UNSHIFTED METASTABLE He I* MINI-BROAD ABSORPTION LINE SYSTEM IN THE NARROW-LINE TYPE 1 QUASAR SDSS J080248.18 + 551328.9

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ABSTRACT

We report the identification of an unusual absorption-line system in the quasar SDSS J080248.18 + 551328.9 and present a detailed study of the system, incorporating follow-up optical and near-IR spectroscopy. A few tens of absorption lines are detected, including He I*, Fe II*, and Ni II*, which arise from metastable or excited levels, as well as resonant lines in Mg I, Mg II, Fe II, Mn II, and Ca II. All of the isolated absorption lines show the same profile of width Δν ~ 1500 km s⁻¹ centered at a common redshift as that of the quasar emission lines, such as [O III], [S II], and hydrogen Paschen and Balmer series. With narrow Balmer lines, strong optical Fe II multiplets, and weak [O III] doublets, its emission-line spectrum is typical for that of a narrow-line Seyfert 1 galaxy (NLS1). We have derived reliable measurements of the gas-phase column densities of the absorbing ions/levels. Photoionization modeling indicates that the absorber has a density of n_H ≈ (1.0–2.5) × 10⁵ cm⁻³ and a column density of N_H ≈ (1.0–3.2) × 10²¹ cm⁻² and is located at R ~ 100–250 pc from the central supermassive black hole. The location of the absorber, the symmetric profile of the absorption lines, and the coincidence of the absorption- and emission-line centroids jointly suggest that the absorption gas originates from the host galaxy and is plausibly accelerated by stellar processes, such as stellar winds and/or supernova explosions. The implications for the detection of such a peculiar absorption-line system in an NLS1 are discussed in the context of coevolution between supermassive black hole growth and host galaxy buildup.

Key words: quasars: absorption lines – quasars: emission lines – quasars: individual (SDSS J080248.18+551328.9)

1. INTRODUCTION

It is now generally believed that active galactic nuclei (AGNs), including their high-luminosity analog quasars, are powered by a supermassive black hole (SMBH) fed by accre- tion flows. To enable the fuel-feeding process, the angular momentum of the interstellar gas in the central region of the host galaxy must be largely removed to bring the gaseous fuel into the nuclear region. Nonaxisymmetric perturbation of gravitational potential, such as that due to stellar bars and interaction with companion galaxies, is proven to be an efficient way to drive potential, such as that due to stellar bars and interaction with nuclear region. Nonaxisymmetric perturbation of gravitational galaxy must be largely removed to bring the gaseous fuel into the galaxy. To enable the fuel-feeding process, the angular momentum of the interstellar gas is proven to be an efficient way to drive circumnuclear flows. Theoretically, the stalled molecular gas will definitely result in nuclear starbursts (Hicks et al. 2009). The energetic stellar processes of nuclear starbursts might funnel gas further inward to intraparsec scales to fuel the black hole accretion (Davies et al. 2007; Schartmann et al. 2009).

The fueling processes should become more observable in AGNs with high mass accretion rates. A subclass of AGNs, namely, narrow-line Seyfert 1 galaxies (NLS1s),11 are generally considered to be AGNs at their early evolutionary stage, with small black hole masses accreting at very close to the maximum allowed accretion rate (see Komossa 2008 for an extensive review). They are traditionally defined by the narrowness of their Balmer emission lines (FWHM_Hβ < 2000 km s⁻¹) and weakness of [O III] emission ([O III]/Hβ < 1; Osterbrock & Pogge 1985; but see also Zhou et al. 2006b for a slightly different definition). Strong Fe II emission is also a significant feature for NLS1s.

Mathur (2000) suggested that NLS1s live in gas-rich galaxies with ongoing star formation. Observationally, star formation in the host galaxies of NLS1s is considerably stronger compared with that of the normal type 1 AGNs using Spitzer mid-infrared spectroscopy (Sani et al. 2010). The observations can be merged into the scenario of coevolution of galaxy and central black

11 Following Komossa et al. (2006), we collectively speak of NLS1s when referring to the class properties of narrow-line Seyfert 1 galaxies and narrow-line type 1 quasars, and we distinguish between a Seyfert galaxy and a quasar according to the classical criterion of B-band absolute magnitude when referring to individual objects.
hole (e.g., Granato et al. 2004). The energetic stellar processes of circumnuclear starbursts might induce the surrounding gas flowing inward more efficiently to trigger high activity of the central black hole (Davies et al. 2007; Schartmann et al. 2009). Provided that the gaseous inflows would occasionally intercept our line of sight toward the active nucleus, they can be observable through the quasar absorption line technique.

In this paper we report the first such candidate absorption-line system toward the narrow-line type 1 quasar SDSS J080248.18 + 551328.9 (hereafter SDSS J0802 + 5513 for brevity), and we present a detailed study of the system incorporating follow-up optical and near-IR (NIR) spectroscopy.

SDSS J0802 + 5513 was initially identified as a quasar during the Sloan Digital Sky Survey (SDSS; York et al. 2000), based on spectroscopic observation on 2003 March 24, and was included in the SDSS quasar catalogue with a redshift of \( z = 0.6640 \pm 0.0005 \) (Schneider et al. 2007, 2010). It was first classified as a low-ionization broad absorption line (LoBAL) quasar by Gibson et al. (2009) according to detection of an Mg \( \text{II} \) broad absorption trough with width \( \Delta v \approx 2,500 \text{ km s}^{-1} \). The authors also reported the possible detection of Fe \( \text{II} \) 2\,414, 2632, 2750 absorption lines. SDSS J0802 + 5513 was later analyzed by Zhang et al. (2010) but rejected as a LoBAL quasar since the Mg \( \text{II} \) absorption line does not show a large enough blueshift, though the absorption trough is broader than their threshold value of \( \Delta v > 1,600 \text{ km s}^{-1} \). Using Kohonen self-organizing maps, Meusinger et al. (2012) again classified SDSS J0802 + 5513 as an unusual LoBAL quasar with a red color and narrow absorption line troughs and confirmed the classification by visual inspection of its SDSS spectrum. The discrepant classification of the absorption lines in the quasar deserves further exploration.

We noticed SDSS J0802 + 5513 during our systematic search for He\( ^{+} \) 2\,3S multiplets in quasars (Liu et al. 2014). Arising from the common metastable He\( ^{+} \) 2\,3S level, the multiplets are rarely seen in the interstellar medium (ISM) of normal galaxies (Rudy et al. 1985). The 2\,3S level is mainly populated by recombination of He\( ^{+} \). With an ionization potential of 4.8 eV, the diffuse stellar radiation background can easily ionize helium atoms at the 2\,3S level, while lacking enough hard photons of \( h\nu > 24.59 \text{ eV} \) to ionize helium atoms at the ground level, whereas the quasar continuum is energetic enough to populate a large number of He atoms at the 2\,3S level. He\( ^{+} \) multiplets are hence a good indicator for distinguishing quasar intrinsic narrow absorption lines (NALs) from intervening NALs that are physically unrelated to the background quasars, complementary to the two often-used indicators (e.g., Hamann et al. 1997; Misawa et al. 2003): (1) time variability and (2) partial coverage of the absorption lines. He\( ^{+} \) multiplets are very useful for determining the covering factor of quasar absorption gas owing to the large oscillator strength differences in the multiplets. This, together with their common highly metastable lower transition 2\,3S level, imbues He\( ^{+} \) multiplets with a high sensitivity to a large dynamic range of column densities when other strong UV resonant lines, such as O \text{I}\text{v}, N \text{v}, C \text{IV}, Si \text{IV}, Al \text{III}, and Mg \text{II}, are heavily saturated.

\footnote{12} In this paper we use *to denote absorption lines that arise from metastable/excited levels. For example, metastable neutral helium absorption lines will be referred to as He\( ^{+} \), and singly ionized iron absorption lines from excited levels as Fe\( ^{+} \).

\footnote{13} The asymptotic maximum value of \( n_\text{exc}/n_\text{ini} \approx 10^8 \) for a temperature of \( 10^4 \text{ K} \) and an electron density of \( n_e \gtrsim 10^4 \text{ cm}^{-3} \) when the collisional de-excitation rate dominates the radiative rate (Rudy et al. 1985).

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real detections, since Mg ii and He I* λ3889 are measured independently. In this figure we also compared the width of Mg ii and He I* λ3889 and found that the former is on average 2 times broader than the latter, with a rather large scatter. This fact was also noted by Arav et al. (2001b) in a case study of BAL quasars with redshifted troughs identified by Hall et al. (2013), which are much broader and often with blueshifted absorption too.

