The Epoch of Major Star Formation
in High-z Quasar Hosts

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The Epoch of Major Star Formation in High-z Quasar Hosts

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Abstract. We present the results of our observing program on NIR spectroscopy of high-redshift (z) quasars which have been undertaken both at Kitt Peak National Observatory and at Mauna Kea Observatory, University of Hawaii. These data are utilized for studying the epoch of major star formation in high-z quasar hosts.

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 α-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.

Since it is considered that the heavy elements in the broad line regions (BLRs) come from stars in a host galaxy, systematic study of chemical properties of BLRs of quasars at high redshift is of particular interest (Hamann & Ferland 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) suggesting long-lasting star formation in the nuclear regions of the quasar hosts ($\sim 1$ Gyr).
In order to study the major epoch of star formation in high-$z$ quasar hosts, we present new results of our NIR spectroscopy of high-$z$ ($z > 3$) quasars; 1) B1422+231 ($z = 3.62$; Patnaik et al. 1992), 2) PKS 1937−101 ($z = 3.79$; Lanzetta et al. 1991), and 3) S4 0636+68 ($z = 3.2$; Stickel & Kuhr 1994).

2 Observational Results

The two quasars, B1422+231 and PKS 1937−101, were observed by using the long-slit Cryogenic Spectrometer (CRSP) with a 256×256 InSb detector array at the f/15 focus of the Kitt Peak National Observatory (KPNO) 4 meter telescope while the other quasar, S4 0636+68, was observed by using the KSPEC at the Cassegrain focus of the UH 2.2 m telescope. The details of the observations and the data reduction are given elsewhere (Kawara et al. 1996; Murayama et al. 1997). The spectra of the three quasars are shown in Fig. 1. We describe their important observational properties below.

2.1 B1422+231

The spectrum in Fig. 1 shows the emission lines, MgII$\lambda$2798, H$\gamma$, H$\beta$, and [OIII] $\lambda$5007 as well as a marginal detection of CIII$\lambda$2326. Note that this is the first detection of [OIII] $\lambda$5007 in a quasar beyond $z = 3$ (Kawara et al. 1996). [OIII] $\lambda$5007 relative to H$\beta$ is smaller in B1422+231 than the LBQS composite (Francis et al. 1991). The broad feature of optical Fe II emission lines is present. The feature shortward of MgII emission line is due to UV Fe II emission.

The flux ratio Fe II(UV + opt)/Mg II of B1422+231 is comparable to that of the LBQS composite spectrum: 12.2 ± 3.9 for B1422+231 and 8.9 for the LBQS composite. Note that Fe II(UV) and Fe II(opt) denote Fe II emission in 2000 − 3000 Å and 3500 − 6000 Å in the rest-frame, respectively. Wills, Netzer, & Wills (1985) give a mean ratio of 7.8 ± 2.6 for nine low-$z$ quasars with $z = 0.15−0.63$. It is thus suggested that the major iron enrichment has already been done in this quasar host.

2.2 PKS 1937−101

The [OIII]/H$\beta$ ratio is similar to that of LBQS composite quasar spectrum. Since the observed K-band spectrum can be fit well solely by the emission lines of [OIII] $\lambda$4959,5007, H$\beta$, H$\gamma$, and the linear continuum, there seems little optical FeII emission which is ubiquitously observed in either high-$z$ quasars (Hill et al. 1993; Elston et al. 1994; Kawara et al. 1996) or most low-$z$ quasars (Boroson & Green 1992). The J-band spectrum shows also little evidence for UV FeII emission feature, either. We fit the continuum emission with a power law of $F_{\nu} \propto \nu^{-0.50}$, 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 UV 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, both the lower flux and the featureless property of the $J$ band spectrum are explained by the absence of UV FeII emission features in PKS 1937−101. In the red edge of the $J$-band spectrum, a blue part of MgII λ2798 emission can be seen.

2.3 S4 0636+68

The NIR spectrum of this quasar was first reported by Elston et al. (1994) who showed that its rest-frame optical spectrum is significantly dominated by FeII emission lines, suggesting an iron overabundance than in the solar neighbourhood. Although our new measurement has confirmed the presence of FeII λ5169 emission, its intensity relative to that of Hβ emission is significantly weaker than that of Elston et al. (1994). The intensity ratio of FeII(opt)/Hβ is estimated to be 3.5±1.1. This value is slightly larger than those of low-z quasars; 1.63±0.88 (Wills et al. 1985). However, we cannot conclude that S4 0636+68 belongs to a class of strong iron quasars (cf. Lípari, Terlevich, & Macchetto 1993).

