Lyα/Hβ RATIO OF SINGLY IONIZED HELIUM IN QUASARS

WEI ZHENG
Center for Astrophysical Sciences, Johns Hopkins University, Baltimore, MD 21218; zheng@pha.jhu.edu
AND
LI-ZHI FANG
Physics Department and Steward Observatory, University of Arizona, Tucson, AZ 85721; fanglz@time.physics.arizona.edu

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ABSTRACT

He II Lyα λ304/Hβ λ1640 emission lines are mainly produced by recombination, and their canonical ratio of \(~10\) may be a sensitive reddening indicator. We obtain the high signal-to-noise ratio optical spectra of two quasars and combine them with the far-ultraviolet spectra that show the He II λ304 emission. For HS 1700 +64, the He II λ1640 emission is not detected, and an upper limit to it sets the ratio greater than 20. This may not be inconsistent with the theoretical value when all observational uncertainties are taken into consideration. For Q0302−003, the ratio is very low and on the order of unity. The most plausible cause for such a low ratio is extinction in the EUV band by very fine grains of dust. Q0302−003 has a prominent narrow component of FWHM \(~2000\) km s \(^{-1}\) in its major emission lines, and it appears that reddening is associated only with the line-emitting region. We suggest that the geometry of the line-emitting region in high-z quasars resembles that in low-luminosity active galaxies, with the presence of dust mostly in the outer part.

Subject headings: dust, extinction — quasars: emission lines

1. INTRODUCTION

The first UV spectroscopic observation of a quasar (3C 273; Davidsen, Hartig, & Fastie 1977) enabled a measurement of the Lyα/Hβ ratio in an active galactic nucleus (AGN). The low ratio of \(~1\) was in line with an independent study using the composite spectrum that was derived from various quasars (Baldwin 1977) but was in sharp conflict with a canonical ratio of \(~10\) predicted by standard photoionization models (Osterbrock 1989). This “Lyα/Hβ problem” raised serious concerns about the validity of photoionization as the main line-emission mechanism in an AGN and prompted extensive theoretical interest in the following years. Improved photoionization models (Ferland & Shields 1985, and references therein) invoke large column densities and moderate degrees of ionization. In a partially ionized zone, the low escape probability for Lyα photons makes a high population of excited states, and collisional excitation from these levels enhances Balmer lines. Calculations using a reasonable AGN continuum lead to an enhancement of Balmer lines by a factor of \(~2\) and hence may not fully explain the observed low Lyα/Hβ ratio. Another explanation introduces intrinsic reddening in the line-emitting region (MacAlpine 1985). The wavelength-dependent extinction reduces the intensities of observed UV lines, thus lowering the Lyα/Hβ ratio. The observed Paα/Hβ ratio, however, appears to be too low for a straightforward full account of a reddening effect (Puetter et al. 1978). Significant evidence exists for dust in the narrow-line region of Seyfert galaxies (Osterbrock 1989; Netzer & Laor 1993) and for a decrease in extinction with increasing luminosity toward quasars (Cheng, Danese, & De Zotti 1983; Rudy et al. 1983); however, Wills et al. (1993) suggested that in intermediate-redshift quasars there may be significant reddening in the narrow line region.

Accurate assessments of the reddening effect depend on the use of good line pairs whose intrinsic ratios are fairly stable. Since singly ionized helium is hydrogenic, the He II λ304/Hβ λ1640 ratio should therefore be the same as that for hydrogen. The He II emission is produced mainly by recombination because its excitation level of 40 eV is considerably higher than the average thermal energy in the line-emitting region. The wavelength of the He II λ304 emission coincides with that of O'''' transition \(2p^2 3P_z \rightarrow 2p3d^2 P_j\), allowing Bowen fluorescence radiation (Eastman & MacAlpine 1985; Netzer, Elitzur, & Ferland 1985). This radiation mechanism, however, does not appreciably affect the He II ratio itself. The He II λ304 emission should be extremely sensitive to reddening. While there are no hurdles in the theoretical aspects, it has taken some 20 yr to advance from measuring this ratio in hydrogen to that in helium.