The sample shows an interesting pattern in the Mg ii line velocity against width ($v_{\text{ave}}$)\(^\Delta \nu\) plane of Figure 1. Line width is strongly correlated with velocity for absorbers in the upper left corner ($\Delta \nu$ and $v_{\text{ave}}$ \(\gtrsim\) 1000 km s\(^{-1}\)), which can be readily classified as BALs. Absorbers located in the lower right corner should fall in the traditional intrinsic NAL category. Considering the velocity zero-point uncertainty of ~100 km s\(^{-1}\) determined by [O III], [O II], Mg ii, and Balmer emission lines (Zhou et al. 2006b; Nestor et al. 2008), absorbers located in the middle part within the two dashed lines can be taken as unshifted, most of which might be of a different origin than the left-hand BAL and NAL outflows. Their relation with those redshifted absorbers located in the lower right corner is not clear, and neither is the nature of the redshifted absorbers (see Shi et al. 2014 for a case study). With an associated quasar showing an NLS1-like emission line spectrum, the broadest Mg ii absorption trough, a common redshift coincidence with that of the quasar emission lines, and the same symmetrical velocity structure of all isolated absorption lines, SDSS J0802+5513 is the most extreme case of the unshifted He I* λ3889 absorbers. Taking advantage of the diffuse absorption line spectrum, a detailed study of this extreme case may shed new light on the nature of this mysterious new kind of absorber. We collected existing photometric data and performed subsequent near-UV (NUV) through optical to NIR spectroscopic follow-ups from 2008 to 2012 using the Blue Channel Spectrographs at the Multiple Mirror Telescope (MMT), the Multi-Object Double Spectrographs (MODS) at the Large Binocular Telescope (LBT), and TripleSpec at the 200-inch Hale Telescope (P200). The photometric and spectroscopic data are summarized in Tables 1 and 2, respectively. We show the data in Figure 2 and give them detailed descriptions in the next two subsections.

2.2. Broadband Photometry

The photometric data include fluxes at 1.4 GHz by the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) in the radio; IR magnitudes from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) and 2MASS (Skrutskie et al. 2006); optical magnitudes from SDSS; and NUV magnitudes from the Galaxy Evolution Explorer (GALEX; Morrissey et al. 2007).

SDSS J0802+5513 has been monitored in the Catalina Real-time Transient Survey over 7 yr (Drake et al. 2012). The light curve in V band shows no significant variations beyond the intrinsic 1σ flux scatter of 15% (see Figure 3). The data suggest that the quasar did not show significant variability. As shown in the first panel of Figure 2, the spectral energy distribution (SED) of SDSS J0802+5513 is apparently red as compared to
Table 1
Broadband Photometry of SDSS J0802+5513

| Band | Flux (mag/m^2) | Facility | Obs. Date (UT) | Reference |
|------|----------------|----------|----------------|-----------|
| NUV  | 22.62 ± 0.26   | GALEX    | 2004 Jun 5     | 1         |
| u    | 20.79 ± 0.06   | SDSS     | 2003 Mar 11    | 2         |
| g    | 19.21 ± 0.02   | SDSS     | 2003 Mar 11    | 2         |
| r    | 18.42 ± 0.01   | SDSS     | 2003 Mar 11    | 2         |
| i    | 17.88 ± 0.02   | SDSS     | 2003 Mar 11    | 2         |
| z    | 17.70 ± 0.02   | SDSS     | 2003 Mar 11    | 2         |
| J    | 16.47 ± 0.10   | 2MASS    | 1999 Apr 27    | 3         |
| H    | 15.94 ± 0.13   | 2MASS    | 1999 Apr 27    | 3         |
| Ks   | 14.66 ± 0.09   | 2MASS    | 1999 Apr 27    | 3         |
| u/1  | 12.93 ± 0.03   | WISE     | 2010 Jan 10    | 4         |
| u/2  | 11.72 ± 0.02   | WISE     | 2010 Jan 10    | 4         |
| u/3  | 8.84 ± 0.03    | WISE     | 2010 Jan 10    | 4         |
| u/4  | 6.46 ± 0.04    | WISE     | 2010 Jan 10    | 4         |
| 1.4 GHz | 7.1 ± 0.5 | NVSS    | 1993 Nov 23    | 5         |
| 1.4 GHz | 6.54 ± 0.14 | FIRST   | 1998 Jul 31    | 6         |

References. (1) Morrissey et al. 2007; (2) Schneider et al. 2010; (3) Skrutskie et al. 2006; (4) Wright et al. 2010; (5) Condon et al. 1998; (6) Becker et al. 1995.

a quasar composite. The quasar composite used in the fit is the combination of SDSS optical ($\lambda \approx 3000$ Å; Vanden Berk et al. 2001), IRTF NIR (3000 Å $\lesssim \lambda \lesssim 3.5$ μm; Glikman et al. 2006; see Zhou et al. 2010 for an application), and Spitzer mid-IR (MIR) to far-IR (FIR) ($\lambda \gtrsim 3.5$ μm; Netzer et al. 2007) composites. We then estimated reddening of the quasar by fitting the quasar composite spectrum to the SED of SDSS J0802+5513 assuming a Small Magellanic Cloud (SMC) type extinction curve (Lequeux et al. 1982; Cartledge et al. 2005).

The best-fitted model is obtained by minimizing $\chi^2$. The best-fitted $E(B-V)$ is 0.36 mag, which agrees well with that indicated by the flux ratios of $\mathrm{Pa\beta}/\mathrm{H\alpha}$ ($E(B-V) \sim 0.4$) and $\mathrm{H\alpha}/\mathrm{H\beta}$ ($E(B-V) \sim 0.3$) as detailed in Section 3.1. It can be seen in the first panel of Figure 2 that this simple model well reproduces the observed SED.

SDSS J0802+5513 is detected by FIRST and NVSS at 1.4 GHz in the radio. No significant variability was observed between the two epochs. Radio-loudness, defined as $R \equiv S_5\text{GHz}/S_2\text{GHz}$, is 110 and 25, respectively, before and after reddening correction. The NVSS flux at 1.4 GHz was used to estimate the 5 GHz emission $S_5\text{GHz}$, and a radio spectral index of $\alpha_r = 0.5$ ($S_\nu \propto \nu^{-\alpha_r}$) was assumed. We corrected the $B$-band flux $S_B$ using the best-fitted reddening value. SDSS J0802+5513 is moderately radio-loud, and it becomes radio-intermediate after reddening correction. SDSS J0802+5513 was also observed at 18 cm by the Multi-Element Radio-Linked Interferometer Network (MERLIN). It is unresolved at 0.3 resolution, corresponding to a linear scale of about 1.6 kpc at the redshift of the quasar (Zuther et al. 2012).

Table 2
Journal of Spectroscopic Observations

| Wavelength Coverage (Å) | Slit (arcsec) | Resolution $\lambda/\Delta\lambda$ | Exposure (s) | Telescope/instrument | Obs. Date UT |
|-------------------------|--------------|----------------------------------|--------------|----------------------|--------------|
| 3800–9200               | 3*           | 2000                             | 4200         | SDSS 2.5m            | 2003 Mar 24  |
| 3200–5200               | 1            | 1800                             | 1500         | MMT/Blue Channel     | 2008 Mar 30  |
| 10000–24000             | 1.1          | 2500                             | 1200         | P200/ TripleSpec     | 2011 Oct 21  |
| 3200–11000              | 0.8          | 2500                             | 2400         | LBT/MODS             | 2012 Jan 29  |

Note. * The SDSS spectrograph is fiber fed with a size of 3′′ in diameter.

2.3. Spectroscopy

The SDSS spectrum that we use is the improved sky-residual-subtracted version as published in Hewett & Wild (2010). To detect any possible absorption-line variations and achieve a higher signal-to-noise ratio ($S/N$), we carried out a follow-up NUV spectroscopic observation at MMT using the blue channel on 2008 March 30. We used the $1'' \times 180''$ slit and an 800 line mm$^{-1}$ grating. A total observation time of 1500 s was equally split into two exposures. The seeing during the observation is about 1′. An He/Ne/Ar lamp is used for wavelength calibration, and the KPNO standard star eg182 is observed for flux calibration. We use the standard IRAF package$^{10}$ to extract the 1D spectrum. The extracted spectrum covers a wavelength range of $\sim 3200–5200$ Å. The median $S/N$ of the MMT spectrum is about 10 pixel$^{-1}$ with a resolution of $R \sim 1800$, similar to that of SDSS ($R \sim 2000$). Compared with the SDSS spectrum, the MMT spectrum shows no significant variations in absorption lines, neither the velocity profiles nor the maximum depths (see Section 3.2 for details).

To observe the He emission line and the expected He$^+ \lambda 10830$ absorption line, we acquired an NIR spectrum using TripleSpec at the P200 telescope via the China Telescope Access Program (TAP). The observation was carried out on 2011 October 21 using the standard slit of $1'' \times 30''$ in A-B-A dithering mode. The total exposure time was 1200 s. Using IDL-based Spextool software (Cushing et al. 2004), the raw data are flat-field corrected, telluric corrected (Vacca et al. 2003), and wavelength (using sky lines) and flux calibrated. The reduced spectrum has a wavelength coverage of $\sim 1.0–2.4$ μm and a resolution of $R \sim 2500$.

To fill the gap between SDSS and P200 spectra and to detect the possible Na i D absorption doublet, we carried out a follow-up spectroscopy using MODS at LBT with a slit width of 0.8. Four 600 s exposures were acquired for each of the blue and red channels. CCD reductions, including bias subtraction and flat-field correction, were accomplished using Python package “modsCCDRed.” Subsequent reductions are carried out using the standard IRAF package. Ne/Hg/Ar/Xe/Kr lamps were used for wavelength calibrations, and the standard star Ferge 67 was observed for flux calibration. The extracted LBT spectrum covers a wavelength range of $\sim 3200–10000$ Å and a resolution of $R \sim 2500$. Na i D absorption doublets were not significantly detected on the moderate-$S/N$ LBT spectrum.

