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# High-redshift Quasars and Early Star Formation

M. DIETRICH[1,2], F. HAMANN[2], I. APPENZELLER[3], M. VESTERGAARD[4], and S. WAGNER[3]
*(1) Department of Physics & Astronomy, Georgia State University, Atlanta, GA 30303, USA*
*(2) Department of Astronomy, University of Florida, Gainesville, FL 32611, USA*
*(3) Landessternwarte Heidelberg-Königstuhl, D-69117 Heidelberg, Germany*
*(4) Department of Astronomy, Ohio State University, Columbus, OH 43210, USA*

**Abstract**

We present results of an analysis of high-redshift quasars ($3.3 \lesssim z \lesssim 5.0$) which we observed in the near-infrared to measure relative Fe II and Mg II emission strengths and thereby estimate the beginning of the first major star formation epoch. A detailed comparison with quasars at low redshift show essentially the same Fe II/Mg II emission ratios and very similar continuum and line spectral properties, indicating a lack of evolution of the relative iron to magnesium abundance of the gas since $z \simeq 5$ in bright quasars. Based on current nucleosynthesis and stellar evolution models, $\alpha$-elements like Mg are produced by massive stars ending in type II SNe, while Fe is formed predominantly in SNe of type Ia. This results in an iron enrichment delay of $\sim 0.2-0.6$ Gyr. We conclude that major star formation activity in the host galaxies of our high-redshift quasars must have started already at $z_f \simeq 6-9$, when the age of the universe was $\sim 0.5$ Gyr ($H_o = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$).

## 1.1 Introduction

Quasars are among the most luminous objects in the universe which can be observed at great distances and large look-back times. Assuming that the gas closely associated with quasars is related to the interstellar medium of the host galaxy it can be used to trace the chemical abundance evolution, particularly at high redshifts. The prominent emission line spectrum of quasars provides several diagnostic line ratios to estimate the gas chemical composition (Hamann et al. 2002). Investigations of the emission line spectra have shown that quasars at redshift $z \gtrsim 3$ have at least solar metallicities or higher (Hamann & Ferland 1993; Ferland et al. 1996; Korista et al. 1996; Hamann & Ferland 1999; Dietrich & Wilhelm-Erkens 2000; Dietrich et al. 2003a,b). These studies indicate that well before the epoch corresponding to $z = 3$ significant star formation must have taken place in the galactic or proto-galactic cores where these quasars reside.

Measurements of specific abundance ratios, such as Fe/$\alpha$ (where $\alpha$ = O, Mg, Si, etc.), can constrain the ages of the stellar population near quasars and thereby define the epoch of the first (local) star formation (Hamann & Ferland 1999; Matteucci & Recchi 2001). $\alpha$-elements are produced predominantly by massive stars on short time scales via supernovae of types II,Ib,Ic. The dominant source of iron is ascribed to intermediate mass stars in binary systems, ending in SN type Ia explosions (Tinsley 1979; Matteucci & Greggio 1986; Matteucci 1994; Yoshii et al. 1996). The amount of iron returned to the interstellar medium in SN II ejecta

Table 1.1. *The investigated high-redshift quasars.*

| quasar | $m_v$ | z | quasar | $m_r$ | z |
|---|---|---|---|---|---|
| Q 0103-260 | 18.82 | 3.36 | BRI 0019-1522 | 19.00 | 4.52 |
| Q 0105-2634 | 17.30 | 3.48 | Q 0103+0032 | 18.60 | 4.44 |
| Q 0256-0000 | 17.50 | 3.37 | PSS J0248+1802 | 18.40 | 4.44 |
| Q 0302-0019 | 17.60 | 3.29 | PC 1158+4635 | 20.21 | 4.73 |
| Q 2050-359 | 18.34 | 3.51 | SDSS 1204-0021 | 20.82 | 5.03 |
| Q 2227-3928 | 18.80 | 3.44 | BRI 2237-0607 | 18.30 | 4.57 |
| Q 2348-4025 | 18.60 | 3.31 | | | |

is rather low (e.g., Wheeler et al. 1989; Yoshii et al. 1998). The significantly different time scales of the release of $\alpha$-elements and iron to the interstellar medium results in a time delay of the order of $\sim$1 Gyr. However, recent studies by Matteucci (1994), Friaça & Terlevich (1998), and Matteucci & Recchi (2001) indicate that this delay may be $\tau_{delay} \simeq 0.2-0.6$ Gyr for massive elliptical galaxies. Detecting strong Fe II emission at high redshift can be taken as an indication that the star formation of the stars which had released the iron had occurred less than $\sim 0.3-0.8$ Gyr earlier. Therefore, the line ratio of Fe emission vs. $\alpha$-element can be employed as a cosmological clock.

