EARLY STAR FORMATION TRACED BY THE HIGHEST REDSHIFT QUASARS

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ABSTRACT

The iron abundance relative to α-elements in the circumnuclear region of quasars is regarded as a clock of the star formation history and, more specifically, of the enrichment by Type Ia supernovae. We investigate the iron abundance in a sample of 22 quasars in the redshift range 3.0 < z < 6.4 by measuring their rest-frame UV Fe II bump, which is shifted into the near-IR, and by comparing it with the Mg II λ2798 flux. The observations were performed with a device that can obtain near-IR spectra in the range 0.8–2.4 μm in one shot, thereby enabling an optimal removal of the continuum underlying the Fe II bump. We detect iron in all quasars including the highest redshift (z = 6.4) quasar currently known. The uniform observational technique and the wide redshift range allow a reliable study of the trend of the Fe II/Mg II ratio with redshift. We find that the Fe II/Mg II ratio is nearly constant at all redshifts, although there is marginal evidence for a higher Fe II/Mg II ratio in the quasars at z ≈ 6. If the Fe II/Mg II ratio reflects the Fe/α abundance, this result suggests that the z ≈ 6 quasars have already undergone a major episode of iron enrichment. We discuss the possible implications of this finding for the star formation history at z > 6. We also detect a population of weak iron emitters at z ≈ 4.5, which are possibly hosted in systems that evolved more slowly. Alternatively, the trend of the Fe II/Mg II ratio at high redshift may reflect significantly different physical conditions of the circumnuclear gas in such high-redshift quasars.

Subject headings: galaxies: evolution — galaxies: high-redshift — quasars: emission lines

1. INTRODUCTION

The iron abundance relative to α-elements has been regarded as a clock of the star formation history (e.g., Hamann & Ferland 1999). Indeed, most of the iron in local galaxies is thought to be produced by Type Ia supernovae (SNe Ia), while α-elements are predominantly produced by SNe II. The difference between the progenitor masses of SNe Ia and SNe II (hence in their lifetimes) translates into an enrichment delay between the Fe and α-elements, which was generally thought to be about 1 Gyr (Wheeler, Sneden, & Truran 1989). However, more recent studies have shown that SNe Ia are also enhanced in young stellar systems (e.g., Mannucci et al. 2003). In particular, the SN Ia progenitors may be as massive as 8 M⊙ (Greggio & Renzini 1983), which have a lifetime of ~3 × 10⁷ yr. As a consequence, the maximum of iron enrichment may occur on relatively short timescales depending on the star formation history and on the initial mass function (Matteucci & Recchi 2001).

The prominent emission lines observed in quasars allow us to investigate the metallicity of galactic nuclei at large cosmological distances (Hamann & Ferland 1999). The main iron feature in quasar spectra is the UV bump at 2200–3090 Å, which is the blend of several thousand Fe II (and some Fe III) lines. The ratio of the Fe II (UV) bump to the Mg II λ2798 doublet is sensitive to the Fe/α abundance ratio but is also sensitive to other physical properties of the emitting region such as microturbulence, density, and ionization parameter (Verner et al. 2003). As a consequence, it is not simple to quantitatively derive the Fe/α ratio from the Fe II (UV)/Mg II ratio alone. The Fe II (UV)/Mg II ratio can be used as a relative indicator of Fe/α among quasars, under the assumption that the physical properties of the emitting regions are the same.

At z > 3 the UV iron bump is shifted in the infrared. Several authors have measured the Fe II/Mg II ratio in high-redshift quasars by means of near-IR spectroscopy (Aoki, Murayama, & Denda 2002; Dietrich et al. 2002, 2003; Freudling, Corbin, & Korista 2003; Iwamuro et al. 2002; Thompson, Hill, & Elston 1999). Yet, the main difficulty in several of these studies (with the exception of Dietrich et al. 2002, 2003) is that most infrared instruments can cover only a fraction of the near-IR spectrum in a single observation, and the broad Fe II pseudocontinuum can well cover the entire observed spectral range, making it very difficult to recover the true underlying continuum.

