The most Distant [OIII]-emitting Quasar PKS 1937–101 at redshift 3.8

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ABSTRACT

We report the discovery of a high-z quasar with unambiguous [OIII]$\lambda5007$ emission; PKS 1937–101 at redshift 3.8. This quasar, however, shows little evidence for rest-frame ultraviolet and optical FeII emission. It is thus shown that PKS 1937–101 does not belong to a class of super iron-rich high-z quasars reported by Elston, Thompson, & Hill (1994). The epoch of major star formation in the host galaxy is discussed briefly.

Subject headings: cosmology: observations - galaxies: evolution - galaxies: formation - quasars: individual (PKS 1937–101) - quasars: emission lines

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1. Introduction

The major epoch of star formation in galaxies is one of the most important topics in modern astrophysics, because it is significantly related to the formation of galaxies and quasars as well as to cosmology. Massive stars formed in the first episode of star formation have a lifetime of $10^6$ to $10^7$ years and then release Type II supernova (SNII) products (primarily the $\alpha$-elements such as O, Ne, Mg, Si, etc., but comparatively little iron). It takes a much longer time for Type Ia supernovae (SNIa) to release iron. The different nucleosynthesis yields and timescales of SNIa’s and SNII’s thus make the abundance ratio [$\alpha$/Fe] a potentially useful cosmological clock with which one can identify the epoch of first star formation in galaxies. It is therefore important to study chemical properties of high-redshift ($z$) objects. The best objects are, however, not galaxies but quasars. Quasars possess broad emission-line gas in the nuclear region, which is photoionized by the central black hole engine. It is generally considered that the heavy elements in the broad line regions (BLRs) come from stars in a host galaxy. Therefore, systematic study of chemical properties of BLRs of quasars at high redshift is of particular interest (Hamann & Ferland 1992, 1993). Rest-frame optical emission lines, which are usually used to study chemical properties of nearby objects, are redshifted to the near-infrared (NIR) in these quasars. Recent NIR spectroscopy of high-$z$ quasars has shown that the rest-frame optical spectra are dominated by singly ionized iron (FeII) emission as well as hydrogen recombination lines (Hill, Thompson, & Elston 1993; Elston, Thompson, & Hill 1994; Kawara et al. 1996), suggesting long-lasting star formation in the nuclear regions of the quasar hosts ($\sim 1$ Gyr).

Recently Kawara et al. (1996) detected [OIII] $\lambda$5007 emission from the high-$z$ quasar B1422+231 at redshift 3.62, and showed that the rest-frame UV and optical spectrum is quite similar to the average spectrum of LBQS (Large Bright Quasar Survey) quasars which are mostly located at $z \sim 1 - 2$ (Francis et al. 1991). However, most high-$z$ quasars studied by Hill et al. (1993) and Elston et al. (1994) turn out to be super iron-rich quasars which are not so frequently observed in nearby quasars (cf. L’ipari, Terlevich, & Macchetto 1993). In order to investigate star formation history of high-$z$ quasar hosts, we need more NIR spectroscopic observations of high-$z$ quasars (cf. Taniguchi et al. 1996). Here, we report our new NIR spectroscopy of a high-$z$ quasar PKS 1937−101, which is a radio-loud quasar with a flat spectrum at a redshift of 3.787 (Bolton, Savage, & Wright 1979; Lanzetta et al. 1991). Despite of its high redshift, its optical apparent magnitude is as bright as $V = 17.0$ mag (Véron-Cetty & Véron 1996) and so the absolute magnitude is $M_V = -28.8$ mag (a Hubble constant $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$, and a deceleration parameter $q_0 = 0$ are assumed). The soft X-ray luminosity is also huge, $L_X \sim 2 \times 10^{47}$ erg s$^{-1}$ (Brinkmann & Siebert 1995). Hence, PKS 1937−101 is one of the most intrinsically luminous quasars ever known.
2. Observations and Data Reductions

