Flux ($10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$)

Fe II

Balmer Continuum

Emission Lines

Rest Wavelength (Å)
Flux ($10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$)

Global power–law continuum

Local linear continuum

Rest Wavelength (Å)
NEW NEAR-INFRARED SPECTROSCOPY OF THE HIGH REDSHIFT QUASAR B1422+231 AT 
\[ Z = 3.62 \]

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ABSTRACT

We present new near-infrared (rest-frame UV-to-optical) spectra of the high redshift, gravitationally lensed quasar B1422+231 (z = 3.62). Diagnostic emission lines of Fe II, O III\lambda5007, and H\beta, commonly used to determine the excitation, ionization, and chemical abundances of radio-quiet and radio-loud quasars, were detected. Our new data show that the ratio Fe II(\text{UV})/H\beta = 18.1\pm4.6 and Fe II(\text{optical})/H\beta = 2.3\pm0.6 are higher than those reported by Kawara et al. (1996) by factors of 1.6 and 3.3, respectively, although the ratio [O III]5007/H\beta = 0.19\pm0.02 is nearly the same between the two measurements. The discrepancy of the line flux ratios between the measurements is likely due to improved data and fitting procedures rather than to intrinsic variability. While approximately half of the high-z quasars observed to date have much more extreme Fe II(\text{optical})/H\beta ratios, the line ratio measured for B1422+231 is consistent with the observed range of Fe II(\text{optical}) ratios of low-z quasars.

Subject headings: quasars: emission lines — quasars: individual (B 1422+231)

1. INTRODUCTION

Since near-infrared (NIR) spectroscopy of high-redshift (z > 2) quasars provides information about their rest-frame optical spectroscopic properties, it is now possible to systematically compare the spectroscopic properties (e.g., excitation, ionization, and chemical abundances) of high-z and low-z quasars. Although the first NIR spectroscopic observations of high-z quasars were made nearly two decades ago (Hyland, Becklin, & Neugebauer 1978; Puetter et al. 1981; Soifer et al. 1981), high-quality NIR spectra have been obtained for only \sim 10 high-z quasars to date (e.g., Carswell et al. 1991; Hill et al. 1993; Elston et al. 1994; Kawara et al. 1996 [hereafter K96]; Taniguchi et al. 1997a; Murayama et al. 1998; see also Taniguchi et al. 1997b). However, despite the relatively small number of objects observed, several very interesting properties of high-z quasars have emerged. In particular, Hill et al. (1993) and Elston et al. (1994; hereafter ETH) suggested that unusually strong optical Fe II emitter may be common in the high-z universe (2 < z < 3.4); to date, five out of eight high-z quasars observed have very strong optical Fe II emission with EW(Fe II)/EW(H\beta) g 1 (see Murayama et al. 1998). By comparison, a much smaller fraction of far-infrared (FIR) selected AGN (LFIR \g 10^{12}L_\odot) have strong optical Fe II emission (cf. Lïpari et al. 1993).

Recently, we obtained NIR spectra of the radio-loud, flat-spectrum, high-z quasar B1422+231 (Patnaik et al. 1992; Lawrence et al. 1992) using the Mayall 4 m telescope at Kitt Peak National Observatory (KPNO) (K96). Although this quasar is at z = 3.62, its optical magnitude is sufficiently bright (m_r = 15.5; Yee & Bechtold 1996), due to gravitational lensing (Patnaik et al. 1992; Lawrence et al. 1992), to allow it to be studied by NIR spectroscopy. The NIR spectra show that the flux ratio F(\text{Fe II} \lambda\lambda4434–4684)/F(H\beta) is much less than that of the other high-z quasars (K96), and in fact is similar to those of radio-loud, flat-spectrum, low-z quasars with “normal” optical Fe II emission. This suggested that high-z quasars may exhibit a range of values of F(\text{Fe II} \lambda\lambda4434–4684)/F(H\beta) similar to what has been observed for low-z quasars. In order to confirm this result, we have obtained new NIR spectra using the University of Hawaii (UH) 2.2 m telescope. In this paper, we present our new NIR spectroscopy of B1422+231 and compare it with our previous measurements.

2. OBSERVATIONS AND DATA REDUCTION

We observed B1422+231 on 1996, April 7 (UT) using the K-band spectrograph (KSPEC; Hodapp et al. 1996) at the Cassegrain focus (f/31) of the UH 2.2 m telescope in combination with the UH tip-tilt system (Jim et al. 1998).

