Revista Mexicana de Astronomía y Astrofísica, **26**, 53-63 (1993)

QUASARS: THE BIRTH OF GALAXIES

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RESUMEN

Se han observado cuásares con corrimientos al rojo mayores que 4, lo que ofrece una de las pocas formas directas de estudiar las condiciones en los centros de las galaxias durante su evolución temprana. El analisis de las líneas anchas de emisión sugiere que el gas emisor tiene metalicidades muy por arriba de la solar, y que las abundancias de los metales aumentan con el corrimiento al rojo y la luminosidad. Estas abundancias son similares a las que se infiere existieron en los núcleos de galaxias masivas temprano en su evolución; ésto sugiere que los cuásares activos ocurren cerca del fin de la época de formación estelar rápida, dominada por estrellas masivas que dieron origen a un medio interestelar enriquecido.

ABSTRACT

Quasars are now observed to redshifts beyond 4, offering one of the few direct probes of conditions in the centers of galaxies early in their evolution. Analysis of the broad emission lines suggests that the emitting gas often has a metallicity well above solar, and that metal abundances increase with redshift and luminosity. These abundances are similar to those inferred to have existed in the cores of massive galaxies early in their evolution, suggesting that observable quasars occur near the end of the epoch when rapid star formation dominated by massive stars has created an enriched interstellar medium.

Key words: **GALAXIES – ABUNDANCES — QUASARS**

I. INTRODUCTION

Quasars are defined as starlike luminous objects, with strong emission lines of the astrophysically abundant elements (Osterbrock 1993). The emission lines are important for two reasons. First, it is possible to estimate the luminosity of the quasar from its emission line spectrum (Baldwin 1977). Hence it may be possible to use quasars as probes of the expansion at redshifts >4, leading to direct measurements of H_0 and q_0, once these luminosity indicators are fully validated. Second, it is also possible to infer the relative abundances and overall metallicity of quasar environments from these same lines (Shields 1976). Here the quasars can be used to probe the chemical enrichment and evolution of the host galaxies. Quasars are thus probes of the universe after the primordial nucleosynthesis, at epochs when the first generations of stars have formed.

Whether powered by black holes or starbursts, quasars are believed to be associated with the early stages of the formation of giant galaxies (Rees 1984; Terlevich and Boyle 1993). The abundances in the cores of these galaxies are expected to be high. For example, observations and models of giant ellipticals suggest that metallicities up to $Z \sim 10\ Z_{\odot}$ are attained in less than 1 Gyr (Arimoto and Yoshii 1987; Bica, Arimoto, and Alloin 1988; Angeletti and Giannone 1990). In the bulge of our own galaxy the stellar metallicities reach as high as $\sim 10\ Z_{\odot}$, with a mean of $\sim 2\ Z_{\odot}$ (Rich 1988). Note that these observations directly measure the metallicity of the stellar population and not the gas. At any stage in the evolution of a star cluster the gas will be as chemically enriched as the most recently formed stars, and thus more enriched than the bulk of the stellar population. Accordingly, metallicities of $\sim 10\ Z_{\odot}$ or higher may be typical of the gas in the evolved cores of massive galaxies. Observations indicate that this gas is eventually expelled or perhaps consumed by a black hole. Nonetheless, the gas clearly remains long enough for the evolution to high Z's to occur. The broad emission lines of quasars and active galactic nuclei (AGN) offer direct probes of the composition and chemical history of this gas in galaxy cores.

Early attempts at determining the abundances of quasar broad line region (BLR) clouds centered on the weak intercombination lines (Shields 1976; Osmer 1980; Uomoto 1984). These lines are not only weak and difficult to measure, but their predicted intensity is sensitive to the gas density above 10^{10} cm^{-3}, so their interpretation requires lower densities by assumption. These studies were partially compromised by the fact that the density and flux of ionizing photons thought to characterize BLR clouds were wrong by several orders of magnitude (see the review by Peterson 1993).