All abovementioned spectra were corrected for the Galactic extinction of $E(B-V) = 0.05$ (Schlegel et al. 1998) assuming an average Galactic ($R_V = 3.1$) extinction law and transformed into the quasar rest frame using a redshift of $z = 0.6640 \pm 0.0005$ as determined by [O II], [S II], Balmer, and Paschen absorption.

$^{10}$ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 2. In the first panel, the merged spectrum of SDSS J0802+5513 in the quasar rest frame is shown with the black curve. The data used include SDSS, MMT, LBT, and P200 spectroscopy (see Table 2 and Section 2.3 for details), which are smoothed by a boxcar of 7 pixels, with bad pixels removed for clarity. A quasar composite spectrum is overplotted in green for comparison. Broadband SED of SDSS J0802+5513 (black squares; photometric data are adopted from GALEX, SDSS, 2MASS, and WISE; see Table 1 for details) is displayed along with the quasar composite reddened by $E(B-V) = 0.36$ using the SMC-type extinction law (red curve). Expanded views of the merged spectrum are shown in subsequent panels.

Figure 3. Catalina V-band light curve for SDSS J0802+5513. Observation MJDs for all the data are labeled by telescope names, with the exception of SDSS and GALEX, whose observing epochs are not covered by Catalina.
emission lines, which is consistent with that ($z = 0.6641 \pm 0.0004$) given in Hewett & Wild (2010) within errors. Since the quasar SDSS J0802+5513 shows no significant variation in years (see Section 2.2), we then recalibrated all spectra to photometric data for correcting aperture and seeing effects. We then combined all the spectra, weighted by their $S/N$, to construct a broadband SED. We display the combined spectrum in the first panel of Figure 2, with expanded views in subsequent panels. It shows narrower Balmer lines and stronger optical Fe II emission lines. [O II] emission is very strong relative to high-ionization forbidden lines such as [Ne III] and [O II]. Quantitative emission-line measurement will be presented in Section 3.1. Besides emission lines, the absorption spectrum of SDSS J0802+5513 is probe from rest-frame NUV through optical to NIR. The most prominent absorption features are the strong He I at 10830 Å and the blended troughs of Fe II UV1 and UV2 around 2600 Å and 2400 Å respectively. Identification and measurement of the absorption lines are described in Section 3.2.

3. SPECTRAL ANALYSIS

3.1. Emission-line Measurement

We adopt a fitting method similar to Zhou et al. (2006b) and Dong et al. (2011) to measure the emission lines of interest, with some modifications to accommodate the existence of BALs. Briefly, the observed spectrum was decomposed into a power law, Fe II emission complex, and emission lines other than Fe II. Given that the SED of SDSS J0802+5513 is red, we fit a reddened power law to emission-line-free windows: 4020–4050 Å, 4205–4235 Å, 5580–5620 Å, 6350–6400 Å, 6810–6850 Å. Then we subtract the best-fitted power law from the observed spectrum and fit the residual by an Fe II template. We employed the Fe II template built by Véron-Cetty et al. (2004). The template was broadened to fit the Fe II emission strong spectral windows: 4170–4260 Å, 4430–4770 Å, 5080–5500 Å and 6050–6200 Å. The best-fitted model of the pseudocontinuum, including a power law and Fe II multiplets, is shown in the left panel of Figure 4.

Emission lines other than Fe II multiplets were measured by fitting the pseudocontinuum-subtracted spectrum. Each of the Balmer and Paschen lines was modeled with two components, a Lorentzian profile for the broad line and a Gaussian for the narrow one. The narrow Balmer and Paschen lines were assumed to have the same width and redshift as that of the low-ionization forbidden lines [S II] and [N II]. All of the narrow emission lines were fitted by a single Gaussian except the [O II] doublet, which was fitted with two Gaussians, one for the blue wing (Komossa 2008) and the other for the core of the lines. The width and redshift of the [O II] core component were tied to those of low-ionization narrow lines. The doublet ratios of [O II] and [N II] are fixed to their theoretical value 3:1 during the fit. We zoomed in the best-fitted model in Hα and Hβ regimes in the right panel of Figure 4.

The measured line parameters are summarized in Table 3. In Dong et al. (2008), the authors investigated the broad-line Balmer decrements for an unreddened sample of Seyfert 1 galaxies and QSOs in SDSS and, they find that the distribution of the intrinsic broad-line Hα/Hβ ratio can be well described by log-Gaussian, with the peak at Hα/Hβ = 3.06 and a standard deviation of about 0.03 dex only. The steep broad-line ratios of Hα/Hβ = 4 in SDSS J0802+5513 thus indicate that the broad-line region (BLR) should be significantly reddened. Using Hα/Hβ as the intrinsic Balmer decrement and an SMC-type extinction curve, we obtain an estimate of $E(B - V)$ = 0.31 ± 0.05. No estimation of intrinsic Paβ/Hα is available in (Dong et al. 2008); we assume an intrinsic Paβ/Hα ratio of 0.06 as calculated in case B for typical BLR conditions (i.e., $T_e = 10,000$ K and $n_e = 10^6$ cm$^{-3}$; Hummer & Storey 1987), and we obtain an estimate of $E(B - V)$ ≈ 0.4 ± 0.04. These agree with the value yielded from SED fitting in Section 2.2 within errors.
emission ([O\textsc{iii}]$\lambda$5007) to get a lower limit of bolometric luminosity $L_{\text{bol}}$. Typical for an NLS1, with narrow Balmer emission line resolution spectra are needed to confirm this.

The emission-line properties of SDSS J0802+5513 are typical for an NLS1, with narrow Balmer emission line FWHM(H\textbeta) $\approx$ 1800 km s$^{-1}$, strong optical Fe\textsc{ii} emission $R_{1570} \equiv (\text{Fe\textsc{ii}} \lambda4434 - 4684/\text{H}\beta) \approx$ 1, and weak [O\textsc{iii}] emission ([O\textsc{iii}]/H\beta) $\approx$ 1.5. The black hole mass acquired is $M_{\text{BH}} \approx 2 \times 10^6 M_\odot$ using the empirical mass/luminosity/line width relation calibrated through reverberation mapping (Peterson & Bentz 2006). In the most conservative case, we integrate the infrared photometries from 2MASS K to WISE $w_4$ to get a lower limit of bolometric luminosity $L_{\text{bol}} = 1.2 \times 10^{46}$ erg s$^{-1}$. Here we assume that the radiation in this wavelength range is from hot dust heated solely by the quasar nucleus given the similarity between infrared SED and the quasar composite, and the dust has a full coverage of the central engine. Here we did not include the emission beyond WISE $w_4$. A more reasonable estimate is at least twice that value considering that FIR is not included and the covering factor of the dusty torus is about 0.5 based on the fraction of obscured AGNs (e.g., Dong et al. 2005; Hasinger 2008). Alternatively, we can estimate the bolometric luminosity using the monochromatic luminosity of $\lambda L_{\lambda,5100} \approx 1.8 \times 10^{46}$ erg s$^{-1}$ at 5100 Å. Using the bolometric correction of $L_{\text{bol}}/\lambda L_{\lambda,5100} = 12$ (Richards et al. 2006), the corresponding bolometric luminosity is $L_{\text{bol}} \approx 2.2 \times 10^{46}$ erg s$^{-1}$ and $L_{\text{bol}} \approx 6.4 \times 10^{46}$ erg s$^{-1}$, respectively, before and after extinction correction. The inferred Eddington ratio is $m \approx 0.4$–1.4, indicating that the central SMBH is undergoing rapid growth. Assuming a mass-to-energy conversion efficiency of $\eta = 0.1$, we inferred a mass accretion rate of $M_{\text{acc}} \sim 2.1$–7.7 $M_\odot$ yr$^{-1}$.

3.2. Absorption-line Measurement

3.2.1. Normalization of Absorption-line Spectra

To normalize the absorption-line spectrum, the absorption-free spectrum of SDSS J0802+5513 must be recovered first. Two techniques are commonly adopted to achieve this goal, namely, spectral decomposition (e.g., Lu et al. 2008) and the template match method (e.g., Zhou et al. 2006a). We split the observed spectrum into three regimes and use different approaches to reconstruct absorption-free spectra, according to the different emission and absorption characteristics. The three spectrum regimes of interest are (1) Fe\textsc{ii} + Mg\textsc{ii} (2100–3200 Å), (2) He\textsc{i}$^\ast$ $\lambda$3889+Ca\textsc{ii} (3700–4000 Å), and (3) He\textsc{i}$^\ast$ $\lambda$10830 (1–1.4 $\mu$m).

