A BALMER-LINE BROAD ABSORPTION LINE QUASAR

PATRICK B. HALL
Department of Physics and Astronomy, York University, 4700 Keele St., Toronto, Ontario M3J 1P3, Canada

ABSTRACT

I report the discovery of blueshifted broad absorption line (BAL) troughs in at least six transitions of the Balmer series of hydrogen (Hβ to H9) and in Ca II, Mg II and excited Fe II in the quasar SDSS J125942.80+121312.6. This is only the fourth active galactic nucleus known to exhibit Balmer absorption, all four in conjunction with low-ionization BAL systems containing excited Fe II. The substantial population in the n = 2 shell of H I in this quasar’s absorber likely arises from Lyα trapping. In an absorber sufficiently optically thick to show Balmer absorption, soft X-rays from the quasar penetrate to large τLyα and ionize H I. Recombination then creates Lyα photons that increase the n = 2 population by a factor τLyα since they require ≃ τLyα scatterings to diffuse out of the absorber. Observing Lyα trapping in a quasar absorber requires a large but Compton-thin column of gas along our line of sight which includes substantial H I but not too much dust. Presumably the rarity of Balmer-line BAL troughs reflects the rarity of such conditions in quasar absorbers.

Subject headings: quasars: general, quasars: absorption lines, quasars: individual (NGC 4151, SDSS J083942.11+380526.3, FBQS J2107−0620, SDSS J125942.80+121312.6)

1. BACKGROUND

Broad absorption line (BAL) active galactic nuclei (AGN) show absorption from gas at blueshifted velocities up to 0.2c. They are seen in about one in four of the luminous AGN known as quasars, and while most BAL AGN only show high-ionization absorption (e.g., N V, C IV), ~10% of BAL AGN also exhibit low-ionization absorption (e.g., Al III, Mg II), including ~3% which in addition show excited Fe II absorption (Trump et al. 2006, and references therein). If all quasars have BAL troughs, these percentages represent the fractions of unobscured lines of sight toward quasars along which these three types of troughs exist. If all quasars go through a BAL phase, they represent the fractional amount of time each type exists. Reality is likely somewhere in between. On the one hand, BAL and non-BAL quasar spectra are very similar, arguing that they are drawn from a single parent population (Weymann et al. 1991; Reichard et al. 2003). On the other hand, the likelihood of observing a low-ionization BAL trough increases during a transition phase between ultraluminous infrared galaxies and quasars (Canalizo & Stockton 2001), although the origin of the BAL troughs in such objects is an open question: a disk wind origin for them remains possible.

The physical parameters of BAL systems need to be constrained to understand their origin(s) and contribution to AGN feedback effects on galaxy formation and evolution. However, saturation and blending effects mean that the physical parameters of typical BAL systems cannot be easily inferred. Instead, it is often the more unusual systems that can provide such constraints. Currently the rarest known absorption in BAL AGN is Balmer-line absorption. It has previously been reported only in NGC 4151 (Hutchings et al. 2002, and references therein) and SDSS J083942.11+380526.3 (Aoki et al. 2006). Weak absorption similar to that found in these objects has also recently been seen in Hβ and Hγ in the quasar FBQS J2107−0620 through high-resolution spectroscopy (Hutsemekers et al., in preparation). Here I report a quasar with very strong Balmer-line absorption found in the Sloan Digital Sky Survey Data Release Five (Adelman-McCarthy et al. 2007). These two new discoveries confirm the observation of Aoki et al. (2006) that Balmer-line BAL troughs are found in iron low-ionization BAL quasars with relatively strong [O III] emission.

2. OBSERVATIONS

The Sloan Digital Sky Survey (SDSS; York et al. 2000) is using a drift-scanning imaging camera (Gunn et al. 1998) on a 2.5-m telescope (Gunn et al. 2006) to image 104 deg2 of sky on the SDSS ugriz AB magnitude system (Fukugita et al. 1996; Hogg et al. 2001; Smith et al. 2002; Pier et al. 2003; Ivezić et al. 2004). Two multi-fiber, double spectrographs are being used to obtain R = 1900 spectra for ~106 galaxies to r = 17.8 and ~105 quasars to i = 19.1 (i = 20.2 for z > 3 candidates). As discussed in Richards et al. (2002), quasar candidates are targeted for spectroscopy because their colors differ from the colors of the stellar locus or because they are unresolved objects with radio emission detected by the FIRST survey (Becker, White, & Helfand 1995). SDSS J125942.80+121312.6 (hereafter SDSS J1259+1213) was observed on Modified Julian Date 53473 with SDSS plate #1695 and fiber #75. It has a Galactic extinction corrected magnitude i = 18.15 ± 0.02 and was targeted both via its colors and its radio emission. Its FIRST peak flux of 2.00 ± 0.14 mJy/beam puts it right on the border between radio-loud and radio-quiet, with RL = 1.00 (Ivezić et al. 2002).