## 1.2 Observation

We observed high-redshift quasars in the near infrared ($\lambda \simeq 1-2.5\mu$m) with SoFI (3.5 m NTT, ESO/La Silla), NIRSPEC (9.8 m Keck, Hawai'i), OSIRIS (4 m, CTIO), and ISAAC (8.2 m VLT, ESO/Paranal). The quasars were selected for their brightness and for a suitable redshift ($3.3 \lesssim z \lesssim 5$) to guarantee that the Mg II 2798 and the broad UV Fe II emission features were shifted to the J- or H-band, respectively (Tab. 1). The study of the individual quasar spectra is supplemented with composite spectra that have been calculated from a large quasar sample (Dietrich et al. 2002a).

## 1.3 Results

The best indicator of the relative iron – $\alpha$-element ratio in quasar spectra is the strength of Mg II 2798 emission compared to broad blends of Fe II multiplets spanning several hundred Ångström (rest-frame) on either side of the Mg II line (Wills et al. 1985; Zheng & O'Brien 1990; Boroson & Green 1992).

Due to the huge number of individual Fe II emission lines ($\sim 10^5$) it is not possible to treat them individually. As demonstrated by Wills et al. (1985), the reconstruction of a quasar spectrum by several well defined components – (i) a power law continuum, (ii) a Balmer continuum emission spectrum, (iii) a template for the Fe II emission, and (iv) a template spectrum for the broad emission lines – is the best approach to measuring the strength of the Fe II emission (e.g., Wills et al. 1985; Dietrich et al. 2002b; Iwamuro et al. 2002).

In Figure 1.1 we show several typical examples of the multi-component fit of the high-redshift quasars we observed. In contrast to earlier studies, our data cover a much wider range of rest frame wavelengths, $\lambda\lambda 2100-5600$Å ($z \simeq 3.4$) and $\lambda\lambda 2100-4300$Å ($z \simeq 4.5$). These wide and continuous wavelength range enabled us to investigate the strong ultraviolet

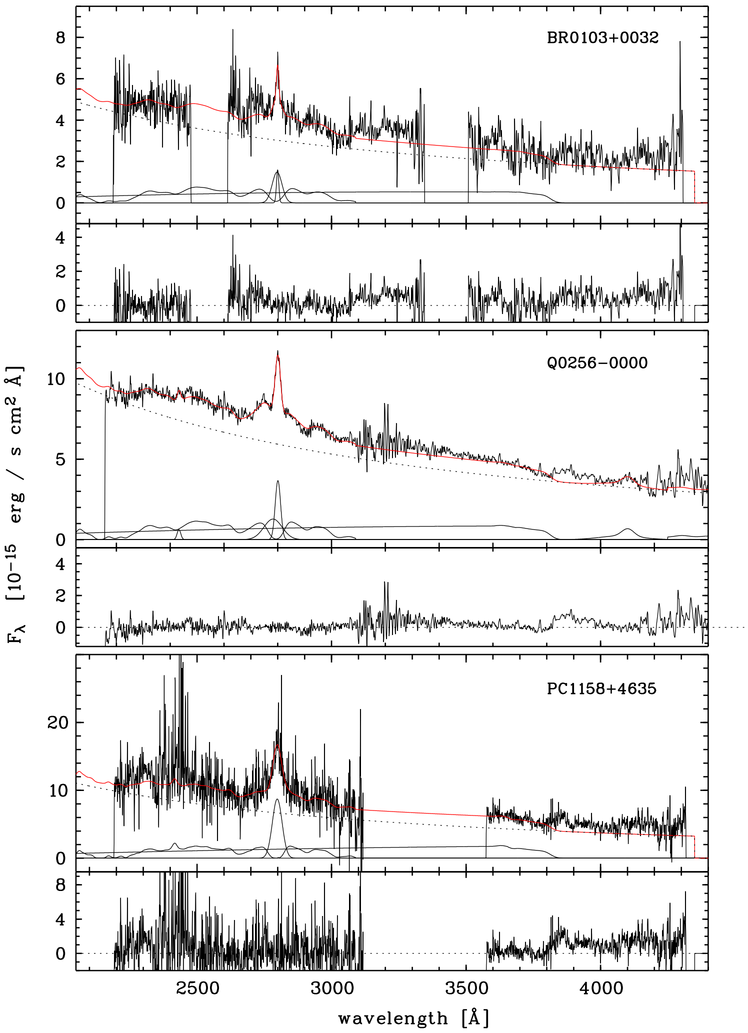


Fig. 1.1. Typical restframe quasar spectra are shown together with the power law continuum fit (dotted line), the scaled and broadened Fe-emission template (from Vestergaard & Wilkes 2001), the scaled Balmer continuum emission, and the Gaussian components to fit the Mg II 2798 line profile. The resulting fit of the multi-component analysis is overplotted as red line. The residuum is shown for each quasar in the corresponding bottom panel.

