Flux ($10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) vs. Wavelength (Å). Peaks at $\text{Mg II}$, $\text{[O II]}$, $\text{H\beta}$, and $\text{[O III]}$ are labeled. The solid line represents S4 0636+68, and the dashed line represents the LBQS Composite (Francis et al. 1991).
Wavelength (Å)

Flux ($10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$)

- **Hβ**
- **[O III]**
- **Lyα**
- **Mg II**

**S4 0636+68**

- **IHK bands (this study)**
- **K band (Elston et al. 1994)**
- **Optical (Sargent et al. 1989)**
- **Optical & IJ bands (Bechtold et al. 1994)**

**LBQS Composite**

- **Francis et al. (1991)**
This Study

Elston et al. (1994)
(x2 scaled)

Flux ($10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$)

Wavelength (Å)
$\frac{\text{EW([O III] } \lambda 4959+\lambda 5007)/\text{EW(H}\beta)}{\text{EW(Fe II } \lambda \lambda 4434-4684)/\text{EW(H}\beta)}$
NEAR-INFRARED SPECTROSCOPY OF THE HIGH REDSHIFT QUASAR S4 0636+68 AT $z=3.2$

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ABSTRACT

We present near-infrared (observed frame) spectra of the high-redshift quasar S4 0636+68 at $z = 3.2$ which was previously thought to be one of a group of “strong” Fe II emitters (i.e., $F(\text{Fe II} \lambda \lambda 4434-4684)/F(\text{H} \beta) > 1$). Our $K$-band spectrum clearly shows emission lines of H$\beta$ and $\text{[O III]} \lambda \lambda 4959, 5007$ as well as optical Fe II emission. Our computed value of $F(\text{Fe II} \lambda \lambda 4434-4684)/F(\text{H} \beta) \simeq 0.8$ for S4 0636+68 is less than previously thought, and in fact is comparable to values found for radio-loud, flat-spectrum, low-$z$ quasars. Therefore S4 0636+68 appears not to be a strong optical Fe II emitter. Although more than half (5/8) of the high-$z$ quasars observed to date are still classified as strong optical Fe II emitters, their Fe II/H$\beta$ ratios, for the most part, follow the same trend as that of low-$z$ quasars, i.e., an anticorrelation in $EW(\text{Fe II})/EW(\text{H} \beta)$ versus $EW(\text{[O III]})/EW(\text{H} \beta)$, with radio-loud quasars having a mean value of $EW(\text{Fe II})/EW(\text{H} \beta)$ approximately half that of radio-quiet quasars at comparable values of $EW(\text{[O III]})/EW(\text{H} \beta)$.

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1. INTRODUCTION

Since optical Fe II emission is often one of the prominent features in the spectra of Type 1 active galactic nuclei (AGN), it is perhaps not surprising that several observational and theoretical studies have been made to explain the strength of this feature in quasars (e.g. Phillips 1977, 1978; Kwan & Krolik 1981; Netzer & Wills 1983; Wills et al. 1985; Collin-Souffrin et al. 1988; Zheng & O’Brien 1990; Joly 1991; Boroson & Green 1992; Lípari et al. 1993; Wang et al. 1996a). Although it is known that the strength of the optical Fe II emission shows an anticorrelation with the strength of [O III] emission (Boroson & Green 1992), the physical properties of the Fe II emitting region are not yet fully understood.

Recent near-infrared (NIR) spectroscopic studies by Hill et al. (1993) and Elston et al. (1994; hereafter ETH) suggest that unusually strong optical Fe II emitters may be common in the high-z universe ($2 < z < 3.4$). Though it is known that some low-z far-infrared (FIR) selected AGN ($L_{\text{FIR}} \gtrsim 10^{11} \, L_\odot$) show strong Fe II emission in their optical spectra (cf. Lípari et al. 1993), such extreme Fe II emitters appear to be rare in the low-z universe. Recently, we obtained NIR spectra of two radio-loud, flat-spectrum, high-z quasars (B 1422+231 at $z = 3.6$ and PKS 1937–101 at $z = 3.8$) and found that their flux ratios of $F(\text{Fe II} \lambda \lambda 4434–4684)/F(\text{H}\beta)$ are much less than those of the other high-z quasars (Kawara et al. 1996; Taniguchi et al. 1996, 1997), and in fact are similar to those of radio-loud, flat-spectrum, low-z quasars with normal optical Fe II emission. These new observations suggest that high-z quasars may exhibit a range of values of $F(\text{Fe II} \lambda \lambda 4434–4684)/F(\text{H}\beta)$ similar to what has been observed for low-z quasars.