In this Letter, the results of the analysis of near-IR spectra of 22 high-redshift quasars are presented. These spectra were obtained with an instrumental setup that can cover the full near-IR spectrum from 0.8 to 2.4 μm in one shot (and with very high throughput), therefore allowing a good estimate of the continuum underlying the Fe II bump. Our observations provide a relatively large sample of Fe II/Mg II measurements over a wide redshift range and obtained with the same technique and fitting method. Therefore, these data allow for a reliable investigation of the redshift dependence of the Fe II/Mg II ratio. Throughout the Letter we adopt H₀ = 70 km s⁻¹ Mpc⁻¹, Ω₀ = 0.3, and Ωₐ = 0.7.

2. OBSERVATIONS

The observations were obtained with the Near Infrared Camera Spectrograph (NICS) at the Italian Telescope Nazionale Galileo, a 3.56 m telescope. Among the various imaging and spectroscopic observing modes (Baffa et al. 2001), NICS offers a unique high-sensitivity low-resolution observing mode, which uses an Amici prism as a dispersing element (Oliva 2003). In this mode it is possible to obtain the spectrum from 0.8 to 2.4 μm in one shot. The throughput of the Amici prism is nearly 2 times higher than other more commonly used dispersers. The spectral resolution with a 0′′75 slit, as it was in our case, is 75 (i.e., 4000 km s⁻¹) and nearly constant over the...
whole wavelength range. This observing mode is appropriate
to study the near-IR continuum of faint sources and to detect broad (~5000 km s\(^{-1}\)) emission lines in faint quasars as well
as pseudocontinua such as the Fe \(\text{II}\) bump that require a careful subtraction of the underlying continuum. Observations were
performed in three observing runs: 2002 November 7–9, 2003
February 25–29, and 2003 May 23–26. Typical integration
times ranged from ~20 minutes for bright objects to ~2 hr for
faint objects. We include also the data of SDSS J1044–0125
obtained previously at the same instrument and already pub-
lished in Maiolino et al. (2001). Several quasars were observed
more than once on different nights to check for any instrumental
or observational artifacts in the individual spectra. Wavelength
calibration was performed by using an argon lamp and the deep
telluric absorption features. The telluric absorption was then
removed by dividing the quasar spectrum by a reference star
and the photometry on the acquisition image or through photometry
reported in the literature.

In total, 22 quasars were observed. These were selected among
the brightest (observable during each run) in each of the follow-
ing redshift ranges: 3.0–3.6, 4.3–5.1, and 5.8–6.4, which ensure
that the Mg \(\text{II}\) and a good fraction of the Fe \(\text{II}\) are observed
outside the deepest atmospheric absorption regions (with the only
exception of SDSS 1044–0125 at \(z = 5.78\), whose Mg \(\text{II}\) is in
a bad atmospheric band, but which could be used to derive the
average quasars’ spectrum; see next section).

3. DATA ANALYSIS AND FITTING TECHNIQUE

In Figure 1 we show the resulting spectrum of the highest
redshift quasar SDSS J114816.64+525150.3, at \(z = 6.40\) (Fan
et al. 2003),5 along with the identification of the major spectral
features. Some blueshift is observed for the C \(\text{IV}\) line. This
shift may be due to an imperfect correction of the atmospheric
absorption dip that occurs at the same wavelength; however,
Barth et al. (2003) also find the same effect, suggesting that
the shift may be real. The spectrum of the highest redshift
quasar shows a prominent Fe \(\text{II}\) bump. All the other spectra
and the detailed analysis of their spectral features will be pre-
sented in a forthcoming paper. Here we focus on the analysis
of the UV iron complex and of the Mg \(\text{II}\) \(\lambda 2798\) blend. The
continuum fitting that we performed was similar to the method
adopted by Dietrich et al. (2002, 2003) and Wills, Netzer, &
Wills (1985); i.e., we included both a power law and a Balmer
continuum. The continuum was fitted in the spectral regions
free of emission features and away from regions of very bad
atmospheric transmission. In Figure 1, we show the power-law
\(F_{\nu} \propto \nu^{\alpha}\), \(\alpha = -1.9\) plus Balmer-continuum fit to the spectrum
of SDSS J114816.64+525150.3. Note that in the highest red-
shift quasars (\(z > 5.8\)) there is a flattening in the continuum
blueward of C \(\text{IV}\), which is also observed in the optical spectra
of quasars at \(3 < z < 5\) (Francis et al. 1991; Vanden Berk et al.
2001), possibly as a consequence of intervening metal absorp-
tion lines. At variance with other authors, who prefer to fit the
power law by sampling the continuum redward of 3100 Å and