Figure 1 shows that the quasar has a blue continuum with P Cygni-like emission and absorption in Mg II, excited-state Fe II and the Balmer series (Hβ through H9, and possibly H10 and H11). The redshift of the quasar, measured from [O II] and consistent with that of [O III] λ5007, is z = 0.7517 ± 0.0001, yielding $M_\text{HI} = -24.88$ ($\lambda L_\lambda = 2 \times 10^{40}$ ergs s$^{-1}$). The broad Mg II and Hβ emission lines peak at $z = 0.748 \pm 0.001$, slightly blueshifted from the narrow-line redshift. The
deeper Balmer absorption is blueshifted further, to \( z = 0.7345 \pm 0.0004 \), which is 2960 \( \pm 70 \text{ km s}^{-1} \) from the narrow-line redshift. The continuum drop shortward of \( \sim 2600 \AA \) rest frame is due to partial covering of the quasar by overlapping absorption from multiple Fe II transitions (e.g., Hall et al. 2002). The smaller absorption depths for neutral H I as compared to low-ionization Fe II and Mg II are consistent with an increasing covering factor with ionization level, often seen in BAL quasars.

Emission and absorption in higher-excitation transitions of Fe II, Ti II and Cr II (Véron-Cetty et al. 2006) can plausibly explain the complex continuum between Mg II and [O II]. (Similar absorption at 2800 \( \AA < \lambda < 3500 \AA \) is seen in the low-ionization BAL quasar SDSS J112526.13+002901.3; Hall et al. 2002.) For example, the lower term of Fe II \( d^2D^1 - x^2P^o \), tentatively identified in Figure 1, is at 5.91 eV above ground. There is no sign of metastable He I absorption, but the limits are not strong since those transitions suffer from confusion with absorption from Fe II and H8. Lastly, the [O III] emission-line profile may have a complex blueshifted component, or it may just be confused with the strong Fe II emission in that region of the spectrum.1

Balmer line absorption is often seen in galaxy spectra, but this object cannot be explained as an unusual galaxy. First, the emission and broad absorption in ultraviolet Fe II and Mg II transitions is consistent only with a BAL quasar. Second, when post-starburst galaxies exhibit strong Balmer absorption, it lies at the same redshift as the [O II] and [O III] emission and is accompanied by a strong Balmer break lacking in this object. Third, when low-ionization outflows are seen in star-forming galaxies, they do not occur at velocities as high as 3000 \( \text{km s}^{-1} \) unless they are clearly BAL troughs associated with an AGN (Rupke, Véilleux, & Sanders 2005).

3. INTERPRETATION

The Balmer absorption troughs in this object have widths which are uniform within the measurement uncertainties: FWZI = 2000 \( \pm 200 \text{ km s}^{-1} \). To estimate the depths of the troughs, the continuum was fitted with a fourth-order polynomial in \( F_\lambda \) vs. \( \log \lambda \) to approximate a power-law with possible slight dust reddening (see Figure 1). The maximum single-pixel depth of each trough was measured from the normalized SDSS spectrum after smoothing by a 7-pixel boxcar. The depths of the troughs (Table 1) decrease slowly as the upper term of the transition increases. The decline is about a factor of two from H\( \beta \) to H9. The absorption therefore must be saturated, since the transition oscillator strengths decline by a factor of twenty-two from H\( \beta \) to H9.