If the strong Fe II emission could be attributed to the overabundance of iron, host galaxies of the high-z quasars with strong Fe II emission would form at $z \sim 10$ because it is usually considered to be the case that the bulk of the iron arises from Type Ia supernovae which occur $\sim 1–2 \, \text{Gyr}$ after the first major epoch of star formation (e.g., Hamann & Ferland 1993, Yoshii et al. 1996). It is therefore important to investigate the chemical properties of high-z quasars systematically.

In this paper we present new NIR spectroscopy of S40636+68, a flat-spectrum radio-loud quasar at $z = 3.2$, which is reported in ETH as a very strong iron emitter. Based on our new measurements, we discuss whether the fraction of high-z quasars with strong optical Fe II emission is substantially higher than that of low-z quasars.

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2The Fe II emission feature actually extends from the near-UV into the red optical region of the spectrum. However, following previous convention, we use the term “optical Fe II emission” in this paper to mean the Fe II emission near $\text{H}\beta$ (i.e., Fe II $\lambda \lambda 4434–4684$).
2. OBSERVATIONS AND DATA REDUCTION

We observed S4 0636+68 on 1996 April 7 (UT) using the $K$-band spectrograph (KSPEC; Hodapp et al. 1994) at the Cassegrain focus (f/31) of the University of Hawaii (UH) 2.2 m telescope in combination with the UH tip-tilt system (Jim et al. 1997). The cross-dispersed echelle design of KSPEC provided simultaneous coverage of the entire 1–2.5 $\mu$m wavelength region. The projected pixel size of the HAWAII 1024 $\times$ 1024 array was $0\farcs167$ along the slit and $\simeq 5.6$ Å at 2 $\mu$m along the dispersion direction. We used a $0\farcs96$ wide slit oriented East-West and centered on the intensity peak of the object. Twenty exposures, each of 180 sec integration 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 3600 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 S4 0636+68 in order to correct for atmospheric absorption. Spectra of an incandescent lamp and an argon lamp were taken for flat-fielding and wavelength calibration, respectively. Typical widths of the spatial profiles of the standard star spectra were $\sim 0\farcs5$ (FWHM) throughout the night.

Data reduction was performed with IRAF\footnote{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.} 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 the normalized dome flat. The target quasar was not bright enough to trace its position in each frame with sufficient accuracy. Therefore, at first, we 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 $\sim 10\%$ of the peak flux along the spatial profile of the standard star. In order to subtract the residual 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 $\mu$m, 20 km s$^{-1}$ at 1.6 $\mu$m, and 19 km s$^{-1}$ at 2.0 $\mu$m, respectively, 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 $\simeq 500$ km s$^{-1}$ at 1.1 $\mu$m, $\simeq 450$ km s$^{-1}$ at 1.6 $\mu$m, and $\simeq 500$ km s$^{-1}$ at 2.0 $\mu$m. The spectra were finally 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 before the correction using Voigt profile fitting. 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 (Laçon & 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 $JHKL$ 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

3.1. The Rest-Frame UV and Optical Spectra of S40636+68

Figure 1 shows the spectra of S40636+68 (solid line) in the $IIK$ bands together with the Large Bright Quasar Survey (LBQS) composite spectrum (dashed line; Francis et al. 1991) shifted to $z = 3.2$. The atmospheric transmission of Mauna Kea is shown in the upper panel. The spectrum clearly shows H$\beta$ at 2.04 $\mu$m and a broad “bump” of Fe II emission between 2.15 $\mu$m and 2.23 $\mu$m. The spike feature in our spectrum marked by ‘X’ is caused by residual atmospheric absorption. Although ETH did not find evidence for [O III] $\lambda\lambda$4959, 5007 emission lines, our $K$-band spectrum shows their presence (which will be discussed later). No prominent emission lines were found in the $I$-, $J$-, and $H$-band regions of the spectrum. Mg II $\lambda$2798 would be expected to appear at $\sim 1.18$ $\mu$m but the $J$-band spectrum (not shown in Figure 1) was too noisy to be able to study Mg II. Since the efficiency of KSPEC in the $J$-band is not high, we do not use the $J$-band data in this paper.

