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HIGH-REDSHIFT QUASARS AS EARLY STAR FORMATION PROBES

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RESUMEN

Para una muestra de 20 cuásares ($3 \lesssim z \lesssim 5$) utilizamos cocientes de líneas de emisión para estimar metalicidades del gas nuclear y el cociente Fe II UV/Mg II fué utilizado para investigar efectos de la escala temporal de enriquecimiento metálico diferencial entre el hierro y los elementos-α. Los cuásares muestran metalicidades solares elevadas ($\sim 5\,Z_{\odot}$) en su regón de líneas anchas y ninguna indicación de evolución de metalicidad hasta corrimientos al rojo $z \simeq 5$. Los cocientes medidos Fe II UV/Mg II están en el intervalo de 3 a 5, típicos de cuásares con alto z; aunque aparece una tendencia débil de cocientes promedio más bajos para $z > 4.7$. Conjuntamente, la metalicidad del gas, el cociente Fe II UV/Mg II, y las escalas temporales estimadas de los modelos para enriquecer al gas, sugieren que un episodio intenso de formación estelar dió inicio a corrimientos al rojo de $z = 8$ a 13.

ABSTRACT

For a sample of 20 quasars ($3 \lesssim z \lesssim 5$) we used emission-line ratios to estimate nuclear gas metallicities and the Fe II UV/Mg II line ratio was employed to probe for effects of differential metal enrichment timescales between iron and α-elements. The quasars show enhanced solar metallicities ($\sim 5\,Z_{\odot}$) in their broad emission-line region and no indication of a metallicity evolution up to redshifts $z \simeq 5$. The measured Fe II UV/Mg II ratios range from 3 to 5, typical for high redshift quasars, with no indication for evolution with redshift. However, there appears to be a weak tendency for a lower mean Fe II UV/Mg II ratio for $z > 4.7$. In concert, the gas metallicity, the Fe II UV/Mg II ratio, and model-based estimated time scales for enriching the gas suggest that an intense episode of star formation began at redshifts $z = 8$ to 13.

Key Words: galaxies: high-redshift — ISM: abundances — stars: formation

1. GENERAL

During the last decade a close connection of galaxy formation, intense star formation, and quasar activity, especially at high redshifts, has been established. This new framework is based on strong correlations between the mass and luminosity of the spheroidal component of a galaxy with the black hole mass (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; McLure & Dunlop 2002) and especially, on the observed relationship between the stellar velocity dispersion σ_* and the black hole mass M_{bh} in active (Ferrarese et al. 2001; Onken et al. 2004) and quiescent galaxies (e.g., Merritt & Ferrarese 2001; Tremaine et al. 2002).

In recent years a variety of galaxy formation models have been proposed to describe chemical evolution, taking into account episodes of merging, early intense star formation, and the impact of quasar activity (e.g., Di Matteo et al. 2004, 2005; Friaça & Terlevich 1998; Granato et al. 2001, 2004; Hopkins et al. 2006; Kauffmann & Haehnelt 2000; Matteucci & Recchi 2001; Romano et al. 2002). To study early phases of galaxy formation, intense star formation episodes and, the chemical enrichment of the gas, quasars are useful tools because their high luminosity enables studies up to the highest observable redshifts.

2. DATA ANALYSIS

Over the last couple of years we have observed near-infrared spectra for 20 high-redshift quasars. These spectra have been supplemented with optical spectra covering the restframe ultraviolet range from Lyα to C III]λ1909, either taken from a sample of $\sim$ 700 quasars published by Dietrich et al. (2002b) or from the publicly available Sloan Digital Sky Survey (SDSS).