The percentage absorption depth in a trough \( l \) is \( D_l = C(1 - e^{-\tau_l}) \) for an absorber with optical depth \( \tau_l \) and percentage covering factor \( C \) in the relevant ion (e.g., Eq. 1 of Hall et al. 2003). By assuming \( C \) and \( \tau_{H\beta}, D_l \) for every Balmer trough can be calculated since their relative \( \tau \) are determined by their known oscillator strengths. Acceptable matches to the maximum absorption depths of the Balmer lines were found with \( \tau_{H\beta} = 19.5 \pm 2.5 \) and \( C = 29 \pm 1\% \) at the velocity of maximum depth (Table 1); note that larger \( \tau \) requires smaller \( C \) for an equally good fit. The additional depth in the H\( \beta \) trough is assumed to come from coverage of the H\( \beta \) emission line.2

This approximate \( \tau_{H\beta} \) assumes the Balmer-line troughs are resolved and takes into account neither possible Balmer emission from the absorber itself (as in the resonance scattering model of Branch et al. 2002; see also Casebeer et al. 2004) nor possible different H I covering factors for the continuum source, Balmer emission lines and Fe II emission-line blends. A high-resolution spectrum is needed to properly model all those parameters and determine how greatly they affect results inferred from an SDSS-resolution spectrum.

Absorption from the \( n = 2 \) shell of hydrogen requires a substantial population in that shell. One obvious population mechanism is collisional excitation into \( n = 2 \) due to a high density. The relevant critical density is \( n_{crit} = 8.7 \times 10^{16} \Lambda_{\text{Ly}^\alpha} \text{ cm}^{-3} \) at \( T = 10,000 \text{ K} \) (Osterbrock & Ferland 2006). It is possible to estimate \( \tau_{Ly\alpha} \) using our estimate for \( \tau_{H\beta} \) and the relationship3

\[
\tau_{Ly\alpha} = \frac{7}{8} \tau_{H\beta},
\]

where the ratio of the populations of the \( n = 1 \) and \( n = 2 \) shells is \( \frac{n_{2}}{n_{1}} \simeq \frac{1}{4} \exp(10.2 \text{ eV} / kT) \). For \( T = 10,000 \text{ K} \), \( \frac{n_{2}}{n_{1}} = 3.50 \times 10^{18} \), and so \( \tau_{Ly\alpha} \simeq (6.6 \pm 0.8) \times 10^{5} \) when \( \tau_{H\beta} = 19.5 \pm 2.5 \). This would imply \( n_{e} \simeq (1.3 \pm 0.2) \times 10^{11} \text{ cm}^{-3} \) if collisional excitation was the only mechanism populating \( n = 2 \).

However, at such large \( \tau_{Ly\alpha} \) there is another effect which populates the \( n = 2 \) shell: Ly\( \alpha \) trapping (Ferland & Netzer 1979). As shown in the previous paragraph, an absorber with Balmer optical depths as large as observed here must have a very large Ly\( \alpha \) optical depth. In such an absorber, soft X-rays from the quasar will ionize H I at large \( \tau_{Ly\alpha} \) and create Ly\( \alpha \) photons at those depths via recombination. Every Ly\( \alpha \) photon so created will be re-absorbed approximately \( \tau_{Ly\alpha} \) times before it escapes, and so the \( n = 2 \) population for a given density and temperature will be increased by a factor of \( \tau_{Ly\alpha} \).

This increase changes the value of \( \tau_{Ly\alpha} \) inferred for a given \( \tau_{H\beta} \), and thus the H I column density needed to explain a given \( \tau_{H\beta} \). When Ly\( \alpha \) trapping is occurring, \( \tau_{Ly\alpha} \simeq (\tau_{Ly\alpha} + \frac{7}{8} \tau_{H\beta} \exp(10.2 \text{ eV} / kT))^{1/2} \). For our observed \( \tau_{H\beta} \) and \( T = 7500 \text{ K} \), appropriate for partially ionized gas illuminated by a quasar (Figure 14.5 of Osterbrock & Ferland 2006), \( \tau_{Ly\alpha} = 5520 \) and \( \frac{n_{2}}{n_{1}} \simeq \frac{1}{2} \exp(10.2 \text{ eV} / kT) \simeq 323 \). The \( H\beta \) optical depth yields an estimate of the column density of neutral hydrogen in the \( n = 2 \) shell (Eq. 12 of Hall et al. 2003), assuming a uniform optical depth over the entire 2000 \( \text{km s}^{-1} \) trough: \( N_{H\beta}(n = 2) \simeq (2.5 \pm 0.3) \times 10^{16} \text{ cm}^{-2} \). Combining the estimates for \( N_{H\beta}(n = 2) \) and \( \frac{n_{2}}{n_{1}} \) yields \( N_{H\beta} \simeq 8.1 \times 10^{18} \text{ cm}^{-2} \) in the absorber. As is usually

---

1 Note that the standard optical Fe II emission template derived from the spectrum of I Zw 1 (Boroson & Green 1992) is not a particularly good match to the Fe II emission in SDSS J1259+0931.

