RevMexAA (Serie de Conferencias), **6**, 221–226 (1997)

EMISSION-LINE PROPERTIES AND ABUNDANCES IN HIGH-REDSHIFT QSOs

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RESUMEN

El número de QSOs luminosos que se conocen con altos corrimientos al rojo ($z > 4$) crece continuamente. Estos objetos son de interés para estudios de brotes de formación estelar pues están relacionados a condensaciones protogalácticas que han tenido o tienen, una gran actividad de formación estelar. Hacemos un resumen del estado del conocimiento de QSOs con $z > 4$. Los resultados espectroscópicos obtenidos recientemente indican abundancias de los elementos pesados mayor que la Solar en el plasma responsable por la emisión de líneas, similar a lo encontrado para los QSO con $z \approx 2-3$. Estos objetos pueden estar caracterizados por la presencia de anomalías espectroscópicas adicionales, aunque estos resultados podrían estar ligeramente afectados por sesgos introducidos por las técnicas de búsqueda de cuasares con grandes corrimiento.

ABSTRACT

An increasing number of luminous QSOs are now known at very high redshift ($z > 4$). These objects are of interest in the context of starbursts in that they are evidently related to early galaxy-like condensations that have undergone or are undergoing substantial star formation activity. This contribution will review the current status of our knowledge of $z > 4$ QSOs. Recent spectroscopic work suggests that heavy-element abundances in the line-emitting plasma in these objects are often greater than solar, similar to results for QSOs at $z \approx 2 - 3$. Additional spectroscopic anomalies may characterize these objects, although these results may be influenced in subtle ways by selection effects related to discovery techniques for high redshift quasars.

Key words: **GALAXIES: ABUNDANCES — GALAXIES: FORMATION — QUASARS: EMISSION LINES**

1. INTRODUCTION

In most interpretations of quasar phenomena, the existence of these sources is coupled in some manner to star formation processes. This statement is true by definition in the starburst model of active galactic nuclei (AGNs; see the review by Cid Fernandes in this volume). In scenarios invoking accretion onto a massive black hole to power QSOs, stellar processing is also expected to be important for the initial collapse and formation of the black hole (e.g., Rees 1984). QSOs thus provide unique probes of galaxy-like objects at high redshift. If the quasar phenomenon traces an episode in the early history of a galaxy, as suggested by evolution in the AGN luminosity function with redshift, then QSOs at high z are signposts of this phase of galaxy evolution. The study of such objects provides a complement to research on normal galaxies that is now reaching to comparably high redshift (e.g., Steidel et al. 1996).

This review will examine our understanding of the properties of QSOs at high redshift, and will focus in particular on objects with $z \gtrsim 4$. At these redshifts, the available time for collapse and formation of galaxies and stars is limited to only $\sim 1 - 2$ Gyr since the Big Bang, for typical choices of cosmological parameters. An increasing amount of information is becoming available on the properties of QSOs at this epoch, including quantitative information on chemical evolution in the host galaxy.

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2. KNOWN QSOS AT $Z > 4$

In the nine years since the discovery of the first QSO at $z > 4$ by Warren et al. (1987), several groups of researchers have expended considerable effort to find more of these objects. A list of $z > 4$ QSOs reported through 1994 is given by Shaver (1995). More recent discoveries are discussed by Kennefick et al. (1995a, b), Darling et al. (1995), Hawkins et al. (1996), and Hawkins & Véron (1996), resulting in a total count of 68 sources (note that Shaver's list includes 0051–27 twice).

A variety of techniques have been employed for finding $z > 4$ QSOs, including selection based on colors, grism spectra, variability, X-ray or radio emission, and serendipity. The majority of known sources have been found via color selection, as described, for example, by Irwin et al. (1991; APM survey) and Kennefick et al. (1995b; POSS II survey). These authors employed large-area surveys with Schmidt Telescope plates from which candidate QSOs were identified primarily on the basis of very red colors as measured by $B-R$ or similar indices. The red color results from a combination of Lyα forest absorption in B and intrinsic Lyα emission falling in R. Details of the APM QSOs are listed in Storrie-Lombardi et al. (1996).