### Table 3

| Transition | Broad-line Flux ($10^{-17}$ erg cm$^{-2}$ s$^{-1}$) | Broad-line Width (km s$^{-1}$) | Narrow-line Flux ($10^{-17}$ erg cm$^{-2}$ s$^{-1}$) | Narrow-line Width (km s$^{-1}$) |
|------------|---------------------------------|-----------------|---------------------------------|-----------------|
| Pa$^\beta$ | 230 ± 20                        | 1800 ± 170      | 32 ± 10                         | 690 ± 120       |
| H$\alpha$  | 1946 ± 28                       | 1800 ± 170      | 235 ± 10                        | 690 ± 120       |
| H$\beta$   | 487 ± 15                        | 1800 ± 170      | 40 ± 15                         | 690 ± 120       |
| [O\textsc{ii}] | ...                            | ...             | 45 ± 6                          | 690 ± 120       |

**Note.** All quoted errors are statistical ones, widths are FWHMs, and the widths of all broad emission lines and narrow lines are tied during the fit, respectively.

The observed spectra of the three regimes are bloated and displayed in Figure 5, with the best-fitted models overlaid. Identified lines are labeled by vertical bars on the top of each panel in the figure and listed in Table 4.

**Figure 5.** Expanded view of the observed spectrum of SDSS J0802+5513 (black) in three absorption-line regimes of interest, overplotted with model absorption-free spectra (green). Identified transitions are plotted as vertical bars on top of each panel, with the bar lengths proportional to log(gf).

Theobserved spectra of the three regimes are bloated and displayed in Figure 5, with the best-fitted models overlaid. Identified lines are labeled by vertical bars on the top of each panel in the figure and listed in Table 4.

Fe\textsc{ii}+Mg\textsc{ii} regime—We employed the spectral decomposition technique for this regime. The observed data were fitted by the combination of three components: a power law, a broadened Fe\textsc{ii} + Fe\textsc{iii} template, and a broad Mg\textsc{ii} emission line. The three components were reddened by the same SMC-like dust with $E(B-V)$ as a free parameter. The Fe\textsc{ii} template built by Tsuzuki et al. (2006) is adopted, and the Fe\textsc{iii} UV47 multiplet template is from Vestergaard & Wilkes (2001). We assumed that the Mg\textsc{ii} broad line has the same profile and redshift as Balmer broad lines obtained in Section 3.1. The best-fitted value of $E(B-V) \approx 0.30$ is consistent with that inferred from broad-band SED fitting ($E(B-V) \approx 0.36$; Section 2.2) and that estimated from broad hydrogen line ratios ($E(B-V) \approx 0.31$–0.4; Section 3.1).
He\(^{+}\) λ3889+\(\lambda\)Ca\(\Pi\) regime—We used the template matching method for this regime owing to the fact that emission features in this regime, mainly arising from Fe\(\Pi\), Ti\(\Pi\), Cr\(\Pi\), etc., are very complex, and no appropriate templates are available for them (Véron-Cetty et al. 2004, 2006). Furthermore, the ratios of optical Fe\(\Pi\) multiplets vary dramatically from object to object (Vestergaard & Wilkes 2001); Fe\(\Pi\) templates built from within 1\(\text{Zw1}\) alone cannot fit this region well. We choose the observed spectra of Fe\(\Pi\) strong quasars as templates to match the spectrum in this regime. The templates are chosen from DR7 quasars with \(\text{EW}_{\text{Fe}\Pi} \geq 4570\) Å and a median \(S/N > 20\) in the [O\(\Pi\)] region. The best-matched template is the spectrum of SDSS J100446.52+600336.1 (as seen in Figure 5).

He\(^{+}\) λ3889+\(\lambda\)Ca\(\Pi\) regime—We used the template matching method for this regime owing to the fact that emission features in this regime, mainly arising from Fe\(\Pi\), Ti\(\Pi\), Cr\(\Pi\), etc., are very complex, and no appropriate templates are available for them (Véron-Cetty et al. 2004, 2006). Furthermore, the ratios of optical Fe\(\Pi\) multiplets vary dramatically from object to object (Vestergaard & Wilkes 2001); Fe\(\Pi\) templates built from within 1\(\text{Zw1}\) alone cannot fit this region well. We choose the observed spectra of Fe\(\Pi\) strong quasars as templates to match the spectrum in this regime. The templates are chosen from DR7 quasars with \(\text{EW}_{\text{Fe}\Pi} \geq 4570\) Å and a median \(S/N > 20\) in the [O\(\Pi\)] region. The best-matched template is the spectrum of SDSS J100446.52+600336.1 (as seen in Figure 5).

Table 4: Absorption Lines Identified in SDSS J0802+5513

| Wavelength (Å) | log(\(gf\)) | Ion | \(E_{\text{low}}\) | \(g_{\text{low}}\) | \(E_{\text{gap}}\) | \(g_{\text{up}}\) |
|---------------|-------------|-----|-----------------|---------------|-----------------|--------------|
| 10830.80      | -0.04       | He\(^{+}\) | 159856          | 3              | 169086          | 9            |
| 3889.80       | -0.72       | He\(^{+}\) | 159856          | 3              | 185565          | 9            |
| 3188.69       | -1.16       | He\(^{+}\) | 159856          | 3              | 191217          | 9            |

Figure 6. Absorption spectrum of isolated lines plotted in a common velocity space. The origin of the velocity scale is set to the systematic redshift of the quasar. Observed data are shown with black curves, with best-fitted models overlaid in green. The green dashed line in the right bottom panel is the predicted profile of the Mg\(\Pi\) doublet using a column density of \(N_{\text{Mg}\Pi} = 15.3\) cm\(^{-2}\), and the green dashed line in the right second panel from the bottom is the fitting of He\(^{+}\) λ3889 scaled by 2.3, assuming a partial coverage factor of 0.85 (see Section 4.1 for details). The Fe\(\Pi\) line blends near Fe\(\Pi\) λ2286 in the bottom left panel are shaded for clarity. Note that Mg\(\Pi\) λ2174 is in fact a doublet with a velocity separation of 770 km s\(^{-1}\). The zero velocity is set for Mg\(\Pi\) λ2796, which is highly blended with Mg\(\Pi\) λ2803. The leftmost 770 km s\(^{-1}\) is solely contributed by Mg\(\Pi\) λ2796, while the rightmost 770 km s\(^{-1}\) by Mg\(\Pi\) λ2803 (shaded for clarity). The region between the two shadowed area is contributed by both lines.

He\(^{+}\) λ10830 regime—The He\(^{+}\) λ10830+Pa\(\delta\) emission blends are seriously affected by the strong He\(^{+}\) λ10830 absorption line, and the red wing of the blends falls at the gap between J and H bands. As seen in Figure 5, the NIR composite spectrum of the quasar derived by Glikman et al. (2006) matches the observed spectrum in this regime quite well. The detected absorption lines (see Table 4) fall into two categories: relatively isolated lines (Figure 6) and heavily blended lines (Figure 7). The normalized absorption-line spectrum is derived by dividing the observed spectrum by the absorption-free spectrum recovered above straightforwardly. This normalization scheme is based on the assumption that the absorption gas covers both the continuum source and BLR of the quasar. The validity of such an assumption can be justified by checking the residual flux at the centroid of strong absorption lines. The residual fluxes at the centroids of Mg\(\Pi\), Fe\(\Pi\) λ2600, and He\(^{+}\) λ10830 lines are so small that it would yield negative values at these wavelengths if we subtracted the broad emission lines. This implies that the absorber at least covers a significant part, if not all, of the BLR. In this case, the continuum source must be fully covered, since the size of the BLR is about two orders of magnitude larger than that of the accretion disk. Indeed, the apparent optical depth ratios of both Ca\(\Pi\) K and H and He\(^{+}\) λλ3189, 3889 doublets support the assumption of full coverage. The column densities of Ca\(\Pi\) and He\(^{+}\) evaluated by the
Figure 7. Comparison between the observed data (black curves with error bars) and the best-fit models (green) in the λ2350 and λ2600 absorption blends. Identified transitions in Fe II, Mn II, and Ni II are labeled as in Figure 5 (see also Table 4 for the line list and related information). We assume that all of the absorption lines have the same redshift and profile as that of the mean of the isolated absorption lines (see Figure 6), and the relative strengths are fixed to their theoretical values. The assumed absorption-line profile is shown as the velocity-dependent curve of optical depth in the orange inset.

Table 5

| Species | Transitions | EW (Å) | $N_{\text{ion}}$ (cm$^{-2}$) |
|---------|-------------|--------|------------------------------|
| Ca II   | 3969.59     | 2.15 ± 0.16 | 13.59 ± 0.07 |
| Ca II*  | 3934.78     | 3.52 ± 0.17 | 13.51 ± 0.05 |
| He I*   | 3889.74     | 2.54 ± 0.18 | 14.73 ± 0.07 |
| He I*   | 3818.66     | 0.82 ± 0.14 | 14.82 ± 0.17 |
| Mg I    | 2852.96     | 4.51 ± 0.53 | 13.53 ± 0.11 |
| Mg II   | 2803.53     | 5.82 ± 0.21* | ... |
| He I*   | 10830.40    | >29.63     | ... |

Note. * Half of the total equivalent width of Mg II doublet absorption lines.

individual line of the doublet based on the full coverage assumption agree with each other within errors (see Table 5 and details in Section 3.2). Note that the full coverage assumption is consistent with the location of the absorption gas estimated in Section 4, which is ∼200 pc from the central SMBH, about three orders of magnitude larger than the BLR.