2 If the total unabsorbed flux has continuum and line components, \( F = F_C + F_L \), then the flux removed by very high optical depth absorption \( (\tau \to \infty) \) is \( A = C_C F_C + C_L F_L \), allowing for different covering factors \( C \) of each component. Since the normalization only used the continuum, the depths in Table 1 are \( D = A/F_C = C_C + C_L F_L / F_C \). Thus, \( D > C_C \) is possible when the line flux \( F_L \) is substantial, as is the case for H\( \beta \) in this object.

3 This relationship comes from the fact that for any transition originating in shell \( k \), \( n_k \propto N_{H}(n = k) \propto \tau_{H\beta} \Delta \nu / \lambda \), see (e.g., Eq. 12 of Hall et al. 2003). Thus, \( n_k / n_1 = \tau_k \lambda_j f_k / \tau_1 \lambda_1 f_1 \) assuming an absorber of fixed width \( \Delta \nu \) with all \( \tau \) independent of velocity.
BAL AGN, $N_H = N_{HI} + N_{HII}$ is likely to be much higher.

Ly$\alpha$ trapping eliminates the need for an absorber with a density above the critical density needed for significant collisional excitation. In fact, $n_{\text{crit}}$ becomes an upper limit on the density in the absorber in order to avoid overpopulating the $n = 2$ shell through collisions as well as Ly$\alpha$ trapping. Since that would produce Balmer-line optical depths greater than are observed, the density in an absorber at $T = 7500$ K must be $n_e < 1.6 \times 10^{13}$ cm$^{-3} = 8.7 \times 10^{16}$($\tau_{\text{Ly} \alpha}$)$^{-1}$ cm$^{-3}$.

For Ly$\alpha$ trapping to occur, the absorber must retain a relatively large neutral hydrogen column despite exposure to the quasar's ionizing continuum. Quasar absorbers with blueshifted neutral hydrogen columns that large located relatively close to the quasar are rare along our sightlines to bright quasars, either because such columns cover a very small total solid angle or are very short-lived phenomena. However, Ly$\alpha$ trapping is expected to occur in quasar low-ionization broad emission line regions. SDSS J1259+0931 may be a case where the continuum source is partially viewed through such gas.

Finally, it should be mentioned that an absorber with a high temperature rather than a high $\tau_{\text{Ly} \alpha}$ could in principle produce the observed Balmer absorption. For example, $T = 85,000$ K yields equal populations in the $n = 1$ and $n = 2$ shells of H I. However, this explanation is unlikely because gas at such temperatures is unstable to rapid cooling (Krolik 1999).

4. CONCLUSIONS

The quasar SDSS J1259+0931 has the strongest Balmer-line BAL troughs discovered to date. The required population of the $n = 2$ shell of H I most likely arises from Ly$\alpha$ trapping in an absorber exposed to the quasar's ionizing continuum but still containing a high column of H I ($N_{HI} \approx 8.1 \times 10^{18}$ cm$^{-2}$). In addition, the detection of this quasar in the rest-frame optical and ultraviolet means the absorber is neither Compton-thick nor particularly dust-rich. The rarity of such Balmer-line BAL troughs (found in $\lesssim 1\%$ of BAL quasars) indicates they have a very small global covering factor or are very transient. However, their incidence may be underestimated because for high-redshift BAL AGN the Balmer lines are redshifted beyond the typical spectral coverage of a discovery spectrum. Even when that is not the case, weak Balmer absorption can easily be missed (e.g., the absorption in FBQS J2107–0620 was discovered only through high-resolution spectroscopic followup).

To improve our understanding of quasar winds requires observations of specific objects for which multiple physical parameters in the absorbers can be constrained. Thus, follow-up observations of SDSS J1259+0931 would be quite valuable. X-ray observations can constrain the total absorbing column. Echelle spectroscopy can put a lower limit on the ionized hydrogen column by searching for absorption from metastable He I, which is populated by recombination from He II. Such spectroscopy would also reveal any variability or structure in the Balmer-line troughs and enable detailed modelling of the Balmer and excited Fe II emission and absorption to constrain the absorber's density and ionization state and thus its distance from the ionizing source. A near-IR spectroscopic search for Paschen absorption can constrain the population in the $n = 3$ shell of H I. Near-IR spectroscopy of H$\alpha$ can help constrain the contribution of any 'fill-in' Balmer emission from the absorber itself. Such emission should be $\approx 4$ times stronger in H$\alpha$ than in H$\beta$ given the Balmer and inferred Lyman optical depths of the absorber (Cox & Mathews 1969). SDSS J1259+0931 is detected by 2MASS with $J = 17.00 \pm 0.16$ and $K_s = 15.32 \pm 0.15$, placing moderate resolution near-IR spectroscopy within the reach of 8m-class telescopes.

