continuum emission mainly comes from the inner accretion disc, which has a size scale of $D_{\text{cont}} \sim 5R_8 = 10G M_{BH}/c^2$ (Wise et al. 2004; Misawa et al. 2005). The deriving $D_{\text{cont}}$ are provided in Table 2. If the variable Mg II absorbers travel with the speed of $v_{max}$ in the time ($t_{across}$) between two observations of the SDSS and LAMOST, we can estimate the across distances of absorbers with $D_{across} = v_{max} \times t_{across}$. The results are provided in Table 2. It is clearly seen that the across distances of absorbers are much larger than the sizes of UV continuum emission sources. If we assume that the across dis-
The Mg II NALs in the LAMOST quasar spectra

Distributions of absorption strengths for the 216 Mg II NALs detected by this paper. Left panel: the y-axis has been normalized by the total number of Mg II NALs. Right panel: the red lines are for the theoretical limits of completely saturated (DR = \( W_{\lambda 2796} / W_{\lambda 2803} = 1 \)) and unsaturated (DR = \( W_{\lambda 2796} / W_{\lambda 2803} = 2 \)) absorption, respectively. The blue line is for the median values of DR as a function of \( W_{\lambda 2796} \).

Time intervals of the quasars between the LAMOST and SDSS observations. Black line is for all the quasars detected by both the LAMOST and SDSS, and red line is for the quasars having Mg II NALs with \(|\Delta W_{\lambda 2796}| \geq 3\sigma_w\), where y-axis values (the red line) have been multiplied by 10 for a convenient inspection.

Changes in quasar emissions are one of the important mechanisms driving changes in associated quasar absorption lines (e.g., Wang et al. 2015; He et al. 2017; Chen et al. 2018a; Lu et al. 2018; Lu & Lin 2018; Chen et al. 2019a). Decreasing emission can result in recombinations of Mg III \( \rightarrow \) Mg II and Mg II \( \rightarrow \) Mg I, and increasing emission can bring about photoionizations of Mg I \( \rightarrow \) Mg II and Mg II \( \rightarrow \) Mg III. It is a pity that we cannot investigate the changes in quasar emissions in this paper, since the LAMOST only provides rough flux calibrations for their quasar spectra (Ai et al. 2016; Dong et al. 2018; Yao et al. 2019). Assume Mg II and Mg III are the dominant ionization state of Mg for the weaken and strengthen Mg II NALs, respectively. Taking the time between two observations of the SDSS and LAMOST as the upper limit of the recombination time of absorbing gas, we can estimate the electron density with \( n_e \gtrsim (\alpha_r t_{\text{across}})^{-1} \) (e.g., Narayanan et al. 2004), where \( \alpha_r \) is the recombination coefficient. Adopting \( \alpha_r = 8.8 \times 10^{-13} \text{ cm}^3 \text{s}^{-1} \) for the Mg II \( \rightarrow \) Mg I and \( \alpha_r = 3.5 \times 10^{-12} \text{ cm}^3 \text{s}^{-1} \) for the Mg III \( \rightarrow \) Mg II (Shull & van Steenberg 1982), we can obtain the lower limit of the electron density of absorbing gas. The results are provided in Table 2.

4 SUMMARY

Using the Data Release 1 — 5 of quasar catalogs from the LAMOST, this paper has collected 12 317 quasars with median \( S/N > 3 \) pixel\(^{-1} \) to search for Mg II NALs in the LAMOST spectra data from blue wings \( v_r = 10,000 \text{ km s}^{-1} \) until red wings of Mg II emission lines. We detected 217 Mg II NALs with \( W_{\lambda 2796} \geq 3\sigma_w \) and \( W_{\lambda 2803} \geq 2\sigma_w \), which are in a redshift range of \( 0.4554 \leq z_{\text{abs}} \leq 2.1110 \).

Among the 12 317 quasars used to search for Mg II NALs in this paper, 6427 quasars were previously observed by the SDSS. For the quasars observed by both the LAMOST and SDSS, 347 and 135 Mg II NALs \( W_{\lambda 2796} \geq 3\sigma_w \) and \( W_{\lambda 2803} \geq 2\sigma_w \) were imprinted in the SDSS
Fig. 9 Distribution of variations of absorption strengths between two-epoch observations. Left panel: Different absorption strengths that have been normalized by uncertainties. Vertical dot and dash lines represent $\Delta W_r/\sigma_w = 0$ and $\pm 3$, respectively. Right panel: Red filled circles represent the variable Mg II NALs with $|\Delta W_{\lambda 2796}| \geq 3\sigma_w$, and blue dash-line is the identical line.

Fig. 10 The variable Mg II NALs in the normalized spectra. The black lines are for the LAMOST spectra, and the blue ones are for the SDSS spectra. The variable Mg II NALs are labeled with cyan lines. The $v_r$ are the velocity offsets of the variable Mg II NALs relative to the quasar emission line redshifts.
The Mg II NALs in the LAMOST quasar spectra

<table>
<thead>
<tr>
<th>LAMOST name</th>
<th>(M_{\text{BH}}) [M(_{\odot})]</th>
<th>(L_{3000}) [erg s(^{-1})]</th>
<th>(R_{\text{HEL}}) pc</th>
<th>(D_{\text{cont}}) [10(^{15}) cm]</th>
<th>(D_{\text{across}}) [10(^{15}) cm]</th>
<th>(v_{\text{max}}) km s(^{-1})</th>
<th>(v_{\text{tr}}) km s(^{-1})</th>
<th>(n_{\sigma}) cm(^{-3})</th>
</tr>
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<tbody>
<tr>
<td>033124.59-000554.1</td>
<td>8.486</td>
<td>45.813</td>
<td>0.291</td>
<td>0.451</td>
<td>39.965</td>
<td>2126</td>
<td>24</td>
<td>0.604</td>
</tr>
<tr>
<td>095108.42+160156.7</td>
<td>9.280</td>
<td>46.350</td>
<td>0.603</td>
<td>2.813</td>
<td>42.531</td>
<td>3685</td>
<td>244</td>
<td>0.985</td>
</tr>
<tr>
<td>101433.21+310721.6</td>
<td>9.027</td>
<td>45.276</td>
<td>0.140</td>
<td>1.568</td>
<td>77.015</td>
<td>5706</td>
<td>116</td>
<td>0.842</td>
</tr>
<tr>
<td>110302.99+084103.3</td>
<td>8.863</td>
<td>45.714</td>
<td>0.254</td>
<td>3.108</td>
<td>71.531</td>
<td>5749</td>
<td>118</td>
<td>0.905</td>
</tr>
<tr>
<td>114744.34+330507.7</td>
<td>8.522</td>
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<td>0.272</td>
<td>0.49</td>
<td>10.881</td>
<td>3510</td>
<td>347</td>
<td>3.666</td>
</tr>
<tr>
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<td>1.568</td>
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<td>71.531</td>
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<tr>
<td>150759.05+020054.8</td>
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</table>

and LAMOST spectra, respectively. Among the 135 Mg II NALs imprinted in the LAMOST spectra, 3 Mg II NALs were missed in the SDSS spectra. Among the 347 Mg II NALs imprinted in the SDSS spectra, 215 Mg II NALs were missed in the LAMOST spectra. The missed Mg II NALs are mainly due to the low signal-to-noise ratios of corresponding spectra. Among the Mg II NALs imprinted in the SDSS or LAMOST spectra, we find that 8 Mg II NALs have been obviously changed with \(\Delta W_{\lambda 2796} \geq 3\sigma_w\) in the time intervals between the SDSS and LAMOST observations. These variable Mg II NALs are probably associated with quasar outflows.

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