In this review we discuss a new approach to measuring the abundances, namely, the use of the very strong NV λ1240 line compared to CIV λ1549 and HeII λ1640. These lines are far less sensitive to collisional quenching than the intercombination lines because they are permitted transitions. They are also observable in a much larger sample of QSOs. The next section shows that the overall intensity of the BLR spectrum is remarkably insensitive to the metallicity of the gas. We must therefore rely on chemical enrichment models to infer the metallicity by first modelling the selective enrichment of nitrogen and the other elements. Our goal is to understand the chemical state of the gas and thereby constrain the evolution/star formation that must have preceded the QSO's formation.

A second major goal is to place limits on the age of the host systems and eventually on the cosmology by establishing Fe as an abundance chronometer. To put this work in context, Figure 1 shows the age of the Universe as a function of redshift. Quasars are now routinely observed at redshifts greater than 4 (Schneider et al. 1991) so they can be used to probe the chemical state of the galaxy cores at an early stage. The relative abundance of Fe (e.g., Fe/O) changes as the environment ages (Wheeler et al. 1989), so it may be possible to use Fe as a "clock" to measure the age of the stellar population directly, and hence infer the cosmology needed to be consistent with this level of enrichment.

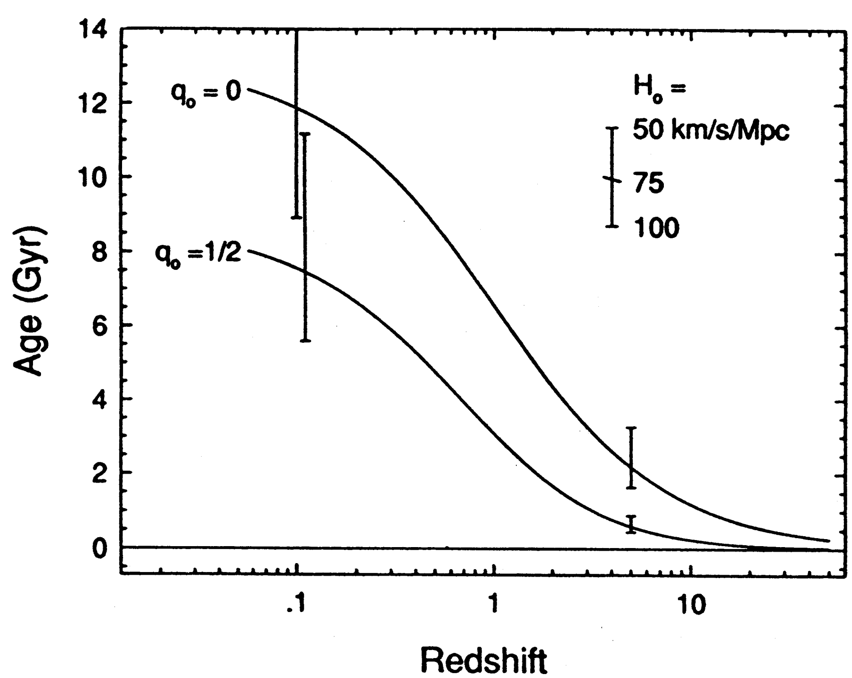

Figure 1. Age of the Universe vs. redshift. Various values of H_o and q_o are indicated.

II. ABUNDANCE DIAGNOSTICS IN QUASARS

In our work we have focused on the NV line and its strength relative to HeII and CIV. This is one of the strongest lines in high redshift quasars, and the only nitrogen line routinely observed at all redshifts. The overall emission line spectrum shows many metallic lines, which of course implies SOME enrichment, but the line strengths are surprisingly insensitive to the global metallicity. Figure 2 shows the results of a series of calculations in which the abundance of elements heavier than helium was varied by a simple scale factor. The resulting metallicity relative to solar (Grevesse and Anders 1989) is indicated on the x-axis.

