Detection of Iron Emission in the $z = 5.74$ QSO
SDSSp J104433.04$-$012502.2$* 

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(Received 2001 September 5; accepted 2002 April 16)

Abstract

We obtained near-infrared spectroscopy of the $z = 5.74$ QSO, SDSSp J104433.04$-$012502.2, with the Infrared Camera and Spectrograph of the Subaru Telescope. The redshift of 5.74 corresponds to a cosmological age of 1.0 Gyr for the current $\Lambda$-dominated cosmology. We found a similar strength of the Fe II (3000–3500 Å) emission lines in SDSSp J104433.04$-$012502.2 as in low-redshift QSOs. This is the highest redshift detection of iron. We subtracted a power-law continuum from the spectrum and fitted model Fe II emission and the Balmer continuum. The rest equivalent width of Fe II (3000–3500 Å) is $\sim 30$ Å, which is similar to those of low-redshift QSOs measured in the same manner. The chemical-enrichment models that assume the lifetime of the progenitor of SNe Ia is longer than 1 Gyr predict that weaker Fe II emission in high-redshift ($z > 3$) QSOs than low-redshift ones. However, none of the observed high redshift QSOs show a systematic decrease of Fe II emission compared with low-redshift QSOs. This may be due to a shorter lifetime of SNe Ia in QSO nuclei than in the solar neighborhood. Another reason for the strong Fe II emission at $z = 5.74$ may be a longer cosmological age due to a smaller $\Omega_\Lambda$.

Key words: galaxies: active — galaxies: quasars: emission lines — galaxies: quasars: individual (SDSSp J104433.04$-$012502.2)

1. Introduction

The enrichment of $\alpha$-elements (e.g., O and Mg) in the universe has different time scales from that of iron-peak elements. While both $\alpha$-elements and iron are produced by SNe II, SNe Ia produce mostly iron. The progenitors of SNe Ia are intermediate-mass stars in binary systems and have a lifetime of $\sim 1$ Gyr, although there is still debate about the progenitors of SNe Ia and their lifetime (e.g., Branch 1998; Hillebrandt, Niemeyer 2000; for recent reviews). The 1 Gyr lifetime of the progenitors of SNe Ia is longer than that of SNe II, which are massive stars. The iron/$\alpha$ abundance ratio shows a rapid increase when SNe Ia start to explode. The $[$O/Fe$]$–$[$Fe/H$]$ relation in the solar neighborhood is reproduced by that scenario assuming a 0.5–3 Gyr lifetime of the progenitors of SNe Ia (Yoshii et al. 1996; Kobayashi et al. 1998). Among high-redshift objects, except for metal absorption-line systems, the QSOs’ spectra show both iron and $\alpha$-element spectral features. In particular, both Mg II $\lambda 2798$ Å and Fe II UV (2000–3000 Å) as well as Fe II (3000–3500 Å) emission lines are emitted from the same ionized zone of the broad-line region gas, and their similar wavelengths mean that the extinction is similar. Therefore, we can use the intensity ratio of their fluxes as an indicator of the iron/$\alpha$ abundance ratios (Wills et al. 1985; Hamann, Feldman 1993). A comparison of the observed intensity ratio, $I(\text{Fe II})/I(\text{Mg II})$, in low-redshift QSOs along with the results of model calculations of the broad-line region suggests an iron overabundance by a factor of $\sim 3$ at low redshift (Wills et al. 1985). The iron overabundance of low-redshift QSOs is reproduced by a QSO chemical-enrichment model assuming rapid star formation and a delay of SNe Ia events (Hamann, Feldman 1993).