3.2.2. Measurements of Absorption Lines

We measured the column densities of isolated lines and blended lines using different schemes, respectively.

The isolated He I* λλ3189, 3889, Fe II λ2586, Ca II K and H, and Mg I lines show nearly identical velocity structure as seen in Figure 6. Each line has three distinct components, as indicated by the vertical dashed lines. The deepest component is centered at the quasar systematic redshift. Two shallower components are symmetrically distributed around the deepest one, with a velocity shift of Δv ∼ ±500 km s$^{-1}$. Assuming the background source fully covered and the absorption lines moderately resolved, we evaluated the optical depth profiles of the six absorption lines as $\tau(v) = -\ln I_r(v)$, where $I_r$ is the residual intensity of the normalized spectrum. Each of the six lines was fitted with three Gaussians. The width and centroid of the corresponding Gaussian are tied during the fit. The best-fitted optical depth as a function of velocity is shown in the inset in Figure 7. The equivalent widths (EWs) of these six lines are measured from the best-fitted models, which are overplotted in Figure 6. We also calculated the column densities of the corresponding lines by integrating their best-fitted apparent optical depth profiles. The measured EWs and column densities are listed in Table 6. Both the Mg II doublet and He I* λλ10830 lines are seriously saturated, and no direct measurement is available. Their absorption troughs are flat-bottomed with residual flux of ≤10% at the deepest points. As a conservative estimate, assuming a covering factor of 85%, we rescaled the best-fitted He I* λ3889 optical depth profile by a factor of 23.3 ($f$ ratio of λ10830 to λ3889; Leighly et al. 2011) to generate an He I* λ10830 absorption line model. The model is overlaid on the observed data in Figure 6. Mg II λ2796 is seriously blended with Mg II λ2803; we used the best-guessed Mg II column density from photoionization simulation in Section 4 to create the model overplotted in Figure 6. In Table 5, we take half of the integrated EW of the blend as a rough estimate for each member of the doublet.

High-ionization BALs like C IV and Si IV are often much stronger and wider than LoBALs like Mg II and Al III (Zhang et al. 2010; Filiz Ak et al. 2014); it is remarkable that He I*, Fe II, Ca II, and Mg I lines, which are arising from ions with very different ionization potentials, have almost the same velocity structure, and this indicates that SDSS J0802+5513 may have an origin other than traditional BALs. He I* λλ3189, 3889, 10830 arise from metastable triplet level He I 2S at a rather high excitation energy of 19.6 eV. The level is populated by recombination from He I* ions (Ji et al. 2012), which are created...
by photons with energies of $h\nu > 24.56$ eV and are destroyed by photons with $h\nu > 54.42$ eV. They survive in much different conditions than that of Ca\(^+\) ions and neutral Mg atoms that give rise to Ca\(^{+}\) K and H and Mg\(^{+}\) lines. Mg atoms are destroyed by photons with $h\nu > 7.65$ eV, and Ca\(^+\) ions are created by photons with energies of $h\nu > 6.11$ eV and are destroyed by photons with $h\nu > 11.87$ eV. The nearly identical profile of He\(^{+}\), Ca\(^{+}\), and Mg\(^{+}\) lines implies that all of the remaining detected absorption lines should have the same velocity structure, because all of them originate from singly ionized ions with surviving conditions in between that of He\(^{+}\) and that of Ca\(^+\) and neutral Mg.

For the Fe\(^{+}\) UV1 and UV2 regimes displayed in Figure 7, the absorption lines are too heavily blended to fit them separately. As listed in Figure 4, we identified Fe\(^{+}\) lines that arise from ground levels and from excited levels up to 7955 cm\(^{-1}\). Ni\(^{+}\) lines from the excited level of wavelength number 8395 cm\(^{-1}\) and Mn\(^{+}\) lines from the ground level are also identified. All of the identified absorption lines were fitted simultaneously using the same optical depth profile generated above from the isolated lines (shown in the inset of Figure 7). We also calculated EWs of individual absorption lines by integrating the normalized flux of their models. The best-fitted column densities are summarized in Table 6, and the best-fitted model is compared with the observed absorption-line spectrum in Figure 7.

This model recovers the observed data very well. This implies that the apparent optical depth (AOD) method, which was adopted to measure the column densities, is reasonable.

As pointed out by Jenkins (1986), large populations of absorption lines can be analyzed collectively using the standard, single-component curve of growth (COG) method. We combine the three components in SDSS J0802+5513 and perform such single-component COG analysis as a double-check to the AOD measurements. Five Fe\(^{+}\) lines with $gf$ span of about 1 dex (Table 4) were used to evaluate the best-fitted COG. We calculated theoretical COGs of various $b$ values and searched for the best match for the measured EWs of the ground-level Fe\(^{+}\) lines. Both $b$ and $N_{Fe, i}$ are free parameters during the fit. The best-fitted COG of Fe\(^{+}\) lines is presented in Figure 8. We interpolated the EW measurements on the best-fitted COG to infer COG column density for other transitions. The differences of column densities evaluated by the AOD and COG methods, $\log(N_{AOD}/N_{COG})$, are plotted in the lower panel of Figure 8. The differences are negligible within errors, for most lines, in order of 0.1 dex. The AOD method relies on two assumptions: (1) the absorption lines are completely resolved and (2) the absorber fully covers the background emission source. The overall agreement between $N_{AOD}$ and $N_{COG}$ indicates that the two assumptions are at least an acceptable approximation.

### 4. PHYSICAL CONDITIONS AND LOCATION OF THE ABSORPTION GAS

In this section we explore the physical conditions of the absorption gas and locate the gas with the aid of photoionization model calculations and using the column densities of various ions/levels reliably measured in Section 3.2. Fe\(^{+}\) absorption lines that arise from excited levels are sensitive to the electron density $n_e$ (e.g., Arav et al. 2001a; Dunn et al. 2010) in absorbers. Moreover, He\(^{+}\) lines are a good diagnostic for constraining ionization parameter $U$, which is defined as

$$\frac{1}{4\pi r^2 n_H c} T = \frac{1}{4\pi r^2 c n_H} \int_{v_0}^\infty \frac{dv}{h\nu}$$

where $v_0$ is the frequency corresponding to the hydrogen edge and $Q$ is the emission rate of hydrogen ionization photons. Once $U$ and $n_e$ are well constrained, the distance of absorption gas can be inferred from Equation (1). We carry out detailed analysis using a photoionization model in Section 4.1, and we discuss in Section 4.2 the possible dependence on metal abundances, SED of the background quasar, and dust reddening effects. We run the photoionization code CLOUDY to carry out the model simulations (version c13.00; see Ferland et al. 1998).

#### 4.1. Basic Model

First, we will show that the column density ratio $N_{Fe, i}/N_{He, i}$ observed in SDSS J0802+5513 requires the absorber to be thick enough to have a partially ionized or neutral zone behind the hydrogen ionization front. We started by considering a gas slab with a density of $n_H$ and a total column density of $N_H$, which is illuminated by quasar radiation (SED from Mathews & Ferland 1987, hereafter MF87). We calculated a grid of models by varying $U$, $n_H$, and $N_H$, with metallicity fixed to solar abundance. As an example, we plot one result of the model calculations in Figure 9. The ionization structure is shown as a function of the depth parameter $N_H$ from the illumination surface. Transitions from different ionization states behave differently in the $N_{ion}-N_H$ plane, yielding a sensitive dependence of ion column density ratios on $N_H$. This implies that these metal ion column density ratios are good constraints to the absorber thickness. Specifically, only the very narrow $N_H$ range, labeled by two vertical dashed lines in Figure 9, can produce the value of $\log(N_{Fe, i}/N_{He, i}) = 0.60 \pm 0.35$ observed in SDSS J0802+5513 for the adopted $U$ and $n_H$. This is understandable considering that Fe\(^{+}\) and other singly ionized metal ions or neutral atoms) and He\(^{+}\) survive at different conditions.
He $^{1+}$ 2$^2$S state is mainly populated by the recombination of an He$^+$ ion with an electron. As $N_\text{H}$ increases, the main ionization state of helium changes from He$^{++}$ to He$^+$, resulting in a sharp increase in He$^+$ 2$^2$S near the ionization front. Further into the cloud, the ionizing photons quickly run out and helium becomes almost neutral, which in turn prevents the generation of He$^{1+}$ 2$^2$S ions. However, the existence of such an ionization front does not prevent the formation of ions with lower ionization potentials, such as Ca $^{2+}$, Mg $^{2+}$, and Fe $^{2+}$. As a result, $N_{\text{Fe}^{2+}}/N_{\text{He}^{1+}}$ continues to increase after the front. Therefore, once the gas abundance and the incident SED are appointed, the $N_{\text{Fe}^{2+}}/N_{\text{He}^{1+}}$ ratio can give a tight constraint to the thickness of the absorber, provided that the absorber is thick enough to generate the maximum $N_{\text{He}^{1+}}$. More importantly, this $N_{\text{He}^{1+}}$ corresponds to a nearly unique value of $U$ for a large range of gas density $n_\text{H}$.