The calculations are for a density of 10^{10} cm^{-3}, a flux of ionizing photons of 10^{20} cm^{-2} s^{-1}, and the quasar continuum described by Mathews and Ferland (1987) with an additional break at 1 μm. The figure shows the intensity of the strong CIV line relative to Lyα. It changes little despite a many order of magnitude change in the metallicity, because this line is one of the major coolants for the gas (Osterbrock 1989; Davidson 1977). The cloud is in thermal equilibrium, so its temperature rises or falls to maintain a balance between heating, by photoionization, and cooling, predominantly by collisional excitation of the observed lines. The message of this figure is somewhat depressing; the intensities of the strong lines tell us little about the total metallicity of the BLR, and the quasar population could actually have a very wide range of metallicities while displaying nearly the same emission line spectrum.

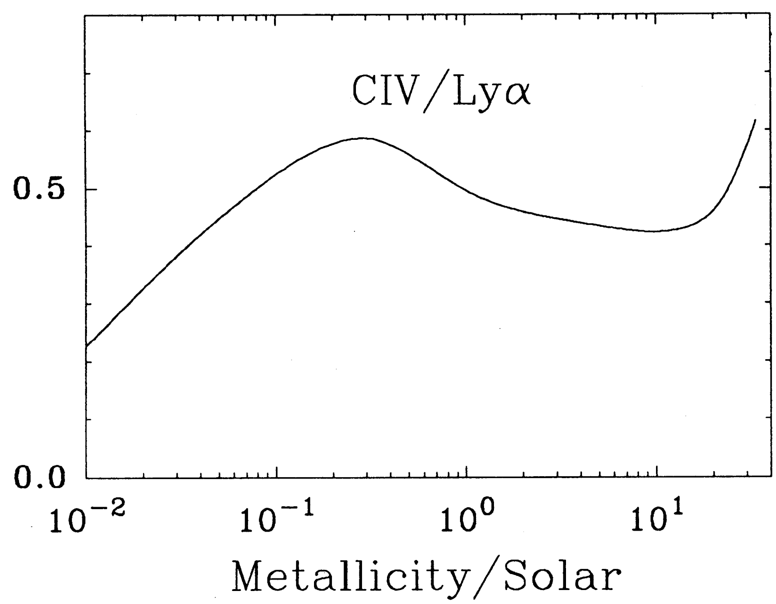

Figure 2. This plot shows the CIV/Lyα ratio for typical BLR parameters, but with the abundances of all the heavy elements scaled to produce the metallicities indicated on the bottom. The line ratio changes by less than a factor of two despite a four order of magnitude change in the C/H abundance ratio.

Although this is true of the total intensities of all strong lines, the relative intensities of the lines *are* sensitive to the selective enrichment of individual elements, and this motivates the approach we have taken. Chemical evolution simulations (see below) indicate that nitrogen is selectively enriched as a cluster ages. If the enrichment is mostly "secondary" the N abundance grows roughly as Z^2 (see Hamann and Ferland 1993, hereafter HF93, for a discussion). By measuring the abundance of nitrogen relative to C or He we can infer the total metallicity by reference to these simulations.

At a given Z, the intensity ratios NV/CIV and NV/HeII are sensitive to both the incident continuum and the physical conditions in the BLR, so it is necessary to make some estimate of the density and flux of ionizing photons typical of a BLR cloud. Figure 3 shows the ratios NV/CIV and NV/HeII, for solar abundances and various densities and fluxes.

The continuum used here, and in the remainder of this section, has been optimized to yield the largest possible line ratios at high Z (Baldwin et al. 1993). The most important factor being the high energy cutoff of the "blue bump", which primarily effects NV/HeII. The maximum line ratios in Fig. 3 obtain along a ridge