PKS 1937–101 was observed by using the long-slit Cryogenic Spectrometer (CRSP: Joyce 1995) with a 256 × 256 InSb detector array at the f/15 focus of the Kitt Peak National Observatory (KPNO) 4 meter telescope on 17 May 1995. A 2.3′′ × 49′′ slit with a scale of 0.36′′ pixel−1 was placed on the intensity peak of the object in the EW direction. The seeing size was 2.7′′. A 200 lines mm−1 grating with a blaze angle of 17.5° was used in second order at J (1.095–1.349 µm), and in first order at K (2.055–2.430 µm). OH airglow lines and HeNeAr lamp spectra were used to calibrate the wavelength scale and to measure the spectral resolution. The accuracy of the wavelength scale calibration is 130 km s−1 at J, and 110 km s−1 at K. The typical FWHMs of the spectral resolution are 2000 km s−1 at J and 2300 km s−1 at K. The object was shifted along the slit by 10 arcsec between exposures. The redshift of PKS 1937–101 is so high (z = 3.8) that the conspicuous rest-frame optical emission lines ([OIII] λ5007, Hβ, and some FeII) are redshifted beyond 2.3 µm. Although the K-band spectral coverage extends to 2.43 µm, the background thermal emission makes it difficult to observe at λ > 2.3 µm. We therefore set the unit integration time of K-band observations as 20 s to avoid the background saturation, and took 120 scans to achieve the total integration time = 2400 s. Another interesting emission line MgIIλ2798 is slightly out of the observable range of J band but we made J-band spectroscopy of PKS 1937–101 to see the ultraviolet FeII features as well as the continuum emission. Because the observing time was limited, we took only two 300 s data of J band (the total integration time = 600 s). The data reduction was done using standard techniques (Joyce 1995). The residual sky emission was removed by fitting the sky emission on adjacent sky pixels. A faint standard star HD 162208 (A0; J=7.215 and K= 7.110) was used to calibrate the flux scale and to correct for telluric extinction. A 10000 K black-body spectrum, which fits to the JHKL magnitudes of the standard star (Elias et al. 1982) within 5% deviation, was used for flux scale calibration. The photometric accuracy is estimated to be 7 % in J and 13 % in K.

3. Results and Discussion

Figure 1 shows the observed J- and K- band spectra of PKS 1937–101 together with the LBQS composite spectrum of quasars at z = 1−2 (Francis et al. 1991). The expected FeII emission features are also shown in the lower panel for reference. The K-band spectrum shows [OIII]λ5007, Hβ, and Hγ ([OIII]λ4363 possibly overlaps with this line). The emission-line properties are summarized in Table 1. The Hβ emission seems narrower than those of typical quasars (see Table 1 and Figure 2). The [OIII]/Hβ ratio is similar to that of LBQS composite quasar spectrum. In Figure 2, we show that the observed K-band spectrum can be fitted well solely by the emission lines of [OIII]λ4959,5007, Hβ, Hγ, and the linear continuum. This fitting gives FeII(4434-4686)/Hβ ≃ 0.1 nominally, being smaller than that of B1422+231 (Kawara et al. 1996). We also show the comparison of the rest-frame optical spectra between PKS 1937–101 and B1422+231 (Kawara et al. 1996) in Fig. 3. There cannot be seen strong optical FeII emission in
the PKS 1937−101 spectrum. However, taking account of the poorer S/N of the PKS 1937−101 spectrum, we give a $3\sigma_{\text{rms}}$ upper limit in Table 1 where $\sigma_{\text{rms}}$ is the root mean square noise of flux in the range between 4434 Å and 4686 Å.

The $J$-band spectrum shows little evidence for ultraviolet FeII emission feature, either. In the red edge of the $J$-band spectrum, a blue part of MgII$\lambda$2798 emission can be seen although we cannot estimate anything about this line. Given the photometric accuracy of our $J$- and $K$-band spectra, the difference of fluxes in the $J$ band between ours and the LBQS composite spectrum may well be real. In fact, we can fit the continuum emission with a power law of $F_{\nu} \propto \nu^{-0.50}$ (see Figure 1), which is almost consistent with the average continuum spectrum of quasars, where the power-law index ranges from $-0.3$ (Francis et al. 1991) to $-0.7$ (Sargent et al. 1989). The ultraviolet spectra of most quasars, regardless of radio loudness (Bergeron & Kunth 1984), are dominated by the FeII features as well as the power-law continuum emission. Therefore, the lower flux and the featureless property of the $J$ band spectrum may provide evidence against the presence of ultraviolet FeII emission features in PKS 1937−101. We therefore conclude that PKS 1937−101 does not belong to a class of super iron-rich high-$z$ quasars reported by Elston et al. (1994).

Our NIR spectroscopy has shown that PKS 1937−101 is the most distant quasar with [OIII] emission but little FeII emission. Here we discuss the nature of high-$z$ quasars in terms of their rest-frame optical spectra. We give a summary of the recent NIR spectroscopy of high-$z$ quasars including PKS 1937−101 in Table 2. There is a tendency that the quasars with $z < 3.5$ show strong FeII emission (Hill et al. 1993; Elston et al. 1994) while those with $z > 3.5$ show strong [OIII] emission (Kawara et al. 1996; this paper). One interesting spectroscopic property known for low-$z$ ($z < 0.5$) quasars is the anticorrelation between the strength of optical FeII and [OIII] emission lines, although its physical mechanism is not fully understood (Boroson & Green 1992). We examine if the high-$z$ quasars follow the same anticorrelation. In Figure 3, we show the relationship of the equivalent width ratios between ([OIII]$\lambda$4959 + $\lambda$5007)/$H\beta$ and FeII$\lambda$4434-4684/$H\beta$. The low-$z$ quasars studied by Boroson & Green (1992) show a loose, but statistically significant anticorrelation. It is also shown that the radio-loud quasars tend to be located in the lower portion of this diagram (i.e., weak FeII emitters). PKS 1937−101, B1422+231 (Kawara et al. 1996), and the radio-quiet, high-$z$ quasars studied by Hill et al. (1993) share the same property as those of low-$z$ quasars. On the other hand, the radio-loud quasars studied by Elston et al. (1994) and Hill et al. (1993) do not follow the same trend as low-$z$ quasars. We have shown that PKS 1937−101 and B1422+231 are members of the class of objects which share the same optical emission-line properties as those of low-$z$ quasars. Since the total number of high-$z$ quasars discussed here is only eight, we need more observations to understand the general nature of high-$z$ quasars.

