STRONG Ca ii ABSORPTION LINES IN THE REDDENED QUASAR SDSS J2339–0912:
EVIDENCE OF THE COLLISION/MERGER IN THE HOST GALAXY?

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ABSTRACT

We report the detection of strong Ca ii/Mg ii absorption lines at the quasar redshift in the narrow-line quasar SDSS J2339–0912 (z = 0.6604). The quasar exhibits strong Fe ii, a small Balmer emission line width, and a very red B − V color. Both the optical continuum and broad emission lines are reddened by SMC-like dust of E(B − V) = 1.0 mag, while its near-infrared color (J − K = 1.60) shows little reddening. The Ca ii absorption lines are saturated and resolved with an FWHM of 362 km s\(^{-1}\) and an equivalent width of W\(_{Ca \, ii, K}\) = 4.2 Å (in the source rest frame). Mg ii absorption lines are also saturated and have a similar line width. The line profile and the fact that there is no evidence of starlight from the host galaxy suggest that these absorption lines are not of a stellar origin. The ratio of column density of Ca ii to that of dust is consistent with that of the interstellar medium (ISM) in our Galaxy. We suggest that both the heavy reddening and the large absorption line width are due to the highly disturbed ISM on the line of sight toward the quasar and that the disturbance is caused by a galaxy collision or even merger in the quasar host galaxy.

Subject headings: dust, extinction — ISM: kinematics and dynamics — quasars: absorption lines

Online material: color figures

1. INTRODUCTION

Quasars are characterized by a blue continuum and strong broad emission lines. However, a fraction of them show red colors due to wavelength-dependent extinction by dust on the line of sight. In the past few years, we have witnessed controversial evidence on whether a large population of such objects exist or not (Cutri et al. 2000; Webster et al. 1995; Richards et al. 2003). The absorption can be caused by the dusty material either in the nucleus (i.e., inside the narrow-line region [NLR]), in the host galaxy, or in the intervening galaxies (Pei et al. 1991). Recent studies of red quasars from the Sloan Digital Sky Survey (SDSS; York et al. 2000) suggested that most quasars are generally reddened by dust at the quasar redshifts (Richards et al. 2003; Hopkins et al. 2004), whether it is in the host galaxies or near the nucleus. Evidence of substantial absorbing material within the NLR is obvious in type 1.8/1.9 quasars selected from the SDSS, since their broad lines are heavily reddened while their narrow lines are not (Dong et al. 2005). Potential use of these reddened quasars in the study of the host galaxy properties has been discussed by these authors.

Reddened quasars are also important in studying the gas/dust environment of quasars and active galactic nuclei (AGNs). The extinction curve is an important element to characterize the reddening in individual quasars. In the past few years, there still has been a controversy regarding what form of extinction curve should be applied to the quasar’s intrinsic reddening (e.g., Czerny et al. 2004; Hopkins et al. 2004).

In this Letter, we report the detection of strong Ca ii and Mg ii absorption lines at the quasar redshift in the heavily reddened narrow-line quasar SDSS J233903.82−091221.2 (hereafter SDSS J2339–0912; z = 0.6604), which was initially discovered by the FIRST bright quasar survey (FBQS J2339–0912; Becker et al. 2001) with a moderate radio flux of 4.3 mJy at 21 cm. We picked it up as an unusual narrow-line Seyfert 1 galaxy (NLS1) during the statistical study of a sample of NLS1s selected from the SDSS Data Releases 2 and 3 (DR2 and DR3; Abazajian et al. 2004, 2005). We study the absorption lines as well as the continuum and emission lines of this object and suggest that the heavy reddening and the large absorption line width are due to the highly disturbed interstellar medium (ISM) on the line of sight toward the quasar, which is caused by a galaxy collision or even merger in the quasar host galaxy.

2. MODELING THE CONTINUUM, ABSORPTION LINES, AND EMISSION LINES

SDSS J2339–0912 is unusual for its very red spectrum in the sample of ∼1500 NLS1s selected from the SDSS DR2+DR3 spectroscopic catalogs. The SDSS optical spectrum, with a total exposure time of 3788 s, is shown in Figure 1. Ca ii K and H\(_\alpha\) absorption lines are evident. Owing to its red color, the signal-to-noise ratio (S/N) drops rapidly toward short wavelength and reaches as low as unity below 4100 Å (2500 Å in the source rest frame). Nonetheless, Mg ii doublet absorption lines are visible, while the corresponding emission lines are hardly detected. At long wavelengths, the spectrum shows prominent Fe ii and H\(_\beta\) lines. The [O iii] λ5007 emission line, blended with Fe ii multiple 42, is visible and weaker than [O iii] λ3727.