As a demonstration, we have run an extensive grid of simulations with $\log U$ varying from $-2.5$ to $0$ with a step of $0.1$ and $n_\text{H}$ varying from $4$ to $8$ with a step of $0.2$. The upper limit of $n_\text{H} = 10^5$ cm$^{-3}$ is determined by the fact that Balmer absorption lines, arising from the excited hydrogen $n = 2$ level generated by collision, are not detectable in SDSS J0802+5513 (Leighly et al. 2011). The lower limit to the density can be set by the equilibrium equation of the lowest Fe$^{2+}$ excited level 385 cm$^{-1}$ (de Kool et al. 2001). Using a two-level approximation,

$$n_1n_{e,1} = n_2(n_{e,2} + n_2A_{21}),$$

where the subscripts 1 and 2 represent ground level and the 375 cm$^{-1}$ level, respectively, and neglecting the collisional term, we derive a lower limit of $n_\text{H} > 10^4$ cm$^{-3}$. The stop column density of $N_{\text{H}} = 10^{23} \text{ cm}^{-2}$ is chosen to enclose a fully developed ionization front for the largest $U$ concerned.\footnote{The H II region scales approximately as $\log_{10}N_\text{H} \approx 23+\log U$.}

In Figure 10, we show the model prediction of $N_{\text{He}^{1+}}$ for a given set of $U$ and $n_\text{H}$. The photoionization parameter is constrained to a very narrow range of $-2 < \log U < -1.8$ by the [stop] observed $N_{\text{He}^{1+}}$.\footnote{The model simulations show an interesting fact that $N_{\text{He}^{1+}}$ is strongly dependent on $U$, but it is insensitive to $n_\text{H}$. This suggests that, for the range of model parameters investigated, $N_{\text{He}^{1+}}$ could be a good indicator of $U$.} Using the median value of $\log U = -1.9$, we calculated the column density ratios of the excited to ground level of Fe$^+$ ions as a function of $n_\text{H}$. Figure 11 presents the results of the 385 cm$^{-1}$ and 668 cm$^{-1}$ levels. The estimated density is $n_\text{H} \approx 10^{5.2 \pm 0.3}$ cm$^{-3}$. Measurement uncertainties of higher levels are too large to estimate the electron density reliably. Note that this density is well within the aforementioned value range of $n_\text{H} \sim 10^4$–$10^8$ cm$^{-3}$.

We recalculated the model using the best estimates of $\log U = -1.9$ and $668$ cm$^{-1}$ relative to the ground level as labeled by the legends on gas density. The measurements are shown as filled squares with 1$\sigma$ statistical errors.

Figure 9. Ionic column densities as a function of the depth parameter $N_\text{H}$ for a specific photoionization model with $U = 10^{-2}$ and $n_\text{H} = 10^5$ cm$^{-3}$. The incident quasar SED is from Mathews & Ferland (1987, MF87), and a solar abundance is assumed. Note the different behavior of different ions. The sensitive dependence of the column density ratio $N_{\text{Fe}^{2+}}/N_{\text{He}^{1+}}$ on $N_\text{H}$ (the right $y$-axis with a different set of tick marks) constrains the total column density of SDSS J0802+5513 to a rather narrow range as labeled by the two vertical dashed lines for the specific model (see Section 4.1 for the model details).

Figure 10. Calculated He$^{1+}$ column densities of the photoionization models with $n_\text{H} \sim 10^4$–$10^8$ cm$^{-3}$ and $U \sim 10^{-2.5}$–$10^0$ (see Section 4.1 for details). Note that $N_\text{H}$ is strongly dependent on $U$ and insensitive to $n_\text{H}$. The dashed lines indicate the constraint $U$ range of SDSS J0802+5513.

Figure 11. Calculated dependence of Fe$^{2+}$ excited level populations (385 cm$^{-1}$ and 668 cm$^{-1}$ relative to the ground level as labeled by the legends) on gas density. The measurements are shown as filled squares with 1$\sigma$ statistical errors.
and $n_H \approx 10^{5.2}$ cm$^{-3}$. The model calculation was stopped at $N_H = 10^{21}$ cm$^{-2}$, where the observed $N_{Fe}^{H\alpha}$ is reached. The model column densities are compared with the observed values in Figure 13. The observed column densities can be well reproduced by the model for all ions but Ca$^{ii}$, which is slightly underestimated. We normalized the MF87 SED to the observed luminosity of SDSS J0802+5513 at the WISE w4 band ($\lambda_{eff} = 22$ $\mu$m) and obtained an estimate of the ionizing photon rate of $Q_{MF87} = 2.3 \times 10^{50}$ s$^{-1}$, which should not be affected by reddening. Substituting $Q_{MF87}$ and the best evaluates of $U$ and $n_H$ into Equation (1), we inferred an estimate to the distance of the absorption gas from the SMBH, $R \approx 200(U/10^{-1.9})^{0.5}(n_H/10^{2.2}$ cm$^{-3})^{0.5}$ pc. The inferred physical thickness of the absorber is $\Delta R \sim N_H/n_H \approx 0.02$ pc, which is rather small compared to its distance from the central engine, $\Delta R/R \sim 10^{-3}$.

4.2. Effect of SED, Metallicity, and Dust

Only the MF87 SED and a solar abundance were considered in the basic model described above. Adopting different metallicities or incident SEDs might introduce systematics to model calculations. Neither was dust reddening taken into account in the calculations, and yet it is in fact observed in SDSS J0802+5513. In order to assess these possible systematics, we repeated the calculations adopting different metallicities and incident SEDs and incorporating the effect of dust (including its effect on heating and cooling in the photoionized gas, as calculated with CLOUDY). Two dust configurations were considered here: (1) Dust is uniformly mixed with the absorption gas. We use the prestored abundance set “H II region with grains” offered by CLOUDY as “Orion nebula dust,” which is essentially the average condition of the Orion Nebula (Baldwin et al. 1991; see the note of Table 7). In this case, metals are depleted into dust and the gas-phase abundance is subsolar. (2) The dust is in front of the absorber (a dust screen case). In this case, the dust resides in a very high ionized foreground gas (Dunn et al. 2010), which does not leave imprints on the observed spectra of the quasar but alters the shape of the incident continuum. In Figure 12, we show the MF87 SED reddened with $E(B-V) = 0.36$ using the model extinction curve of the “SMC bar” from Weingartner & Draine (2001) since there is no observed extinction curve available in the extreme-ultraviolet (EUV). Also displayed in the figure is the standard AGN SED in the hazy document (CLOUDY command: AGN $T = 1.5e5$ K, $a(ox) = -1.4$, $a(uv) = -0.5$, $a(x) = 0.1$). This SED has a big blue bump peaked at a lower energy than MF87, and we refer to it as “SOFT SED.”

In all cases, $U$ and $N_H$ are adjusted to best match the observed $N_{Fe}^{H\alpha}$ and $N_{He}^{H\alpha}$, and $n_H$ is fixed to be $10^{3.3}$ cm$^{-3}$. The results are summarized in Table 7 and are compared with observations in Figure 13. It can be seen there that models assuming a solar gas-phase abundance reproduce the observed column densities quite well, while dusty-gas models assuming an intrinsic solar abundance underestimate $N_{Ca}^{H\alpha}$ and $N_{Mg}^{H\alpha}$. This is expected, since in these models the gas-phase calcium and magnesium are heavily depleted into dust grains. The best-fit models yield Ca/H = -7.7 and Mg/H = -5.5, more than one order of magnitude lower than the solar values. An intrinsic supersolar abundance is needed for the dusty-gas models to compensate metal depletion. To summarize, all of the acceptable models require $U \sim 10^{-2}$–$10^{-1.5}$ and $N_H \sim 10^{21}$–$10^{21.5}$ cm$^{-2}$. The

\begin{table}
\centering
\caption{CLOUDY Models}
\begin{tabular}{lccccccccc}
\hline
SEDA & $Z$ & $U$ & $N_H$ & HeI* & FeI* & CaII & MgI & MnII & NiII \\
\hline
Observation & $\ldots$ & $\ldots$ & $\ldots$ & 14.73 & 15.34 & 13.59 & 13.53 & 13.40 & 15.34 \\
MF87 & HII/DUSTb & -1.50 & 21.49 & 15.75 & 15.34 & 11.05 & 13.00 & 13.22 & 13.89 \\
MF87 & solar & -1.80 & 21.21 & 14.75 & 15.34 & 13.07 & 13.57 & 13.29 & 15.11 \\
SOFT & HII/DUST & -1.50 & 21.46 & 14.80 & 15.34 & 11.35 & 12.78 & 13.21 & 14.11 \\
SOFT & solar & -2.00 & 20.99 & 14.62 & 15.34 & 13.20 & 13.47 & 13.31 & 15.10 \\
Reddened MF87 & solar & -1.3 & 22.12 & 14.74 & 15.34 & 12.18 & 13.06 & 13.26 & 15.02 \\
\hline
\end{tabular}
\end{table}

Notes.
\begin{itemize}
\item[a] MF87: Mathews & Ferland 1987: AGN: CLOUDY command. AGN $T = 1.5e5$ K, $a(ox) = -1.4$, $a(uv) = -0.5 a(x) = -1$.
\item[b] Abundance set of H II region with dust; see Baldwin et al. (1991) and CLOUDY HAZY documentation.
\item[c] Abundance set of solar; see Grevesse & Noels (1993) and CLOUDY HAZY documentation.
\item[d] Total Ni II column density is inferred from observed column density of Ni II 8395 Å, using the Boltzmann equation.
\end{itemize}
The case of SOFT SED for clarity. R is larger than the physical thickness ($\Delta R$) with a distance of hundreds of parsecs. Dusty-gas models in general require larger U and accordingly infer a smaller distance compared with dust-free models.