In Figure 2, we compare our results with previous optical-NIR spectroscopic studies of S40636+68 (Sargent et al. 1989; Bechtold et al. 1994; ETH). Their basic data are summarized in Table I. Our $K$-band spectrum is twice as bright as that of ETH. On the other hand, our $I$-band spectrum is 40% fainter than that of Bechtold et al. (1994). These flux discrepancies may be due to possible time variation inherent in the object or to calibration errors in the absolute photometry. However, since the two optical spectra taken at different observing dates over two years are quite consistent with each other (Sargent et al. 1989; Bechtold et al. 1994), it seems unlikely that this quasar is highly variable. Therefore, we consider the possibility that the discrepancy may be mostly due to calibration errors. First, we note that our $IIK$ spectra were taken simultaneously and thus there is no internal calibration error in our spectra. Second, the optical spectra of Sargent et al. (1989) and Bechtold et al. (1994) show good agreement with each other and thus their photometric calibration seems reliable. Further, the optical power-law slope, $\alpha = -0.68$ ($f_{\nu} \propto \nu^{\alpha}$), given in Sargent et al. (1989) can be consistently extrapolated onto our $K$-band spectrum; the spectral index using the emission-free regions in both the optical spectrum (Sargent et al. 1989) and our $K$-band spectrum (1330–1380 Å, 1430–1460 Å, and 5400–5850 Å in the rest frame) is estimated to be $\alpha = -0.69$. Since the seeing during our observations was $\simeq 0'5$
(FWHM) and our slit size was 1″, we think that we have detected nearly all of the light from the quasar. Though the details of the observing conditions and slit size are not given in ETH (see Table 1), seeing conditions on Mauna Kea are often better than at KPNO, judging from our experience at KPNO (see Kawara et al. 1996; Taniguchi et al. 1997), and, therefore we expect that our new measurement is more reliable.

3.2. The Rest-frame Optical Emission-line Properties of S40636+68

The main aim of our current observations is to provide a more accurate measure of the optical Fe II/Hβ ratio in S40636+68. Figure 3 compares our result with that of the ETH. (Note that the flux of ETH spectrum is scaled by a factor of two for proper comparison.) Center positions of Hβ, [O III] λλ4959, 5007, and the Fe II multiplet (42) at a redshift \( z = 3.2 \) are marked in Figure 3. The peak positions of Hβ, [O III] λλ4959, 5007, and Fe II λ5169 (one of Fe II multiplet 42 lines), coincide between the two spectra. The K-band spectrum of ETH appears to be dominated by very strong Fe II emission with weak, or nondetected [O III] λλ4959, 5007. ETH actually stated that [O III] λλ4959, 5007 was not detected, although they noted that their spectrum had small bumps of low significance at the position of the [O III] lines. On the other hand, our K-band spectrum clearly shows emission peaks which can be identified with [O III] λλ4959, 5007.

To measure the Fe II fluxes in our spectrum, we fit emission-line features simultaneously with a least-squares algorithm. Such fitting results depend on the adopted continuum spectrum. As shown in Boroson & Green (1992), a local linear continuum is usually adopted to fit Hβ, [O III] λλ4959, 5007, and the Fe II features. However, we have already obtained a global power-law continuum using the rest-frame UV and optical spectra as shown in Figure 2. Therefore, we performed spectral fitting for two cases: 1) local linear continuum and 2) global power-law continuum. In the fitting procedure, we assumed \( F([\text{O III}] \lambda 5007)/F([\text{O III}] \lambda 4959) = 2.97 \) (Osterbrock 1989). We also assumed that the emission line profiles of Hβ and the [O III] λλ4959, 5007 doublet are Gaussian. As for the optical Fe II emission features, we used an Fe II spectrum of a low-z BAL quasar, PG 0043+039 (Turnshek et al. 1994), as our Fe II template. All the emission lines are assumed to have the same redshift. Since it is known that high-ionization broad lines (e.g., C IV λ1549) are often blueshifted with respect to low-ionization lines (Gaskell 1982; Wilkes 1984; Carswell et al. 1991; Nishihara et al. 1997 and references therein), we use only low ionization lines in our analysis.