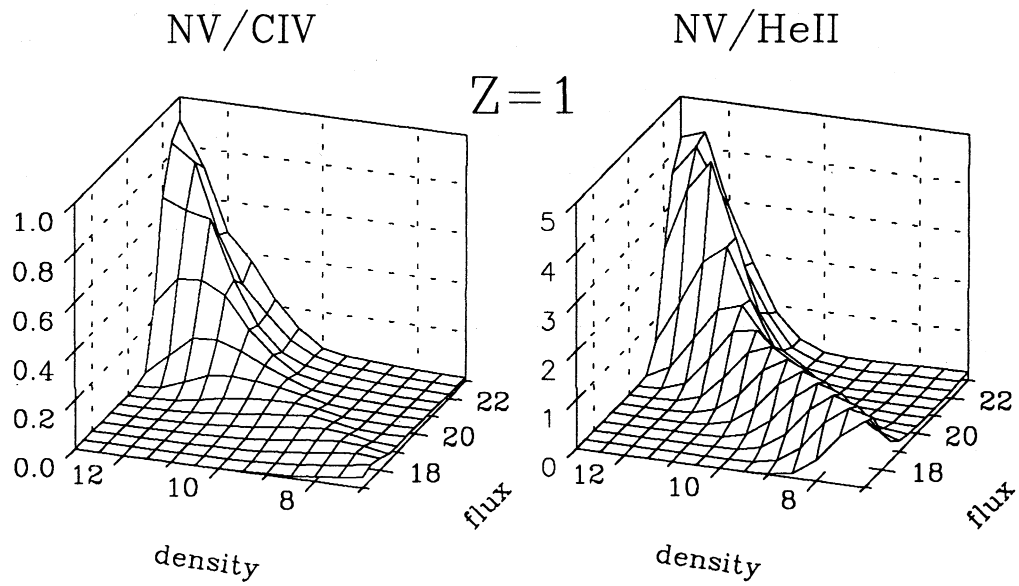

Figure 3. NV/CIV and NV/HeII ratios as a function of the log of the density and the log of the flux in ionizing photons. Solar abundances are assumed. The continuum is the optimal continuum derived by Baldwin et al. (1993).

of constant ratio density/flux, a ratio often referred to as the ionization parameter. Along this ridge the photoionization simulations show that the cloud density must be less than 10^{12} cm^{-3}. Above this density many lines (Si IV λ1397 and OVI λ1034 in particular) reach intensities much larger than observed (see also Baldwin et al. 1993 for a discussion of the upper limit to the cloud density). We see that for solar abundances and densities $\sim 10^{10}$ cm^{-3} we expect NV/CIV ~0.2 and NV/HeII ~1. These line ratios are in agreement with those observed in low luminosity Seyfert galaxies (see for instance, the spectrum of NGC 5548 presented in Clavel et al. 1991). However, both ratios are roughly an order of magnitude *smaller* than is observed in many high redshift, high luminosity, objects (see below, also, Baldwin et al. 1989; HF93). Note that the disparity between the predictions and observations would be even larger had we used a non-optimized continuum, such as in Mathews and Ferland (1987). This disparity in the high luminosity quasars is nothing new; photoionization simulations of BLR clouds have long under-predicted the intensity of NV λ1240 relative to other ultraviolet lines (see the review by Davidson and Netzer 1979).

We have used both line ratios to determine the relative nitrogen abundance and, by reference to the evolutionary calculations in the next section, the total metallicity Z. The NV/CIV line ratio is advantageous in low signal to noise spectra because the ratio is of order unity or larger for many high redshift quasars. The NV/HeII ratio is far more difficult to measure because the helium line is weak, but it is less sensitive to even extreme inhomogeneities in the BLR because the NV emitting region lies within the HeII zone.

Figure 4 shows the results of a series of calculations in which the abundances were increased along an evolutionary track very similar to, but allowing higher Z's than, the elliptical galaxy model (M4) below. Both ratios increase, although by less than one would naively expect from the change in the relative abundances. This is due both to optical depth effects (all three lines are quite optically thick), and the thermostatic effect described above.