Quasar spectra contain contributions from several emission sources, including a power-law nuclear continuum, Balmer continuum emission, Fe II line emission, and emission from other metal line transitions. We adopted the multi-component fit approach (Wills et al. 1985) that we have successfully applied in prior studies of high-z quasars (for more de-

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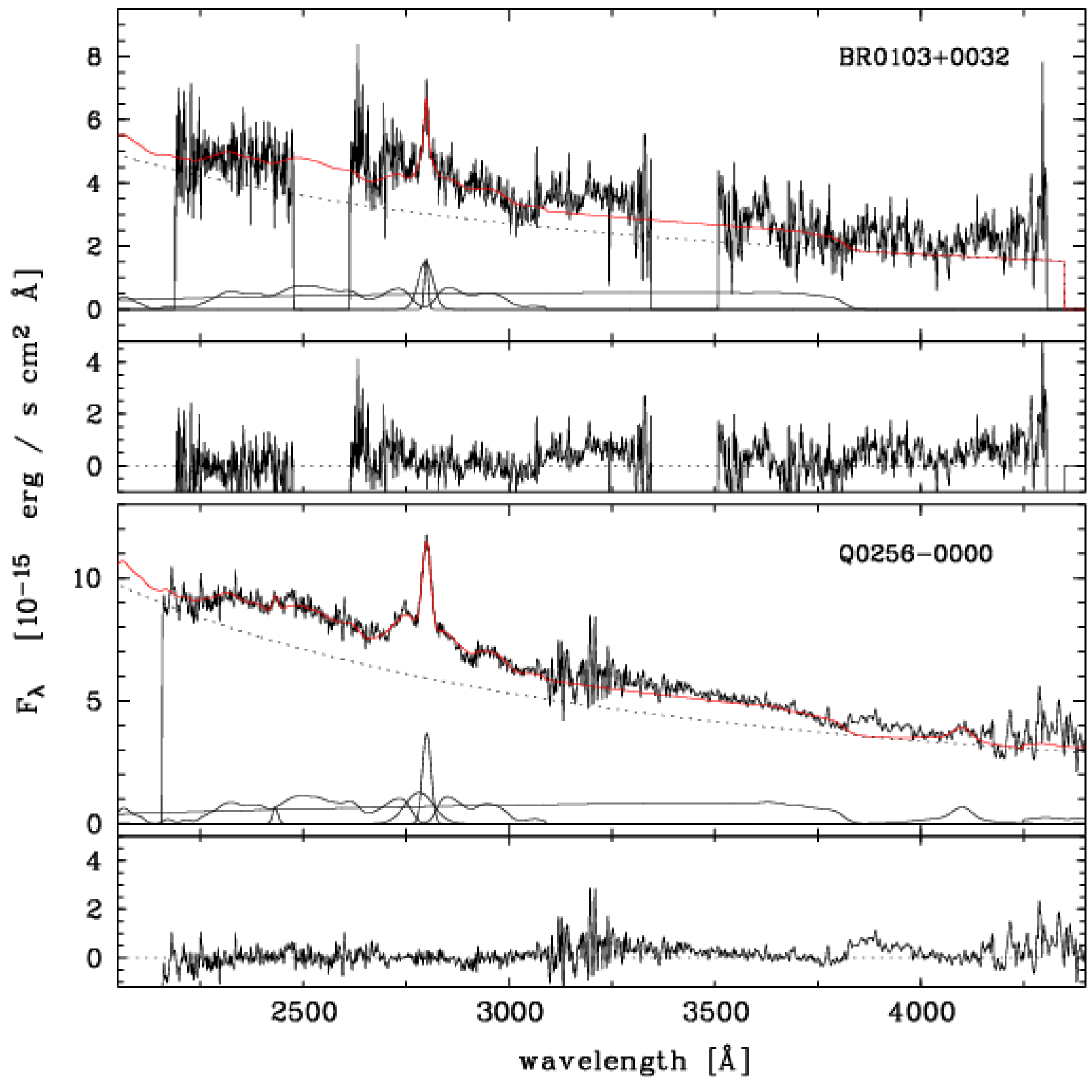