The fitting results are presented in Figure 3 and Table 2 for each of the two assumed continua. The difference in the line flux ratios between the two cases is less than the measurement errors. Although we do not know which continuum case is more realistic, we adopt the results using the linear continuum fit for further discussion in order to compare our results with those of Boroson & Green (1992) and Hill et al. (1993) since they also adopted a local linear continuum.
In order to examine whether or not the detection of the [O III] lines are real in our spectrum, we compare our fit including the [O III] doublet with a fit excluding the [O III] doublet, where the local linear continuum has been adopted in both fits. A F-statistics test indicates that the fit with [O III] is improved over the 4900–5050 Å region from the fit excluding [O III] at a significance level of 99.8%. Therefore, we conclude that the “bumps” at the [O III] positions are really the [O III] λλ4959, 5007 doublet rather than Fe II λλ4924, 5018 of the 42 multiplet. We obtained an average redshift \( z = 3.200 \pm 0.002 \).

Our fit assuming a local linear continuum gives the flux ratio \( F(\text{Fe II} \lambda \lambda 3500–6000)/F(\text{H} \beta) \), for S40636+68 is 3.5 ± 1.1 (Table 2). This value is greater than the mean value of 1.63 ± 0.88 for the six low-\( z \) quasars studied by Wills et al. (1985) and the value of 2.9 for 3C 273 which is the strongest optical Fe II quasar in the sample of Wills et al. (1985). However, \( F(\text{Fe II} \lambda \lambda 4434–4684)/F(\text{H} \beta) \) for S40636+68 is 0.83 ± 0.26 which is only half of the average value of 1.77 ± 0.17 for the four high-\( z \) quasars studied by Hill et al. (1993). Lípari et al. (1993) defined quasars with \( F(\text{Fe II} \lambda \lambda 4434–4684)/F(\text{H} \beta) \gtrsim 1 \) as “strong” iron emitters. According to this criterion, we conclude that S40680+68 is not a strong Fe II emitter, contrary to the conclusion of ETH.

### 3.3. Statistical Properties of High-\( z \) Quasars vs. Low-\( z \) Quasars

In order to assess the significance of our new result for the ratio \( F(\text{Fe II} \lambda \lambda 4434–4684)/F(\text{H} \beta) \) in S40680+68 we first compare the rest-frame optical emission line properties of low-\( z \) and high-\( z \) quasars. Figure 3 shows the relationship of equivalent width (EW) ratios between \( EW([\text{O III}] \lambda 4959 + \lambda 5007)/EW(\text{H} \beta) \) and \( EW(\text{Fe II} \lambda \lambda 4434–4684)/EW(\text{H} \beta) \) for low-\( z \) and high-\( z \) quasars compiled from the literature (Boroson & Green 1992; Hill et al. 1993; ETH; Kawara et al. 1996; Taniguchi et al. 1997). There is a distinct anticorrelation for the low-\( z \) quasars as noted before (cf. Boroson & Green 1992) although the reason for the anticorrelation between [O III] λλ4959, 5007 and optical Fe II λλ4434–4684 is still unknown. The low-\( z \) radio-loud quasars tend to have small ratios both in \( EW([\text{O III}] \lambda 4959 + \lambda 5007)/EW(\text{H} \beta) \) and \( EW(\text{Fe II} \lambda \lambda 4434–4684)/EW(\text{H} \beta) \). Five of the eight high-\( z \) quasars show strong Fe II (i.e., Fe II/\( \text{H} \beta > 1 \)) emission. The remaining three high-\( z \) quasars, which have Fe II/\( \text{H} \beta < 1 \), are all radio-loud and lie within the locus of values
traced by low-\(z\) radio-loud quasars in Figure 5\[4\]. Also, the three radio-quiet quasars among the five high-\(z\) quasars with strong Fe II emission appear to lie within the upper envelope of values observed for low-\(z\) radio-quiet quasars. In summary, although over half (5/8) of the high-\(z\) quasars appear to be by definition strong Fe II emitters, all but two (the radio-loud Fe II quasars S5 0014+81 and B2 1225+317: ETH; Hill et al. 1993) of the high-\(z\) quasars follow a similar trend as that shown by the low-\(z\) quasars, i.e. an anticorrelation of \(EW(\text{Fe II} \lambda \lambda 4434-4684)/EW(\text{H}\beta)\) versus \(EW(\text{[O III]} \lambda 4959 + \lambda 5007)/EW(\text{H}\beta)\), with radio-loud quasars having on average smaller values of \(EW(\text{Fe II} \lambda \lambda 4434-4684)/EW(\text{H}\beta)\) than radio-quiet quasars at any given value of \(EW(\text{[O III]} \lambda 4959 + \lambda 5007)/EW(\text{H}\beta)\).