The majority of emission-line-selected QSOs have been reported by Schneider et al. (1991, and references therein). Their search employed automated selection of candidates from grism spectra acquired with a CCD. The majority of QSOs identified from this search are somewhat fainter than the color-selected sources, due to the greater depth and smaller area of the grism survey.

3. SPECTROSCOPIC PROPERTIES

While considerable effort has been applied to the discovery of $z > 4$ QSOs, only limited attention has been given so far to the intrinsic emission properties of these sources. Many of the spectra acquired and published for these objects were obtained primarily for identification purposes, and are consequently characterized by limited signal-to-noise ratio and/or spectral coverage. Discussions of emission properties in available spectra, emphasizing the C IV line, were presented by Schneider et al. (1989, 1991).

In order to investigate the emission characteristics of $z > 4$ QSOs in more detail, we have initiated a program of spectroscopy using the Multiple Mirror Telescope (MMT), in collaboration with Craig Foltz (MMT Observatory), and Fred Chaffee (MMT and Keck Observatories). The observations are acquired in the observed-frame far-red region with ~ 10 Å resolution, so as to span Lyα $\lambda1216$ – He II $\lambda1640$ in the source rest-frame. The goal of this program is to study the emission features in this bandpass in detail in order to see if these luminous and potentially very young sources exhibit characteristic differences in comparison with lower redshift objects. A particular emphasis in this study is the use of N V $\lambda1240$ as an abundance diagnostic (see §3.3).

Targets for observation were taken from the list of known $z > 4$ QSOs and selected on the basis of observability considerations. We have initially emphasized observation of sources with large apparent brightness, which are consequently drawn primarily from color-selected samples (§2). Examples of resulting spectra are shown in Figure 1. The spectrum of BR 2248-1242 is particularly noteworthy for the large equivalent widths and narrow profiles of its emission lines. Our observational program is still in progress, and the following sections describe some preliminary results based on analysis of spectra for 15 sources.

3.1. General Characteristics

To first order, the spectra for the $z > 4$ QSOs are similar in emission properties to spectra for AGNs at lower redshift. One measure of this similarity is illustrated in Figure 2, which shows a plot of the rest equivalent width of the C IV $\lambda1549$ feature as a function of continuum luminosity L_ν measured at 1450 Å. QSOs at lower redshift show a well-defined negative correlation between EW(C IV) and L_ν (the Baldwin effect; Baldwin 1977), and the dotted line depicts a fit to the observed correlation for QSOs at $z = 2-3$ derived by Osmer et al. (1994). Measurements for $z > 4$ QSOs are shown for our MMT data along with published values for additional (mostly grism-selected) objects studied by Schneider et al. (1991). The $z > 4$ QSOs are generally consistent with the trend and scatter (cf., Osmer et al. 1994) found for AGNs at lower redshift and luminosity.

The $z > 4$ QSO spectra resemble their lower redshift counterparts in other ways. Figure 3 shows the behavior of C IV peak/continuum ratio and rest-frame EW(C IV) as a function of C IV full width at half maximum (FWHM). Evidence of a negative correlation is seen in both plots, consistent with behavior reported previously for objects at lower redshift (e.g., Francis et al. 1992). Storrie-Lombardi et al. (1996) also demonstrate that characteristic offsets in velocity are observed between different emission lines in individual $z > 4$ APM QSOs, in accord with previous findings for lower z.