\footnote{Visiting Astronomer of the University of Hawaii 2.2 meter telescope.}
The cross-dispersed echelle design of KSPEC provided simultaneous coverage of the entire 1–2.5 μm wavelength region. The projected pixel size of the HAWAII 1024 × 1024 array was 0.′6176 along the slit and ≃ 5.6 Å at 2 μm along the dispersion direction. We used a 0.′96 wide slit oriented East-West and centered on the intensity peak of component B (Patnaik et al. 1992) of B1422+231 (see Figure 1). However, comparing the two images given in Figure 1, we find that actual light from component B is 59% of the total measured flux and the remaining 41% is associated with light contamination from components A and C. Therefore, the flux of our spectra is 1.7 times as bright as real component B flux.

Thirty exposures, each of 180 sec integration, taken under photometric conditions, were obtained by shifting the position of the object along the slit at intervals of 5″ between each integration. The total integration time was 5400 sec. An A-type standard star, HD 106965 (Elias et al. 1982), was observed for flux calibration. Another A-type star, HD 136754 (Elias et al. 1982), was also observed before and after observing B1422+231 to correct for atmospheric absorption. Spectra of an incandescent lamp and a type star, HD 136754 (Elias et al. 1982), was observed for flux calibration. Another A-type standard star spectra were also observed throughout the night. Note that our previous NIR spectroscopy of this quasar at KPNO was obtained using a 1.44 arcsec slit under 1.4 – 2.1 arcsec seeing conditions (K96).

Data reduction was performed with IRAF\(^2\) using standard procedures as outlined in Hora & Hodapp (1996). Sky and dark counts were removed by subtracting the average of the preceding and following exposures, and then the resulting frame was divided by a normalized dome flat. The target quasar was not bright enough to trace its position in each frame with sufficient accuracy. Therefore, we first fit the spectral positions of the standard star spectra with a third-order polynomial function which properly traces the echelle spectrum. These fitting results were then applied to the quasar spectra. Using this procedure, we extracted the quasar spectra with an aperture of 3″ which was determined to be the typical width where the flux was ~10% of the peak flux along the spatial profile of the standard star. In order to subtract the sky emission, we used the data just adjacent to the 3″ aperture. The wavelength scale of each extracted spectrum was calibrated to an accuracy of 18 km s\(^{-1}\) at 1.1 μm, 20 km s\(^{-1}\) at 1.6 μm, and 19 km s\(^{-1}\) at 2.0 μm, based on both the argon emission lines of the calibration lamp and on the telluric OH emission lines. The spectral resolutions (FWHM) measured from the argon lamp spectra were ≃ 500 km s\(^{-1}\) at 1.1 μm, ≃ 450 km s\(^{-1}\) at 1.6 μm, and ≃ 500 km s\(^{-1}\) at 2.0 μm. Finally, the spectra were median combined in each band. Atmospheric absorption features were removed using the spectra of the A-type star HD 136754 because A-type stars are best suited for correcting for atmospheric absorption features. However, since A-type stars inherently have hydrogen recombination absorption lines (e.g., the Brackett series in H and K bands and the Paschen series in I and J bands), we removed these features using Voigt profile fitting before the correction. In order to check whether this procedure worked we also applied the same atmospheric correction for the spectra of M-type stars whose data were obtained on the same night. Comparing our corrected spectra of the M-type stars with their published spectra (Lançon & Rocca-Volmerange 1992), we found that our correction procedure works appropriately. Finally, in order to calibrate the flux scale, we used the spectrum of the standard star HD 106965 (A2, K = 7.315) divided by a 9000 K blackbody spectrum, which fits the HJKL magnitude of the standard (Elias et al. 1982) with only 1.2% deviation. Photometric errors were determined to be < 10% over all observed wavelengths.

### 3. RESULTS AND DISCUSSION

Figure 2 shows the spectra of B1422+231 (red line) in the JHK bands together with both our previous measurement at KPNO (blue line; K96) and the Large Bright Quasar Survey (LBQS) composite spectrum shifted to z = 3.62 (black dashed line; Francis et al. 1991). Since the efficiency of KSPEC in the J-band is not high, we have not used the J-band data in this paper.

Although our new measurement was made with a narrower slit (0.′96 wide) than that used by K96 (1.′44 wide), the H- and K-band fluxes are slightly higher than those of the previous measurement. K96 tried to carefully correct for the effect of seeing on the relative flux calibration among the spectral bands because they could take only one band spectrum at a time. However, the time variation of the seeing in their observations made it difficult to perform the correction very accurately. Since our new I to K-band NIR spectra were obtained simultaneously, our new measurement should be more reliable than that of K96. Our new I-band spectrum detects C III]λ1909 emission clearly. Further, some unidentified emission features at 2000 Å and 2080 Å as well as the dip at 2200 Å in the rest frame, which are shown in the average spectrum of LBQS quasars (Francis et al. 1991), are also seen. The presence of [O III]λ5007 emission has also been confirmed.

