THE REDSHIFTED HYDROGEN BALMER AND METASTABLE He I ABSORPTION LINE SYSTEM IN MINI-FEOLBAL QUASAR SDSS J112526.12+002901.3: A PARSEC-SCALE ACCRETION INFLOW?

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Received 2016 May 13; revised 2016 July 7; accepted 2016 July 24; published 2016 September 27

ABSTRACT

The accretion of the interstellar medium onto central super-massive black holes is widely accepted as the source of the gigantic energy released by the active galactic nuclei. However, few pieces of observational evidence have been confirmed directly demonstrating the existence of the inflows. The absorption line system in the spectra of quasar SDSS J112526.12+002901.3 presents an interesting example in which the rarely detected hydrogen Balmer and metastable He I absorption lines are found redshifted to the quasar’s rest frame along with the low-ionization metal absorption lines Mg I, Fe II, etc. The repeated SDSS spectroscopic observations suggest a transverse velocity smaller than the radial velocity. The motion of the absorbing medium is thus dominated by infall. The He I+ lines present a powerful probe to the strength of ionizing flux, while the Balmer lines imply a dense environment. With the help of photoionization simulations, we find that the absorbing medium is exposed to the radiation with ionization parameter $U \approx 10^{-1.8}$, and the density is $n(H) \approx 10^9$ cm$^{-3}$. Thus the absorbing medium is located ~4 pc away from the central engine. According to the similarity in the distance and physical conditions between the absorbing medium and the torus, we strongly propose the absorption line system as a candidate for the accretion inflow, which originates in the inner surface of the torus.

Key words: galaxies: active – quasars: absorption lines – quasars: individual (SDSS J112526.12+002901.3)

1. INTRODUCTION

Active galactic nuclei (AGNs) are some of the most luminous objects in the universe. Observed as bright stellar-like point sources, they are located in the cores of massive galaxies. Their extremely high luminosity and rapid variability require that gigantic energy is generated and released in a rather small volume with a linear size that is no larger than a few parsecs. The accretion of the interstellar medium (ISM) onto super-massive black holes (SMBHs) is widely accepted as the process driving these central engines (Lynden-Bell 1969). The gravitational potential of the infalling matter is transferred into radiation by the viscous stress on the accretion disks surrounding the SMBHs (Rees 1984). Moreover, massive outflows from the inner part of the accretion disks are expected, not only to carry away the angular momentum of infalling matter to maintain the accretion, but also to explain the observed correlation between the properties of central SMBHs and their host galaxies. This correlation requires a mechanism of feedback from the central engines to regulate the star formation in the host galaxies (Granato et al. 2004; Scannapieco & Oh 2004; Hopkins et al. 2008).

The feedback is believed to have a solid direct observational basis since both the asymmetric emission-line profiles (Gaskell 1982; Richards et al. 2002; Wang et al. 2011) and the intrinsic absorption lines blueshifted to the quasars’ rest frames (Weymann et al. 1981) are detected and explained as gaseous outflows. The latter, however, are found with large outward velocity varying from a few thousand km s$^{-1}$ to about 0.2 c. Usually the profiles of these absorption troughs also display great widths, larger than 2000 km s$^{-1}$. Thus, they are classified as broad absorption lines (BALs). A great deal of research, for samples (Weymann et al. 1991; Hewett & Foltz 2003; Reichard et al. 2003; Zhang et al. 2010) or for individual objects (Wampler et al. 1995; de Kool et al. 2001, 2002; Leighly et al. 2011; Zhang et al. 2015a), has been published to investigate the geometry and evolution of the global structure of the outflows, or the physical conditions of individual outflowing clouds.

However, observational evidence of the more basic process, the accretion, remains questionable. Until now, few have been confirmed to directly demonstrate the existence of the accretion inflow in the vicinity of AGNs. Since the inflows are suggested to originate from the torus (Beckert & Duschl 2004; Vollmer et al. 2004), the most possible place to discover it is the gap between the inner surface of the torus and the outer region of the accretion disk. However, the ionizing flux here from the central engine is relatively weak so the emission of the illuminated inflow would be overwhelmed by the broad emission lines. The absorption lines provide a more accessible way for the detection if the medium intercepts our line of sight (LOS) toward the central radiation source. The problem is that these inflows are not expected to lie far from the equatorial plane, so the LOS would be obscured by the torus.