Fe II emission based on a reliable continuum fit which was hard to achieve in earlier studies with smaller and non-continuous wavelength coverage. We are presently involved in a collaboration to use empirical Fe II, Fe III emission templates (Vestergaard & Wilkes 2001) and state-of-the-art computer models (Verner et al. 1999) to quantify the abundance sensitivities of the iron line emission.

We measured the Fe-emission for a rest wavelength range of $\lambda\lambda 2200-3090$Å in each

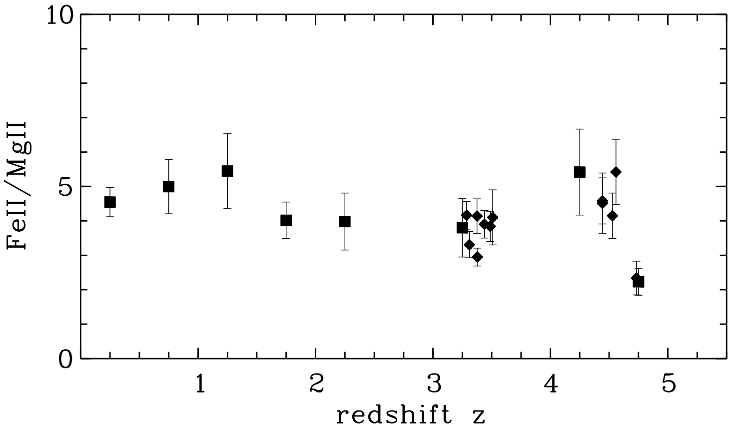


Fig. 1.2. The Fe II/Mg II line ratio of the $z \simeq 4.5$ quasars in comparison with quasars at $z \simeq 3.4$ (Dietrich et al. 2002b) are plotted as filled diamonds as a function of redshift. The Fe II/Mg II ratio of composite spectra (filled boxes) of quasars with nearly constant and comparable luminosity like the individual high-redshift quasars are displayed to illustrate the lack of evolution of the Fe II/Mg II ratio.

of the high-redshift quasars. We find no indication for an evolution of the Fe II/Mg II ratio from $z \simeq 3.2$ up to $z \simeq 4.8$ (Fig. 1.2), and including the result of the comparison of the SDSS 1204-0021 spectrum with a mean high-redshift quasar spectrum, even up to $z \simeq 5$. To study the evolution of the Fe II/Mg II ratio in more detail, particularly from the local universe to $z \simeq 5$, we analyzed composite quasar spectra which we calculated using subsets of a large quasar sample (Dietrich et al. 2002a). To search for a dependence on cosmic time, i.e. redshift, we selected a narrow luminosity range comparable to the luminosities of the individual high-redshift quasars, to minimize luminosity effects on the emission line strength like the Baldwin effect (see review by Osmer & Shields 1999) and computed composite spectra for redshift bins with $\Delta z = 0.5$ centered on redshift $z = 0.25, 0.75, ..., 4.25$, and 4.75, respectively.

## 1.4 Discussion and Conclusion

The Fe II/Mg II emission line ratios which we measure for our high-redshift quasar sample, as well as for the composite quasar spectra of nearly constant luminosity show no evolution of the relative iron emission strength (Fig. 1.2). This lack of evolution of the relative iron emission for quasars from $3 \lesssim z \lesssim 5$ and particularly compared to local quasars suggests that Fe is already significantly abundant at high redshifts which is consistent with results presented by Wills et al. (1985), Thompson et al. (1999), Murayama et al. (1999), and Iwamuro et al. (2002). Therefore, an episode of intense star formation began before the observed quasar epochs. Although our observations indicate a lower Fe II/Mg II ratio at $z \simeq 5$, recent NICMOS/HST observations of three $z \simeq 6$ quasars show no declining Fe II/Mg II ratio (Freudling et al. 2003). Since there is some evidence that luminous quasars may residing in galaxies with a massive spheroidal component (e.g., Nolan et al. 2001) the Fe enrichment delay may only be $\tau_{delay} \simeq 0.2 - 0.6$ Gyr (Friaça & Terlevich 1998; Matteucci & Recchi

2001). A redshift $z \gtrsim 4.5$ corresponds to an age of the universe of less than $\sim 1.3$ Gyr ($H_o = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$). Assuming $\tau_{evol} \simeq 0.3-0.8$ Gyr for the iron release to the interstellar medium, the first major star formation epoch started at $z_f \simeq 6-9$ for observed quasars at $z \gtrsim 4.5$. The result of an early star formation epoch is also consistent with cosmic structure formation models (Gnedin & Ostriker 1997) which are suggesting that the rapid assembly of (at least some) massive spheroidal systems, accompanied by intense star formation, started at $z \simeq 6-9$ (e.g., Kauffmann & Haehnelt 2000; Granato et al. 2001; Romano et al. 2002). It is interesting to note that this redshift is comparable to the epoch of re-ionization of the universe (Haiman & Loeb 1998; Becker et al. 2001; Fan et al. 2002).

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