The continuum flux of component B between 1330 Å and 1380 Å, which was obtained by Impey et al. (1996) 13 months before our observations, was assumed for the continuum level on the short wavelength side of our spectra. We applied the factor 1.7 to this continuum level in order to correct the contaminated light from component A and C for our spectra (see previous section). The continuum level on the long wavelength side of our spectra was chosen by fitting a power-law continuum plus a Fe II template simultaneously to minimize the residual between 4450 Å and 4750 Å and beyond 5100 Å. We used the Balmer continuum template that was generated to approximate the emission-line strengths seen in 0742+318 (see Figure 3d of Wills et al. 1985). The Fe II emission profile of the very strong Fe II-emitting low-ionization BAL quasar PG 0043+039 (Turnshek et al. 1994) was used as the Fe II template. Due to a relatively poor fit over the entire wavelength range when using a single template, two Fe II templates were used: one for shortward of 3000 Å and the other for longward of 3000 Å. The power-law continuum that we derive is given by \( f_\nu \propto \nu^{-0.88} \). This spectral index is steeper than the \( f_\nu \propto \nu^{-0.54} \) power-law derived in K96. Yee & Bechtold (1996) report that

\(^2\)Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
B1422+231 had become brighter by 0.12 mag during 13 months (see also Kundić et al. 1997), but variability of 0.12 mag would change the spectral index to −0.88 ± 0.08 at most. Therefore, it is unlikely that the difference of the spectral index between K96 and our current work is due to the variability inherent in this quasar. Thus, we conclude that the change in the calculated spectral index is due to our improved absolute NIR spectrophotometry by simultaneous observations of HIK bands using KSPEC.

Figure 3 shows the rest frame spectrum of B1422+231 with the power-law subtracted and the best fit synthetic spectrum comprised of Fe II and Balmer continuum emission as well as other broad-lines. The fluxes, equivalent widths, and line widths of the detected emission lines are summarized in Table 1 together with the previous measurements of K96. Our new data show that the ratio Fe II(UV)/Hβ and Fe II(optical: λλ3500–6000)/Hβ are higher than those of K96 by factors of 1.6 and 3.3, respectively. These differences are mainly due to adopting the different power-law continuum described above. However, our new Fe II(optical)/Hβ ratio for B1422+231 is still in the observed range for low-z, radio-load quasars (Boroson & Green 1992; see Taniguchi et al. 1997; Murayama et al. 1998). The [O III]λ5007/Hβ ratio is nearly the same between the two measurements. We also note that there appears to be evidence for excess emission at λ < 2100 Å in the rest frame (see the second panel of Figure 3).

Our new measurements yield a flux ratio of Fe II(UV)/Fe II(optical) ∼ 8.0. Since Wills et al. (1985) give a range of 4 < Fe II(UV)/Fe II(optical) < 12 for low-z quasars, B1422+231 is typical of low-z quasars in this respect. We also obtain a flux ratio of Fe II(optical: λλ4484–4684)/Hβ ∼ 0.53 which is significantly smaller than the range of values (1.5–2) found by Hill et al. (1993) for quasars with z ∼ 2–5. This demonstrates that it is perhaps dangerous to attempt a measurement of the iron abundance using solely optical Fe II emission features as suggested by Wills et al. (1985).

Finally we speculate about the formation epoch of the host galaxy of B1422+231. Our new measurement has confirmed that the Fe II(total)/Hβ ratio for B1422+231 is higher-than-normal with respect to what is found for low-z quasars. Since the low-z quasars are believed to be associated with nuclei of massive galaxies, their chemical abundances are expected to be higher than or roughly equal to solar. Therefore, the observed higher Fe II(total)/Hβ ratio suggests that the iron abundance of B1422+231 is at least comparable to the solar value. If this is the case, it is expected that the majority of iron would come from Type Ia supernovae. Yoshii, Tsujimoto, & Nomoto (1996) derived ∼ 1.5 Gyr for the lifetime of SN Ia progenitors from an analysis of the O/Fe and Fe/H abundances in solar neighborhood stars. If the Fe enrichment started at 1.5 Gyr after the onset of the first epoch of star formation, the host galaxy of B1422+231 would have formed at z ∼ 9 or earlier for q0 = 0 and H0 = 75 km s⁻¹ Mpc⁻¹ (K96).