Recently, more than 20 high-redshift ($3.3 < z < 4.7$) QSOs have been observed with near-infrared spectroscopy; also Mg II, Fe II UV, and Fe II (3000–3500 Å) emission lines were measured (Kawara et al. 1996; Murayama et al. 1999; Thompson et al. 1999; Dietrich, Hamann 2001; Dietrich et al. 2002). Their $I(\text{Fe II(UV)})/I(\text{Mg II})$ are 7–10 and comparable to that of low-redshift QSOs (Wills et al. 1985). These ratios are interpreted as suggesting QSO ages of $> 1$ Gyr in terms of the chemical-enrichment model (Hamann, Feldman 1993; Yoshii et al. 1998). The chemical-enrichment model (Yoshii et al. 1998) indicates that the $I(\text{Fe II(UV + optical)})/I(\text{Mg II})$ remains less than 2 until 1 Gyr has passed since the first star formation occurred. After 1 Gyr has passed, $I(\text{Fe II(UV + optical)})/I(\text{Mg II})$ rapidly increases to $\sim 12$ at 1.5 Gyr. The highest redshift for which $I(\text{Fe II})/I(\text{Mg II})$ was observed was 4.7 (Thompson et al. 1999; Dietrich, Hamann 2001), which...
corresponds to an age of 1.3 Gyr in a cosmology with the current (most likely) cosmological parameters.\textsuperscript{1} The large value of the $I$(Fe II)/$H$(Mg II) suggests that the first star formation occurred at $z \gtrsim 10$, which corresponds to 0.5 Gyr (Dietrich, Hamann 2001).

The QSO at $z = 5.74$, SDSSp J104433.04−012502.2 (hereafter SDSS 1044−0125; Fan et al. 2000) was discovered in the spring of 2000 by the Sloan Digital Sky Survey (York et al. 2000). It is a luminous QSO ($L_{\text{v},2500} = 5.2 \times 10^{41} \text{erg s}^{-1} \text{Hz}^{-1}$) and the highest redshift object as of 2001 February when the observation was made. Maiolino et al. (2001) have found a broad absorption line in its spectrum, suggesting that heavy absorption by gas with a column density of $N_\text{H} > 10^{24} \text{cm}^{-2}$ is the reason for its X-ray faintness (Brandt et al. 2001), Goodrich et al. (2001) made moderate-resolution near-infrared spectroscopy and revised the redshift to 5.74 by measuring the peak of the C IV emission line. Since its redshift of 5.74 corresponds to a cosmological age of 1.0 Gyr, SDSS 1044−0125 is less than 1 Gyr old and the progenitor of SNe Ia in the QSO would not have exploded yet. The Fe II emission of SDSS 1044−0125 is expected to be weak. The Mg II emission line is difficult to observe because it is redshifted to a spectral region of low atmospheric transparency.

2. Observations and Data Reduction

The near-infrared ($J$, $H$, and $K$-band) spectra of SDSS 1044−0125 were obtained with the Infrared Camera and Spectrograph (IRCS; Kobayashi et al. 2000) at the Cassegrain focus of the Subaru Telescope on the nights of 2001 February 4 and 5 (UT). Both nights were photometric, but the seeing was unstable. It changed from 0\arcsec4 to 1\arcsec2 in the $K$-band. The projected pixel size of the 1024×1024 ALADDIN II array was 0\arcsec058 along the slit, and 3.7, 4.7 and 6.1 $\mu$m along the dispersion direction in the $J$-, $H$-, and $K$-bands, respectively. A slit width of 0\arcsec9 was used, resulting in resolutions in the $J$-, $H$-, and $K$-bands of 74, 117, and 198 $\AA$ FWHM, respectively. We obtained 12, 12 and 64 exposures, each with 300 s integration, in the $J$-, $H$-, and $K$-bands, respectively, shifting the position of the QSO along the slit at intervals of 7\arcsec between each integration. The total integration times on the QSO were 3600, 3600, and 19200 s in the $J$-, $H$-, and $K$-bands, respectively. Observations of a nearby G5 star, HD 93019, were made before and after the observation of the QSO at approximately the same airmass to correct the spectra for telluric absorption, and for a flux calibration. The spectra of a halogen lamp and an argon lamp were obtained for flat field and wavelength calibrations, respectively.