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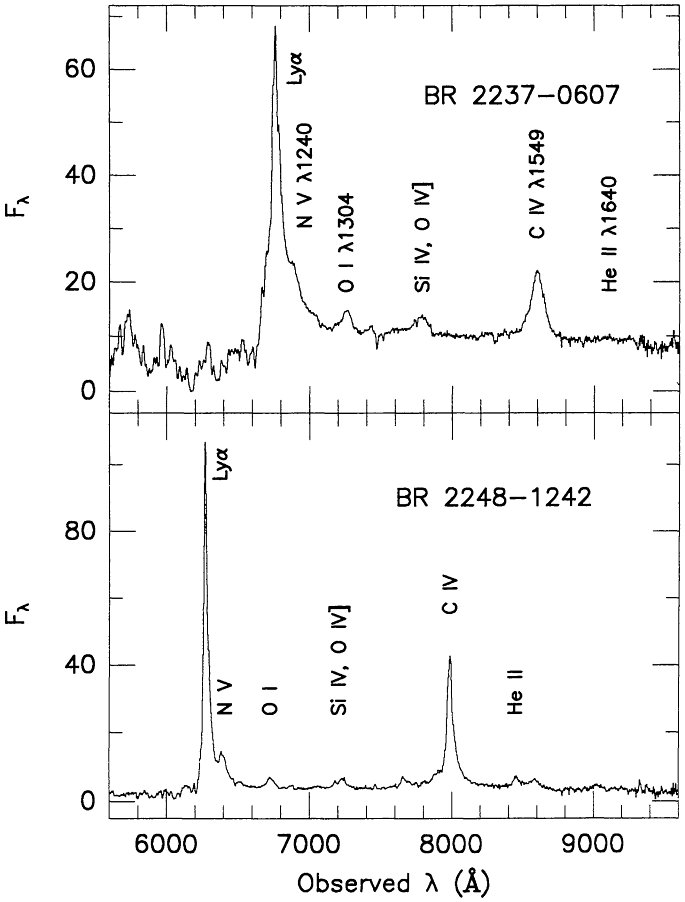

Fig. 1. Examples of MMT spectra for two QSOs at $z > 4$: BR 2237–0607 (top), and BR 2248–1242 (bottom).

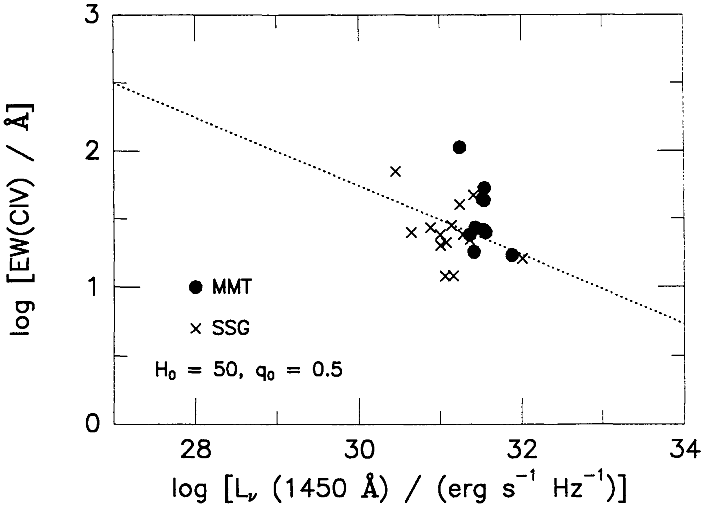

Fig. 2. Rest-frame EW(C IV) as a function of rest-frame 1450 Å luminosity for $z > 4$ QSOs. Filled circles represent MMT measurements with continuum photometry from Storrie-Lombardi et al. (1996); crosses are measurements published by Schneider et al. (1991). The dotted line represents the empirical trend found by Osmer et al. (1994) for QSOs at $Z = 2 - 3$.

