HIGH-REDSHIFT QUASARS AND STAR FORMATION IN THE EARLY UNIVERSE

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ABSTRACT

In order to derive information on the star formation history in the early universe, we observed six high-redshift ($z \approx 3.4$) quasars in the near-infrared to measure the relative iron and Mg II emission strengths. A detailed comparison of the resulting spectra with those of low-redshift quasars 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 $z \approx 3.4$ in bright quasars. On the basis of current chemical evolution scenarios of galaxies, where magnesium is produced in massive stars ending in Type II supernovae (SNe II), while iron is formed predominantly in SNe Ia with a delay of $\sim 1$ Gyr and assuming as cosmological parameters $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, we conclude that major star formation activity in the host galaxies of our $z \approx 3.4$ quasars must have started already at an epoch corresponding to $z_f \approx 10$, when the age of the universe was less than 0.5 Gyr.

Subject headings: galaxies: abundances — galaxies: evolution — quasars: emission lines — quasars: general

1. INTRODUCTION

Quasars are among the most luminous objects in the universe. Because of their high luminosity, bright quasars can be observed at practically any distance at which these objects are expected to occur. Among the characteristic properties of quasars are prominent emission lines from the gas ionized and heated by a central radiation source. Assuming that this gas originates from the interstellar medium of the quasar host galaxies, line diagnostics applied to the prominent emission lines provide an important tool to study the chemical composition and enrichment history of the quasar host galaxies at all cosmological epochs. Earlier studies of the emission-line spectra have demonstrated that quasars at redshift $z \geq 3$ have metallicities of up to an order of magnitude larger than the solar value (e.g., Hamann & Ferland 1992, 1993, 1999; Ferland et al. 1996; Korista et al. 1996; Pettini 1999; Dietrich et al. 1999; Dietrich & Wilhelm-Erken 2000). These results show that well before the epoch corresponding to $z = 3$, significant star formation must have taken place in the galactic or protogalactic cores where these quasars reside.

Some information on the exact epoch of the first star formation activity in these objects can be derived from the relative abundance of $\alpha$-process elements and iron. According to present chemical enrichment scenarios, $\alpha$-element nuclei are produced predominantly in SNe II with massive progenitors on timescales of $\tau_{\text{evol}} \approx 2 \times (10^6-10^7)$ yr after the beginning of the star formation epoch. On the other hand, the dominant source of iron is assumed to be SNe Ia at the end point of the evolution of intermediate mass stars in binary systems, about $\tau_{\text{evol}} \approx 1$ Gyr after the onset of the star formation epoch (e.g., Tinsley 1979; Matteucci & Greggio 1986; Wheeler, Sneden, & Truran 1989; Yoshii, Tsujimoto, & Nomoto 1996). The amount of iron returned to the interstellar medium in SNe II ejecta is rather low (Yoshii et al. 1996; Yoshii, Tsujimoto, & Kawara 1998). The significantly different timescales of the release of $\alpha$-elements and iron to the interstellar medium results in a time delay on the order of $\sim 1$ Gyr in the Fe II enrichment. Detecting Fe II emission at high redshift comparable to the relative strength observed in quasars at lower redshift indicates that the formation of the stars that had released the iron had occurred at least $\sim 1$ Gyr earlier. Therefore, the line ratio of $\alpha$-element versus iron emission can be used as a cosmological clock.

Given the complexity of the Fe II emission spectrum, accurate iron abundances are not yet easy to deduce, and the full synthesis of the individual active galactic nuclei (AGN) spectra is required (Verner et al. 1999), which seriously complicates such measurements. However, the UV Fe II multiplets around Mg II ($\lambda \lambda 2000-3000$ Å), the most common strong iron multiplets among AGNs (Wills et al. 1980; Grandi 1981; Netzer et al. 1985), are probably the most promising for obtaining at least some information on the relative iron abundance (e.g., Wampler & Oke 1967; Wills, Netzer, & Wills 1985, hereafter WNW85; Hamann & Ferland 1999). A suitable spectral feature for testing the presence of $\alpha$-elements is the Mg II resonance doublet at $\lambda \lambda 2795, 2803$ (hereafter Mg II $\lambda 2798$). Since Mg II and Fe II have similar ionization potentials and are expected to originate in the same partially ionized zone of the excited gas, the ratio of these lines provides a valuable measure to estimate the $\alpha$-element versus iron abundance ratio, at least on a relative scale (Hamann & Ferland 1999). Observations of the Mg II $\lambda 2798$ and of the rest-frame UV multiplets of Fe II in the spectra of several high-redshift quasars have been published by Hill, Thompson, & Elston (1993); Elston, Thompson, & Hill (1994); Kawara et al. (1996); Taniguchi et al. (1997); Yoshii et al. (1998); Murayama et al. (1998, 1999), Thompson, Hill, & Elston (1999); Kuhn et al. (2001); and Green, Forster, & Kuraszkiewicz (2001). Generally, fairly strong Fe II emission was found, indicating a very early cosmic epoch of the first star formation in the high-$z$ quasar host galaxies.
In order to derive more accurate and more quantitative information on the first star formation epoch in such objects, we studied a small sample of six quasars with redshifts \( z \approx 3.4 \) using uniformly processed and analyzed high-quality near-infrared (NIR) spectra covering (in the observer’s frame) the wavelength range \( 1.0 \leq \lambda \leq 2.5 \mu m \). The quasars were selected to be accessible at the time of observation and to be bright enough to be observed within reasonable integration times with ESO’s 3.5 m New Technology Telescope (NTT). Assuming \( H_0 = 72 \text{ km s}^{-1}\text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \) (Carroll, Press, & Turner 1992; Carlbarg et al. 1999; Perlmutter et al. 1999; Freedman et al. 2001), this redshift corresponds to a cosmic epoch of \( \sim 1.8 \text{ Gyr} \), i.e., about 10% of the current cosmic age. For the selected redshifts, the strong Mg II \( 2798 \) emission line and most of the strong UV Fe II emission at 2300–2600 Å are redshifted into the NIR J band, while the H\( \beta \) and [O III] \( \lambda\lambda4959, 5007 \) lines together with the optical Fe II emission are shifted to the K-band wavelength region.