\footnote{5 The best redshift fitting the observed wavelength of Mg \(\text{II}\) in our spectrum is 6.40, in agreement with the redshift obtained by Willott, McLure, \& Jarvis (2003) and Barth et al. (2003).}

the continuum between C \(\text{IV}\) and Ly\(\alpha\) (but leaving positive
continuum residuals between C \(\text{IV}\) and Fe \(\text{II}\)), we prefer to fit
separately the continuum on either side of C \(\text{IV}\) with two dif-
f erent power laws. This also ensures that the continuum fit of
the quasars at \(z > 5.8\) is consistent with the continuum fit of
the lower redshift quasars.

In Figure 2 we show the averages of the quasars’ residual
spectra after continuum subtraction (and normalized to the con-
tinuum flux near the Mg \(\text{II}\) line) and grouped in the three main
redshift ranges discussed above. In each spectrum, the regions
of strong atmospheric absorption were discarded, but the spread
in redshift allows to cover continuously the whole spectral
region around Fe \(\text{II}\) and Mg \(\text{II}\). Beneath each average spectrum
we show the number of quasar spectra that populate each spec-
tral region. While both the low-redshift and the high-redshift
average spectra clearly show a prominent Fe \(\text{II}\) bump, the aver-
age of the intermediate redshift quasars is characterized by
a significantly lower intensity of the Fe \(\text{II}\) bump (middle panel).
This might be partly due to the region at \(\lambda < 2500\) Å being
poorly populated, since severe atmospheric absorption sepa-
rating the J and H bands affects several quasars in this spectral
region at these redshifts. However, the Fe \(\text{II}\) emission close to
Mg \(\text{II}\) is not affected by this problem. Therefore, we believe
that the weakness of Fe \(\text{II}\) in the average spectrum of inter-
mediate redshift quasars is real.

The Mg \(\text{II}\) line and the residuals in the region around the
Fe \(\text{II}\) bump (2200–3090 Å rest frame) were fitted, for each object,
by using the Vestergaard & Wilkes (2001) iron template,
smoothed to the velocity dispersion of Mg \(\text{II}\), and a broad Gauss-
ian at the wavelength of the Mg \(\text{II}\) line. These fitting components
for the case of SDSS J114816.64+525150.3 are shown in Figure
1. The Fe \(\text{II}\) flux was integrated between the rest-frame
wavelengths 2200 and 3090 Å. In Table 1 we report the Fe \(\text{II} / \text{Mg II}\) ratio for all quasars observed by us. We also list the rest-
frame luminosity \(\lambda L_{\lambda}\) at 1450 Å (note that thanks to our wide
spectral coverage, we can measure this quantity directly in sev-
eral quasars or by performing only a minor extrapolation).
We note that the continuum and Fe fitting techniques, as well as the instrumental setup, have often been different among previous works on this subject. As a consequence, a comparison of the results between these different studies may be subject to strong uncertainties (although some authors attempt to correct as much as possible for these systemic differences, e.g., Dietrich et al. 2003). Within this context we emphasize that our survey provides uniform and homogeneous Fe II/Mg II measurements for a set of 22 quasars spanning a wide redshift range (3.0–6.4) obtained with the same instrumental setup (which covers the entire near-IR in one spectrum), same spectral resolution (constant over the whole spectral range), and same fitting technique. Therefore they represent a self-consistent sample that is well suited to study the trend of Fe II/Mg II with redshift.