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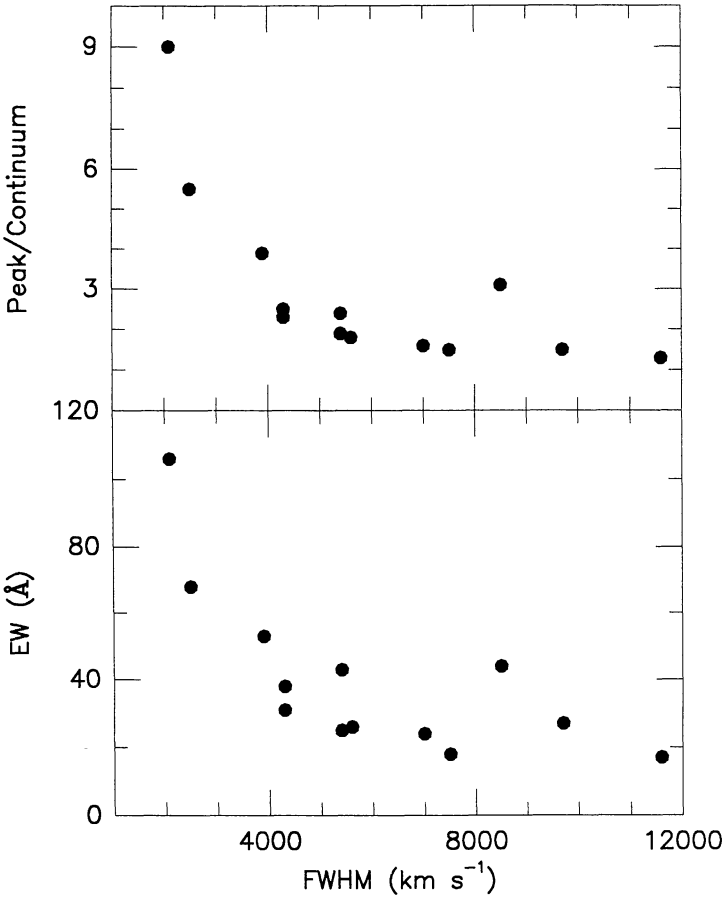

Fig. 3. Emission-line peak/continuum ratio and rest-frame equivalent width as a function of FWHM, for C IV measured in the MMT sample.

3.2. Anomalous O I Emission?

One apparent exception to the spectral consistency of low-z and $z > 4$ QSOs appears in the strength of the O I λ1304 feature. On average, EW(O I) ≈ 4.5 Å for our MMT sources, which is ~ 50% higher than is typical for low-z QSOs. This line has a strength approaching that of the 1400 Å feature in the spectra shown in Figure 1.

The O I line is noteworthy in that it is apparently dominated by a fluorescence process resulting from pumping via line coincidence with H Lyβ, rather than by collisional excitation (see, e.g., Netzer 1990 for a discussion). This fluorescence process is expected to be efficient in regions of large Hα optical depth and will scale with the O/H abundance ratio. The unusual strength of O I in the high-z sources could thus stem from high metallicities in these objects, although this explanation may not be unique, given the complex formation process for this line. The observed feature may also be contaminated, in principle, by emission in Si II λ1307, although the measured wavelength does not support identification of this transition as the dominant contributor. The strength of Si II emission observed in QSOs at lower redshift is itself potentially complicated and poorly understood (Baldwin et al. 1996).

There is some indication that the enhanced strength of O I emission may be part of a larger pattern of correlated behavior in the $z > 4$ QSO spectra. This possibility is suggested by the prevalence of QSOs with relatively narrow, peaky emission-line profiles in the objects we have studied to date (see, for example, Fig. 1). These characteristics can be interpreted in the context of earlier work on the statistical properties of AGN spectra that provide evidence for 2 or 3 distinguishable nebular components that dominate production of the broad-line spectrum (e.g., Francis et al. 1992; Brotherton et al. 1994; Baldwin et al. 1996). These components

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include a narrow-line component with FWHM $\approx$ 2000 km s^{-1} that emits preferentially in transitions of low-ionization species such as Al III, Fe II, C II, and C III (the so-called "Intermediate Line Region," or ILR), and a blueshifted broad component with FWHM $\gtrsim$ 7000 km s^{-1}, emitting preferentially in high ionization lines including those of C IV, Lyα, N V, and O VI.

Baldwin et al. (1996) note explicitly that O I can probably be identified with the narrow component (their "Component A"), which can be described physically by clouds with relatively high density n and moderate ionization parameter U ($n \approx 10^{13}$ cm^{-3}, $U \approx 10^{-2.5}$), where U is a dimensionless ratio of ionizing photon density to electron density at the irradiated cloud face. The strong O I emission and tendency toward narrow, peaky line profiles in $z > 4$ QSOs may thus point to a characteristic difference in the structure and physical conditions in these systems in comparison with their lower-redshift counterparts. Scrutiny of additional sources is clearly desirable in order to test whether this trend is consistent or merely an anomaly of our current small sample.