The data were reduced using IRAF.\textsuperscript{2} Dark frames of the same integration times as for the QSO and the star, HD 93019, were subtracted from the data frames. The following procedures were separately applied for each wavelength band. After masking the bad pixels, flat fielding was done with an averaged and normalized flat frame. The sky was removed by subtracting an adjacent exposure with the QSO at a different position along the slit. The sky-subtracted QSO frames at the same position along the slit, but different airmass, were averaged because the low S/N of a single frame hampered a check of whether the telluric absorption features were removed. Although the S/N of the QSO’s spectra was improved due to averaging, the continuum of the QSO in the averaged frame was not bright enough to trace its position. Therefore, we first traced the spectra of the telluric absorption correction star, HD 93019. This trace was used for extracting the QSO’s spectra and the comparison spectra. The extracted one-dimensional comparison spectra were used for a wavelength calibration of the QSO’s extracted one-dimensional spectra. After a wavelength calibration of the one-dimensional spectra, the spectra of the QSO at different positions along the slit were combined to produce the QSO’s spectrum in each wavelength band. The spectra of HD 93019 were extracted from the sky-subtracted frames, and then wavelength-calibrated using one-dimensional extracted comparison spectra. The spectra of HD 93019, obtained at different positions along the slit, but the same airmass, were combined to give a spectrum at each airmass in each wavelength band. For a relative-flux calibration, we divided the spectra of HD 93019 by a 5560 K blackbody spectrum to make relative sensitivity functions, including telluric absorption. Since the QSO spectra obtained at different airmasses were combined into a single spectrum, we averaged the relative-sensitivity functions at different airmasses to correct for the telluric absorption and instrument sensitivity. The S/N ratios of the QSO spectra in the $J$-, $H$-, and $K$-bands are $\sim 5$, $\sim 2$, and $\sim 12$, respectively.

Although the detector covered between 1.18 and 1.38 $\mu$m in the $J$ band, the sensitivity of the grism used was low shortward of 1.24 $\mu$m and longward of 1.35 $\mu$m, and the signal from the QSO in that wavelength range was almost nothing. We therefore used the region between 1.24 $\mu$m and 1.35 $\mu$m for the $J$-band spectrum.

3. Results

Figure 1 shows the rest-frame spectra of SDSS 1044−0125 in the $J$- and $K$-bands together with the spectra obtained by Maiolino et al. (2001). The spectra of SDSS 1044−0125 were deredshifted by adopting $z = 5.74$ (Goodrich et al. 2001), and were smoothed 4.8 $\AA$ in the $J$-band and 13.5 $\AA$ in the $K$-band, respectively. Since our spectra were obtained under unstable seeing conditions, light from the QSO falling into the 0\arcsec9 slit varied among the exposures. The absolute flux density scale of the $J$-band to the $K$-band spectrum is unknown. Maiolino et al. (2001) simultaneously obtained the $J$-, $H$-, and $K$-band spectra of SDSS 1044−0125. We scaled our $J$- and $K$-band spectra to the spectra from Maiolino et al. (2001) at 1850−1965 $\AA$ in the $J$-band and 3000−3500 $\AA$ in the $K$-band, respectively. An emission feature is recognized at 1900 $\AA$ in the rest frame. This feature is a complex of Si III\[ and C III\[ as found by Maiolino et al. (2001). Since our $H$-band spectrum of SDSS 1044−0125 has a very low S/N, we did not use the $H$-band data. As shown by Maiolino et al. (2001), the spectrum of SDSS 1044−0125

\textsuperscript{1} We adopt $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 65 \text{ km s}^{-1} \text{Mpc}^{-1}$ throughout the paper (Schmidt et al. 1998; Perlmutter et al. 1999; de Bernardis et al. 2000; Melchiorri et al. 2000).