The spectrum was brought to the rest frame using the redshift determined by [O iii] λ3727 and corrected for Galactic reddening of E(B − V) = 0.027 mag. The continuum and Fe ii emission lines are modeled as follows:

\[
f(\lambda) = A(E_{B-V}, \lambda)[bB(\lambda) + cC(\lambda)],
\]

where \(B(\lambda)\) is the Fe ii templates obtained by Véron-Cetty, Joly, & Véron (2004) covering the wavelengths between 3535 and 7534 Å, and \(C(\lambda) = (\lambda/4000 \: \text{Å})^{-1.7}\) is the power-law continuum (Francis 1996). We assume that Fe ii has a Lorentzian profile, as Balmer lines (see below). We do not include UV Fe ii multiplets in the fit because the S/N at the blue part of the spectrum is very low. For the same reason, we do not include the Balmer continuum model. Adopting a single-power-law prescription for the quasar continuum should be reasonable considering the low
S/N of the spectrum at the blue end. The best-fitted model is obtained by minimizing $\chi^2$. Emission lines apart from the Fe $\text{ii}$ and absorption lines were masked out during the fitting. We have tried different extinction curves, but only an SMC-like curve can give a good fit, while others lead to a much worse result (see § 3). The final fit is also shown in Figure 1. This simple model reproduces quite well the overall observed continuum and Fe $\text{ii}$ spectrum. The best-fitted $E(B-V)$ is 0.97 mag for SMC-like dust.

Emission- and absorption-line parameters are measured after the continuum and Fe $\text{ii}$ emission is subtracted. H$\beta$ is fitted with a Lorentzian and [O $\text{iii}$] and [O $\text{ii}$] lines as Gaussians. These models can fit the observed profile quite well. The width of H$\beta$ (2194 ± 108 km s$^{-1}$) and the reddening-corrected Fe $\text{ii}$/H$\beta$ ratio ($R_{4570}$ ≡ Fe $\text{ii}$ $\lambda\lambda4434$–4684/H$\beta$ = 1.20) are consistent with the definition of NLS1s (Goodrich 1989). With a reddening-corrected luminosity $L_{\lambda}(5100) = 2 \times 10^{46}$ ergs s$^{-1}$, it undoubtedly is a reddened narrow-line quasar. The [O $\text{ii}$]/[O $\text{iii}$] ratio is 1.65 ± 0.32. But the [O $\text{ii}$] line profile is affected by red noise in the spectrum due to the sky lines, and thus its profile is determined less reliably.

A Gaussian absorption-line profile is used to fit the Ca $\text{ii}$ H, K doublet. The widths of the two lines are set to be identical during the fit. Given the spectral resolution, it is not surprising that this model gives an acceptable fit. The equivalent width (EW) of the Ca $\text{ii}$ H line is 4.20 ± 0.24 Å in the source rest frame; its width is 362 ± 34 km s$^{-1}$ FWHM, corrected for the instrumental broadening of 170 km s$^{-1}$. The observed ratio of the EWs of K to H lines, $W_{\text{Ca} \text{ii} \text{K}}/W_{\text{Ca} \text{ii} \text{H}}$, is 1.35 ± 0.13, indicating the saturation. Mg $\text{ii}$ doublet absorption line profiles are saturated also and have widths similar to the Ca $\text{ii}$ doublet. But they cannot be measured exactly because of the low S/N of the data. The derived emission- and absorption-line parameters are listed in Table 1.

### Table 1

| Line | Centroid ($\lambda$) (Å) | Width ($\lambda$) (Å) | FWHM (km s$^{-1}$) |
|------|---------------------------|----------------------|------------------|
| [O $\text{ii}$] $\lambda5007$ …… | 5005.9 ± 0.4 | 2.5 ± 0.1 | 372 ± 31 |
| H$\beta$ ……………………. | 4858.9 ± 0.5 | 39.5 ± 1.5 | 2194 ± 108 |
| Fe $\text{ii}$ $\lambda4570$ ……… | … | 44.6 | … |
| Ca $\text{ii}$ H ……………… | 3966.7 ± 0.2 | 3.1 ± 0.2 | 400 ± 34 |
| Ca $\text{ii}$ K …………….. | 3932.1 ± 0.2 | 4.2 ± 0.2 | 400 ± 34 |
| [O $\text{ii}$] $\lambda3727$…….. | 3728.5 ± 0.3 | 8.8 ± 0.1 | 310 ± 24 |

**Note:** The line centroid and EW are given in the source rest frame. The FWHM has not been corrected for the instrumental broadening.