3.3. Selection Effects

The influence of subtle selection effects must also be understood before identifying the prevalent ILR signatures in our spectra as characteristic of $z > 4$ QSOs in general. A bias toward selection of QSOs with narrow, peaky profiles can potentially result in grism searches since identification of candidate objects depends at some level on the prominence and contrast of the emission features. (Automated analysis techniques can minimize and quantify any such bias; see Schmidt et al. 1995 and references therein.) In the present instance, however, the majority of objects observed in our MMT program are color-selected, which seems less likely to introduce a profile bias.

Broadband color selection of QSOs may nonetheless introduce a bias toward discovery of sources with peaky emission lines. Observed emission-line equivalent widths are increased from their rest-frame values by a factor of $(1 + z)$, with the result that $z > 4$ QSOs may have EW(Lyα + N V) $\gtrsim$ 500 Å. Broadband magnitudes for bandpasses centered on this feature can thus be significantly affected by the line strength, especially when taking into account the continuum depression introduced by the Lyα forest shortward of the emission line. The photographic bandpasses containing the emission feature in the Schmidt telescope surveys (R or F) also tend to be somewhat narrow, with widths of only $\sim$ 600 Å. Near the magnitude limit of a survey, objects with large equivalent width are thus expected to be detected preferentially. A larger EW(Lyα + N V) also leads to a redder $B - R$ color and hence further increases the likelihood of detection in color-selected samples. These biases are discussed quantitatively by Kennefick et al. (1995b; see particularly their Fig. 6).

If objects with large emission equivalent widths are preferentially selected, these sources can also be expected to have narrow, peaky profiles, due to the empirical correlation illustrated in Figure 3. A suggestion of this bias is present in Figure 2, in that the plotted points for the color-selected QSOs show a weak tendency to scatter above the extrapolated Baldwin relation and to exhibit larger equivalent widths than the grism-selected sources. There is some indication, however, that O I emission remains relatively strong even in the sources we have observed with only modest EW(C IV). Additional study is required in order to distinguish selection effects and intrinsic phenomena in this sample.

3.4. N V and Abundances

The abundances of heavy elements in AGN emission-line plasma are of great interest for the understanding of their galactic hosts, but are generally difficult to measure from the strong collisionally-excited lines due to thermostatic feedback effects. Shields (1976) suggested the use of ultraviolet intercombination lines as abundance diagnostics, but these features are often weak and may be subject to collisional suppression. An alternative approach for constraining the heavy-element content of QSO broad-line regions (BLRs) was developed by Hamann & Ferland (1992, 1993), who combined galaxy chemical evolution models with photoionization calculations relevant for the BLR. Their results demonstrated that the strength of N V λ1240 provided a potentially robust indicator of metallicity due to the dominance of secondary enrichment for nitrogen production in vigorously star-forming environments.

The strong N V emission characteristic of QSOs at $z = 2-3$ can be explained by a highly enriched interstellar plasma consistent with standard chemical evolution scenarios for young, massive elliptical galaxies or galaxy bulges. The gas phase metallicity in these cases is approximately solar or up to several times solar; corroborative evidence for supersolar abundances in these sources is increasingly emerging from studies of *absorption* lines intrinsic to luminous QSOs (e.g., Korista et al. 1996; Hamann 1996; Turnshek et al. 1996).

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A major goal of our MMT study of $z > 4$ QSOs is to quantify emission ratios of N v λ1240/C iv λ1549 and (especially) N v λ1240/He ii λ1640, both of which can be used to provide lower bounds to nitrogen abundance and, in the context of a chemical evolution model, the overall metallicity in the emitting plasma (see Hamann & Ferland for details). Due to the limited available time since the Big Bang at this redshift, we might expect to catch QSOs in a characteristically younger and less evolved (i.e., less enriched) phase than is the case for QSOs at intermediate z. Alternatively, line ratios that remain consistent with supersolar enrichment at these epochs would strengthen the evidence that QSOs are tracing early sites of massive star formation in galaxies.