Some of the quasars observed by us were also observed by other authors and deserve some comparison, even with the caveats discussed above. BR 2237–0607 and BR 0019–1522 were observed by Dietrich et al. (2003), who find higher Fe II/Mg II ratios than we do, but the inconsistency is not large when errors are taken into account. BR 2237–0607 was also observed by Iwamuro et al. (2002), who obtain a ratio consistent with ours. SDSS J103027.10+052455.0 was observed with the Hubble Space Telescope Near-Infrared Camera and Multi-Object Spectrometer by Freundling et al. (2003), and they derived a much lower value for the Fe II/Mg II ratio (2.1 ± 1.1) than found by us (8.64 ± 2.47). However, Freundling et al. did not measure Mg II directly in this object but instead estimated the Mg II flux from the measured C III] flux and an assumed C III]/Mg II ratio similar to the average of other quasars. Also, they did not sample the continuum reddward of the Fe II bump. SDSS J114816.64+525150.3 was observed by Barth et al. (2003), who found a lower Fe II/Mg II value (4.7 ± 0.4) than ours, although marginally consistent with errors (1.5 σ). Their spectral coverage does not extend enough to sample the continuum outside the iron bump; this might have led them to underestimate the underlying continuum.

In Figure 3 we show the average of the Fe II/Mg II ratios within the three redshift ranges discussed above. In the same figure we also plot the Fe II/Mg II ratio obtained by Dietrich et al. (2003) from composite optical spectra of quasars at lower redshift matching nearly the same luminosity range as the objects in our sample. No trend of the Fe II/Mg II with luminosity.

![Table 1](image)

**TABLE 1**

| Name       | z     | Fe II/Mg II | log \( L_\lambda \) |
|------------|-------|-------------|---------------------|
| BR 0019–1522 | 4.52  | 2.02 ± 1.01 | 46.76               |
| PSS J0134+3307 | 4.53  | 1.68 ± 0.42 | 46.87               |
| SDSS J021102.72–000910.3 | 4.73  | 4.10 ± 2.05 | 46.17               |
| SDSS J075618.14+410408.6 | 5.09  | 3.43 ± 1.37 | 46.54               |
| SDSS J103027.10+052455.0 | 6.28  | 8.65 ± 2.47 | 46.68               |
| SDSS J104433.04–012502.2 | 5.78  | ...         | 46.88               |
| SDSS J110445.05+463718.3 | 6.23  | 8.03 ± 1.22 | 46.81               |
| SDSS J114816.64+525150.3 | 6.40  | 8.20 ± 2.10 | 46.98               |
| SDSS J130608.26+035626.3 | 5.99  | 9.03 ± 2.26 | 47.32               |
| SDSS J160501.21–011206.6 | 4.92  | 5.30 ± 1.35 | 46.46               |
| SDSS J1633+1411 | 4.35  | 3.23 ± 1.28 | 47.02               |
| HS 1649+3905 | 3.05  | 7.40 ± 0.74 | 46.72               |
| SDSS J173352.23+540030.5 | 3.42  | 7.74 ± 1.16 | 46.99               |
| SDSS J173744.88+582829.6 | 4.94  | 3.55 ± 1.42 | 46.75               |
| SS 1759+75 | 3.05  | 5.01 ± 2.01 | 47.41               |
| PSS J2154+0335 | 4.36  | 5.83 ± 1.75 | 47.81               |
| SDSS J220008.66+001744.8 | 4.77  | 5.50 ± 1.65 | 46.56               |
| BR 2237–0607 | 4.56  | 3.00 ± 1.20 | 47.42               |
| LBQS 2231–0015 | 3.02  | 5.77 ± 0.86 | 47.06               |
| SDSS J234625.67–001600.5 | 3.50  | 11.7 ± 2.92 | 46.90               |

* Rest-frame luminosity \( L_\lambda \) at 1450 Å.

* The Mg II of this object was not measured because it is located in the atmospheric absorption between H and K. However, this quasar was used to obtain the average spectrum in Fig. 2.

Fig. 3.—Filled circles: Average of Fe II/Mg II ratios of the quasars in our three main redshift bins. Open circles: Fe II/Mg II ratio obtained by Dietrich et al. (2003) from optical composite spectra of quasars at lower redshift.
was found within the luminosity range of our sample, which spans about 1.5 orders of magnitude.