2. OBSERVATIONS

As a result of searches for the He II Gunn-Peterson effect in the intergalactic medium, the UV spectra of several hundred quasars have been studied with the Hubble Space Telescope (HST). The UV spectra of most high-z quasars are cut off by intervening Lyman limit systems, and so far only four quasars have been found to exhibit a detectable flux below the wavelength of the redshifted He II λ304 emission: Q0302−003 \((z = 3.286; Jakobsson et al. 1994), PKS 1935−692 \((z = 3.185; Tytler et al. 1995), HS 1700+64 \((z = 2.743; Davidsen, Kriss, & Zheng 1996), and HE 2347−4342 \((z = 2.885; Reimers et al. 1997). The He II λ304 emission, even with a profile that is partially absorbed, makes it possible to carry out the Lyα/Hβ test for ionized helium. We used the UV data of HS 1700+64 obtained with the Hopkins Ultraviolet Telescope (HUT) during the Astro-2 mission and that of Q0302−003 obtained with the HST Goddard High Resolution Spectrograph (G HRS) at an improved signal-to-noise ratio (S/N) and resolution.

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1 Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities of Research in Astronomy, Inc., under NASA contract NAS5-26555.
We obtained the optical spectra of these two quasars on several occasions. The results presented here are mainly from two observing runs in 1996 July and 1996 November. At the 2.3 m Bok telescope of Steward Observatory, University of Arizona, we used the B&C spectrograph with a Loral 1200 × 800 CCD detector and a long slit of 2.5. On July 16 (UT), the observations of HS 1700 + 64 were made with a grating of 600 line mm⁻¹ for 10,060 s, yielding a resolution of ~3.7 Å between ~5400 and 7600 Å. On November 4 and 6 we observed Q0302−003. On the first night, a total exposure of 21,600 s was made using a grating of 832 line mm⁻¹ that allows a spectral coverage from ~5900 to 7600 Å with a resolution of 2.4 Å. On the other night, the total exposure was 25,200 s, and a grating of 400 line mm⁻¹ was used, covering ~5600 and 8800 Å with a resolution of ~5.8 Å. With the seeing of ~1.5, all the observations were made with a series of exposures of 30 minutes each. On each night, low-resolution spectra were also obtained to cover the wavelength band near the Lyα emission.

The data were processed and analyzed using standard IRAF tasks. The A- and B-band absorption was corrected with the templates derived from the standard stars. The removal was only partial because some exposures were obtained with large air mass without corresponding spectra of nearby template stars. Spectra taken on different dates were combined, using exposure times as the weight. The spectra of HS 1700 + 64 and Q0302−003 are displayed respectively in Figures 1 and 2. The spectrum of HS 1700 + 64 covers too small a wavelength region shortward of the C IV wavelength to allow an accurate determination of the continuum level. We used another spectrum taken in 1994 June with the same telescope that covers wavelengths as low as 5000 Å. The fitted continuum matches that spectrum well. We therefore feel that the continuum used in the fitting is appropriate.

| LINE   | WAVELENGTH (Å) | HS 1700 + 64 Flux | EW | Q0302−003 Flux | EW |
|--------|----------------|------------------|----|----------------|----|
| He II  | 304            | 63 ± 13          | 32 | 4.9 ± 1.0      | 8  |
| Lyα    | 1216           | 202 ± 8          | 142| 155 ± 9°       | 305|
| C IV   | 1549           | 117 ± 15         | 116| 23.5 ± 1.8°    | 91 |
| He II  | 1640           | 0.3 ± 28         | 0.3| 4.5 ± 0.4      | 16 |

* Fluxes are in units of 10⁻¹⁵ ergs s⁻¹ cm⁻² Å⁻¹, corrected for Galactic absorption.