Recently Wang et al. (1996b) studied the relation between optical Fe II strength and properties of the UV spectra for 53 low-\(z\) (\(z \lesssim 0.2\)) quasars and found that there is a significant anticorrelation between the equivalent widths of optical Fe II \(\lambda \lambda 4434-4684\) and C IV \(\lambda 1549\). We examine whether the high-\(z\) quasars follow this anticorrelation (Table 3 and Figure 6). It is perhaps expected that the high-\(z\) quasars would have smaller \(EW(\text{C IV} \lambda 1549)\) than low-\(z\) quasars simply because of the known anticorrelation between \(EW(\text{C IV} \lambda 1549)\) and UV continuum luminosity (Baldwin effect: Baldwin 1977; Baldwin et al. 1978). Not as evident perhaps is that, except for 0933+733, the \(EW(\text{Fe II} \lambda \lambda 4434-4684)\), appears to show the same range of values as do the low-\(z\) quasars at comparable low values of \(EW(\text{C IV} \lambda 1549)\). However, five of the remaining seven high-\(z\) quasars (B2 1225+317, 1246−367, S4 0636+68, B 1422+231, and PKS 1937−101) have smaller \(EW(\text{Fe II} \lambda \lambda 4434-4684)\) than any of the low-\(z\) quasars with comparable \(EW(\text{C IV} \lambda 1549)\) (see the lower-left region of the diagram in Figure 6), thus, adding the high-\(z\) sample to the low-\(z\) sample appears to decrease somewhat the significance of the anticorrelation between \(EW(\text{Fe II} \lambda \lambda 4434-4684)\) versus \(EW(\text{C IV} \lambda 1549)\), (although it is possible that not having a less luminous high-\(z\) sample may cause a selection effect). We thus consider it possible that the Fe II \(\lambda \lambda 4434-4684\) emitting region may not have a physical link directly with the C IV \(\lambda 1549\) emitting region. However, it seems clear that there is no object with large EWs in both Fe II \(\lambda \lambda 4434-4684\) and C IV \(\lambda 1549\), and furthermore, the upper bound of \(EW(\text{Fe II} \lambda \lambda 4434-4684)\) still decreases with increasing \(EW(\text{C IV} \lambda 1549)\) for the combined high-\(z\) and low-\(z\) samples. Hence, it is suggested that there may still be an indirect relation between the Fe II \(\lambda \lambda 4434-4684\) and C IV \(\lambda 1549\) regions.

In summary, the relations among the emission-line properties shown in Figures 3 and 1 appear to be valid for both the low-\(z\) and high-\(z\) quasars with only a few exceptions. This implies that the emission mechanism and the physical properties of the emission-line region in high-\(z\) quasars may not be significantly different from those in low-\(z\) quasars.

\[4\]We note that a radio-loud high-\(z\) (\(z = 2.09\)) quasar 1331+170 also appears to lie within the locus of values found for the low-\(z\) radio-loud quasars (i.e., 1331+170 appears to have “quite weak” optical Fe II emission and \(EW(\text{[O III]} \lambda 4959 + \lambda 5007)/EW(\text{H}\beta) \sim 0.7\) (Carswell et al. 1991).
We are very grateful to the staff of the UH 2.2 m telescope. In particular, we would like to thank Klaus Hodapp for his encouragement and Andrew Pickles for his technical support and assistance with the observations. This work was financially supported in part by Grants-in Aid for Scientific Research (Nos. 07044054 and 09640311) from the Japanese Ministry of Education, Science, Sports, and Culture and by the Foundation for Promotion of Astronomy, Japan. TM thanks the support of Research Fellowships from the Japan Society for the Promotion of Science for Young Scientists. All the figures in this paper were prepared with GP, the graph plotting tool developed by Keiichi Edamatsu. This research has made use of the NASA/IPAC Extragalactic Database (NED) and the NASA Astrophysics Data System Abstract Service.