4. DISCUSSION

Some evidence for iron supersolar abundance was found by Wills et al. (1985) in low-to-intermediate redshift quasars. In our spectra, we detect iron emission also in all high-redshift quasars. The ratio of Fe II/Mg II is nearly constant over the redshift range 0–6.4. The analysis of the high-redshift quasars indicates a possible increase in the Fe II/Mg II ratio at redshifts \( z \approx 6 \). If the Fe II/Mg II flux ratio is tracing the Fe/\( \alpha \) abundance ratio, this result would imply that the iron abundance is nearly constant or even slightly increasing from redshift zero to redshift 6.4, i.e., when the age of the universe was about 800 Myr. While this finding is difficult to reconcile with the scenarios expecting a delay of 1 Gyr or more for the iron enrichment, models of rapid and strong star formation at high redshift offer a plausible explanation. Indeed, Matteucci & Recchi (2001) have shown that models of early formation of elliptical galaxies, with very efficient star formation and lasting \( \sim 0.4 \) Gyr, imply a peak of SN Ia production (hence of iron enrichment) already at 0.3 Gyr after the onset of star formation. They have also shown that in the case of an instantaneous burst the SN Ia production peaks at only 50 Myr after the burst. As a consequence, our results can be explained with two possible scenarios:

1. A major episode of star formation in these highest \( z \) quasar hosts occurred at \( z \geq 9 \), to allow the estimated 0.3 Gyr required for SNe Ia to enrich the interstellar medium (ISM) within the context of models for star formation in elliptical hosts. The assumption that high-redshift quasars are hosted in young elliptical galaxies may be reasonable, based on the studies of quasar hosts at lower redshift (Kukula et al. 2001; Dunlop et al. 2003). Nonetheless, it is also important to keep in mind that there is no direct observational evidence that these highest \( z \) quasars reside in “normally” evolving elliptical galaxies.

2. An “instantaneous” burst of star formation occurred as late as \( z \sim 7 \), and SNe Ia had enough time to enrich the ISM within \( \sim 50 \) Myr of the burst. The ideal case of a single instantaneous burst is not likely to represent the scenario of spheroids and galaxies formation in general, for which a star formation extended in time is more plausible. However, a single instantaneous burst may have occurred in the nuclear region of these quasars, causing a rapid iron enrichment limited mostly to the central region.

It is interesting to note that the first scenario (early formation of elliptical galaxies) implies a redshift for the first major episode of star formation \( (z \geq 9) \), which is consistent with the redshift of the reionization \( (z \approx 20 \pm 10) \) inferred from the recent Wilkinson Microwave Anisotropy Probe results (Bennett et al. 2003), while the second scenario would be more consistent with the secondary reionization \( (z \approx 6) \) proposed by Cen (2003) and Wyithe & Loeb (2003).

We also find a population of quasars at \( z \sim 4.3–5.1 \) with low iron emission (Table 1). These objects are responsible for the apparently lower Fe II bump in the average spectrum of the quasars in this redshift bin (Fig. 2). Other quasars with such low Fe emission in this redshift range were also found by Dietrich et al. (2003) and Iwamuro et al. (2002; see also Fiore et al. 2003). Statistically we cannot make any strong statement on the fraction of quasars with low Fe II. However, they could represent a population of quasars hosted in stellar systems that evolved more slowly than the quasars with higher Fe emission.

An alternative explanation for the Fe II/Mg II trends discussed above is that the physical conditions of the broad-line region in high-redshift quasars are significantly different than in quasars at lower redshift. In this case, the observed Fe II/Mg II ratio at high redshift would reflect the combined effects of abundance variations and variations of other physical parameters such as density, ionization parameter, and microturbulence. Disentangling these effects requires our observations to be complemented with the detection of the optical iron bump (Verner et al. 2003), which is shifted beyond the \( K \) band at \( z > 5 \). Observations sensitive enough to detect the optical iron bump at these redshifts will probably have to await the James Webb Space Telescope.

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