3 Discussion

We discuss the nature of high-z quasars in viewed from their rest-frame optical spectra. 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. It should be, however, mentioned that the strong optical FeII emission of S4 0636+68 reported by Elston et al. (1994) is not confirmed in this study. One interesting spectroscopic property known for low-z 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 Fig. 2, we show the relationship of the equivalent width ratios between ([OIII] λ4959+λ5007)/Hβ and FeII λ4434-4684/Hβ. The low-z quasars studied by Boroson & Green (1992) show a loose, but statistically significant anticorrelation. It is also known 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 as low-z quasars although our new measurement of S4 0636+68 shows that the ratio is consistent with those of low-z quasars. If there would be many strong iron radio-loud quasars at high redshifts, we would have to introduce a new class of quasars which has not yet been observed at low redshifts.

Finally, we discuss the epoch of major star formation in the host galaxies of B1422+231 and PKS 1937−101.

1) B1422+231: We show that the ratio of Fe II/Mg II, including UV Fe II emission lines, in the broad-line gas of some quasars at $z = 3.6$ is almost
Fig. 1. The rest-frame optical spectra of the three high-z quasars; S4 0636+68, B1422+231, and PKS 1937–101. The dashed spectrum in each panel is the mean spectrum of LBQS quasars taken from Francis et al. (1991).

identical to those at the low-redshift quasars. This may imply that the Fe/Mg abundance at the center of some quasar host galaxies did not change after $z = 3.6$. It is generally considered that Mg is preferentially produced in massive star supernovae (SNe II, Ib, and Ic) on short time scales (2–10 Myr), while Fe is mainly created by accreting white dwarf supernovae (SNe Ia) in much longer time scales (1–2 Gyr). The Fe/Mg abundance ratio should be $1/4$ of the solar value until SNe Ia start to produce significant amount of Fe. When SNe Ia dominate the Fe production, the Fe/Mg abundance increases up to the values in low-redshift quasars and is kept nearly constant since then. Although it is not straightforward to derive the Fe/Mg abundance from the present data, the
Fig. 2. Diagram between (\([\text{OIII}]\lambda 5007+\lambda 4959)/H\beta\) equivalent width ratio and \(\text{FeII}\lambda 4434-4684/H\beta\) one for low-\(z\) (small symbols; Boroson & Green 1992) and high-\(z\) (\(z > 2\)) quasars (large symbols; Hill et al. 1993; Elston et al. 1994; Kawara et al. 1996; this study). 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: 1. B2 1225+317, 2. Q1246−057, 3. Q0933+733, 4. Q1413+117, 5. S4 0636+68, 6. Q0014+813, 7. B1422+231, and 8. PKS 1937−101. The filled diamond shows our result for S4 0636+68.

Similarity in Fe II/Mg II between B1422+231 and low-redshift quasars (and the LBQS composite spectrum) suggests that the host galaxy of B1422+231 had already been in the late evolutionary phase of the Fe enrichment at \(z = 3.6\). Yoshii, Tsujimoto, & Nomoto (1996) derived \(\sim 1.5\) Gyr for the lifetime of SN Ia progenitors from the analysis of the O/Fe and Fe/H abundances in solar neighbourhood stars. If the Fe enrichment started at 1.5 Gyr after the onset of the first star formation, the host galaxy of B1422+231 would have formed at \(z \geq 15\) for \(q_0 = 0.0\) and \(H_0 = 100\) km s\(^{-1}\) Mpc\(^{-1}\) while at \(z \geq 6\) for \(q_0 = 0.0\) and \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\).

2) PKS 1937−101: The little evidence for Fe emission lines suggests that the major epoch of star formation in this quasar host is different from that in B1422+231. The \(\alpha\) 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 burning in stellar envelope (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 has shown that the major Fe enrichment has not yet been made in PKS 1937−101. The bulk of iron come from SNIa’s whose progenitors’ lifetime is very likely to cluster around $\sim 1.5$ Gyr (Yoshii et al. 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; $\sim 10^8$ - $1.5 \times 10^9$ 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). Provided that the smaller $H_0$ is more preferable, the present observation is consistent with this prescription.

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