Fig. 1. The multi-component fit approach is displayed for two quasars of our sample. The power law continuum fit (dotted line), the Balmer continuum emission template, the Fe II UV emission template and the Gaussian fits to the Mg II λ2798 emission line are shown, as well as the resulting fit (red). In the bottom panel the residuum spectra are shown for these two quasars.

tails see Dietrich et al. 2002a,b). We assume that a quasar spectrum can be described as a superposition of (i) a power law continuum ($F_\nu \sim \nu^\alpha$), (ii) Balmer continuum emission, (iii) a pseudo-continuum due to merging Fe II emission blends (Vestergaard & Wilkes 2001), and (iv) an emission spectrum of individual broad emission lines, such as C IV, C III], Mg II, etc. The components (i) to (iii) are simultaneously fitted to a quasar spectrum, to determine the minimum χ^2 of the fit. A reliable estimate of the underlying continuum strength is crucial for the determination of the Fe II emission strength and requires spectra spanning a wide range in wavelength (Figure 1).

3. RESULTS AND DISCUSSION

3.1. *Estimates of the Central Gas Metallicity*

We employed the relations of emission-line ratios with gas chemical composition as suggested by Hamann et al. (2002) to estimate the gas metallicity for the high redshift quasars. We used emission line ratios of N V/C IV, N V/O VI, N V/He II, N III]/O III], N III]/C III], N IV]/C IV, and N IV]/O III] if available. The spectra of Q 0103–260, Q 0256–0000, Q 0302–0019, BR 0305–4957, and PKS 2126-158 are part of a large quasar sample compiled by Dietrich et al. (2002b). We adopt as the gas metallicity the aver-

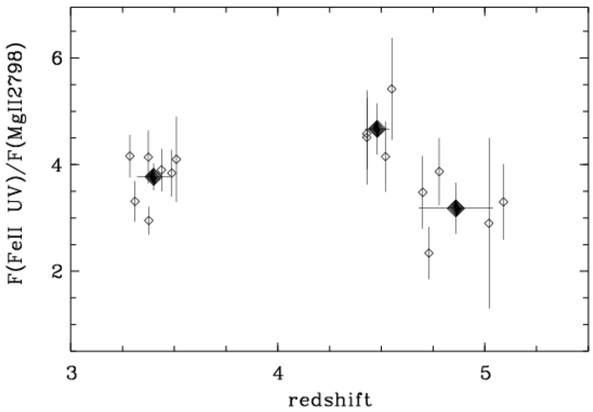

Fig. 2. The Fe II UV/Mg II λ2798 line ratio versus redshift. The individual measurements are plotted as open diamonds while the weighted average Fe II UV/Mg II ratios for $\langle z\rangle = 3.4$, $\langle z\rangle = 4.5$, $\langle z\rangle = 4.9$ are displayed as filled diamonds. The error bars on the weighted mean Fe II UV/Mg II ratios are the weighted average errors of the individual Fe II UV/Mg II line ratios.

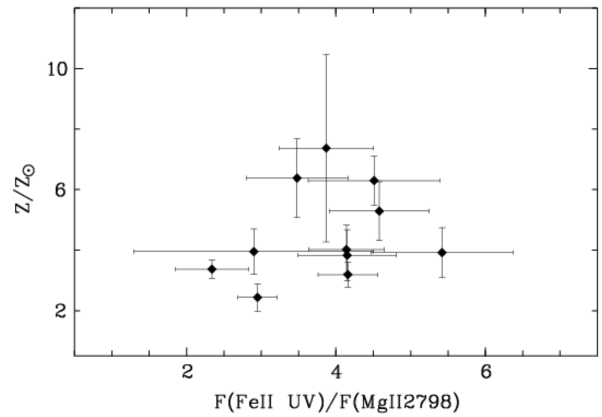

Fig. 3. Comparison of the Fe II UV/Mg II λ2798 line ratio versus the mean gas metallicity of the high-redshift quasars for which we could estimate the gas chemical composition.

age of the individual estimates. We find that the chemical composition is in the range of $Z \simeq 2.4$ to 6.8 $Z_\odot$ with an average of $Z = (4.6 \pm 0.6)\,Z_\odot$, consistent with results of similar studies (Dietrich et al. 2003a,c; Nagao et al. 2006; Jiang et al. 2007).