### 3. Discussion

#### 3.1. The Extinction Curve of Dust reddening

The extinction laws in the quasar and Seyfert galaxies have become an important topic in the past few years. By combining the column density derived from the X-ray absorption and the UV/optical reddening, Maiolino et al. (2001) found that the $A_l/N_l$ for Seyfert galaxies is significantly lower than the Galactic one by a factor ranging from 3 to 100 (also Loaring et al. 2003; but see Weingartner & Murray 2002 and Carrera et al. 2004 for different opinions). The lack of a prominent absorption feature at 9.7 μm and 2175 Å leads the former authors to propose that large grains are responsible for the reddening, with a flat extinction curve in the UV. By comparing the composite spectra derived from samples of radio-selected quasars with different orientations, Gaskell et al. (2004) derived an extinction curve much flatter than the Galactic one in the UV. However, it was found that SDSS red quasars have colors consistent with significant reddening by an extinction curve similar to that of the SMC (Richards et al. 2003; Hopkins et al. 2004). Strong evidence shows that the extinction curve is even steeper than that of SMC in two unusual broad absorption line QSOs with continuum reddening $E(B-V) = 0.5$ (Hall et al. 2002b). Consistent with the latter, Zuo et al. (1997) determined the reddening by comparing the spectra of two images of gravitationally lensed QSO 0957+561 with different reddening. They derived a high dust-to-gas ratio and an extinction curve steeper than the Galactic one in the UV. On the basis of the SDSS composite reddened quasars, Czerny et al. (2004) proposed the extinction can be modeled by an amorphous carbon sample of amorphous carbon.
reddening of SDSS J2339−0912. The inconsistent results drawn from the optical to near-UV spectrum and from the near-infrared photometry are likely due to the intrinsic difference in the near-infrared emission of the two objects. First, the near-infrared spectral energy distribution (SED) of PG quasars shows large scatter and seems not to be correlated with the SED in the optical and UV (Neugebauer et al. 1987). Especially, the reddened SED of PG 2344+092 $(z = 0.677)$ approximately matches the SED of SDSS J2339−0912 (Fig. 2). Second, if this inconsistency is interpreted as different extinction laws in the near-infrared, a wavelength-independent extinction curve over a wavelength range from $8000\,\AA$ to $1.3\,\mu m$ is required, which is not consistent with any known extinction curve. Finally, variability is not likely responsible for the discrepancy because the J-band flux of SDSS J2339−0912 is fairly consistent with the reddened one of SDSS J0809+4619.

Although the reddening of the broad-line region is evident, we cannot infer the reddening of the NLR. The EW of $[O\,III] \lambda 5007$ is already in the lower end among PG quasars. If the $[O\,III]$ line is not reddened while the continuum is with $E(B-V) \approx 1.0$ mag, the intrinsic EW of $[O\,III] \lambda 5007$ would be 0.2 Å, at the extreme low end. On the other hand, the large $[O\,III] \lambda 5272$ to $[O\,III] \lambda 5007$ ratio suggests reddening is not important for the NLR, if $[O\,II]$ and $[O\,III]$ originate from the same region.

3.2. The Origin of the Absorbing Material

$Ca\,II$ absorption in this quasar is not of a stellar origin, because there is no other feature indicative of old stellar populations in the spectrum such as the 4000 Å break. The presence of saturated $Ca\,II$ and $Mg\,II$ absorption lines and the well-fitted Gaussian profile of $Ca\,II$ lines suggest that the absorption is caused by warm diffuse gas on the line of sight toward the quasar. Thick cold dusty material is also present on the line of sight, according to the heavy reddening of both the continuum and the broad emission lines. It should be noted that there are large residuals under the $Ca\,II$ absorption lines, suggesting that either (1) the absorber partially covers the source or (2) it consists of several optically thick clouds. Partial covering is not important if the warm gas coexists with the dusty material, as we argue below, because the attenuation of the UV flux by reddening is extremely large. In case 2, a lower limit on the column density can be imposed if we assume that the absorption line consists of several equally saturated, unresolved components. Using the growth curve of the absorption lines, we obtain a lower limit on the column density of $\lesssim 5 \times 10^{13}\,cm^{-2}$ from the ratio of the $Ca\,II$ doublet and the EWs. The exact value can only be obtained through high-resolution spectroscopic observation.

With our estimated (lower limit on the) $Ca\,II$ column density, the ratio of $N(Ca\,II)/E(B-V)$ is very close to those observed in the Galaxy or toward the Magellanic Clouds. Wakker & Mathis (2000) found that the $H\,I$ column density is correlated with the column density of $Ca\,II$ with a standard deviation of 0.40 dex for high- and intermediate-velocity clouds in the Galaxy. More recently, Smoker et al. (2003) studied $Ca\,II$ absorption on the lines of sight to 88 mainly B-type stars and found that $log[N(Ca\,II)/N(H\,I)]$ ranges from $-7.4$ to $-8.4$, 0.5 dex higher than that found by Wakker & Mathis (2000). For the Galactic clouds, Bohlin et al. (1978) found $N(H\,I)/E(B-V) = 4.8 \times 10^{21}\,cm^{-2}$, which gives $13.3 \,cm$ log $N(Ca\,II)/E(B-V) < 14.3$, consistent with the value obtained in SDSS J2339−0912. Thus, we propose that the warm gas responsible for the $Ca\,II/Mg\,II$ absorption in SDSS J2339−0912 coexists with the dusty material responsible for the reddening, with a gas-to-dust ratio similar to the ISM in our Galaxy.