\textsuperscript{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.
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Fig. 1. (Upper panel:) Atmospheric transmission curve. These data, produced using the program IRTRANS4, were obtained from the UKIRT WWW page. (Lower panel:) Our spectra of SDSS 1044−0125, which was smoothed and shifted to the rest wavelength by the redshift of 5.74 (red line), and the result by Maiolino et al. (black line). The $F_\lambda$ scale of our SDSS 1044−0125 spectra was shifted to the spectra obtained by Maiolino et al. (2001). The smoothed LBQS composite spectrum is plotted for comparison. It was shifted for clarity by 8. The dashed line is a power-law continuum ($F_\nu \propto \nu^{-0.54}$). See text for details.

is similar to that of the Large Bright Quasar Survey (LBQS) composite spectrum\(^3\) using the total data set (Brotherton et al. 2001), which is a low-redshift optically-selected QSO template. The spectrum of SDSS 1044−0125 between 2900 Å and 3400 Å is similar to the LBQS composite spectrum. The bump between 2900 Å and 3000 Å is Fe\(\text{II}\) emission (Vestergaard, Wilkes 2001) and the increase in flux from 3000 Å to 3400 Å is also due to Fe\(\text{II}\) emission and the Balmer continuum (Wills et al. 1985; Verner et al. 1999).

We measured the Fe\(\text{II}\) emission-line strength as follows. Since our spectrum covered a limited wavelength range, we determined the power-law continuum ($F_\nu \propto \nu^{-\alpha}$) at 1465 Å and 2231 Å in the spectrum of Maiolino et al. (2001). After subtracting the power-law continuum from the $K$-band spectrum of SDSS 1044−0125, we assume that the SDSS 1044−0125 spectrum could be fitted with a Fe\(\text{II}\) template and the Balmer continuum, so that

$$F_{\lambda, \text{SDSS}} = a F_{\lambda, \text{Fe\(\text{II}\)}} + b F_{\lambda, \text{Balmer continuum}}.$$  \(^{(1)}\)

We performed a $\chi^2$ fitting between 2855 Å, which is the shortest end of the $K$-band spectrum, and 3600 Å, and derived the scaling parameters, $a$ and $b$. The Fe\(\text{II}\) template was adopted from Wills et al. (1985). It was calculated assuming the

\(^{(3)}\) (http://sundog.stsci.edu/first/QSOComposites/)
broadened the Fe II template by convolving it with a Gaussian.

There is a possibility of contamination of the O III fluorescence emission. We also measured the Fe II strength of the LBQS λ(1982), with the assumed Balmer hydrogen density, \( n_H = 10^{9.5} \) cm\(^{-3}\) and the ionization parameter, \( U_{\text{ion}} = 1.2 \times 10^3 \) cm\(^{-s}\). The product of the optical depth at 2343 Å, \( \tau(2343) \), times the turbulent velocity \( (V_t) \), was assumed to be constant. We chose the template under the conditions \( \tau(2343) = 5 \times 10^3 \) and \( V_t = 7 \) km s\(^{-1}\), because the relative strength between Fe II multiplets was the most similar to the data of SDSS 1044−0125 among the templates available. We broadened the Fe II template by convolving it with a Gaussian of FWHM \( = 6000 \) km s\(^{-1}\), which is the line width of the C IV emission line (Goodrich et al. 2001). The assumed Balmer continuum was a partially optically-thick case given by Grandi (1982), with \( T_{\text{B}} = 1.0 \), \( v_{\text{B}} = 3646 \) Å and \( T = 10000 \) K:

\[
F_\nu \propto B_\nu(T)(1 - e^{-\tau}) \quad \text{with} \quad \tau = \tau_{\text{B}}(v/v_{\text{B}})^{-3}.
\]