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Fig. 1.— Comparison of the observed-frame $IHK$ spectra of S40636+68 (solid line) and the LBQS composite spectrum of Francis et al. (1991; dashed line). The upper panel shows the atmospheric transmission for Mauna Kea produced using the program IRTRANS4. These data were obtained from the UKIRT worldwide web pages (http://www.jach.hawaii.edu/UKIRT/home.html).

Fig. 2.— The combined optical and near-infrared spectra of S40636+68 from the literature plus our $IHK$-band spectra. The best power-law fit to the optical–infrared continuum is indicated by the solid line. The dotted line is the LBQS composite spectrum (Francis et al. 1991).

Fig. 3.— The solid line shows our observed-frame $K$-band spectrum of S40636+68 and that of Elston et al. (1994) (dashed line). The spectrum of Elston et al. (1994) is scaled by a factor of two for comparison. The spike feature marked by ‘X’ is caused by residual atmospheric absorption. The center positions of H$\beta$, [O $\text{III}$] $\lambda\lambda 4959, 5007$, and the Fe $\text{II}$ multiplet 42 are indicated by marks. A redshift of $z = 3.2$ is assumed. The upper panel shows the atmospheric transmission.

Fig. 4.— The profile fitting of the $K$-band spectrum. The synthesized spectrum is over-plotted by the dashed line on the original spectrum (solid line). Note that the flux is multiplied by $(1+z)$ for deredshifting. A linear continuum and each emission-line component are also shown.

Fig. 5.— Diagram between equivalent width ratios of $EW([\text{O III}] \lambda 5007+\lambda 4959)/EW(\text{H}\beta)$ and $EW(\text{Fe II } \lambda\lambda 4434–4684)/EW(\text{H}\beta)$ for low-$z$ (small symbols) and high-$z$ quasars (large symbols). Sample data are compiled from Boroson & Green (1992), Hill et al. (1993), Elston et al. (1994), Kawara et al. (1996), Taniguchi et al. (1997). Radio-quiet quasars, flat-spectrum radio-loud quasars, and steep-spectrum radio-loud quasars are shown by open circles, filled circles, and filled squares, respectively. B2 1225+317 (radio-loud) is shown by the filled triangle because its radio spectrum is unknown.

Fig. 6.— Diagram between equivalent width of $EW(\text{C IV } \lambda 1549)$ and $EW(\text{Fe II } \lambda\lambda 4434–4684)$. Large symbols are high-$z$ quasars listed in Table 3 and small symbols are low-$z$ quasars studied by Wang et al. (1996b). Radio-quiet quasars, flat-spectrum radio-loud quasars, and steep-spectrum radio-loud quasars are shown by open circles, filled circles, and filled squares, respectively. B2 1225+317 (radio-loud) is shown by the filled triangle because its radio spectrum is unknown.
Table 1. Journal of observations for the published spectra of S4 0636+68.

| Band | Reference         | Observing Date | Telescope\(^a\) | Aperture |
|------|-------------------|----------------|-----------------|----------|
| Optical | Sargent et al. 1989 | 1987 Oct 19 | Hale5           | 1\" slit |
| Optical | Bechtold et al. 1994 | 1989 Nov 2–3 | SO2.3           | 4\"5 slit |
| \(I\) | Bechtold et al. 1994 | 1989 Dec 12 | MMT             | 3"       |
| \(K\) | Elston et al. 1994 | 1992 Dec      | KPNO2.1         | Not reported |
| \(IJHK\) | This study         | 1996 Apr 7    | UH2.2           | 0\"96 slit |