TABLE 1

| LINE | WAVELENGTH (Å) | FLUX (10⁻¹⁵ erg cm⁻² Å⁻¹) |
|------|----------------|---------------------------|
| C IV | 5790           | 1.5                       |
| He II| 304            | 1.0                       |
| Lyα | 1216           | 0.5                       |
| Al III| 1850          | 0.3                       |

The color excess $E_{B−V}$ was calculated as 0.05 for HS 1700 + 64 and 0.12 for Q0302−003, according to the estimated column density of Galactic neutral hydrogen (Stark et al. 1992). Such a conversion was based on the average Galactic dust-to-gas ratio derived by Bohlin, Savage, & Drake (1978), which yields a larger correction than using (1978). In the optical spectrum there is no noticeable emission feature at the expected He II λ1640 wavelength. To obtain an upper limit, we assumed a Gaussian profile with a fixed centroid wavelength at 6138 Å and an FWHM of 12,000 km s⁻¹. The He II λ1640 flux is $(0.3 ± 2.8) × 10⁻¹⁵$ ergs s⁻¹ cm⁻² Å⁻¹, yielding an $I(λ1640)/I(λ1660)$ ratio of greater than 20. Such a value may not be very reliable since a slight shift in the continuum level may change the ratio significantly. The current broadband data of standard stars may not allow a

![Graph](image-url)
confirmation of broad features at the 1% level. Therefore the result may not be inconsistent with the canonical value of 10. The emission centered on 6385 Å does not correspond to known emission features in quasars, and we tentatively linked it to Si I λ1701 (Verner, Barthel, & Tytler 1994) or an Fe II feature (Francis et al. 1991).

For Q0302−003, there is a significant narrow component for the Lyα and C IV emission. Each of the Lyα, C IV, and N v were fitted with a pair of Gaussian components. The narrow component has an FWHM of ~2000 km s\(^{-1}\) and accounts for about half of the line intensity. The derived \(I(\lambda 304)/I(\lambda 1640)\) ratio is ~1.1, significantly lower than the predicted value with pure recombination.

3. DISCUSSION

The \(I(\lambda 304)/I(\lambda 1640)\) ratio is quite different in these two quasars. Indeed the line profiles in Q0302−003 are narrower, which makes it easier to identify the weak He II λ1640 feature. The S/N level is high enough that an He II λ1640 feature should be detected even with a line width of ~12,000 km s\(^{-1}\). In Figure 1 the profile of an assumed He II λ1640 feature is plotted, with an intensity 20% of the He II λ304, which should have been detected. It appears that difference is not simply attributable to line widths.

The intensity of He II λ304 emission is affected by the Lyman line and continuum absorption by numerous intervening absorbers along the line of sight. This can be corrected if a high-resolution spectrum at longer wavelengths yields a list of absorption lines. Our estimate, based on the statistical result of Møller & Jakobsen (1990), suggests an optical depth of 0.2 at a rest-frame wavelength of 300 Å for a \(z = 3.3\) quasar. Therefore, this Lyman valley correction is not very significant.

The UV and optical observations are not simultaneous, and both quasars are probably variable. A comparison of the UV spectra of HS 1700+64 obtained between 1991 and 1995 finds a significant discrepancy in flux level, and the optical spectra taken between 1994 and 1996 show that the Lyα equivalent width varies by a factor of 2. The C IV equivalent width of Q0302−003 has increased by ~50% as compared with the data of Sargent, Steidel, & Boksenberg (1989). Furthermore, the photometric quality of our optical spectra is questionable. A typical light loss with a small slit during an optical spectroscopic observation is ~15%. These factors add uncertainties to the \(I(\lambda 304)/I(\lambda 1640)\) ratio. The derived line ratio is also subject to the reddening formulation. If we use the formula of Burstein & Heiles (1978), this ratio would be even lower.

We have carried out photoionization calculations (Ferland 1996) with various parameters. With a broad range of density, column density, flux, and shape of the ionizing continuum, the \(I(\lambda 304)/I(\lambda 1640)\) ratio varies within a narrow range between 9 and 11. It is therefore not practical to attribute the observed low value to special conditions in the line-emitting region. Note that a part of the He II λ304 emission may receive a contribution from the O III λ305 emission that is produced by a Bowen fluorescence mechanism (Eastman & MacAlpine 1985). If this were the case, the actual \(I(\lambda 304)/I(\lambda 1640)\) ratio would be even lower.