5. ORIGIN OF THE ABSORPTION GAS

The physical conditions and location of the absorption gas are well constrained by analyzing the absorption lines with the aid of photoionization model calculations. It is in the vicinity of the central engine, with a distance of hundreds of parsecs. A laminal geometry of the absorber is inferred by comparing the physical thickness ($\Delta R \sim 0.02$ pc) with the distance. In addition, the kinematics of the absorption gas is derived by the profile of isolated lines. The centroid of the absorption lines observed in SDSS J0802+5513 perches right at the systematic redshift, and the line profile is almost symmetric in velocity space, spreading from $\sim -750$ km s$^{-1}$ to $\sim +750$ km s$^{-1}$. This information provides us with important clues on the origin of the absorption gas.

The seemingly relatives to SDSS J0802+5513 are iron low-ionization broad absorption line (FeLoBAL) quasars, which are defined by the presence of BALs in excited states of Fe$\text{II}$ and/or Fe$\text{III}$, in addition to commonly detected LoBALs, such as Mg$\text{II}$ and Al$\text{III}$ (e.g., Casebeer et al. 2008). The physical conditions of absorbing gas can be well constrained in a few FeLoBAL quasars, e.g., SDSS J0318$-$0600 (Bautista et al. 2010; Dunn et al. 2010), SDSS J0838$+$2955 (Moe et al. 2009), FBQS 0840$+$3633 (de Kool et al. 2002), and QSO 2359$-$1241 (Bautista et al. 2010; Arav et al. 2001a). The inferred distance of the absorption gas, $R$, is typically of subkiloparsec or kiloparsec scale, similar to that of SDSS J0802+5513. A similar thickness within an order of magnitude of $\Delta R \sim 0.01$ pc is found for this FeLoBAL gas as well. Such a laminal geometry, $\Delta R / R \lesssim 10^{-4}$, indicates that the absorption gas is generated right at the place it is observed. If the absorber were produced in the immediate vicinity of the central SMBH, it would dissipate long before it arrives at the inferred location owing to Kelvin–Helmholtz instability. Therefore, the absorption gas of SDSS J0802+5513 should be generated in situ as that of the well-studied FeLoBAL quasars, the ionized gas of which is a consequence of radiative shocks from interaction of a quasar blast wave with dense interstellar clumps (Faucher-Giguère et al. 2012). However, the FeLoBALs are typically blueshifted by several thousand kilometers per second with respect to the quasar systematic redshifts, unlike what we observed in SDSS J0802+5513. The symmetric line profile is hard to explain by the shock model, since an impact velocity is always needed to induce the shock stress. Although most of the traditional BALs do not show the redshifted absorbing trough significantly, Hall et al. (2013) has identified a small sample of longward-of-system BAL quasars, which are somewhat similar to the absorption troughs in SDSS J0802+5513. The authors employed high-velocity infalls or rotationally dominated outflows to interpret the rarely observed phenomenon. For individual quasars of the sample (SDSS J101946.08$+$051523.7 and possibly also SDSS J131637.26$+$003636.0), the absorbers are inferred to have a high density ($n_e \approx 10^{10.5}$ cm$^{-3}$) and a small distance ($R \lesssim 0.5$ pc) from the central SMBH, which are very different from that in SDSS J0802+5513 ($n_e \approx 10^5$ cm$^{-3}$ and $R \sim 100$–250 pc). Therefore, the outflowing mechanism cannot explain the line profile observed in J0802+5513.

Other mechanisms that may drive the absorption gas in SDSS J0802+5513 involve various stellar processes, such as stellar winds and nova or supernova ejecta. A supernova may cast off gas shells with masses of $M \gtrsim 1 M_\odot$ to velocities of $v \sim 10^3$–$10^4$ km s$^{-1}$, sufficient to produce the expansion velocity of the absorption gas observed in SDSS J0802+5513. Though the masses of nova shells $M \lesssim 10^{-4} M_\odot$ are much less than those of supernovae, their expansion velocities are typically $v \sim 10^3$ km s$^{-1}$ (Osterbrock & Ferland 2006), similar to the maximum velocity of the absorption gas of SDSS J0802+5513. Before exploding as supernovae, winds of massive stars can remove more than half of the original mass. In some extreme cases, the terminal velocities of such stellar winds can reach as high as $v \gtrsim 2 \times 10^3$ km s$^{-1}$. The typical velocities are
a few hundred kilometers per second (Lamers & Cassinelli 1999), within the velocity range of the gas expansion in SDSS J0802+5513. Thus, the absorption gas of SDSS J0802+5513 could be generated by the stellar processes in the circumnuclear starburst rings, which are frequently observed in active galaxies.

An early study of 30 nearby Seyfert galaxies found in their well-resolved images that 57% have inner rings, 43% have outer rings, and ~30% have both (Simkin et al. 1980). This finding was confirmed by subsequent UV and optical observations of Seyfert 2 galaxies (e.g., González Delgado et al. 1998, 2001; Cid Fernandes et al. 2001, 2004). These observations reveal a typical size of a few hundred parsecs. About 40% of nuclear starbursts are very vigorous ($L_{SB} \gtrsim 10^{10} L_{\odot}$) and compact (~100 pc). A similar conclusion was reached from NIR spectrophotometry of the central ~300 pc of 24 Seyfert galaxies (Riffel et al. 2009). The authors found signatures of young stellar populations in 50% of the Seyfert 2 and most of the Seyfert 1 galaxies. Such circumnuclear starbursts were suggested to be directly coupled to the dusty torus, which is the key ingredient of AGN unification schemes (Antonucci 1993; Urry & Padovani 1995).

The sizes of circumnuclear starbursts are similar to the estimated distance of the absorption gas in SDSS J0802+5513 ($R \sim 100$–250 pc from the galactic center). Interestingly, the gas-to-dust ratio of $N(H\text{I})/E(B-V) = 3 - 9 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$, as the model evaluations in Section 4, is close to that of the ISM in the Milky Way ($N(H\text{I})/E(B-V) = 4.8 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$; Bohlin et al. 1978). Also, the inferred ratio of log $N(Ca\text{ii})/E(B-V)$ ≈ 4.0 for the absorption gas in SDSS J0802+5513 is within the range of $13.3 \lesssim \log N(Ca\text{ii})/E(B-V) \lesssim 14.3$ as found in the Galactic ISM. Thus, we propose that the absorption gas in SDSS J0802+5513 coexists with the reddening material, which is very likely the ISM of the host galaxy skirting the dusty torus presumed by AGN unification models. This scenario also explains the rareness of absorption systems like SDSS J0802+5513. The line of sight should rightly penetrate the edge of the obscuring material, where the radiation from the central SMBH is mildly reddened.

Assuming that stars are uniformly distributed in the circumnuclear starburst ring, we estimate the infalling mass rate induced by stellar processes:

$$M_{\text{in}} \sim \frac{M v_{\text{max}}^2}{R} \approx m_{H} \times (N_{H}/2) \times \left(\frac{2 \pi R \times H}{R^2}\right) \times (v_{\text{max}}/2) \approx 5 M_{\odot} \text{yr}^{-1},$$

where $m_{H} = 1.67 \times 10^{-24}$ g is the proton mass, $N_{H} \approx 10^{21}$–$10^{21.5}$ cm$^{-2}$ is the column density, $v_{\text{max}} \approx 750$ km s$^{-1}$ is the maximum expansion velocity, $R \approx 100$–250 pc is the distance, and $H \approx R$ is the “height” of the absorption gas. We estimated $H \approx R$ assuming that the absorption gas was at the periphery of the dusty torus and an absorbed AGN fraction of $f \sim 50\%$. Intriguingly enough, such a rough estimate is within the mass accretion rate range of SDSS J0802+5513 inferred in Section 3.1.

The proposed stellar processes are closely related to ongoing or recent star formation in the host galaxy. As a narrow-line quasar, SDSS J0802+5513 may share some common properties with NLS1s, e.g., enhanced star formation (Sani et al. 2010). In Figure 14, we show the distribution of $[O\text{iii}]$ EWs and $[O\text{iii}]/[Ne\text{iii}]$ flux ratios for SDSS DR7 quasars. SDSS J0802+5513 has a larger $[O\text{ii}]$ EW and a higher $[O\text{ii}]/[Ne\text{iii}]$ ratio as compared to the bulk of DR7 quasars, indicating possible enhanced star formation in this object. Under the assumption that all the $[O\text{ii}]$ emission is contributed by star formation, we estimate an upper limit of star formation rate of $11 M_{\odot} \text{yr}^{-1}$ using the calibration of Kennicutt (1998) and tried to distinguish different stellar processes, namely, stellar winds and supernova explosions.