We covered practically the whole rest-frame wavelength range \( \lambda\lambda 2100–5600 \) continuously. This made it possible to derive reliable continuum fits and, thus, at least internally rather accurate flux values for the UV and optical Fe II emission.

2. OBSERVATIONS AND DATA ANALYSIS

The coordinates, redshifts, and the apparent brightness of the six quasars are listed in Table 1. All observations were carried out on 1999 October 19–22 using the SofI (Son of ISAAC) NIR spectrometer and camera attached to the ESO 3.5m New Technology Telescope (NTT). Assuming \( H_0 = 72 \text{ km s}^{-1}\text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \) (Carroll, Press, & Turner 1992; Carlbarg et al. 1999; Perlmutter et al. 1999; Freedman et al. 2001), this redshift corresponds to a cosmic epoch of \( \sim 1.8 \text{ Gyr} \), i.e., about 10% of the current cosmic age. For the selected redshifts, the strong Mg II \( 2798 \) emission line and most of the strong UV Fe II emission at 2300–2600 Å are redshifted into the NIR J band, while the H\( \beta \) and [O III] \( \lambda\lambda4959, 5007 \) lines together with the optical Fe II emission are shifted to the K-band wavelength region.

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The observing epochs and exposure times for the quasars and standard stars are listed in Table 2. Making use of the SofI long-slit mode we changed the location of the object along the slit by 60° (with an additional random offset within 5°) for subsequent exposures to optimize the sky correction.

The dark frames were recorded with the same exposures as the science frames. The average dark frames of a specific exposure time were spatially extracted, and the one-dimensional count rate distributions were fitted with a low-order polynomial. The low-order polynomial fits were subtracted to correct for the dark current signal.

For wavelength calibration we took xenon-neon comparison spectra in the blue and red setting of the gratings in lamp-on and lamp-off mode. The latter measures the IR background contamination. Its subtraction allows access to weaker spectral lines. Because the location of the spectral lines were reproduced within less than 0.3 pixels, we used a single XeNe spectrum for the wavelength calibration for all three nights. In the blue wavelength range (0.95–1.64 \( \mu m \)), the two-dimensional wavelength calibration based on 19 spectral lines yielded a pixel scale of 6.93 pixel \( ^{-1} \) and a wavelength mean error of 0.50 \( \mu m \). For the red wavelength range (1.52–2.52 \( \mu m \)) the corresponding values (based on 16 spectral lines) are 10.19 pixel \( ^{-1} \) and 0.83 \( \mu m \). The FWHM spectral resolution measured using strong night-sky emission lines was about \( R \approx 600 \) (blue) and \( R \approx 700 \) (red).

Flat-field frames taken with the internal lamps turned out not to be usable because of offsets (of up to four columns in the spatial direction). Furthermore, normalized dome flat-field exposures of the same night introduced additional structures on large scales. Therefore, we used the science

| Quasar | R. A. (J2000.0) | Decl. (J2000.0) | Apparent Magnitude* | \( z \) |
|--------|----------------|----------------|---------------------|-----|
| Q0103–260.......| 01 06 04.3 | -25 46 53 | 18.82 | 3.375 |
| Q0105–2634.......| 01 08 12.4 | -26 18 20 | 17.30 | 3.488 |
| Q0256–0000.......| 02 59 05.6 | +00 11 22 | 17.50 | 3.377 |
| Q0302–0019.......| 03 04 49.9 | -00 08 13 | 17.60 | 3.286 |
| Q2227–3928.......| 22 30 32.9 | -39 13 07 | 18.60 | 3.438 |
| Q2348–4025.......| 23 51 16.1 | -40 08 36 | 18.10 | 3.310 |

Table 1 (Elias et al. 1982; Perryman et al. 1997) several comparisons spectra in the blue and red setting of the gratings in lamp-on and lamp-off mode. The latter measures the IR background contamination. Its subtraction allows access to weaker spectral lines. Because the location of the spectral lines were reproduced within less than 0.3 pixels, we used a single XeNe spectrum for the wavelength calibration for all three nights. In the blue wavelength range (0.95–1.64 \( \mu m \)), the two-dimensional wavelength calibration based on 19 spectral lines yielded a pixel scale of 6.93 pixel \( ^{-1} \) and a wavelength mean error of 0.50 \( \mu m \). For the red wavelength range (1.52–2.52 \( \mu m \)) the corresponding values (based on 16 spectral lines) are 10.19 pixel \( ^{-1} \) and 0.83 \( \mu m \). The FWHM spectral resolution measured using strong night-sky emission lines was about \( R \approx 600 \) (blue) and \( R \approx 700 \) (red).

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| Star | R. A. (J2000.0) | Decl. (J2000.0) | Apparent Magnitude* | Type |
|------|----------------|----------------|---------------------|------|
| HD 19904 | 03 10 43 | -39 03 06 | 6.64 | AIV III/IV |
| HD 25402 | 04 00 32 | -41 44 54 | 8.36 | G3V |
| HD 38921 | 05 47 22 | -38 13 52 | 7.54 | A0V |
| HD 205772 | 21 38 41 | -41 02 53 | 7.66 | A5IV/V |
| HD 210395 | 22 11 02 | -39 32 51 | 7.98 | G3V |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Véron-Cetty & Véron 2001.