Recent models tend to prefer a clumpy torus to explain the lack of 10 μm Si emission features in the spectral energy distribution (SED) of type 1 AGNs (Nenkova et al. 2002). The impact of such models to our concern is that we could thus have chances to look through the low-density part among the dense clumps, especially when the angle of the LOS from the equator is relatively large where the torus medium would be a bit more diffuse. The probability must be quite low. However, once this occurs, the LOS could also intercept the assumed inflow to unveil its existence by the redshifted absorption profile as a result of the inward motion.
The Sloan Digital Sky Survey (SDSS) provides the largest quasar sample, containing 105,783 objects in the 7th data release for SDSS-I/II (Schneider et al. 2010), and 297,301 objects in the 12th data release for SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; Alam et al. 2015). The scale of the sample makes the detection of absorptions for the inflows much more available. In fact, Hall et al. (2002) reported a few quasars with BAL troughs extending redshifted to the objects’ rest frames. The most interesting one is SDSS J112526.12+002901.3 (hereafter J1125+0029), which shows two redshifted absorption troughs of hydrogen Balmer lines at about 70 and 650 km s\(^{-1}\), respectively. Both components are also present in the absorptions of metastable He\(^+\) \(\lambda\)3889, while very strong Mg II and UV Fe II absorptions are found at around the same velocity, though their exact profiles are unclear due to the overlapping. The rarely detected Balmer and He\(^+\) absorptions, combined with low-ionization metal lines like Fe II, are powerful diagnostics to the physical conditions of the absorbing medium (Leighly et al. 2011; Ji et al. 2012; Liu et al. 2015). Therefore, J1125+0029 gives a suitable example to investigate the nature of the redshifted absorption line system.

This paper is organized as follows. In Section 2, we describe the data of repeated spectroscopic observations including the SDSS-I/II, BOSS, and MMT. In Section 3, we measure the Balmer and He\(^+\) absorption lines in the spectra using the curve of growth (COG) analysis. The physical conditions of the absorbing medium are estimated using the photoionization simulations in Section 4, which provide the basis for the discussion about the origin of the absorption line system in Section 5. Finally, we give a brief summary in Section 6. The flux calibration and variability of the spectroscopic data is discussed in the Appendix. Throughout this paper, we assume a cosmology with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_M = 0.3\) and \(\Omega_{\Lambda} = 0.7\).

2. THE OBSERVATIONS

J1125+0029 was observed as a quasar candidate for spectroscopy in SDSS-I/II (York et al. 2000) on UT 2000 March 11 and SDSS-III BOSS (Dawson et al. 2013) on UT 2011 January 14. The SDSS-I/II spectrum has a resolution of \(R \approx 1800\), covering a wavelength range from 3800 to 9200 Å. To reduce the contamination from the sky line subtraction residual on H\(^\gamma\) and H\(^\beta\) peaks, we employ the sky-residual subtracted SDSS DR7 spectrum,\(^4\) post-processed by Wild & Hewett (2005). The BOSS spectrum covers a wider wavelength range from 3600 to 10000 Å. It seems the residual of sky line subtraction at the red end of the BOSS spectrum has little effect on our measurement. The spectroscopic data are then corrected for Galactic extinction using the mean extinction curve in Fitzpatrick & Massa (2007), with selective extinction \(E(B - V) = 0.031\) in the Galactic dust map of Schlegel et al. (1998). The narrow [O II] \(\lambda\)3728 emission presents a good measure of the systemic redshift (Hewett & Wild 2010; Shen et al. 2016). By fitting a Gaussian profile to the [O II] \(\lambda\)3728 line, we suggest a systemic redshift of 0.8632 ± 0.0002. In

\(^4\) The spectrum can be accessed through the Johns Hopkins University SDSS server: http://www.sdss.jhu.edu/skypca/spSpec.
Figure 1, the SDSS-I spectrum around Hβ, Hγ, Hδ, and He I* λ3889 blended with Hα are plotted in velocity with respect to the quasar’s rest frame. The BOSS and MMT fluxes are scaled in the same way as the BOSS spectrum. The UV FeII troughs between rest frame 2400 and 2550 Å, of which the majority are dominated by transitions from the ground term. Using the standard IRAF package to extract the 1D spectrum and the fluxes are carefully calibrated. The spectrum covers Hβ and narrow [O III] λλ4960, 5008 emission. The MMT spectrum around the Hβ absorption is also plotted in the top panel of Figure 2, scaled in the same way as the BOSS spectrum. The profile seems to be in good agreement with the BOSS observation, indicating that no variation of absorption can be detected from 2011 to 2012, about seven months in the quasar’s rest frame.

3. ABSORPTION MEASUREMENT

In Shi et al. (2016), we study the Balmer BAL quasar SDSS J125942.80+121312.6 (hereafter J1259+1213) in detail with the help of photoionization models. Many similarities can be found in the absorption features between J1125+0029 and J1259+1213. First, in both spectra, we observe the overlapping troughs of low-ionization metal lines like UV FeII and MgII as well as the isolated Balmer lines and He I*. Second, the UV FeII troughs between rest frame 2400 and 2550 Å, of which the majority are dominated by transitions from the terms with excitation energy \( E_\text{ex} > 2.5 \text{ eV} \), show relative depths of \( \sim 0.5 \). This implies a highly excited high column density FeII absorber, in which the resonant absorptions should be saturated, while large residual fluxes can be measured under the UV1 and UV2,3 multiplets from the ground term. Using the SDSS quasar composite (Vanden Berk et al. 2001) intrinsically reddened by the SMC-type extinction curve (Gordon et al. 2003) to match the fluxes in the absorption-free windows around rest frame 2100 Å and longward of 3700 Å, we find that the residuals under the UV1 and UV2,3 troughs are considerably larger than the UV FeII emission bump of the composite. Third, the Hβ troughs are only slightly stronger than the Hγ troughs, given that the oscillator strength of Hβ is more than twice as large as the oscillator strength of Hγ.