\(^a\)Hale5 — Hale 5 m Telescope + Double Spectrograph;  
SO2.3 — Steward Observatory 2.3 m Telescope + Boller & Chivens Spectrograph;  
MMT — Multiple Mirror Telescope + Germanium Spectrometer;  
KPNO2.1 — Kitt Peak National Observatory 2.1 m Telescope + Cryogenic Spectrometer;  
UH2.2 — University of Hawaii 2.2 m Telescope + KSPEC.
| Line           | $F/F(H\beta)^{a,b}$ | $EW$(rest)$^c$ (Å) | $FWHM_f$ (km s$^{-1}$) | $FWHM_{cor}^e$ (km s$^{-1}$) |
|---------------|---------------------|-------------------|----------------------|------------------------|
| Local linear continuum |                      |                   |                      |                        |
| $H\beta^a$   | 1                   | 32 ± 4            | 4996                 | 4971                   |
| $[O\,II] \lambda$5007 | 0.16 ± 0.07  | 5.5 ± 2           | 2275                 | 2225                   |
| Fe II $\lambda$$\lambda$3500–6000$^f$ | 3.5 ± 1.1 | 115 ± 32          | ...                  | ...                    |
| Fe II $\lambda$$\lambda$4434–4684$^g$ | 0.83 ± 0.26 | 26 ± 7            | ...                  | ...                    |
| $[O\,II] \lambda$3727 | < 0.30$^h$    | < 7.0$^h$         | ...                  | (1000)                 |
| Global power-law continuum |                      |                   |                      |                        |
| $H\beta^b$   | 1                   | 42 ± 6            | 5920                 | 5900                   |
| $[O\,II] \lambda$5007 | 0.19 ± 0.09  | 8.5 ± 4           | 3592                 | 3561                   |
| Fe II $\lambda$$\lambda$3500–6000$^f$ | 4.7 ± 1.1 | 189 ± 34          | ...                  | ...                    |
| Fe II $\lambda$$\lambda$4434–4684$^g$ | 1.1 ± 0.25 | 43 ± 8            | ...                  | ...                    |
| $[O\,II] \lambda$3727 | < 0.24$^h$    | < 7.1$^h$         | ...                  | (1000)                 |

$^a$ $F(H\beta) = (2.3 \pm 0.3) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.
$^b$ $F(H\beta) = (2.9 \pm 0.4) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.
$^c$ Rest frame equivalent width.
$^d$ Full width at half maximum.
$^e$ Full width at half maximum corrected for instrumental broadening.
$^f$ To compare with the sample of Wills et al. (1985).
$^g$ To compare with the sample of Hill et al. (1993).
$^h$ 3-σ upper limits assuming $FWHM_{cor} = 1000$ km s$^{-1}$. 
Table 3. Rest frame equivalent width of C IV $\lambda 1549$ and Fe II for high-z quasars.

| Name          | Redshift | $M_B$ | $EW$(C IV $\lambda 1549$) (Å) | $EW$(Fe II)$^b$ (Å) | References |
|---------------|----------|-------|-------------------------------|---------------------|------------|
| B2 1225+317   | 2.219    | −30.0 | 6.9                           | 42$^c$              | 1, 2       |
| 1246−057      | 2.244    | −29.1 | 29                            | 58$^c$              | 2, 3       |
| 0933+733      | 2.551    | −29.5 | 29                            | 185$^c$             | 2, 4       |
| S4 0636+68    | 3.200    | −31.3 | 14                            | 26                  | 5, 6       |
| S5 0014+81    | 3.398    | −31.7 | 12                            | 90$^d$              | 5, 7, 8    |
| B 1422+231    | 3.620    | −30.7 | 61$^e$                        | 6.6$^f$             | 9, 10      |
| PKS 1937−101  | 3.787    | −30.3 | 26$^e$                        | < 29                | 11, 12     |

$^a$The absolute $B$ magnitude from Véron-Cetty & Véron (1996).

$^b$Equivalent width of optical Fe II measured between 4434 Å and 4684 Å.

$^c$These values were derived from the flux ratios of Fe II/H$\beta$ tabulated in Hill et al. (1993) and the linear continuum shown in their Figure 2.

$^d$Rough estimate by us from the spectrum given in Elston et al. (1994).

$^e$These values were measured by us from the spectra in the literature.

$^f$This value is re-measured by us because Kawara et al. (1996) did not provide the equivalent width of Fe II.

References for Table 3.

(1) Wilkerson et al. 1978; (2) Hill et al. 1993; (3) Junkkarinen et al. 1987; (4) Steidel & Sargent 1991; (5) Sargent et al. 1989; (6) This study; (7) Sargent et al. 1988; (8) Elston et al. 1994; (9) Hammer et al. 1995; (10) Kawara et al. 1996; (11) Fang & Crotts 1995; (12) Taniguchi et al. 1997.