The low \(I(\lambda 304)/I(\lambda 1640)\) ratio in Q0302−003 may signal internal reddening in the line-emitting region. Dust grains with dimensions of ~3 × 10\(^{-6}\) cm are believed to produce Galactic extinction (Savage & Mathis 1979) that generally follows a 1/\(\lambda\) law. If intrinsic extinction is produced by even smaller grains, and the wavelength dependence of the extinction law applies to wavelengths as short as 300 Å, then \(E_{B-V} = 2.5\), where \(E\) denotes a band around 300 Å, is needed to explain the discrepancy between the observed and theoretical ratio of \(I(\lambda 304)/I(\lambda 1640)\). This would translate into \(E_{B-V} = 0.5\). If this is the case, the significant presence of dust may be a reality in the broad-line region of some high-redshift quasars.

The quantitative formalism should be more complicated than that. While the extinction curves between 1 μm and 1000 Å can be approximated with a 1/\(\lambda\) law, very little is known about the extinction properties below 1000 Å. Hawkins & Wright (1989) and Martin & Rouleau (1991) calculated the EUV extinction curve for graphite silicate dust. Their results show decreasing extinction from 1000 to 100 Å. Pei (1992) suggested that a numerical formula can be...
applied to other galaxies, possibly to those of higher redshifts, without assuming a Galactic dust-to-gas ratio. If such extinction is real, the same extinction affects the intensity of other UV lines as well. The intrinsic hydrogen Ly\/Hz ratio in these objects may actually be higher than the observed ones. It is likely the average ratio would be ~6, closer than the theoretical value of ~10. This will, in turn, help explain the classical Ly\/Hz puzzle. If significant reddening does exist in the quasar broad-line region, the observed Ly\/Hz ratio may be corrected upward by an additional factor of ~2.

Even for these two quasars, the \( I(\lambda 1216)/I(\lambda 204) \) ratio is very different. In HS 1700 + 64, this ratio is about 3, while in Q0302 - 003, it is about 30. Significant extinction in the EUV band can explain both abnormal line ratios. Therefore, the likely cause for the low ratio in Q0302 - 003 is extinction in the broad-line region by very small grains.

It may not be coincidental that narrow line widths and possible significant reddening are present in the same object. Seyfert 2 galaxies often show a higher degree of extinction (Osterbrock 1989), and the narrow-line region in Seyfert 1 galaxies generally exhibits a more significant reddening effect than the broad-line region (Binette et al. 1993). The spectrum of Q0302 - 003 shows a significant narrow component with FWHM ~ 2000 km s\(^{-1}\) for major emission lines. Although this line width is not considered very narrow for Seyfert galaxies, it is for high-z quasars. Generally, narrow lines in high-z quasars (Sargent et al. 1989) are not as common as in Seyfert galaxies. For example, Wills et al. (1993) found no detection of narrow line components in their radio-loud quasars of 0.26 < z < 0.77. They suggested a significant reddening with \( E_{B-V} \approx 0.5 \). We suggest that the geometry of the line-emitting region in high-z quasars resembles that in low-luminosity active galaxies, with the presence of dust mostly in the outer part.

Making an analogy of Seyfert galaxies and some low-redshift quasars, we suggest that Q0302 - 003 has a narrow-line region that contains a significant amount of dust. We suggest that the geometry of the line-emitting region in high-z quasars resembles that in low-luminosity active galaxies, with the presence of dust mostly in the outer part (Binette et al. 1993).

Does reddening apply to the EUV continuum? Recent studies (Netzer et al. 1995; Bechtold 1997) found that the Ly\/Hz ratio ranges between about 1 and 40 and is approximately proportional to \( f(1216)/f(4861) \), the ratio of continuum flux at adjacent points (Bechtold et al. 1997). Such a correlation may suggest a possible reddening effect that applies to both continuum and lines. In such cases, the equivalent widths of concerned lines should be fairly constant. Given the significant difference in the equivalent widths of He II lines in our quasar samples, we see no compelling reason that the continuum emission from the central source is heavily reddened. Significant reddening would also affect the intensities of infrared lines, and future studies of these lines may provide additional evidence for fine dust in the quasar environment.