3.2. *Fe II UV/Mg II Emission Line Ratios*

The epoch of first major star formation in quasar host galaxies also can be constrained using the relative iron to α-elements abundance ratio. Different timescales of the enrichment processes for α-elements, (type II SNe with massive short-lived progenitors) and iron (assumed to be dominated by intermediate mass stars in binary systems ending as Ia SNe), imply an enrichment delay of iron (Tinsley 1979; Wheeler, Sneden, & Truan 1989; Yoshii et al. 1996). It is suggested that the delay is of the order of $\sim 0.2 - 0.6$ Gyr for elliptical galaxies (Friaça & Terlevich 1998; Matteucci & Recchi 2001). Hence, the abundance ratio of iron vs. α-elements can be used as a cosmological clock (e.g., Hamann & Ferland 1999).

The ultraviolet Fe II emission-line fluxes of the high-z quasars were measured from the scaled Fe II templates for a wavelength range of $\lambda\lambda 2200-3090$ Å. The integrated flux of Mg II λ2798 was determined from the sum of the Gaussian components used to fit the line (Figure 1). In Figure 2 the Fe II UV/Mg II ratios which are in the range of ~ 3 to ~ 5, are displayed as a function of redshift. A possible luminosity dependence of the Fe II UV/Mg II ratio can be neglected because these high-redshift quasars have comparable luminosities ($\lambda L_\lambda(1450\text{Å}) \simeq 10^{47}$ erg s^{-1}). The Fe II UV/Mg II ratios of the quasars indicate a lack of evolution up to redshifts of $z \simeq 4.5$, consistent with similar studies (e.g, Thompson et al. 1999; Iwamuro et al. 2002; Maiolino et al. 2003; Jiang et al. 2007; Kurk et al. 2007). However, the five quasars with $z \gtrsim 4.7$ show a trend to lower Fe II UV/Mg II ratios toward higher redshifts (Figure 2). We have calculated the weighted mean of the Fe II UV/Mg II ratio for the quasars with redshifts $z < 4.7$ and $z \geq 4.7$, respectively. For the quasars with $z < 4.7$ we find a weighted mean of $\langle$Fe II UV/Mg II$\rangle = 3.7 \pm 0.1$, while the quasars with $z \geq 4.7$ show $\langle$Fe II UV/Mg II$\rangle = 3.1 \pm 0.3$. The weighted means of these two subgroups are different at a 2-σ to 3-σ level only.

Recent studies of high-z quasars (Jiang et al. 2007; Kurk et al. 2007) measured Fe II UV/Mg II ratios which differ by a factor of ~ 2 for individual objects. Obviously, based on the few high-z quasars with Fe II UV/Mg II ratio measurements, further investigations are required to provide support for a potential decline of this ratio toward higher redshifts.

In Figure 3 the distribution of the estimated gas metallicities (§ 3.1) are shown together with the corresponding Fe II UV/Mg II ratios. There appears to be a very marginal tendency toward higher Fe II UV/Mg II ratios for quasars with higher gas metallicity. But is has to be taken into account that the Fe II emission line strength depends on several parameters and that metallicity has only a minor impact (Baldwin et al. 2004; Verner et al. 2004; Sigut et al. 2004). Hence, based on only eleven high-z quasars is it premature to draw any conclusions from the distribution of these measurements.

Assuming that it takes 0.5 to 0.8 Gyr to enrich the gas of these high-z quasars to super-solar metallicities, the first star formation epoch can be estimated to begin when the Universe was $\sim$ 650 to 350 Myr old, i.e. at redshifts of $z \simeq 8$ to 13.

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