In Shi et al. (2016), we find that a high density and high column density gaseous medium can account for the BAL troughs of all observed ions in J1259+1213, including Balmer lines, He I*, MgII, and FeII. The absorbing medium covers part of the continuum source and little of the broad emission-line region (BELR), as the latter is two orders of magnitude larger in size. Accordingly, we also suppose that the low-ionization metal absorption lines in J1125+0029 originated from the same medium as the redshifted Balmer lines and He I* λ3889, and this medium only obscures a fraction of the continuum source.

According to such an assumption, to extract the normalized profile for the measurement of absorptions, the emission lines and unabsorbed continuum should be properly modeled. We would first remove the contribution of emission lines from the spectrum and then divide the residual by the model continuum. We fit the spectrum longward of rest frame 3500 Å, following...
the steps described by Dong et al. (2008) with small modification. The continuum is modeled using a single power-law continuum multiplied by the SMC-type extinction law (Gordon et al. 2003). The continuum windows assumed nearly emission-free are rest frame 3540–3560, 3810–3830, 4005–4035, 4150–4170, and 4550–4570 Å. The narrow emission lines, such as [O II] λ3728 and [Ne III] λ3868, are modeled with a single Gaussian profile. The broad Balmer emissions Hβ and Hγ are assumed to have the same redshift and profile, and modeled using three Gaussian profiles. Other weak broad emissions are modeled using one Gaussian profile. The fitting results are shown in Figure 3. The measured value of full width at half maximum (FWHM) for the broad Hβ emission in the SDSS-I/III spectrum is 7230 km s⁻¹.

The emission model subtracted spectrum around Hβ, Hγ, Hδ, He, HeⅡλ 3889 plus Hγ, and Hβ is normalized using a model power-law continuum and the result for the SDSS-I/II observation is plotted in Figure 4. Since the HeⅡ and Balmer absorption lines show similar profiles, we assume that the HeⅡ and Balmer absorbers share the same kinematic structure and can fit two Gaussians to the normalized flux of all these lines simultaneously. The velocity shifts with respect to the QSO’s rest frame are 72 ± 39 and 651 ± 41 km s⁻¹ for the two components, respectively, including the uncertainty of systemic redshift. The FWHMs are 199.4 ± 16.4 km s⁻¹ for the blue component and 398.6 ± 32.6 km s⁻¹ for the red component. Spanning ~1200 km s⁻¹, the whole absorption line system can be classified as mini-BAL. Since the resolution of SDSS-I/II is ~1800, the FWHMinst for the instrumental profile is ~167 km s⁻¹. Applying the simple relation FWHMobs = FWHMtrue + FWHMinst, the intrinsic b-values for two components are 64 and 215 km s⁻¹, respectively.

The equivalent widths (EWs) and the 1σ uncertainties can be measured directly using the normalized fluxes and the fluctuations in the wavelength range defined by the Gaussian profiles. Since the absorbing medium only covers part of the continuum source, the apparent EWs are the reduced values of the true EWs by a factor of C_f, EWapp = EWtrue × C_f, where C_f ≲ 1 is the covering factor. The values of covering factors and ionic column densities N_{col}(ion) can be derived using the COG analysis. In Figure 5, for each component with the known b-value, the solid line shows the COG, while the dotted line shows the apparent EWs predicted by COG given the covering factors, log EW_{app}/λ = log EW_{true}/λ + log C_f. For those measured absorption lines (represented using filled circles), the ordinated values show the measurements for apparent EWs, while the abscissa values, N_{col}(ion)λ_{rest}, would be determined by the ionic column densities N_{col}(ion). Appointing the unknown C_f, N_{col}(H^0_{α=2})), and N_{col}(He^0_{γ}) as adjustable parameters, we can get the optimal values and 1σ uncertainties for them by fitting the COG to the measured data points.