† Elias et al. 1982.

m_v.
TABLE 2

| Object  | Range | Date    | $t_{int}$ | Number of Experiments | Total$_{int}$ | Comment |
|---------|-------|---------|-----------|------------------------|---------------|---------|
|         | (1)   | (2)     | (3)       | (4)                    | (5)           | (6)     |
| Quasar  |       |         |           |                        |               |         |
| Q0103 – 260 …… blue 1999 Oct 19/20 240 12 2880 seeing ~0.8 |
|         | red 1999 Oct 19/20 240 18 4320 seeing ~0.6 |
|         | blue 1999 Oct 20/21 240 8 1920 |
|         | red 1999 Oct 20/21 240 10 2400 |
| Q0105 – 2634 …… blue 1999 Oct 20/21 240 12 2880 seeing ~1.1 |
|         | red 1999 Oct 20/21 240 6 1440 seeing ~1.2 |
|         | blue 1999 Oct 21/22 180 14 2520 seeing ~2.2, clouds |
| Q2227 – 3928 …… blue 1999 Oct 19/20 180 16 2880 seeing ~1” |
|         | red 1999 Oct 19/20 180 8 1440 |
|         | blue 1999 Oct 20/21 240 6 1440 |
|         | red 1999 Oct 20/21 240 10 2400 |
|         | blue 1999 Oct 21/22 240 5 1200 seeing ~1.4, clouds |
| Q2348 – 4025 …… blue 1999 Oct 20/21 240 6 1440 seeing ~2.0 |
|         | red 1999 Oct 20/21 240 6 1440 seeing ~1.5 |
|         | blue 1999 Oct 21/22 240 6 1440 seeing ~1.7, clouds |
|         | red 1999 Oct 21/22 240 12 2880 seeing ~1.7, clouds |
|         | blue 1999 Oct 22/23 180 16 2880 clouds |
| Star    |       |         |           |                        |               |         |
| HD 19904 ……… blue 1999 Oct 19/20 5 4 20 seeing ~0.5 |
|         | red 1999 Oct 19/20 5 4 20 |
|         | blue 1999 Oct 20/21 5 4 20 seeing ~1.5 |
| HD 25402 ……… blue 1999 Oct 19/20 5 4 20 |
|         | red 1999 Oct 19/20 5 4 20 seeing ~0.6 |
|         | blue 1999 Oct 20/21 5 4 20 seeing ~1.2 |
| HD 38921 ……… blue 1999 Oct 19/20 5 4 20 seeing ~0.6 |
|         | red 1999 Oct 19/20 5 4 20 |
| HD 205772 ……… blue 1999 Oct 19/20 10 8 80 |
|         | red 1999 Oct 19/20 5 4 20 |
|         | blue 1999 Oct 20/21 5 4 20 |
|         | red 1999 Oct 20/21 5 4 20 |
|         | blue 1999 Oct 21/22 5 4 20 clouds |
|         | red 1999 Oct 21/22 5 4 20 clouds |
|         | blue 1999 Oct 22/23 5 8 40 |
| HD 210395 ……… blue 1999 Oct 19/20 5 4 20 |
|         | red 1999 Oct 19/20 5 4 20 |
|         | blue 1999 Oct 20/21 5 4 20 |
|         | red 1999 Oct 20/21 5 4 20 |
|         | blue 1999 Oct 21/22 5 8 40 clouds |
|         | red 1999 Oct 21/22 5 8 40 clouds |

We derived and subtracted the night-sky intensity for each frame individually because the night-sky intensity showed significant variations on timescales of 180–240 s. For this purpose a third-order polynomial fit was calculated for each wavelength element to fit the spatial intensity distribution of the night-sky emission. The fit was based on 22” wide regions that were at least 5” separated from the targets, quasar and standard star, both of which were point-source—
like. The remaining residua after the sky correction were removed by subtracting the object-free part of a sky-corrected frame containing the same residua.

The observed standard stars were used to correct for strong atmospheric absorption bands separating the $J$ and $H$ bands and the $H$ and $K$ bands, respectively, and other atmospheric (absorption) features. The range of the atmospheric transmission properties during the observing run is shown in Figure 1.

To obtain a sensitivity function to transform the observed count rates to flux units, we assumed that the IR spectral energy distribution of an A-type star and G-type star can be described with a blackbody energy distribution. We used the blackbody temperatures given by Kurucz (1992) for the different spectral types of the stars we observed. We applied $T_{\text{eff}} = 5850$ K (HD 25402, HD 210395), $T_{\text{eff}} = 8250$ K (HD 19904, HD 205772), and $T_{\text{eff}} = 9750$ K (HD 38921) to compute a blackbody energy distribution for the observed wavelength range. Next, these blackbody spectra were scaled to match the apparent magnitude of the observed standard stars in the $J$, $H$, and $K$ bands. For each standard star a sensitivity curve was calculated. For HD 25402 and HD 210395 we had to calculate the apparent NIR magnitudes based on the apparent $V$-band magnitude, while for HD 19904, HD 38921, and HD 205772 we could use the $J$, $H$, and $K$ magnitudes given by Elias et al. (1982). In general, the sensitivity functions given for these two subsets are identical within less than 4%. But they differ by $\sim 10\%$ at the long-wavelength end of the blue and red wavelength range. Hence, we used the $J$, $H$, and $K$-band based sensitivity functions provided by HD 19904, HD 38921, and HD 205772 to derive a mean sensitivity function for the blue and red wavelength ranges.

The quasar spectra were extracted using the Horne (1986) extraction routine. The width of the spatial profile for the quasar spectra was the same as measured for the stars. Hence, the quasar spectra were treated as point sources. Since some individual spectra of low quality were eliminated during the coaddition procedure, the effective integration time for the quasars is somewhat lower than the sum of the individual exposure times (Tables 2 and 3).