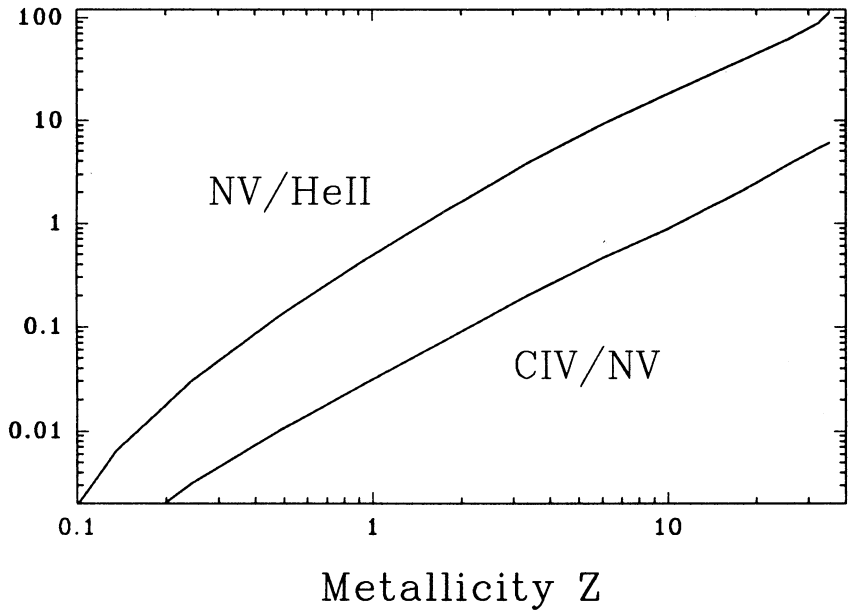

Figure 4. The CIV/NV and NV/HeII intensity ratios vs. metallicity computed for a case with a density of 10^{10} cm^{-3}, a flux of ionizing photons of 10^{20} cm^{-2} s^{-1}, and the continuum optimized to produce the largest line ratios at high Z.

Comparisons between the calculations and observations led us to argue that high metallicities are needed to reproduce the observed spectrum of high luminosity, high redshift objects (Hamann and Ferland 1992; HF93; Baldwin et al. 1993). Typically $Z \leq 10\ Z_{\odot}$ is able to account for the lines in these sources, while $Z \sim 1\ Z_{\odot}$ is more typical at low redshift and low luminosity. Figure 5 shows the NV/CIV and NV/HeII ratios as a function of the density and flux for $Z=10\ Z_{\odot}$. These plots show that the simulations can just reproduce the largest observed ratios if the cloud parameters are optimal (i.e., an ionization parameter corresponding to the ratio density/flux=$10^{10}/10^{20}$ cm s^{-1}). If the cloud parameters are not just right, then the emitted line ratio will be smaller than the peak, and even more extreme abundances will be needed to match the observations (see §IV below).

III. CHEMICAL ENRICHMENT MODELS

Galactic chemical enrichment models make specific predictions for the elemental abundances in the gas as the system evolves. Here we discuss some results derived for closed systems that are formed by the infall of primordial gas. The calculations are described in detail in HF93 and form the basis for the prescription for enhanced metallicities used above. The enrichment of the gas from its initial primordial composition (76% H and 24% He by mass) follows "standard" stellar nucleosynthesis that has been tested in models of the Milky Way and nearby galaxies. The sources of enrichment include stellar winds, planetary nebulae, and types I and II supernovae. Stars are formed across the mass range from ~0.1 to 100 $M_{\odot}$, although a lower mass cutoff of $2.5 M_{\odot}$ is also considered. The star formation is regulated by power law initial mass functions (IMFs) of the form $\Phi \propto M^{-x}$, where M is the stellar mass and $\int \Phi\ dM = 1$. The finite stellar lifetimes are included. The stellar birthrate is scaled linearly with the gas density, although this particular choice does not effect our conclusions because only the gross timescales in the different models are important. With the nucleosynthesis fixed, we vary just the slope of the IMF and the star formation and infall timescales to derive simple models of the chemical history of the broad line gas.