Fitting the measured EW values with the COG for the two spectra, respectively, for the blue component we have C_f = 0.53 ± 0.18, log N_{col}(H^0_{α=2}))(cm⁻²) = 14.74 ± 0.24, and log N_{col}(He^0_{γ}))(cm⁻²) = 14.69 ± 0.34 in the SDSS-I/II observation, and C_f = 0.73 ± 0.20, log N_{col}(H^0_{α=2}))(cm⁻²) = 14.39 ± 0.20, and log N_{col}(He^0_{γ}))(cm⁻²) = 14.59 ± 0.24 in the BOSS observation. For the red component, C_f = 0.37 ± 0.23, log N_{col}(H^0_{α=2}))(cm⁻²) = 14.72 ± 0.31, and log N_{col}(He^0_{γ}))(cm⁻²) = 14.77 ± 0.30 in the SDSS-I/II observation, and
4. PHOTOIONIZATION MODELS FOR THE ABSORBING MEDIUM

We use the photoionization code CLOUDY (version 10.00, last described by Ferland et al. 1998) to simulate the ionization process, assuming a simple model of slab-shaped geometry, unique density, and homogeneous chemical composition of solar values for the absorbing medium. The incident SED applied is the combination of a UV bump described as $I_{\nu}^{\text{UV}} \propto \exp(-h\nu/kT_{BB}) \exp(-kT_{BB}/h\nu)$ and power-law $\nu^{\alpha_{\text{ox}}}$, incorporated in CLOUDY. This is considered to be typical for observed AGN continuum. The UV bump is parameterized by the UV power-law index $\alpha_{\text{UV}} = -0.5$, and exponentially cut off with temperature $T_{BB} = 1.5 \times 10^{5}$ K at high energy and $kT_{BB} = 0.01$ Ryd at infrared. The power-law component has an index of $\alpha_X = -2$ beyond 100 keV, and $-1$ between 1.36 eV and 100 keV. The overall flux ratio of X-ray to optical is $\alpha_{\text{OX}} = -1.4$. The physical conditions of the absorbing medium are characterized by the ionization parameter $U$ at the irradiated surface, the total hydrogen density $n(H)$, and the total hydrogen column density $N_{\text{H}}(H)$ which indicates the thickness of the medium.

The H$^+$ UV absorption is originated from the metastable He$^0$ 2$S$ level, which in the photoionization dominated medium is populated through the recombination of He$^+$ in the ionized zone. Ji et al. (2015) presented a detailed investigation on the H$^+$ ionization structure using the photoionization simulations. They found that if the medium is thick enough that the ionizing front is well developed, the value of $U$ can solely determine the column density of He$^+$. Given $\log N_{\text{H}}(\text{He}^0_{\lambda=3889})(\text{cm}^{-2}) = 14.69 \pm 0.34$ and $14.77 \pm 0.30$ for the blue and red components, we obtain log $U = -1.9 \pm 0.3$ and $-1.8 \pm 0.3$ according to the Figure 10 in Ji et al. (2015), respectively.

The hydrogen $n = 2$ shell could be populated through a couple of mechanisms, including recombination, collisional excitation, and Ly$\alpha$ resonant scattering. Therefore, Balmer absorption lines can originate in both ionized and neutral zones, showing more complicated dependence on the density and total column density of the medium as well as the strength of ionizing flux, while the density of $n(H) > 10^6 \text{ cm}^{-3}$ is generally required. In Figure 6, panels (a) and (b), we plot the column density of H$^0_{n=2}$ as functions of $n(H)$ and $N_{\text{H}}(H)$ predicted by the photoionization simulations given the values of $U$, and the measured values are highlighted by the colored areas.

To further constrain the physical conditions of the absorbing medium, the measurements for other ions in the same medium are required, such as Fe$^+$. However, unlike the case of J1259+1213, where the optical absorption troughs of Fe$^+$, $\lambda$4233, $\lambda$4924, $\lambda$5018, and $\lambda$5169 from excited Fe$^+$ are presented as isolated, which can be directly demonstrated as being associated with Balmer lines and reliably measured. In the spectra of J1125+0029, these lines can hardly be detected due to the poorer signal-to-noise ratio (S/N). The UV Fe II absorption troughs are so heavily saturated and blended that we cannot find isolated absorption lines to estimate the column density on any individual level of Fe$^+$. However, being aware of the obvious similarity in appearance between these two objects, we guess that in J1125+0029 the UV Fe II troughs also come from the same absorbing gas as Balmer lines. This means that each individual Fe II trough would also have two components with the same central velocities, widths, and covering factors as Balmer lines since Fe$^+$ and H$^0_{n=2}$ originate from similar regions in the photoionized medium.

Following the method described in Shi et al. (2016), we can construct the synthetic model UV Fe II absorption spectra based.
Figure 5. COG analysis for the Balmer and He i’ absorption lines. The solid lines are the COGs specialized by measured b-values for the blue and red components, respectively. For the blue component (panels (a) and (b)), the blue data points and the blue dotted lines are the measured lines and the apparent COGs reduced by C_f for the SDSS-I/II observation, and the cyan ones for the BOSS observation, while for the red component (panels (c) and (d)) the red ones are for the SDSS-I/II observation and the orange ones for the BOSS observation. By fitting the apparent COGs to the line measurements, we can derive the optimal values for N_{col}(H^\text{I}'), N_{col}(He^0), and C_f. The vertical bars associated with the data points are the errors of EWs. The horizontal bars show the fitting errors for the ionic column densities. The data points with solid error bars represent the measurements for Balmer lines, while those with dashed error bars represent the He i’ λ3889. In panels (a) and (c), these values are fitted freely. In panels (b) and (d), the ionic column densities are supposedly unchanged between the two spectroscopic observations.