$Ca\,II$ absorption has been detected in some damped Ly$\alpha$ (DLA) systems (Khare et al. 2004). These systems are believed to be observed when the line of sight to a quasar passes through galactic disks. Identification of these systems at low or intermediate redshifts reveals a number of types of galaxy, including disk galaxies, low surface brightness galaxies, and dwarf galaxies. Evidence for the presence of dust in such systems has been derived from the comparison of continuum and emission lines between quasars with DLA and those without; the dust-to-gas ratio has been found to be 0.05–0.20 that of the Galaxy for the systems at relative high redshifts 1.8 $\lesssim Z \lesssim 3.4$ and with column densities $1 \times 10^{20}\,cm^{-2}$ $\lesssim N_H \lesssim 5 \times 10^{21}\,cm^{-2}$ (Pei et al. 1991). Heavy reddening and $Ca\,II$ absorption were also reported in two gravitationally lensed quasars by lensing galaxies at intermediate redshifts $E(B-V) = 0.5$ for APM 08279+5255; Pettitjean et al. 2000; $W_{Ca\,II} = 5.3\,\AA$, $E(B-V) = 1.34$ for PMN J0134−0931: Hall et al. 2002a]. It is interesting to note that $W_{Ca\,II}/E(B-V)$ measured in PMN J0134−0931 is similar to that in SDSS J2339−0912, while a meaningful comparison is not permitted for APM 08279+5255 since Pettitjean et al. (2000) only gave the $Ca\,II$ EWs of two narrow components.

Strong $Ca\,II$ absorption due to the ISM at the exact quasar redshift is rarely reported.1 For one side of the Galactic disk, the reduced EW ($W_{Ca\,II}/\sin b$) at infinity is 130 mA according to Smoker et al. (2003). To give rise to the observed $W_{Ca\,II} = 4.2\,\AA$ in SDSS J2339−0912, a nearly edge-on disk is required. Large $N(Na\,I)/N(Ca\,II)$ ($>1$) is usually considered as evidence of disk material (Sembach & Danks 1994). As-

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1 Blueshifted $Ca\,II$ absorption lines have been detected in Mrk 231 and several other low-ionization broad absorption line quasars, ultraluminous infrared galaxies, as well as AGNs, which are considered to be caused in the dense outflow from the quasars or galactic winds induced by intense starbursts (e.g., Rupke et al. 2002).
assuming the Na i absorption-line profile is similar to that of Ca ii, we obtain an upper limit on EW(Na i λ3303) of 2.8 Å in the source rest frame and N(Na i)/N(Ca ii) < 16. Although this limit is not useful to constrain the origin of the absorbing gas, future observations may allow us to do this.

The disk can be associated with the quasar host galaxy or a close companion of the host. However, the large width of the absorption line is difficult explain unless the disk is severely disturbed. The warm gas is expected to be highly dispersive. If the galactic disk is not severely disturbed, the warm gas would relax onto the disk plane, and its orbit would be almost circular. In the host galaxy case, the gas velocity would be essentially perpendicular to the line of sight toward the galactic center, so that the projected velocity on the line of sight would be very small. In the companion galaxy case where the line of sight toward the quasar intersects only one side of the disk, the rotation speed should be at least 720 km s⁻¹ to produce a Ca ii profile of ~360 km s⁻¹ FWHM. Following the Tully-Fisher relation (Pierce & Tully 1992), the maximum absolute magnitude of the companion galaxy would be ~24 mag at the B band, more luminous than the reddened quasar (B = −23.6 mag).

We suggest that the absorber is the warm diffuse gas in the galactic disk of the host galaxy or a close companion of the host and that it is highly disturbed by a galaxy collision or even merger. Disturbed gas has been proposed in the study of the low-redshift quasar absorption systems in a few quasar-galaxy pairs and was considered to be evidence of a recent merger or an ongoing encounter with a companion (Carilli & van Gorkom 1992). The detection of blueshifted Na i D absorption lines in ultraluminous infrared galaxies (Rupke et al. 2002), which are thought to be galaxies in collision, further supports this idea. The large line width and high column density of Ca ii presented in SDSS J2339−0912 require much stronger perturbation or even the merging of two galaxies. Future high-S/N and high-resolution spectra in the near-UV/optical can allow us to precisely resolve the line structure of Ca ii and other metals, yielding the chemical abundance and the kinematic structure of the absorbing gas.

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