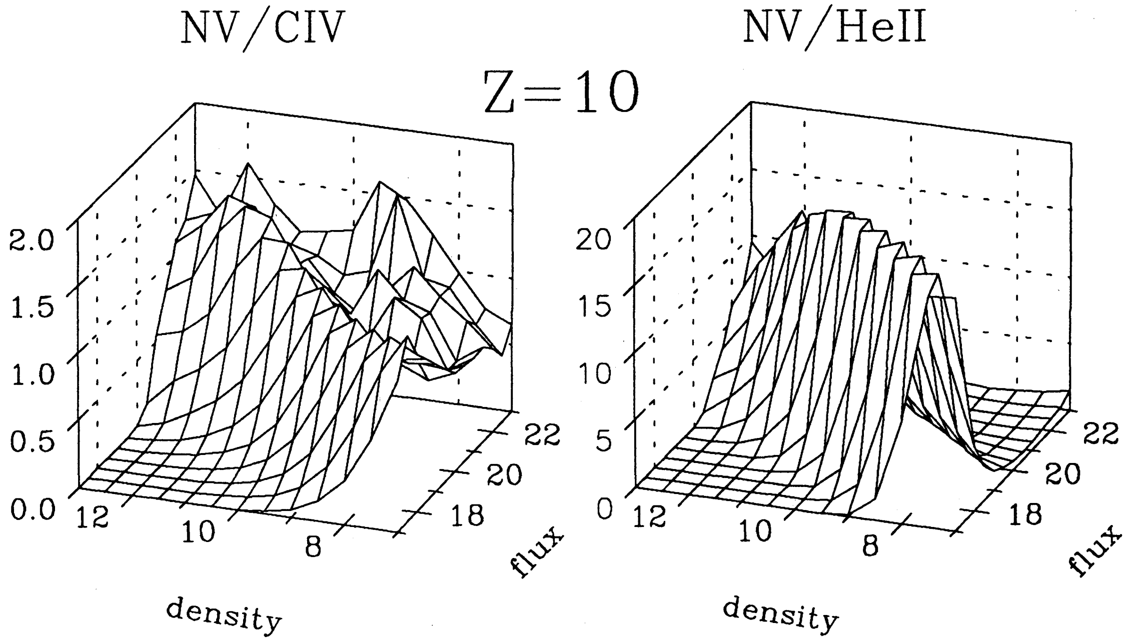

Figure 5. The NV/HeII and NV/CIV intensity ratios are shown vs. density and flux in ionizing photons for a metallicity of $10Z_{\odot}$.