Figure 6. The spectroscopic COG analysis for SDSS I-1151+3713. In Figure 6, we also show the full 371 levels Fe II absorption spectra. The best-fitting parameters leading to the minimum χ_0^2 are log n(H)(cm^{-3}) ~ 9 and log N_{col}(H)(cm^{-2}) ~ 22 for each component. Thus, it would be convenient and reasonable to suppose the physical states of the two components are identical. In Figure 6, panel (c), we plot the distribution of χ_0^2 for the models in which the parameters for the blue and red components are the same.

The optimal values for the parameters n(H) and N_{col}(H) are the values that present the measured value of N_{col}(H^\text{I}′_{n=2}) and the minimum of χ_0^2, while the 1σ uncertainty for these parameters are given by the area defined by the 1σ uncertainty of N_{col}(H^\text{I}′_{n=2}) and the contour of χ_0^2,min + 1. Thus we have log n(H)(cm^{-3}) = 9 ± 0.3 and log N_{col}(H)(cm^{-2}) = 21.9 ± 0.2.

Other low-ionization ions, such as Ti^+ +, Cr^+ +, and Ni^+ +, can also be included in the synthetic model spectra following the same method as Fe^+. In Figure 7, we also plot this complete model for the Fe II selected optimal models. The inclusion of the absorptions from these ions makes the model a better match for the observation, with the only exception of Mg II. The model Mg II absorption is much shallower than the observation. Since we suppose that the absorbing medium covers part of the accretion disk, the fluxes under Mg II troughs should consist of the fluxes of Mg II emission and unobscured part of continuum. But the observed fluxes under Mg II troughs are smaller than Mg II emission peak in the quasar composite. Such deviation could be ascribed to the difference between the Mg II emission in the composite and the true Mg II emission in our source, because there is considerable object to object variation in quasar emission lines. If we suppose the Mg II emission in J1125+0029 is much weaker than that in the composite, the disagreement can be reduced. Leighly et al. (2011) used a dozen real non-absorption quasars to match the NIR spectrum of FBQS J1151+3822, and chose the best matched one as a template to measure the He i’ λ10830. Zhang et al. (2014) and Liu et al. (2015) also developed a similar pair-matching method to improve the estimate of unabsorbed level. We search all SDSS DR7 non-BAL quasar spectra with mean S/Ns per pixel greater than 15 for the suitable template. The spectrum of SDSS J142923.92+024023.1 showing very weak Mg II
emission best meets our request if it is reddened with $E(B-V) = 0.045$. The synthetic spectrum is plotted in the bottom panel of Figure 7. Compared to the synthetic spectrum based on the reddened composite, the result is improved not only for the MgII doublets but also for the UV FeII from rest frame 2320 – 2640 Å.

5. DISCUSSION

The mass of the central SMBH can be estimated according to the relation in Wang et al. (2009), assuming the BELR is virialized, $\log(M_{\text{BH}}/10^9 M_{\odot}) = (1.39 \pm 0.14) + 0.5 \log(L_{5100}/10^{44} \text{ erg s}^{-1}) + (1.09 \pm 0.23) \log(\text{FWHM}(H\beta)/1000 \text{ km s}^{-1})$, where $L_{5100}$ is the $\lambda L_\lambda$ at rest frame 5100 Å. Thus, we have $M_{\text{BH}} = 1.5 \times 10^8 M_{\odot}$ with an uncertainty of a factor of $\sim 2.5$ (from the intrinsic scatter of $\sim 0.4$ dex for this single-epoch method compared to the results of reverberation mapping, Ho & Kim 2015). And adopting the correction factor by Runnoe et al. (2012), the bolometric luminosity is $L_{\text{bol}} = (8.1 \pm 0.4) \times 10^{46} \text{ erg s}^{-1}$. Assuming an accretion efficiency of 0.1, the mass accretion rate is then $M_{\text{BH}} \approx 6.8 \times 10^7 M_{\odot} \text{ yr}^{-1}$. Extrapolating the best-fitting SDSS composite presented in Figure 1, we can derive the continuum flux at 1215.67 Å. Then, given the model incident SED used in simulations and the systemic redshift, the pre-extinction monochromatic luminosity of ionizing continuum at the Lyman limit can be roughly estimated. For the SDSS-I/II spectrum, this value is $L_\nu(912) = 5.0 \times 10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$. 