The individual spectra of the quasars were corrected for atmospheric absorption using appropriately scaled transmission functions provided by observed spectra of the standard stars. To correct for cosmic-ray events the individual one-dimensional spectra were compared with one another. We calculated for each wavelength element the mean and standard deviation among the available one-dimensional spectra, excluding the smallest and largest flux measurement. If these excluded measurements deviate by more than 3 times the standard deviation, they were replaced by the calculated mean value, respectively. For each quasar, weighted mean spectra were calculated. The weight was given by the mean signal-to-noise ratio in the continuum across the spectrum. Finally, we transformed the quasar spectra to those emitted in the quasar rest frame. Following Peterson (1997, p. 156) the flux conversion was carried out according to

$$F_{\text{obs}}(\lambda_0) = F_{\text{rest}}(\lambda_1)/ (1+z)^3.$$  

The resulting rest-frame quasar spectra are displayed in Figure 2.

### 3. MODELING OF THE QUASAR SPECTRA

While at least the narrow emission component of the strong and relatively isolated Mg II $\lambda 2798$ doublet appears to be measured easily in quasar spectra, the Fe II emission forms broad emission blends caused by the superposition of several ten thousand discrete lines and the intrinsically large quasar emission-line widths (e.g., WNW85; Verner et al. 1999). Owing to the large number of merging lines and the difficulty of deriving a local continuum level, it is not possible to measure these lines individually. However, as suggested and demonstrated by WNW85, it is possible to derive the Fe II emission strength by decomposing the quasar spectrum into several well-defined components. Therefore, we assumed our observed spectra to consist of a superposition of the following four components: (1) a power-law continuum ($F_{\lambda} \sim \nu^a$), (2) Balmer continuum (BaC) emission, (3) a pseudocontinuum owing to merging Fe II emission blends, and (4) an emission spectrum of other individual broad emission lines.

#### 3.1. Nonstellar Continuum

We first determined component (1), the underlying nonstellar power-law continuum, from spectral windows that are free (or almost free) of contributions by components (2)–(4). For this purpose it was very important to have spectra covering the (rest frame) optical region up to $\sim 5500$ Å with one of the continuum windows at $\sim 5100$ Å, which is nearly free of emission-line contamination and hydrogen continua. Only minor Fe II emission can be expected for this wavelength region (WNW85; Verner et al. 1999) and so will not significantly affect the continuum setting. For three of our quasars (Q0103-260, Q0256-0000, and Q0302-0019) we also have rest-frame UV spectra avail-
Fig. 2.—Quasar spectra transformed to the rest frame. Flux density is given in units of \(10^{-15}\) ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\). The location of the strong atmospheric absorption bands is indicated by the horizontal bars for each quasar.
able, covering O \( \lambda 1034 \) to C \( \lambda \lambda 1909 \) (M. Dietrich & F. Hamann 2002, in preparation) with continuum windows at \( \lambda \lambda \approx 1330-1380 \) Å and \( \lambda \lambda \approx 1440-1470 \) Å, which are nearly uncontaminated by line emission as well (Verner et al. 1999). For those quasars where we had no access to the short wavelength UV part of the spectrum, we used continuum windows at \( \sim 2100 \) Å to estimate the continuum strength. The uncertainty introduced by estimating the continuum based on at least two of the spectral ranges described above is estimated to be on the order of \( \sim 10\% \). The UV data allow us even better constraints to be placed on the nonstellar continuum for these objects.

3.2. Balmer Continuum

The BaC emission was modeled according to the following procedure: assuming case B conditions, the flux ratio of the integrated BaC emission and of H\( \beta \lambda 4861 \) is given by \( I(BaC)/I(H\beta) = 3.95 T_e^{2.4} \), with \( T \) in units of \( 10^4 \) K (e.g., WNW85). But for significant optical depth in the Balmer emission lines and especially in the BaC, large deviations from this simple relation are expected. Optically thick BaC emission can be described by a blackbody spectrum at all wavelengths (e.g., Malkan & Sargent 1982). But since the absorption cross section decreases as \( (v/v_{BE})^3 \), the continuum emission will become optically thin at some wavelength. To get an estimate of the BaC emission spectrum for the purpose of model fitting, we assumed clouds of uniform temperature \( (T_e = 15,000 \) K) that are partially optically thick. In this case the BaC spectrum can be described by

\[
F_{BaC} = F'_v B_v(T_e)(1 - e^{-\tau_v}) - \tau_v v \geq v_{BE},
\]

with \( B_v(T_e) \) the Planck function at the electron temperature \( T_e \) (Grandi 1982). The value \( \tau_v \) is the optical depth at the frequency \( v \); \( \tau_v \) can be calculated in terms of the optical depth \( \tau_{BE} \) at the Balmer edge using

\[
\tau_v = \tau_{BE} \left( \frac{v}{v_{BE}} \right)^{-3},
\]

and \( F'_v \) is a normalized estimate for the BaC flux density at the Balmer edge at \( \lambda = 3646 \) Å. After subtraction of the power-law continuum component, the strength of the BaC emission can be estimated from the flux density at \( \lambda \approx 3675 \) Å, since at this wavelength there is no significant contamination by Fe II emission (WNW85; Verner et al. 1999). The \( \lambda 3675 \) rest-frame flux density level was therefore used to normalize the BaC spectrum. At wavelengths \( \lambda \geq 3646 \) Å, higher order Balmer lines are merging to a pseudocontinuum, yielding a smooth rise to the Balmer edge (WNW85).

We used the results of the model calculations provided by Storey & Hummer (1995) (case B, \( T_e = 15,000 \) K, \( n_e = 10^8-10^{10} \) cm\(^{-3} \)). We calculated several BaC spectra for \( T_e = 15,000 \) K and \( 0.1 \leq \tau_e \leq 2 \) to obtain BaC template spectra. These BaC templates were supplemented for \( \lambda > 3646 \) Å with high-order Balmer emission lines with \( 10 \leq n \leq 50 \), i.e., H\( \delta \) and higher.