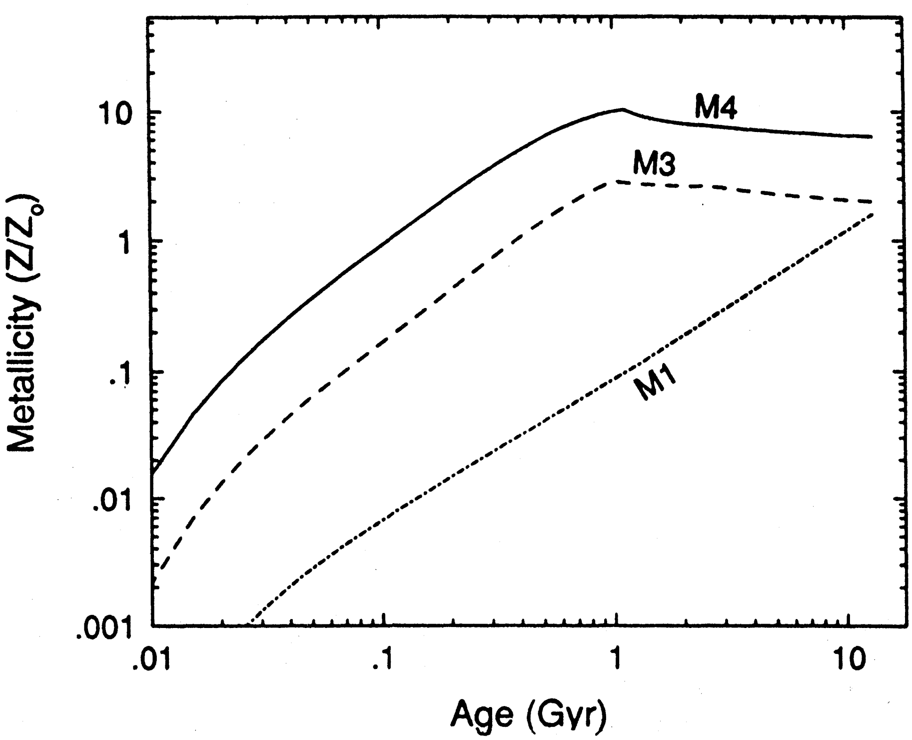

Figure 6. Metallicity vs. Age in 3 chemical evolution models.

Figure 6 shows the metallicity evolution in three models that we will compare in § IV to the QSO observations. The models are labeled as in HF93 for easier reference. Model M1 is a reference model of the galactic solar neighborhood, where the infall timescale of primordial gas is 3 Gyr and the IMF has a slope x=1.6 for M≥ $M_{\odot}$ and 1.1 for M < $M_{\odot}$. The stellar birthrate is set so that Z = 1 $Z_{\odot}$ at the time of the sun's formation (~8.5 Gyr) and the fraction of mass in gas is ~15% at the present epoch (13 Gyr). Model M3 uses the same IMF as M1, but the infall timescale is shortened to ~0.05 Gyr to be roughly consistent with the timescales for massive galaxy core collapse, and the stellar birthrate is increased by more than two decades so that the mass fraction in gas is ~15% at only 0.5 Gyr. Model M4 uses the short timescales of M3 but a flatter IMF of slope x=1.1 for all masses. This leads to greater processing by high mass stars and thus higher Z's. The metallicities rise quickly in both M3 and M4 until ~1 Gyr, where the star formation stops because the gas is nearly exhausted. After that time the models evolve "passively", with the ejecta of low mass stars reducing Z slightly. The possibility that galactic winds might "turn on" and expel the gas at these low gas densities is discussed by HF93.

It is important to note that M4 is nearly identical to the models developed by others for massive elliptical galaxies (Arimoto and Yoshii 1987; Matteucci and Tornambé 1987; Angeletti and Giannone 1990). Also, models of the bulge of our galaxy use parameters that are intermediate between M3 and M4 (Matteucci and Brocato 1990; Köppen and Arimoto 1990).

Figure 7 shows the abundance evolution in the models relative to oxygen and normalized to solar ratios. The He abundance (not shown) changes by less than a factor of 2 while all of the metals increase by decades. The abundance ratios are roughly solar at the time of the sun's formation (~8.5 Gyr) in the solar neighborhood model M1. However, even though the nucleosynthesis parameters are fixed, the shorter timescales and flatter IMF produce a chemical mixture that is very different than solar in M3 and M4. In particular, note the delayed rise and subsequent overabundance in both N and Fe. Unfortunately, the contributions to the N enrichment from "primary" and "secondary" CNO processing are uncertain (see HF93 for discussion and references). The models in Figure 7 have an "a" designation to note that N is formed exclusively as a secondary element. Including some primary N (the "b" models in HF93) causes a slightly earlier rise of N in M3, but does not significantly effect the giant elliptical model M4. The delay in the Fe enrichment is caused by the finite lifetimes of the precursors to type Ia supernovae - believed to be close intermediate mass binaries. The lifetimes of these systems, although somewhat uncertain, do not depend on any of the evolution model parameters. Therefore the Fe enrichment can be used as an absolute clock to constrain the ages of the host galaxies (Matteucci and Brocato 1990; Wyse and Gilmore 1988).