The best-fit results are shown in figure 2 and in table 1. The 68% (~1σ) confidence ellipses are also shown in figure 3. Combined with the power-law continuum flux at 3250 Å, the rest equivalent width (EW) of Fe II (3000–3500 Å) is ~30 Å. There is a possibility of contamination of the O III fluorescence line \( \lambda 3133\) and He II \( \lambda 3203\). If significant emission of \( \lambda 3133\) existed, a 3200 Å bump of the QSO would start at ~50 Å shorter wavelength than the spectra of the SDSS 1044−0125. Here, we judged no significant contamination of the O III fluorescence line. Meanwhile, we could not estimate He II \( \lambda 3203\). The residual at 3200 Å may be due to He II (figure 2). However, a dip at 3300 Å is not reproduced by only He II \( \lambda 3203\); therefore we think that most of a bump between 3100 and 3400 Å is Fe II emission. We also measured the Fe II strength of the LBQS composite spectrum and the composite quasar spectrum from the Sloan Digital Sky Survey (SDSS) (Vanden Berk et al. 2001) in the same manner as for SDSS 1044−0125. The power-law continua were decided at the minimum between 1450 and 1470 Å and the minimum between 2200 and 2250 Å. The indexes of the power-law continuum for the LBQS and SDSS composites are 0.48 and 0.56, respectively. We performed a \( \chi^2 \) fitting between 2855 and 3600 Å using the same Fe II template and the Balmer continuum using for SDSS 1044−0125. The derived Fe II (3000−3500 Å) EW of the LBQS composite and that of SDSS composite are 32 Å and 34 Å, respectively. Because this value is the same as that of SDSS 1044−0125, the strength of Fe II (3000–3500 Å) in SDSS 1044−0125 is similar to that of low-redshift QSOs.

### 4. Discussion

Although we could not observe the Mg II \( \lambda 2798 \) emission line, the N V, C IV, and C III] emission-line strengths in SDSS 1044−0125 are similar to that of low-redshift QSOs (Goodrich et al. 2001; Maiolino et al. 2001). This fact suggests that the strength of Mg II of SDSS 1044−0125 would be the similar to that of low-redshift QSOs. We measured the intensity of the Mg II emission line in the LBQS composite and the SDSS composite. The \( I(\text{Fe II}(3000–3500 \text{ Å})) / I(\text{Mg II}) \) in the LBQS composite and the SDSS composite are 0.69 and 0.70, respectively. Although we assumed the strength of Mg II of SDSS 1044−0125 will be similar to that of low-redshift QSOs, and there is a 50% error in the measurement of the Fe II of SDSS 1044−0125, the \( I(\text{Fe II}(3000–3500 \text{ Å})) / I(\text{Mg II}) \) in SDSS 1044−0125 would at least be similar or larger than the result (0.15–0.4) from a solar abundance Broad Line Region model calculation (Wills et al. 1985). Since a redshift of 5.74 corresponds to only 1.0 Gyr past from the Big Bang, the iron abundance of the QSO is predicted to be a solar value, assuming a high star-formation efficiency (Hamann, Ferland 1993; Yoshii et al. 1998) which could reproduce the Balmer continuum using for SDSS 1044−0125. The Fe II emission in SDSS 1044−0125 is a factor of ~2 stronger than the prediction by the chemical-enrichment model of QSOs. These chemical-enrichment models assume the typical lifetime of the progenitor of SNe Ia to be more than 1 Gyr; therefore, the iron enrichment relative to the α-element delays. The 0.5–3 Gyr lifetime of the progenitor of SNe Ia naturally explains the \( [\text{O/Fe}]/[\text{Fe/H}] \) relation in the solar neighborhood (Yoshii et al. 1996; Kobayashi et al. 1998); however, the lifetime of the progenitor of SNe Ia is not theoretically constrained very much because the lifetime of the companion in the case of a white-dwarf model accreting from matter from the companion or intrinsic separation in the case of merging white dwarfs model (Iben, Tutukov 1984; Tutukov, Yungelson 1994) is unknown. The merging white-dwarf model predicts a shorter lifetime (0.3–0.4 Gyr) of the progenitor (Tutukov, Yungelson 1994).

All observed high-redshift (\( z > 3 \)) QSOs, which are all luminous and must be massive galaxies, have a similar \( I(\text{Fe II}) / I(\text{Mg II}) \) ratio to that of low-redshift QSOs, and no systematic decrease appears from them (Kawara et al. 1996; Murayama et al. 1999; Thompson et al. 1999; Dietrich, Hamann 2001; Dietrich et al. 2002). This line ratio suggests an iron overabundance, even if

### Table 1. The result of fit.

| \( \alpha \) | \( \chi^2 \) (d.o.f.) | Fe II* [rest EW (Å)] |
|---|---|---|
| 0.54 | 210 (52) | 31 ± 15 |

\* Fe II is measured between 3000 and 3500 Å.
the age of the universe is ~1 Gyr, although there might be hidden physics which controls the Fe II emission-line strength to be constant even if the abundance is changed. The progenitor of SNe Ia in the nucleus of QSOs, where the gravitational potential is deeper and the star density is higher, may be different from that in the solar neighborhood (Thompson et al. 1999).