While measurement of the N v feature is complicated by blending with Lyα, our preliminary conclusion is that QSOs at $z > 4$ show strong N v emission with an amplitude similar to that seen in quasars at $z \approx 2-3$ (i.e., metallicity $Z \gtrsim Z_{\odot}$ in most cases). The spectra shown in Figure 1 roughly bracket the range of observed N v/He ii values, with approximate ratios of ~ 3 for BR 2248−1242 and > 21 for BR 2237−0607, corresponding to $Z \gtrsim 2\ Z_{\odot}$ and $Z \gtrsim 10\ Z_{\odot}$, respectively. A recent episode of vigorous star formation may thus be a requisite for generation of a luminous AGN even at these early times.

4. CONCLUSIONS

The growing numbers of QSOs identified at $z > 4$ provide a new opportunity for probing young galaxy-like objects and associated star formation at very early times. Spectroscopic data for these objects do not show dramatic differences in comparison with observations for quasars at lower z. Subtle differences may be present, however, and in particular there is evidence of unusual strength in the O i λ1304 line for the $z > 4$ sources that may stem from high oxygen abundance or a characteristic structural difference in the BLR. Verifying such differences will require analysis of more objects and careful consideration of selection effects embedded in QSO samples identified by color techniques. A more direct indicator of abundances in the line-emitting plasma, N v λ1240, suggests that the emitting plasma in $z > 4$ QSOs is described by metallicities with $Z \gtrsim Z_{\odot}$, which strengthens evidence linking the early formation of massive star-forming galaxies and generation of luminous AGNs.

REFERENCES

Baldwin, J. A. 1977, ApJ, 214, 769
Baldwin, J. A., et al. 1996, ApJ, 461, 664
Brotherton, M. S., Wills, B. J., Francis, P. J., & Steidel, C. C. 1994, ApJ, 430, 495
Darling, J., de Carvalho, R. R., Kennefick, J., & Djorgovski, S. G. 1995, BAAS, 27, 1411
Francis, P. J., Hewett, P. C., Foltz, C. B., & Chaffee, F. H. 1992, ApJ, 398, 476
Hamann, F. 1996, ApJS, submitted
Hamann, F., & Ferland, G. 1992, ApJ, 391, L53
____________. 1993, ApJ, 418, 11
Hawkins, M. R. S., Shaver, P. A., Clements, D., & van der Werf, P. 1996, MNRAS, 280, L1
Hawkins, M. R. S., & Véron, P. 1996, MNRAS, in press
Irwin, M., et al. 1991, in The Space Distribution of Quasars, ed. D. Crampton (San Francisco: ASP), 117
Kennefick, J. D., et al. 1995a, AJ, 110, 78
Kennefick, J. D., Djorgovski, S. G., & de Carvalho, R. R. 1995b, AJ, 110, 2553
Korista, K., Hamann, F., Ferguson, J., & Ferland, G. 1996, ApJ, 461, 641
Netzer, H. 1990, in Active Galactic Nuclei (Berlin: Springer)
Osmer, P. S., Porter, A. C., & Green, R. F. 1994, ApJ, 436, 678
Rees, M. J. 1984, ARA&A, 22, 471
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1995, ApJ, 110, 68
Schneider, D. P., Schmidt, M., & Gunn, J. E. 1989, AJ, 98, 1507
____________. 1991, AJ, 101, 2004
Shaver, P. A. 1995, in Seventeenth Texas Symposium, ed. H. Boringer et al. (New York: New York Academy of Sciences)
Shields, G. A. 1976, ApJ, 204, 330
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M. J., & Hazard, C. 1996, ApJS, in press
Turnshek, D. A., et al. 1996, ApJ, 463, 110
Warren, S. J., et al. 1987, Nature, 325, 131

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