3.3. Fe II Emission

Calculating the Fe II emission spectrum is much more difficult, and the influence of unknown parameters such as metallicity, pumping by the incident continua, line fluorescence, emission-line transport, and turbulence velocities, which affect the emergent Fe II spectrum, are still not well understood (e.g., WNW85; Netzer et al. 1985; Bautista & Pradhan 1998; Sigut & Pradhan 1998; Verner et al. 1999; Collin & Joly 2000). However, in spite of these uncertainties, WNW85, Laor et al. (1997), McIntosh et al. (1999), and others have shown that the Fe II emission spectrum of Seyfert 1 galaxies and quasars can be modeled. Therefore, we fitted the Fe II emission in our quasar spectra using scaled and broadened empirical Fe II emission template spectra to derive relative Fe II emission strength values. For the UV wavelength range these templates had been extracted from Hubble Space Telescope observations of I Zw 1 by Vestergaard & Wilkes (2001). The optical Fe II emission template, extracted from ground-based spectra of I Zw 1, was kindly provided by T. Boroson.

3.4. Strong Broad Emission Lines

The broad emission lines of Mg \( \lambda 2798 \) and of H\( \beta \lambda 4861 \) were fitted in our spectra with Gaussian components to measure the integrated line flux. Generally, the Mg \( \lambda 2798 \) emission-line profile could be reconstructed with two Gaussian components, one narrow and one broad and blueshifted. For the H\( \beta \lambda 4861 \) emission-line profile we used the same approach. While the width of the narrow components in both lines tend to be of the same order [FWHM \( (\text{Mg} \, \lambda 2798) = 2850 \pm 460 \) km s\(^{-1} \) and FWHM \( (\text{H} \beta) = 2950 \pm 360 \) km s\(^{-1} \)], the broad component that we used for H\( \beta \) was significantly broader than for \( \text{Mg} \, \lambda 2798 \) [FWHM \( (\text{H} \beta) = 10,000 \pm 1000 \) km s\(^{-1} \) and FWHM \( (\text{Mg} \, \lambda 2798) = 6200 \pm 700 \) km s\(^{-1} \)]. However, the approach to reconstruct the Mg \( \lambda 2798 \) and H\( \beta \) emission-line profiles with two Gaussian components was chosen only to measure the line flux; each individual component has no physical meaning by itself.

3.5. Internal Reddening

The effect of internal reddening on broad emission lines is still unclear. In recent years growing evidence has appeared for the presence of large amounts of dust \( (M_dust \geq 10^2 M_\odot) \) in the host galaxies of high-redshift quasars (e.g., Guilotteet al. 1997, 1999; Carilli et al. 2000; Omont et al. 2001). It is assumed that the dust is distributed in a kiloparsec-scale warped disk (Sanders et al. 1989) that is illuminated by the central AGN. The observed dust emission spectra from 3 to 30 \( \mu m \) can be explained by such a model as shown by Andreani, Franceschini, & Granato (1999) and Willott, Rawlings, & Jarvis (2000). However, since the present spectra are typical quasar spectra with prominent broad emission lines, it is unlikely that the broad-line region (BLR) is significantly blocked by dust (e.g., Netzer & Laor 1993). Even if the radiation has to pass through an (external) dust screen, the extinction of the Mg \( \lambda 2798 \) and the UV Fe II emission (having about the same mean wavelength) will be comparable, and the line ratio is not expected to be significantly modified. However, in the case of dust located within the line-emitting gas, the situation is more complicated. Since Mg \( \lambda 2798 \) has a larger optical depth than that of the Fe II emission, the Mg \( \lambda 2798 \) line emission will suffer more resonance scattering, resulting in a longer effective internal lightpath, and thus be more weakened than the Fe II emission. This would result in a larger Fe II/Mg \( \lambda 2798 \) ratio. To investigate the influence of internal dust reddening, detailed model calculations are required. Such calculations are beyond the scope of the current paper; however, this effect will be investigated for an
The quasars were selected to have \( z \leq 2 \) and to cover a luminosity range comparable to the \( z \approx 3.4 \) quasars under study. The criterion of comparable luminosity minimizes luminosity effects on the emission-line strength like the Baldwin effect (e.g., Osmer & Shields 1999). The average luminosity of the quasars that contribute to the local mean quasar spectrum amounts to \( \log \lambda L_\lambda(1450 \text{ Å}) = 43.5 \pm 0.3 \text{ ergs s}^{-1} \). The average luminosity of the six high-\( z \) quasars is \( \log \lambda L_\lambda(1450 \text{ Å}) = 43.9 \pm 0.2 \text{ ergs s}^{-1} \).

In Figures 3 and 4 we present the multicomponent fit for the six high-\( z \) quasar spectra and in Figure 5 for the local mean quasar spectrum. The individual components are also shown together with the fit. In addition, the resulting residual spectra are displayed, too. Although the observed quasar spectra are well represented by the multicomponent models, several broad emission features can be seen in the residua. The broad residuum in the wavelength range \( \lambda \lambda \approx 3800\text{–}4000 \text{ Å} \) is caused by the Balmer emission lines \( \text{H} \delta \text{ up to H} \eta \), because the BaC emission template we used includes Balmer emission lines with \( 10 \leq n \leq 50 \). The second strong residual emission at \( \lambda \lambda \approx 3200 \text{ Å} \) is associated with the Fe II emission blends M6 and M7, which are not included in the UV Fe-emission template we used. In the residuum spectra of Q0103 – 260, Q0302 – 0019, and of the local mean quasar spectrum, some emission is detected for \( \lambda \approx 2200 \text{ Å} \). This additional emission can be ascribed to