Figure 6. Predicted ionic column densities for Balmer lines from the photoionization simulations by CLOUDY with $\log U = -1.8$ for the blue component (panel (a)) and $\log U = -1.9$ for the red component (panel (b)) as functions of $n(H)$ and $N_{\text{col}}(H)$. The numbers labeling the contours are the logarithms of ionic column densities. The cyan areas represent the measured values with $1\sigma$ error for Balmer lines. In panel (c), we plot the distribution of $\chi^2$, which evaluates the difference between the SDSS-I/II observation and the synthetic model spectra in the overlapping UV FeII troughs between rest frame 2320 and 2780 Å. The numbers labeling the contours are $\chi^2 - \chi^2_{\text{min}}$. Supposing the physical parameters for the two components are the same, we find that the optimal values are $\log n(H)(\text{cm}^{-3}) = 9 \pm 0.3$ and $\log N_{\text{col}}(H)(\text{cm}^{-2}) = 21.9 \pm 0.2$.

Figure 7. Synthetic model spectrum for the optimal photoionization model. The red line represents the profile of FeII and MgII absorptions, and the blue line includes absorption from CrII and NiII in addition. The cyan line is the template employed as unabsorbed background radiation to construct the synthetic spectrum, and the green line is the corresponding power-law continuum. In the top panel, a reddened SDSS quasar composite is used as unabsorbed template. In the bottom panel, the reddened spectrum of SDSS J142923.92+024023.1 is used as a template. The residual of the synthetic model spectra is also plotted (the underlying data points).
Given the luminosity and SED of the ionizing continuum, we can derive the distance of the absorbing medium to the central engine according to the physical conditions constrained by the photoionization models, as $\frac{L(<912)}{4\pi d^2} = U(n)\overline{E_{ph}}(<912)$. $L(<912)$ is the ionizing luminosity of the continuum source, determined by $L_{\alpha}(912)$ and the incident UV used in simulation models. Furthermore, $\overline{E_{ph}}(<912)$ is the average energy for all ionizing photons, which can also be evaluated according to the model SED. With log $U = -1.8 \pm 0.3$ and log $n$(H)(cm$^{-3}$) = $9 \pm 0.3$ from the optimal photoionization models, the distance of the inner surface of the absorbing medium is $r_{abs} = 4.2^{+5.0}_{-3.5}$pc. The listed uncertainty only includes the uncertainties of $U$ and $n$(H). The uncertainty of the AGN ionizing luminosity introduced due to the extrapolation of the power-law continuum is more difficult to assess. A change of 100% for the luminosity can lead to a change of 41% for the distance, making it a relative minor factor.

In their first paper, reporting the redshifted absorption line systems in quasars’ spectra including J1125+0029, Hall et al. (2002) suggested a rotation-dominated disk wind at the phase when the outflow just rises from the accretion disk to explain the redshifted troughs. With the release of BOSS spectra, Hall et al. (2013) returned to the issue. Comparing the BOSS and SDSS-I/II spectra of J1125+0029, especially the Mg II troughs, they suggested that the blueshifted part of the Mg II absorption weakened more than the redshifted part, to account for the variability (for more details, see the Appendix). The different behavior in the blueshifted and redshifted absorption is believed to be consistent with the picture of a rotational wind when the cloud moves from the approaching side to the receding side. Such wind is suggested located 1255 $R_{sch}$ (5.5 $\times$ 10$^{17}$ km s$^{-1}$ with an uncertainty of a factor of 2.5) from the SMBH (Murray & Chiang 1998; Elvis 2000). Another explanation for the redshifted troughs mentioned in Hall et al. (2013) is the gravitational redshift, requiring the absorbing medium to be located at even smaller radii, $\sim$100 $R_{sch}$.

The absorbing medium described by our photoionization models seems to be much more distant than that implied in these explanations. Furthermore, according to the COG analysis in Section 3, we can estimate the transverse velocities of the absorbing medium by the variations of covering factors for Balmer lines between the SDSS-I/II and BOSS observations. In the simplest picture, these changes ($\Delta C_f = 0.02$ for the blue component and 0.07 for the red component) stand for a continuous movement of the medium across our LOS. The radius of the accretion disk where the radiation peaks at 4863 Å can be evaluated from $\sigma T_{eff}^4 = \frac{3}{4\pi GM}f(R, \alpha)$ (Equation 2) in Collin et al. (2002). With $\sigma T_{eff}^4 = h\nu$ and the boundary condition $f(R, \alpha) \approx 1$, we obtain $R(4863) \approx 6.1 \pm 2.1 \times 10^{17}$ cm. Considering the uncertainty of $C_f$ Though, for the blue component, the probability that the transverse velocity is smaller than the radial velocity is only 0.56, and for the red component, the upper limit of transverse velocity at a confidence level of 0.98 is 145 km s$^{-1}$, which is much smaller than the corresponding redshifted velocity. The infall seems to be a more reasonable explanation.