I thank N. Murray, D. Hutsemékers, and the referee. P. B. H. is supported by NSERC. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, Cambridge University, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington. This research has also made use of the Atomic Line List v2.04 at http://www.pa.uky.edu/~peter/atomic/.

REFERENCES

Adelman-McCarthy, J., Agüeros, M., Allam, S., Anderson, K., Anderson, S., Annis, J., Bahcall, N., Bailer-Jones, C., et al. 2007, ApJS, submitted

Aoki, K., Iwata, I., Ohita, K., Ando, M., Akiyama, M., & Tamura, N. 2006, ApJ, 651, 84

Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559

Boroson, T. A., & Green, R. F. 1992, ApJS, 80, 109

Branch, D., Leighly, K., Thomas, R., & Baron, E. 2002, ApJ, 578, L37

Canalizo, G. & Stockton, A. 2001, ApJ, 555, 719

Casebeer, D., Baron, E., Branch, D., & Leighly, K. 2004, in AGN Physics with the Sloan Digital Sky Survey, ed. G. T. Richards & P. B. Hall, 231

Cox, D. P. & Mathews, W. G. 1969, ApJ, 155, 859

Feigelson, E. D. & Netzer, H. 1979, ApJ, 229, 274

Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1738

Gunn, J., Siegmund, W., Mannery, E., Owen, R., Hull, C., Leger, R., Carey, L., Knapp, G., et al. 2006, AJ, 131, 2332

Fan, X., Carr, M., Rockosi, C., Sekiguchi, M., Berry, K., Elms, B., de Haas, E., Ivezić, Z., et al. 1998, AJ, 116, 3040

Hall, P. B., Anderson, S., Strauss, M., York, D., Richards, G., Fan, X., Knapp, G., Schneider, D., et al. 2002, ApJS, 141, 267

Hart, P. B., Hutsemékers, D., Anderson, S. F., Brinkmann, J., Fan, X., Schneider, D. P., & York, D. G. 2003, ApJ, 593, 189
| Hβ | Hγ | Hδ | H7 | H8 | H9 | Ca II, K | Mg II | Fe II |
|----|----|----|----|----|----|---------|-------|------|
| 36% | 29% | 27% | 23% | 18% | 17% | 7% | 58% | ~50% |
| 29.0% | 29.0% | 27.6% | 23.7% | 18.9% | 14.6% | · | · | · |
| 0.119 | 0.0446 | 0.0221 | 0.0127 | 0.00803 | 0.00543 | · | · | 0.943 |
| 4862.683 | 4341.684 | 4102.892 | 3971.195 | 3890.151 | 3836.472 | 3934.777 | λλ2798.75 | <2632.106 |

* H7 is blended with Ca II, H λ3969.591, but that does not affect measurement of its observed depth.

b Uncertainties on the observed depths are 2-3% (1σ). The model depths are given for τHβ = 19.5 and C = 29%. For further details on the observed and model depths, see §3.

c The fij values are the oscillator strengths, and can be used along with the wavelengths to calculate predicted relative strengths of the Balmer absorption troughs. For reference, fij = 0.640 for Hα λ6564.61 and fij = 0.416 for Lyα λ1216.6701. The fij value for Mg II is the sum for both members of the doublet.
Fig. 1.— Full SDSS spectrum of SDSS J125942.80+121312.6, smoothed by a 7 pixel boxcar, with $F_\lambda$ in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and $\lambda$ in Å. Uncertainties in the smoothed flux are shown by the thinner line along the bottom of the plot. Observed wavelengths are shown on the bottom axis, while rest frame wavelengths at the narrow-line emission redshift of $z = 0.7517$ are shown along the top axis. Dotted lines show the expected location of emission lines at the emission redshift, while dashed lines show absorption at the peak absorption redshift of $z = 0.7345$. The dot-dashed line shows the fit to the effective continuum.