### Table 4

| Feature | Q0103 – 260 | Q0105 – 2634 | Q0256 – 0000 | Q0302 – 0019 | Q2227 – 3928 | Q2348 – 4025 | Local Quasar |
|---------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| C ii ] 2326 | ...         | ...         | ...         | ...         | ...         | ...         | 0.05 ± 0.01 |
| [Ne iv ] 2423 | ...         | ...         | ...         | ...         | ...         | ...         | ...         |
| Mg ii ] 2798 | 1.00 ± 0.05 | 1.00 ± 0.04 | 1.00 ± 0.03 | 1.00 ± 0.03 | 1.00 ± 0.03 | 1.00 ± 0.06 | 1.00 ± 0.05 |
| [Ne iv ] 2369 | ...         | ...         | ...         | ...         | ...         | ...         | ...         |
| Hδ ] 4101 | ...         | 0.34 ± 0.04 | 0.26 ± 0.04 | ...         | ...         | ...         | ...         |
| Hγ ] 4340 | 0.52 ± 0.11 | 0.37 ± 0.06 | 0.34 ± 0.05 | 0.43 ± 0.08 | ...         | ...         | ...         |
| Hβ ] 4535 | 1.84 ± 0.13 | 0.84 ± 0.07 | 1.32 ± 0.08 | 1.01 ± 0.05 | 1.12 ± 0.07 | 0.73 ± 0.08 | ...         |
| [O iii ] 4959 | 0.03:        | ...         | 0.06 ± 0.01 | 0.18 ± 0.01 | ...         | ...         | ...         |
| [O iii ] 5007 | 0.10:        | ...         | 0.22 ± 0.02 | 0.59 ± 0.02 | 0.015:      | ...         | ...         |
| Fe ii ] 4570 | 0.99 ± 0.16 | 1.01 ± 0.13 | 0.57 ± 0.06 | 0.58 ± 0.07 | 0.64 ± 0.09 | 0.78 ± 0.10 | ...         |
| Fe ii ] 4696, 5018 | 0.36 ± 0.06 | 0.37 ± 0.05 | 0.21 ± 0.02 | 0.22 ± 0.03 | 0.24 ± 0.03 | 0.28 ± 0.04 | ...         |
| Fe ii ] 5190 | 0.58 ± 0.09 | 0.59 ± 0.08 | 0.33 ± 0.03 | 0.34 ± 0.04 | 0.38 ± 0.05 | 0.46 ± 0.06 | ...         |
| Fe ii optd | 1.95 ± 0.31 | 1.99 ± 0.26 | 1.12 ± 0.11 | 1.15 ± 0.14 | 1.26 ± 0.17 | 1.53 ± 0.19 | ...         |
| Fe ii ] 2080 | ...         | 0.18 ± 0.02 | ...         | ...         | ...         | ...         | 0.23 ± 0.02 |
| Fe ii ] 2500 | 2.43 ± 0.29 | 2.26 ± 0.26 | 1.73 ± 0.15 | 2.44 ± 0.23 | 2.29 ± 0.24 | 1.94 ± 0.23 | 2.25 ± 0.23 |
| Fe ii ] 2600 | 0.59 ± 0.07 | 0.54 ± 0.06 | 0.42 ± 0.04 | 0.59 ± 0.06 | 0.55 ± 0.05 | 0.47 ± 0.06 | 0.54 ± 0.06 |
| Fe ii ] 2900 | 1.03 ± 0.12 | 0.95 ± 0.11 | 0.73 ± 0.06 | 1.03 ± 0.10 | 0.96 ± 0.10 | 0.82 ± 0.10 | 0.95 ± 0.10 |
| Fe ii UV | 4.14 ± 0.50 | 3.84 ± 0.44 | 2.95 ± 0.26 | 4.16 ± 0.40 | 3.90 ± 0.40 | 3.31 ± 0.38 | 3.82 ± 0.40 |
| Fe ii UV + Fe ii opt | 2.13 ± 0.40 | 1.93 ± 0.33 | 2.64 ± 0.33 | 3.62 ± 0.53 | 3.10 ± 0.51 | 2.16 ± 0.32 | ...         |
| Fe ii UV + Fe ii opt | 6.09 ± 0.68 | 5.83 ± 0.63 | 4.07 ± 0.36 | 5.31 ± 0.50 | 5.15 ± 0.53 | 4.84 ± 0.55 | ...         |
| Balmer cont | 3.86 ± 0.60 | 5.45 ± 0.60 | 5.15 ± 0.50 | 5.40 ± 0.49 | 5.17 ± 0.49 | 6.16 ± 0.67 | 5.02 ± 0.51 |
| \( \tau_{\text{rec}} \) (Mg ii ] 2798) | 1.0 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 |
| \( L_\lambda(\text{ergs s}^{-1} \text{ cm}^{-2}) \) | 73.6 ± 3.5 | 267.4 ± 11.0 | 200.7 ± 7.0 | 341.5 ± 10.0 | 156.0 ± 5.0 | 155.6 ± 10.0 | 317.2 ± 16.7 |

a \( \lambda\lambda 4250\text{–}4770 \)
b \( \lambda\lambda 4800\text{–}5050 \)
c \( \lambda\lambda 5085\text{–}5500 \)
d \( \lambda\lambda 4250\text{–}5500 \)
e \( \lambda\lambda 4245\text{–}2130 \)
f \( \lambda\lambda 2420\text{–}2660 \)
g \( \lambda\lambda 2660\text{–}2790 \)
h \( \lambda\lambda 2790\text{–}3030 \)
i \( \lambda\lambda 2200\text{–}3090 \)
j \( \lambda\lambda 2200\text{–}3650 \)
Fig. 3.—Rest-frame quasar spectra together with results of the multicomponent analysis are shown for Q0103—260, Q0105—2634, and Q0256—0000. Top panel: The quasar spectrum is shown together with the power-law continuum fit (dotted line), the scaled and broadened Fe-emission template, the scaled BaC emission, and the Gaussian components to fit the Mg II λ2798 and Hβ λ4861 emission-line profiles. The resulting fit is overplotted as a solid line. Bottom panel: The quasar spectrum is shown after subtraction of these components.
Fe II emission that is not contained in our Fe emission template but can be expected on the basis of model calculations (Verner et al. 1999).