The distance of the infalling medium is also larger than the radius of H$\beta$ BELR by a factor of ~10, but how about the torus? The torus has long been suggested to be the reservoir of ISM feeding the central engine and the direct source of the accretion inflow (Krolik & Begelman 1988). In recent works, a clumpy model for the torus is required to reproduce the IR SED, especially the lack of the 10 μm Si emission feature (Nenkova et al. 2002). Such a model is supported by Beckert & Duschl (2004) and Vollmer et al. (2004), who linked the clumpy torus in AGNs with the circumnuclear disk (CND) surrounding the central black hole of our Galaxy, which consists of several hundred clouds of gas and dust. The transfer from the thin CND to the thick obscuring torus depends on the accretion rate. The radial accretion flow is now naturally regarded as the result of a cloud–cloud collision through which these clouds lost energy and then fall inward. If the falling clouds are located a bit far away from the equatorial plane, they could be observed in the foreground of the accretion disk since at such viewing angles the disk would not be severely obscured due to the relatively low local filling factor.

The inner radius of the torus used to be approximated as the evaporation radius, $R_{evap} = 1.3L_{UV,46}^{1/2}T_{1500}^{-2.8}$ pc $\approx$ 1.3 pc following Barvains (1987) for our object, where $L_{UV,46}$ is the UV luminosity in units of 10$^{46}$ erg s$^{-1}$ estimated using $L_{\lambda}(1450)$, and $T_{1500}$ is the grain evaporation temperature in units of 1500 K, which $\approx$ 1. By comparing $R_{evap}$ with the results of reverberation mapping, Kishimoto et al. (2007) suggested that the inner radius was overestimated in this way by a factor of approximately three. Kawaguchi & Mori (2011) argued that the inner radius should increase with the viewing angle of the torus due to the anisotropic illumination of the disk, to explain the intrinsic scatter in reverberation mapping (Reminding in J1125+0029, the SED is immediately reddened by the dust associated with the object, implying that the LOS is not very close to the equatorial plane of the torus). Infrared interferometry, another direct radius measurement, presents the results a factor of two larger than those from reverberation mapping (Koshida et al. 2014). Thus, we, to date, the uncertainty of the inner radius estimate is also quite large, comparable to the uncertainty of our photoionization models. However, we can still conclude that the absorbing medium is not far away from the inner surface of the torus.

The infalling absorbing medium is estimated close to the inner surface of the torus, and the density of the medium is found to be similar to the gas density of the torus. Therefore, we strongly suppose the redshifted absorption line system in J1125+0029 representing the accretion flow originated from the torus as our LOS toward the continuum source lying through the low-density part of the clumpy torus. The relation between the two components of the absorbing medium remains unclear. Since the physical conditions and the distance of both components are almost the same, they might reflect the approaching and receding parts of a spinning cloud in the accretion flow with the centroidal infalling velocity $v_{infall}$ $\approx$ 350 km s$^{-1}$.

The mass of the absorbing medium is $M_{abs} = \mu m_p N_{col}(H) S$, where $\mu$ is the mean atomic mass per proton, $m_p$ is the mass of proton, and $S$ is the projection area. Assuming the observed absorbing medium is typical of all accretion clouds and these clouds are uniformly distributed at the inner surface of the torus, we can estimate the mass inflow rate as $M_{inflow} \approx \pi R_{evap}^2 C_{f,torus} \mu m_p N_{col}(H)/v_{infall}$, where $C_{f,torus} \approx 0.6$ is the global covering factor of the torus (Lawrence & Elvis 2010), and $v_{infall}$ is the infalling timescale of the accretion clouds. If we approximate that $t_{infall} = R_{evap}/v_{infall}$, $M_{inflow} \approx 0.43 M_\odot$ yr$^{-1}$, which is too small compared with $M_{BH}$. Because $v_{infall}$ is the radial velocity at the initial stage of infall, we think $t_{infall}$ is overestimated in this way. Since the accretion inflow lies close to the equatorial plane, the radiation from the central engine would be obscured, which reduces the radiation pressure, we can use the free-fall timescale.
Thus, \( \dot{M}_{\text{inflow}} \) is of the same magnitude as \( \dot{M}_{\text{BH}} \). Furthermore, in reality, the properties of clouds in the inflow would be dependent on the height. In J1125+0029, our LOS might only pass through the outskirts of the torus. The closer to the equatorial plane the clouds are, the denser they would be. Thus, the mass inflow rate could be even higher.

6. SUMMARY

The redshifted absorption line systems are rarely detected features in the quasar spectra. A couple of theoretical pictures were prompted to explain the phenomena, but no decisive conclusion has been achieved, unless the physical conditions and the spacial structure of the absorbing medium are available. In the SDSS-I/II and BOSS spectra of quasar J1125+0029, a redshifted absorption line system is identified including lines of hydrogen Balmer series, metastable He I, Mg II, Fe II, etc. These lines are powerful diagnostics of the physical properties of the absorbing medium. Performing a careful measurement of the ionic column densities and covering factors for Balmer and He I* lines and using the photoionization simulations, we find that the medium is located \( \sim 4 \) pc away from the central engine and its motion is dominated by infall. Since the distance is consistent with the radius of the inner surface of the torus and the physical conditions of the medium are also similar to the torus, we suggest this absorption line system as a candidate for the accretion inflow that originated from the torus, which fuels the SMBH.