Several stellar evolution phases can produce energetic stellar winds. Post-main-sequence stars near the ends of their lives often eject large quantities of mass ($10^{-3} M_{\odot} \text{yr}^{-1}$), but the velocities of those winds are typically 10 km s$^{-1}$, far less than the velocity of gas in SDSS J0802+5513. The terminal velocity of early-type stars may meet the velocity requirement, yet with lower mass-loss rate. The wind in early-type stars is only efficient at high luminosity $L > 10^4 L_{\odot}$ (Kudritzki & Puls 2000), with a mass-loss rate of the order of $10^{-5} M_{\odot} \text{yr}^{-1}$ or even smaller ($10^{-7} M_{\odot} \text{yr}^{-1}$) for B stars (Krticka 2014). The corresponding stellar mass should be $>20 M_{\odot}$. To account for the accretion rate, $5 \times 10^7$ such stars are needed. For a Salpeter initial mass function from 0.1 to 125 $M_{\odot}$, the required $5 \times 10^6$ massive stars is equivalent to a total stellar mass of $10^8 M_{\odot}$. Assuming a typical lifetime of 1 Myr for such high-mass ($>20 M_{\odot}$) stars, we can deduce that a star formation rate of $100 M_{\odot} \text{yr}^{-1}$ is needed to supply the mass inflow. The required star formation rate is approximately an order of magnitude larger than the observed star formation rate in SDSS J0802+5513 even assuming that all the $[O\text{ii}]$ emission (see Table 3) is contributed by star formation. It seems that the possibility of stellar wind accretion can be ruled out, although this probably could be the case in AGNs with much lower accretion rate such as Sgr A* (Cuadra et al. 2006), where a total stellar mass-loss rate of $21$ Hasinger (2008) found that the absorbed AGN fraction is $f \sim 20\%$–$80\%$ for $L_X \sim 10^{42}$–$10^{46}$ erg s$^{-1}$, and $f$ increases with decreasing X-ray luminosity $L_X$. 

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10⁻³ M⊙ yr⁻¹ (Najarro et al. 1997) is sufficient. Either a large amount of obscured star formation (Xiao et al. 2012) exists given the existence of moderate dust extinction in SDSS J0802+5513, or mechanisms other than stellar winds should be invoked.

On the other hand, supernova explosions could inject nearly all the mass of their progenitor into their surroundings and have been proposed to work even at the very inner region of AGNs (Wang et al. 2010). Supernova explosions observed today are related to their past star formation history, in that a progenitor with mass M*, will explode t(M*) years later after its formation, with t(M*) = (M/3M⊙)⁻². If a constant star formation rate of 10 M⊙ yr⁻¹ such as in SDSS J0802+5513 holds for the past 100 Myr, i.e., the typical AGN life cycle (Wang et al. 2006), all star with mass larger than 7 M⊙ will explode today. Assuming a Salpeter initial mass function, a large fraction f∗ = 0.38 of star formation mass will be recycled into the ISM (Wang et al. 2010). In the case of SDSS J0802+5513, this adds up to a mass-loss rate of 4 M⊙ yr⁻¹, giving its star formation rate of 10 M⊙ yr⁻¹. It seems that supernovae could supply enough gas provided that the star formation in the near past (100 Myr) is at least as intense as what is going on right now in SDSS J0802+5513.

Underlying stellar populations in the host galaxies of AGNs could shed light on their past star formation history. It is difficult to extract information of the stellar component for high-redshift AGNs as they outshine their hosts. For low-redshift AGNs, for example, in the quasar He⁺ absorber IRAS 14026+4341 (Jiang et al. 2013), Hamilton et al. (2002) measured the brightness of the host galaxy by subtracting the nucleus in the high-resolution image observed by Hubble Space Telescope/WFPC2, yielding a brightness ratio of host galaxy to nucleus ~12%. In the case of SDSS J0802+5513, the residual fluxes underneath the flat-bottomed absorption troughs are at similar levels to those observed in IRAS 14026+4341. The residual fluxes in multiple wavelengths provide a unique chance to put a constraint on the stellar population of the host under the assumption that most of the residual light can be accounted for by the stellar component (Brotherton et al. 1997). Four such troughs are available in SDSS J0802+5513, namely, Fe ii UV1 and UV2 at 2600 Å and 2400 Å, respectively, Mg ii doublet at around 2800 Å, and He i λ10830, spanning from NUV to NIR. In Najita et al. (2000), four low-ionization BAL troughs in a reddened BAL quasar F1556-3517, located at 1860–2800 Å are utilized to put a constraint on stellar populations. From the observed upper limit on the strength of the 4000 Å break, the author favors a reddened 50 Myr stellar population over a 1 Gyr one. Besides the evidence proposed in Najita et al. (2000), a further constraint can be put on SDSS J0802+5513 with the aid of our new NIR spectroscopy of He i λ10830. As shown in Figure 15, SSPs with ages of 100 Myr and 1 Gyr from Bruzual & Charlot (2003) are normalized to the flux level at 10830 Å of SDSS J0802+5513; a 100 Myr SSP reddened by E(B−V) = 0.36 using an SMC-type extinction curve is shown as a green line, while a 1 Gyr SSP is shown as a red line. In this way, we can infer that the host galaxy should consist of a significant population of reddened young (several hundred megayears or less) stars, indicating that the recent star formation is probably as intense as required for supernova-explosion-powered winds. The above discussion should be understood with the caveat that, without further observations, we cannot tell whether some of the light underneath the absorption trough is contributed by scattered light of the background quasar.

We conclude that supernova explosions seem to be the most promising paradigm that drives the gas flow in SDSS J0802+5513, and we will end our discussion with a possible destiny of the gas following the line of reasoning. While the inflowing gas in SDSS J0802+5513 keeps feeding its central black hole, the outflowing gas would reach the outskirts of its host in 50 Myr, when the host will evolve into a poststarburst galaxy given the estimated age of the underlying stellar population. The large-scale outflows are ubiquitous in poststarbursts, and the origin of these outflows remains a myth; both AGNs and starbursts have been proposed to drive the wind. Studies on objects similar to SDSS J0802+5513 could help to resolve the problem.

6. SUMMARY AND FUTURE PERSPECTIVES

We present detailed analysis of SDSS spectra and newly obtained MMT, P200, and LBT spectra for SDSS J0802+5513. The object is classified as an NLS1 based on the widths of Balmer emission lines and Fe ii emission strength. It is moderately dust reddened with an extinction of E(B−V) = 0.36. Its spectra show rare absorption lines of He i and Fe ii*, as well as lines from Ca ii, Mg ii, Ni ii, and Mn ii. The absorption lines show an identical profile ranging from −750 to 750 km s⁻¹, with its centroid at the same redshift as that determined from emission lines. This object is the first unshifted He i mini-BAL reported. Extensive photoionization models are calculated using CLOUDY, and He i is shown to be a good indicator of ionization parameter. With the aid of the models, the physical parameters of the absorption gas are constrained to be log U ~ −1.8, N_H ~ 10¹³ cm⁻², and n_H ~ 10⁵ cm⁻³. The gas is estimated to be R ~ 100–250 pc away from the central black hole. Various origins of the absorption gas are discussed, and current observations suggest that stellar processes are at work in driving the gas flow. Without further knowledge whether there exists hidden star formation in SDSS J0802+5513, mass losses from stellar winds of high-mass stars fail to account for the deduced mass inflowing rate of 5 M⊙ yr⁻¹. The current data support supernova explosions as the main paradigm funneling
the gas in SDSS J0802+5513. Follow-up observations of SDSS J0802+5513 are needed to better study its properties: (1) MIR spectroscopies are needed to confirm whether there is any hidden star formation, which will put a firm constraint on the driving source of the gas flow; (2) polarization observations are needed to see whether any polarized (scattered) light exists underneath the absorption trough, and narrowband imaging centered at the absorption troughs will help to constrain the stellar population; (3) high-resolution spectroscopies are useful to resolve the heavily blended absorption lines and to improve column density measurements; and (4) X-ray observations are helpful to determine the total column density of the absorption gas.

Finally, we note that though very rare, there are objects similar to SDSS J0802+5513. We show the spectra of the seven unshifted He\(^{1+}\) absorber candidates in Figure 16. Interestingly, all but one (SDSS J130952.89+011950.6) show a red color, like SDSS J0802+5513. Given the ubiquity of star formation rings in low-redshift AGNs (Simkin et al. 1980), we might expect to detect many more similar objects than observed. The rarity could have an important implication on the geometry of the absorbers. If the nuclear star formation is coplanar with the dusty torus of quasars, optical spectroscopic surveys like SDSS will have little chance to detect such dusty absorbers. Only when our sight lines are coincidently penetrating the edge of the torus with a moderate optical depth, such as those partially obscured quasars (Dong et al. 2005), can we detect many more similar objects than observed. The rarity could have an important implication on the geometry of the absorbers. If the nuclear star formation is coplanar with the dusty torus of quasars, optical spectroscopic surveys like SDSS will have little chance to detect such dusty absorbers. Only when our sight lines are coincidently penetrating the edge of the torus with a moderate optical depth, such as those partially obscured quasars (Dong et al. 2005), can we detect many more similar objects than observed.

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