In addition to the relative flux of the Fe emission blends we list in Table 4 also flux values for some other permitted and forbidden emission lines of interest in the observed wavelength interval. The flux is given in units of the corresponding Mg II λ2798 flux (i.e., the table lists in all cases the ratio between the observed emission flux and the flux of the Mg II λ2798 line observed in the same spectrum). The absolute Mg II rest-frame intensity is given at the bottom of Table 4.

For the Fe II emission we list the integrated flux of most of the UV and optical blends and multiplets, using the following designations (e.g., Phillips 1978; Wills et al. 1980): Fe II λ24570: multiplets 37, 38, 43 (4250–4770 Å); Fe II λ4924, 5018: multiplet 42 (4800–5085 Å); Fe II λ5190: multiplets 42, 48, 49, 55 (5085–5500 Å); Fe II opt total: Fe II flux λ4250–5500; Fe II λ2080: multiplets UV83, UV91, UV93, UV94 + Fe III UV48 (2030–2130 Å); Fe II λ2500: multiplets UV1, UV3, UV4, UV5, UV35, UV36, UV64 (2240–2660 Å); Fe II λ2680: multiplets UV200, UV235, UV263, UV283 (2660–2790 Å); Fe II λ2900: multiplets UV60, UV78, UV277, UV215, UV231, UV255 (2790–3030 Å); Fe II UV: total Fe II flux 2200–3090 Å. The multiplets listed are the strongest ones expected in each range. Note that, since the total flux values for entire blends or sums of multiplets often contain additional weak lines, these values are somewhat larger than the sums of the individual prominent blends.

According to Table 4 the mean emission-line ratio of $I(H\beta)/I(Mg \ II \ λ2798)$ for the individual quasars is $1.14 \pm 0.16$, which, within the uncertainties, is consistent with the relative line strength of Hβ reported by WNW85 (0.82 ± 0.25). The greater relative strength of Hβ λ4861, measured here, might be caused by including a very broad component to measure the line strength. The outer wings of the broad Gaussian component, which we used to determine $I(H\beta)$, contributes up to ∼20% of the total $I(H\beta)$.

The strength of the BaC emission in units of $I(Mg \ II \ λ2798)$ as listed in Table 4 shows some variation between the six high-z quasars. In particular, Q2227 – 3928 shows quite weak BaC emission. The relative BaC strength without Q2227 – 3928 amounts to $I(BaC)/I(Mg \ II) = 5.20 ± 0.38$. Including Q2227 – 3928, the value drops to $I(BaC)/I(Mg \ II) = 4.57 ± 0.71$. However, within the errors the relative BaC emission strength is consistent with the strength we measured for the local mean quasar spectrum, $I(BaC)/I(Mg \ II)_{local} = 5.02 ± 0.51$.

Whether the ratio of the optical-range Fe II -emission of the high-z quasars relative to Mg II differs from the Fe II/Mg II ratio of the local quasar population cannot be studied because our local mean quasar spectrum does not cover the optical Fe II emission at λ > 4200 Å. The average relative strength of the optical Fe II emission of the six high-z quasars was found to be $I(Fe \ II \ opt)/I(Mg \ II) = 1.50 ± 0.16$. This value is in good agreement with the ratio $1.21 ± 0.73$ given by WNW85, who studied quasars with $0.12 ≤ z ≤ 0.63$. This comparison with the WNW 85 Fe II/Mg II ratio for local quasars thus indicates no significant difference, i.e., no evolution of the Fe II/Mg II ratio up to $z ≈ 3.4$.

More interesting is the integral strength of the UV Fe emission (2200–3090 Å) relative to Mg II λ2798. We obtain for the six high-z quasars an average of $I(Fe \ II \ UV)/I(Mg \ II) = 3.72 ± 0.20$. Within the uncertainties there is no difference compared with $I(Fe \ II \ UV)/I(Mg \ II) = 3.82 ± 0.40$ derived from the local mean quasar spectrum (Table 4).

We anticipate that the approach adopted in this work is relatively more accurate than those adopted in the studies by Thompson et al. (1999), Kawara et al. (1996), and Murayama et al. (1999). This is partly due to our use of data with a large, mostly continuous spectral coverage, which allow a much better determination of the underlying continuum. Also, a better account was made of the BaC emission through a direct fitting thereof, thanks again to the long and continuous spectral coverage. Finally, we use empirical UV Fe II emission templates (Boroson & Green 1992; Vester-
II Fe
theoretical models applied to observed AGN spectra much closer to the contradiction, given the larger uncertainties in the earlier quoted values, they are not in immediate lower than the Thompson et al., Kawara et al., and the strengths, and is clearly an approximation. Although, the relative line strengths, \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \), measured here are somewhat lower than the Thompson et al., Kawara et al., and the Murayama et al. quoted values, they are not in immediate assumptions on the relative strengths of the emission lines and is clearly an approximation. Therefore, the relative line strengths, \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \), measured here are somewhat lower than the values reported in earlier studies by WNW85 as discussed by Dietrich et al. (2001), as opposed to the theoretical templates from the study by WNW85. As discussed by Thompson et al. (1999) the latter approach includes several assumptions on the relative strengths of the emission lines and is clearly an approximation. Therefore, the relative line strengths, \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \), measured here are somewhat lower than the Thompson et al., Kawara et al., and the Murayama et al. quoted values, they are not in immediate contradictions.

By combining the above result for the UV and optical Fe II emission we obtain for our high-z quasars \( I(\text{Fe} \ II \ UV + \text{Fe} \ II \ opt)/I(\text{Mg} \ II) = 5.22 \pm 0.29 \). This value is lower than most numbers quoted in the literature but again close to the \( I(\text{Fe} \ II \ UV + \text{Fe} \ II \ opt)/I(\text{Mg} \ II) \) value predicted by theoretical models (Netzer & Wills 1983; WNW85).