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2Our new measurement of one of the super iron-rich high-$z$ quasars studied by Elston et al. (1994) has shown that S4 0680+68 at redshift 3.2 does not belong to this class (Taniguchi et al. 1996; Murayama et al. 1997).
Finally we comment on the epoch of major star formation in the host galaxy of PKS 1937–101. The α elements, such as O and Mg, come from SNII’s of massive star origin and thus are quickly expelled into the interstellar space after the major episode of star formation (within a few $10^6$ to $10^7$ years). It is considered that the N enrichment is delayed ($\sim 10^8$ years) because it is partly a secondary element formed by CNO cycle in hydrogen-burning shell of intermediate mass stars (Hamann & Ferland 1993). The rest-frame ultraviolet spectra of PKS 1937–101 taken by Lanzetta et al. (1991) and Fang & Crotts (1995) show evidence for NVλ1240 emission. Therefore, the nuclear gas has already been polluted with N, implying that the elapsed time from the major star formation is longer than $\sim 10^8$ years (Hamann & Ferland 1993). However, our observation suggests that the major Fe enrichment has not yet been made in PKS 1937–101. If this is the case, our observations provide a constraint on the epoch of major star formation in the host galaxy. The bulk of iron come from SNIa’s whose progenitors’ lifetime is very likely to cluster around $\sim 1.5$ Gyr (Yoshii, Tsujimoto, & Nomoto 1996). Therefore, the Fe enrichment may start at 1.5 Gyr after the onset of the first, major star formation in quasar host galaxies. These arguments, therefore, specify the epoch of major star formation in PKS 1937–101; $\sim 10^8$ - 1.5×$10^9$ years before redshift 3.787. Namely, the initial star formation would occur at $3.9 < z < 6.7$ for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$, while at $4.0 < z < 17$ for $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$. Recent theoretical prescription on the star formation at high-z universe suggests that the major epoch of star formation may occur $z < 5$ although subgalactic structures may exist even at $z > 10$ (Rees 1996; Ostriker & Gnedin 1996). Provided that the smaller $H_0$ is more preferable, the present observation is consistent with this prescription.

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Fig. 1.— The spectrum of PKS 1937−101 at \(z = 3.787\) in the observed frame. The composite spectrum of 700 LBQS quasars at \(z \sim 1 - 2\) is also shown. The dashed curve shows the power-law \(F_{\nu} \propto \nu^{-0.5}\) continuum fit for the emission- and absorption-free continua of the observed \(J\)- and \(K\)-band spectra. The bars at the both sides of the \(J\)- and \(K\)-band spectra show the photometric accuracy. It is noted that there are two possible absorption features at \(\lambda = 12575\) Å and \(\lambda = 12890\) Å. If they are attributed to MgII absorbers, their redshifts would be 3.493 and 3.604, respectively. The top panel shows the atmospheric transmission curve at the Kitt Peak. The lower panel shows the expected FeII emission feature for reference.

Fig. 2.— The \(K\)-band spectrum of PKS 1937−101. The profile fit is made for \(H_\gamma\), \(H_\beta\), and \([\text{OIII}]\lambda4959,5007\). The \(H_\beta\) emission is deconvolved into the narrow (FWHM \(\approx 1970\) km s\(^{-1}\)) and broad (FWHM \(\approx 7710\) km s\(^{-1}\)) components (see Table 1). The continuum is fitted linearly. We do not use the data of both \(\lambda_{\text{rest}} < 4200\) Å and \(\lambda_{\text{rest}} > 5100\) Å in the fitting because the spectral quality is not good due to the low atmospheric transmission. In the lower panel, the residual of the fit is compared with the expected FeII emission feature.

Fig. 3.— The comparison of the rest-frame optical spectra between PKS 1937−101 and B1422+231 (Kawara et al. 1996).