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REFERENCES

Baldwin, J. A. 1977, MNRAS, 178, 67P
Bechtold, J., et al. 1997, in ASP Conf. Ser. 113, Emission Lines in Active Galaxies: New Methods and Techniques, ed. B. M. Peterson, F.-Z. Cheng, & A. S. Wilson (San Francisco: ASP), 123
Binette, L., Wang, J., Villar-Martín, M., Martin, P. G., & Margris C., G. 1993, ApJ, 414, 535
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Burstein, D., & Heiles, C. 1978, ApJ, 225, 40
Cheng, F. Z., Danese, L., & de Zotti, G. 1983, MNRAS, 204, 13P
Davidsson, A. F., Hartig, G. F., & Fastie, W. G. 1977, Nature, 269, 203
Davidsson, A. F., Criss, G. A., & Zheng, W. 1996, Nature, 380, 47
Eastman, R. G., & MacAlpine, G. M. 1985, ApJ, 299, 785
Ferland, G. J. 1996, Internal Report, Univ. Kentucky Dept. of Phys. & Astron.
Ferland, G. J., & Shields, G. A. 1985, in Astrophysics of Active Galaxies and Quasi-Stellar Objects, ed. J. S. Miller (Mill Valley: Univ. Sci.), 299
Francis, P. J., Hewett, P. C., Holtz, C. B., Chaffee, F. H., & Weymann, R. J. 1991, ApJ, 373, 465
Hawkins, I., & Wright, E. L. 1989, in Extreme Ultraviolet Astronomy, ed. R. F. Malina & S. Bowyer (New York: Pergamon), 333
Hogan, C. J., Anderson, S. F., & Ruggs, M. H. 1997, AJ, 113, 1495
Jakobsen, P., Boksenberg, A., Deharveng, J. M., Greenfield, P., Jedrzejewski, R., & Paresce, F. 1994, Nature, 370, 35
MacAlpine, G. M. 1985, in Astrophysics of Active Galaxies and Quasi-Stellar Objects, ed. J. S. Miller (Mill Valley: Univ. Sci.), 259
Martin, P. G., & Rouleau, F. 1991, in Extreme Ultraviolet Astronomy, ed. R. F. Malina & S. Bowyer (Oxford: Pergamon), 341
Müller, P., & Jakobsen, P. 1990, A&A, 228, 299
Netzer, H., Elitzur, M., & Ferland, G. J. 1985, ApJ, 299, 752
Netzer, H., et al. 1995, ApJ, 448, 27
Netzer, H., & Laor, A. 1993, ApJ, 404, L51
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: Univ. Sci.)
Pei, Y. C. 1992, ApJ, 395, 130
Pei, Y. C., Smith, H. E., Soifer, B. T., Willner, S. P., & Pipher, J. L. 1978, ApJ, 226, L53
Reimers, D., et al. 1989, A&A, 218, 71
Reimers, D., Köhler, S., Wisotzki, L., Groote, D., Rodriguez-Pascual, P., & Wamsteker, W. 1997, A&A, 327, 890
Rudy, R. J., Schmidt, G. D., Stockman, H. S., & Moore, R. L. 1983, ApJ, 271, 59
Sargent, W. L. W., Steidel, C. C., & Boksenberg, A. 1989, ApJS, 69, 703
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73
Stark, A. A., Gammie, C. F., Wilson, R. W., Bally, J., Linke, R. H., Heiles, C., & Hurwitz, M. 1992, ApJS, 79, 77
Tytler, D., Fan, X.-M., Burles, S., Cowley, L., Davis, C., Kirkman, D., & Zuo, L. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 289
Verner, D. A., Barthel, P. D., & Tytler, D. 1994, A&A, 108, 287
Wills, B. J., et al. 1993, ApJ, 410, 534