Another interpretation of the strong Fe II emission at z = 5.74 is that cosmological parameters are different from those which we adopted. The relation between age and redshift depends on the cosmological parameters; i.e., the Hubble constant (H0) and the matter density (ΩM). In a flat universe the age is \( t \propto H_0^{-1} \Omega_p^{-1/2} \) at a high-redshift regime (z > 3). If we assume H0 to be 50 km s\(^{-1}\) Mpc\(^{-1}\), the cosmological age at z = 5.74 would be 1.4 Gyr, which is consistent with the model predicting an iron overabundance (Yoshii et al. 1998). The H0 of 50, however, is too much smaller than that derived from such as the Cepheid distance, the Tully–Fisher relation, the fundamental plane of elliptical galaxies, the surface brightness fluctuations, and SNe Ia (Mould et al. 2000). The estimate of the matter density (ΩM) on the other hand, has a rather large uncertainty. The measurement of the inhomogeneity of the cosmic-background radiation (de Bernardis et al. 2000; Melchiorri et al. 2000) and the observations of high redshift SNe Ia (Schmidt et al. 1998; Perlmutter et al. 1999) indicate a flat universe and 0.1 ≲ ΩM ≲ 0.4 (de Bernardis et al. 2000). If we adopt a ΩM of 0.2 instead of 0.3, the cosmological age at z = 5.74 would extend to 1.3 Gyr. The large \( I(\text{Fe II}) / I(\text{Mg II}) \) may suggest a smaller ΩM.

5. Conclusion

We obtained near-infrared spectra of the z = 5.74 QSO, SDSS 1044–0125, with the Infrared Camera and Spectrograph of the Subaru Telescope. We found the strength of the Fe II emission to be similar to that of low-redshift QSOs. This is the highest redshift detection of iron. Its equivalent width of Fe II (3000–3500 Å) is ~30 Å, which is similar to those of low-redshift QSOs. We estimated \( \frac{I(\text{Fe II})}{I(\text{Mg II})} \sim 0.7 \). Because the redshift of 5.74 corresponds to an age of 1.0 Gyr in the case of the current Λ-dominated cosmological parameter, this ratio is larger than the prediction of chemical-enrichment models that assume the lifetime of the progenitor of SNe Ia to be longer than 1 Gyr. There is no systematic decrease in the Fe II emission in the observed high-redshift QSOs (z > 3) from low-redshift ones. This suggests that short-lived SNe Ia progenitors may be more common in a QSO nucleus than in the solar neighborhood. It is necessary to search whether there is no hidden physics of the Fe II emission mechanism in order to definitely show the possibility of short-lived SNe Ia progenitors. Another interpretation of a high \( I(\text{Fe II}) / I(\text{Mg II}) \) at z = 5.74 is that the actual ΩM may be smaller than that we adopted; i.e., the cosmological age at z = 5.74 may be longer than 1 Gyr.

We are grateful to the IRCs instrument team, especially H. Terada and N. Kobayashi for their help and valuable comments during our observations. We also thank B. Wills for kindly providing an Fe II model template, her valuable comments, and improving the English expression. Discussions with M. Yoshida, T. Yamada, and N. Arimoto have improved this paper. The data reduction was done using the facilities of the Astronomical Data Analysis Center, National Astronomical Observatory of Japan, which is an inter-university research institute operated by the Ministry of Education, Culture, Sports, Science and Technology. This work was financially supported in part by Grant-in-Aids for the Scientific Research (No. 13740122) or the Japanese Ministry or Education, Culture, Sports, Science and Technology.

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