The \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \) ratio that we find for our local quasar sample is comparable to the corresponding value reported for the mean quasar spectrum of the LBQS sample (containing quasars with redshifts in a range of \( z \approx 1-2 \)) with \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \approx 3.7 \) (Francis et al. 1991) but below the ratios given by Thompson et al. (1999; 4.3-5.3) and Murayama et al. (1999; 8.9). As discussed above, this difference is likely due to our better observational data and the more accurate approach adopted here.

5. DISCUSSION AND CONCLUSION

As pointed out in § 4 our accurate derivation of the relative Fe II emission strength for a sample of six high-z quasars, give lower or much lower \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \) ratios than the values reported in the literature for intermediate and high-redshift quasars (e.g., WNW85; Thompson et al. 1999; Murayama et al. 1999). Since the earlier results are consistent with our data to within their higher error limits, we assume that the differences result from our improved multicomponent fit of the observed spectra, which was facilitated by the wide wavelength range and accurate calibration of our observational data. On the other hand, the \( I(\text{Fe} \ II \ UV)/I(\text{Mg} \ II) \) ratios for our \( z \approx 3.4 \) quasars reported in this paper are comparable to the corresponding mean ratio for low-z quasars, which we determined from the local mean quasar spectrum (M. Dietrich & F. Hamann 2002, in preparation). As our high-z and local quasars do not differ significantly in any other spectral property, it appears unlikely that the strong Fe II emission seen also at \( z = 3.4 \) can be explained by any other mechanism than comparable relative abundance of Fe in our \( z \approx 3.4 \) quasars. Since, as pointed out in § 1, according to the present chemical evolution theory of galaxies Fe is produced mainly by SNe Ia that begin to explode about \( 1.8 \) Gyr after the beginning of star formation, the observed high Fe content of the BLR gas of our quasars confirms that the star formation in the host galaxies of high-z quasars started at a very early epoch.

An evolutionary model of the Fe enrichment in a galaxy following the initial starburst has been calculated by Yoshii et al. (1998). Although, as pointed out by Yoshii et al., evidence that the initial mass function may have been different for the first stars make such model calculations quantitatively somewhat uncertain, it is clear from these computations that the relative Fe abundance is rather low initially and starts to grow steeply about 1.0 Gyr after the beginning of the star formation, reaching a maximum (at about 3 Gyr in the Yoshii et al. model), before declining to the local value (see also Mattucci & Padovani 1993; Hamann & Ferland 1993). The same temporal evolution of the Fe/Mg ratio is found for the giant elliptical galaxy model (M4a) presented by Hamann & Ferland (1993). Their model predicts a strong increase of Fe/H at \( \sim 1 \) Gyr after the beginning of the star formation, with the most rapid rise of the Mg/Fe ratio during the 1-1.38 Gyr period. Comparing our relative Fe II emission strength with the model of Yoshii et al. (1998) and Hamann & Ferland (1993) we estimate an age of \( \sim 1.5 \) Gyr (with a formal error of \( \pm 0.5 \) Gyr) for the stellar population that produced the observed iron in our high-z quasars. (Because of our smaller Fe II/Mg II emission ratio this value is slightly lower than the corresponding age derived by Yoshii et al. for B 1422+231 at \( z = 3.6 \)). As discussed, for example, by Yoshii et al. (1998) and Thompson et al. (1999), a starburst age of this order and in this redshift range provides severe constraints on the allowed cosmological parameters as realistic cosmologies require a cosmic age at the epoch of the light emission that is larger than the age of the star burst. Like the earlier results of Yoshii et al. (1998) and Thompson et al. (1999), our new data basically rule out cosmologies with \( \Omega_M = 1 \). On the other hand, if the cosmological parameters are known, it is possible to infer from the observed starburst age the redshift at which the star formation started. Although there is still some uncertainty about the cosmological parameters, at present a universe with \( H_0 = 72 \) km \( s^{-1} \) Mpc \(^{-1} \) (Freedman et al. 2001), \( \Omega_M = 0.3 \), and \( \Omega_\lambda = 0.7 \) appears to be a good approximation. For these parameters the age of the universe at the time when the light was emitted by our \( z \approx 3.4 \) quasars was about 1.8 Gyr. Hence, the star formation age of \( \sim 1.5 \) Gyr derived for our high-z quasars results in an epoch of the beginning of star formation in these objects of \( \sim 0.3 \) Gyr, corresponding (with the above parameters) to \( z_f \geq 10 \). The redshift \( z_f \) can also be reduced if smaller values for \( H_0 \) and/or \( \Omega_M \) are assumed. On the other hand, for \( \Omega_\lambda = 0.7 \), \( \Omega_M = 0.3 \), and \( H_0 > 95 \) km \( s^{-1} \) Mpc \(^{-1} \), the age at \( z = 3.4 \) becomes shorter than the timescale for the production of the observed amount of Fe in SNe Ia, which seems to rule out such high values of \( H_0 \). However, we would like to note that the above age estimates are based on a relatively crude chemical evolution model and on the assumption that the SNe Ia in the early universe have similar properties as those observed in the local universe. If, as suggested by various theoretical studies, SNe Ia can, under certain conditions, also be produced by massive stars with a much shorter evolutionary timescale than that assumed in the standard scenarios, some SN Ia progenitors could have much shorter lifetimes (e.g., Iben & Tutukov 1984; Smecker-Hane & Wyse 1992). It cannot be excluded that in the Population III of massive galaxies at early cosmic epochs short-lived SN Ia progenitors were more common than in the local universe. In this case the above estimates would provide upper limits only. To constrain the cosmological parameters further it will be important to extend this type of analysis to known quasars with \( z > 5 \).

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