Fig. 4.— Diagram between \(([\text{OIII}]\lambda5007+\lambda4959)/H_\beta\) equivalent width ratio and FeII\(\lambda4434-4684/H_\beta\) one for low-\(z\) (small symbols) and high-\(z\) quasars (large symbols). Radio-quiet, radio-loud with flat spectrum, and radio-loud with steep spectrum are shown by open circles, filled circles, and filled squares, respectively. B2 1225+317 is shown by the filled triangle because its radio spectrum is unknown. The numbers given for the high-\(z\) quasars correspond to those in Table 2.
Table 1: Emission line properties of PKS 1937−101

| Line             | $F/F(H\beta(N+B))^a$ | EW(rest)$^b$ (Å) | FWHM$^c$ (km s$^{-1}$) | FWHM$^{d}_{\text{cor}}$ (km s$^{-1}$) |
|------------------|----------------------|------------------|-----------------------|--------------------------------------|
| $H\gamma + [\text{OIII}]\lambda 4363$ | 0.21 ± 0.13          | 11.7 ± 7.4       | 6500                  | 5900                                 |
| $H\beta(N)$     | 0.46 ± 0.13          | 30.5 ± 8.5       | 1970                  | $<$1970                              |
| $H\beta(B)$     | 0.54 ± 0.19          | 36.1 ± 13        | 7710                  | 7350                                 |
| $[\text{OIII}]\lambda 5007$     | 0.27 ± 0.05          | 18.8 ± 4.5       | 2450                  | 960                                  |
| FeII($\lambda 4434-4684$)$^e$   | $< 0.49^f$           | $< 29^f$         | -                     | -                                    |

$^a$ N = narrow component, and B = broad component. $F(H\beta(N+B)) = 3.9 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

$^b$ The rest frame equivalent width.

$^c$ Full width at half maximum.

$^d$ Full width at half maximum corrected for instrumental broadening.

$^e$ To compare with those of low-z quasars studied by Boroson & Green (1992).

$^f$ Upper limit (3 $\sigma$).
| No. | Name            | Redshift | Type$^a$     | $M_V^b$ | [OIII]/H$\beta^c$ | FeII/H$\beta^d$ | References$^e$ |
|-----|-----------------|----------|--------------|---------|------------------|-----------------|----------------|
| 1   | B2 1225+317     | 2.219    | Loud         | −28.5   | < 0.05           | 1.95            | 1              |
| 2   | Q1246−057       | 2.244    | Quiet (BAL)  | −27.6   | < 0.10           | 1.80            | 1              |
| 3   | Q0933+733       | 2.528    | Quiet        | −28.0   | < 0.21           | 1.78            | 1              |
| 4   | Q1413+117       | 2.551    | Quiet (BAL)  | −28.3   | 0.42             | 1.54            | 1              |
| 5   | Q0636+680       | 3.195    | Loud (Flat)  | −29.8   | < 0.1$^f$        | 2.3$^f$         | 2              |
| 6   | Q0014+813       | 3.398    | Loud (Flat)  | −30.2   | < 0.6$^f$        | 2.3$^f$         | 2              |
| 7   | B1422+231       | 3.620    | Loud (Flat)  | −29.2$^g$| 0.26             | 0.16            | 3              |
| 8   | PKS1937-101     | 3.787    | Loud (Flat)  | −28.8   | 0.36             | < 0.49$^h$      | 4              |

Table 2: A summary of NIR spectroscopy of high-z quasars

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$^a$ Loud = Radio loud, Flat = flat-spectrum source, Quiet = radio quiet, BAL = broad-absorption-line feature.

$^b$ The absolute $V$ magnitude. A Hubble constant, $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$, and a deceleration parameter, $q_0 = 0$, are assumed.

$^c$ The flux ratio. $[\text{OIII}] = [\text{OIII}]\lambda4959 + [\text{OIII}]\lambda5007$.

$^d$ The flux ratio. $\text{FeII} = \text{FeII}\lambda4570 = \text{FeII}\lambda4434-4684$.

$^e$ References: 1. Hill et al. (1993), 2. Elston et al. (1994), 3. Kawara et al. (1996), 4. This paper.

$^f$ Rough estimates by us from the spectra given in Elston et al. (1994).

$^g$ Gravitationally amplified. Possible magnification factor is 15 - 30 and thus the absolute magnitude should be reduced by this factor (Hogg & Blandford 1994; Kormann, Schneider, & Bartelmann 1994).

$^h$ Upper limit ($3\sigma_{rms}$).
Flux ($10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$)

MgII $\gamma$ + [OIII] $\beta$ [OIII]

Abs 1 Abs 2

(Francis et al. 1991)

PKS1937–101

LBQS Composite Spectrum

Transmission

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

Rest Wavelength (Å)

- Residual
- Expected FeII Spectrum
PKS1937–101

B1422+231

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

Wavelength (Å)