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APPENDIX

Comments on continuum fitting

In our spectral fitting procedure, we have used the global continuum which was determined using the continuum from the rest-frame UV to optical. However, local continua have often been used to measure the optical Fe II/Hβ ratio for low-z quasars because of the lack of rest-frame UV spectra (e.g., Boroson & Green 1992). Since the adopted continuum affects the measurements of emission-line fluxes (see Murayama et al. 1998), we examine such differences in the flux measurement for the case of B1422+231. In Figure 4, we show the spectral fitting results for both global continuum and the local continuum cases. It is shown that the local continuum fit tends to give lower fluxes for the concerned emission lines; the measured fluxes for Hγ+[O III]λ4363, Hβ, [O III]λ 5007, and optical Fe II are given in Table 1. Comparing these fluxes with those measured using a global fit to the continuum, we find that the optical Fe II flux based on the local continuum is four times lower than that determined using a global continuum fit, although the [O III]λ5007 flux is nearly the same using both the local and global continuum fits. Therefore, we suggest that previous measurements of optical Fe II/Hβ ratios for low-z quasars and Seyfert nuclei may be underestimated by a factor of a few. We also note that a local continuum fit should be used if one would like to first compare new results with previous published values.

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Fig. 1.— The NIR (K-band) image of B1422+231 taken with the field viewer of KSPEC. The weakest component D (0″.94 E and 0″.81 S from component B) can barely be seen. In the lower panel, we show our 1 arcsec slit position.

Fig. 2.— Comparison of the observed-frame HHK spectra of B1422+231 (red line) and both our previous measurement at KPNO (K96; blue line) and the LBQS composite spectrum of Francis et al. (1991; black dashed line).

Fig. 3.— The upper panel gives the rest frame spectrum of B1422+231 and the same spectrum with the power-law continuum subtracted, together with the power-law continuum and a synthetic spectrum comprised of Fe II and Balmer continuum emission plus other emission lines. Note that the rest frame spectrum was derived by dividing the observed frame spectrum by (1 + z) after converting observed wavelengths into the rest-frame wavelengths. The spectrum shown in the second panel is the extracted Fe II emission of B1422+231 together with the best-fit Fe II template. The third and bottom panels show the best-fit templates of the Balmer continuum and other emission lines respectively.

Fig. 4.— The profile fit of the K-band spectrum. The upper panel shows the result using the global power-law continuum while the lower panel shows the result using the local continuum. Note that the flux is multiplied by (1 + z) for deredshifting.
Table 1. Comparison of emission-line properties of B 1422+231 between Kawara et al. (1996: K96) and this study.

| Line                          | $F/F(H\beta)$ | $EW(\text{rest})^a(\text{Å})$ | $FWHM^b_{\text{cor}} (\text{km s}^{-1})$ |
|-------------------------------|---------------|-------------------------------|------------------------------------------|
|                               | K96           | This study                    | K96                                      | This study |
| C III $\lambda$1909           | ...           | 2.31 ± 0.50                   | ...                                      | 32.2 ± 6.8 | 6260          |
| Mg II $\lambda$2798          | 0.97 ± 0.06   | ...                           | 19.5                                     | ...        | 2500          |
| [O II] $\lambda$3727         | < 0.04$^c$    | < 0.09$^c$                    | < 1.1$^c$                                | < 2.6$^c$  | (1000)        |
| $H\gamma$ + [O III] $\lambda$4363 | 0.28 ± 0.04  | 0.68 ± 0.17                   | 10.6                                     | 23.4 ± 5.8 | 3500          | 8635         |
| $H\beta$                     | 1             | 44.9                          | 39.6 ± 2.3                               | 4786       | 4786          |
| [O III] $\lambda$5007        | 0.20 ± 0.02   | 0.19 ± 0.02                   | 9.2                                      | 8.0 ± 0.7  | 840           | 1357         |
| Fe II UV$^e$                  | 11.2 ± 3.5    | 18.1 ± 4.6                    | ...                                      | 340 ± 85   | ...            |
| Fe II optical$^f$            | 0.68 ± 0.22   | 2.26 ± 0.62                   | ...                                      | 86 ± 23    | ...            |
| Fe II optical$^g$            | ...           | 0.53 ± 0.15                   | ...                                      | 20 ± 5     | ...            |
| Balmer continuum             | 6.91 ± 1.17   | 9.4 ± 1.9                     | ...                                      | ...        | ...            |
|                               | Global power-law continuum | | | |
|                               | Local linear continuum$^h$ | | | |

$^a$Rest frame equivalent width.  
$^b$Full width at half maximum corrected for instrumental broadening.  
$^c$3-$\sigma$ upper limits assuming $FWHM_{\text{cor}} = 1000$ km s$^{-1}$.  
$^d$F$(H\beta) = (5.9 \pm 0.3) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.  
$^e$Fe II UV $\lambda\lambda$2000–3000. To compare with the results of Wills et al. (1985).  
$^f$Fe II optical $\lambda\lambda$3500–6000. To compare with the results of Wills et al. (1985).  
$^g$Fe II optical $\lambda\lambda$4434–4684. To compare with the results of Hill et al. (1993).  
$^h$See Appendix.  
$^i$F$(H\beta) = (7.8 \pm 0.5) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.  

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