This work is supported by the National Basic Research Program of China (the 973 Program 2013CB834905) and the National Natural Science Foundation of China (NSFC-11421303 and 11473025). This research uses data obtained through the Telescope Access Program (TAP), which has been funded by the Strategic Priority Research Program The Emergence of Cosmological Structures (Grant No. XDB09000000), the National Astronomical Observatories, the Chinese Academy of Sciences, and the Special Fund for Astronomy from the Ministry of Finance.
higher than those of BOSS. Since the strong rapid variability is common for quasars, the difference could reflect the intrinsic variability of luminosity of the object from the SDSS-I/II observation to the BOSS observation (5.8 years in the quasar’s rest frame). On the other hand, the spectrophotometric calibration errors in BOSS are reported larger than in SDSS-I/II (Margala et al. 2015), and this systematic is wavelength dependent. On average, the miscalibration of the BOSS spectra accounts for an ~19% excess at 3600 Å and a ~24% decrement at 10000 Å with a smooth transition between.

Dawson et al. (2013) described the reduction process for the BOSS spectroscopic data. The process is performed independently for targets observed on different fibers, thus the systematics on the objects of the same plate may be different. We find six objects observed repeatedly on the same SDSS-I/II and BOSS plates as J1125+0029. Three of them are main-sequence stars of which the SEDs are highly invariable. Assuming the flux calibration for the SDSS-I/II spectra is reliable, we can use these objects to assess the fiber-to-fiber difference of the flux calibration errors for the BOSS data. In Figure 8, we plot the SDSS-I/II and BOSS spectra for these stars, and also the ratio of the BOSS fluxes to the SDSS-I/II fluxes. For two objects, the ratio varies as functions of the wavelength, with the flux shortward of ~4500 Å being overestimated and the flux longward of ~4500 Å being underestimated, which is consistent with the conclusion of Margala et al. (2015). However, the object-to-object variation is also remarkable. For SDSS J112837.73-000112.5, the ratio declines from ~1.7 at 3800 Å to <0.5 at 9200 Å, while for SDSS J112640.14+002347.0 the ratio is ~0.9 regardless of the wavelength. Thus the systematics for specified objects can hardly be corrected according to the standard stars on the same plate. J1125+0029 was monitored photometrically by the V-band Catalina survey from 2005 April to 2014 January (see Figure 9). The SDSS images for the object were taken at 1999 March 21 and 2007 April 20. Furthermore, the BOSS

\[^{5}\text{http://nesssi.cacr.caltech.edu/DataRelease/}\]
spectrum was obtained 2.0 years after the latest SDSS image observation in the quasar’s rest frame. Since the object seems to fade steadily in this time interval according to the Cataлина light curve, the BOSS spectrum cannot be calibrated using any set of SDSS photometry.

The narrow [O II] $\lambda3728$ emission detected in both spectra is not believed to vary significantly in the short term, thus it presents a useful tool to check the flux calibration problem. The measured strength of [O II] $\lambda3728$ in the SDSS-I/II spectrum is 61% larger than that in the BOSS spectrum. In Figure 10, we plot the BOSS spectrum multiplied by a scaling factor of 1.61 to be compared to the SDSS-I/II spectrum. Although the details of wavelength-dependent calibration error are still unknown, at least we now realize that the variability of luminosity is not as great as it looks at first sight.

However, what we pay more attention to in this work is the absorption variability. In Hall et al. (2013), the authors scaled the BOSS spectrum of J1125+0029 by a constant times a power law to match the SDSS-I/II spectrum in absorption-free continuum regions near rest frame 2100 and 2910 Å. They suggested that the strengthened Mg II emission alone is not sufficient to explain the change of Mg II troughs. The absorption variability is still required in which the blueshifted part of Mg II absorption weakens more than the redshifted part. This does not seem consistent with what we conclude from the Balmer and He I* lines (see Section 3). Thus, further investigation is necessary. In Figure 11, we plot the SDSS-I/II and scale BOSS spectra following the method by Hall et al. (2013). The fluxes of scaled BOSS spectrum are more than 1σ higher than those of SDSS spectrum at the bottom of Mg II and UV Fe II troughs. We find that if the assumed strength emission component are blueshifted to the quasar’s rest frame by $1130 \text{ km s}^{-1}$, the residual, plotted in green, can be well modeled if the Mg II doublets and UV Fe II emission template (constructed by Tsuzuki et al. 2006) are convolved using a Gaussian profile with FWHM = 4140 km s$^{-1}$. Therefore, we think the strengthening of broad emission alone can explain the observed changes, and the absorption profiles for Mg II and UV Fe II could be assumed unchanged just like Balmer and He I* lines.

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