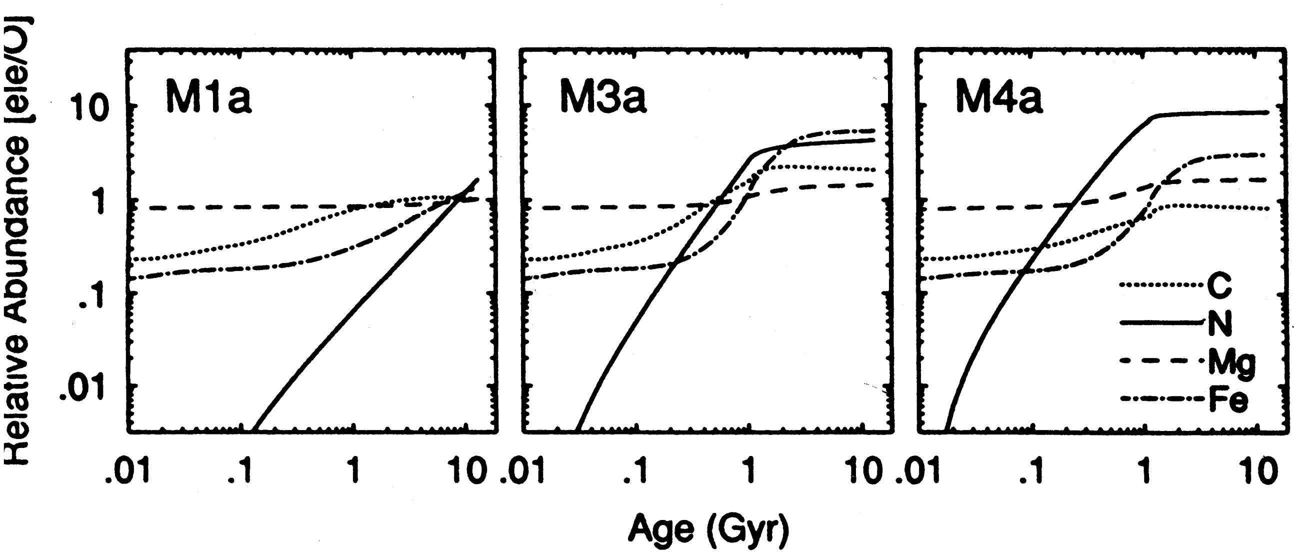

Figure 7. Abundance ratios [ele/O] for the evolution models discussed in the text.

IV. COMPARISONS WITH OBSERVATIONS

We now use the abundance results to directly predict the evolution of the line ratios as a function of age and metallicity in QSOs. Figure 8 shows the results of a series of calculations using a density of 10^{10} cm^{-3}, a flux of 10^{20} cm^{-3} s^{-1}, and a continuum like Mathews and Ferland (1987) but with α_{ox} = -1.24 and an infrared break at 1 μm. Further details on both the models and the data sample are presented in HF93 and Baldwin et al. (1993). The evolutionary ages are converted to redshifts in Fig. 8 assuming the evolution begins at the Big Bang in a cosmology with $q_o = 1/2$ and H_o = 75 km/s/Mpc.

One of the main results is that the short timescales, flatter IMF, and subsequently high Z's in the giant elliptical model M4 are necessary to fit much of the high redshift data. Steeper IMFs like the solar neighborhood can produce some of the smaller line ratios if the timescales are similarly short (model M3). The timescales in M3 and M4 are such that the gas is essentially consumed and the metallicities peak at $\sim$10 $Z_\odot$ in M4 and nearly 3 $Z_\odot$ in M3 at an age of $\sim$1 Gyr (redshift $\sim$3). This is roughly the *longest* time able to fit the data in this cosmology. (If $q_o \sim 0$ the same amount of evolution might occur over as much as 3 to 4 Gyr; see Fig. 1.) Faster evolution would be needed if galaxy formation is delayed after the Big Bang. Theoretically, the essential evolution in M3 and M4 (for large N/He, N/C, and Z) could occur in as little as $\sim$0.1 to 0.2 Gyr if the infall (galaxy formation) is instantaneous and the star formation rate is many times faster than in "standard" elliptical models. The only limiting factor is that at least several generations of high mass stars must process the gas.

The theoretical line ratios shown in Fig. 8, and thus the relationship between the measured line ratios and the metallicities, depend on the parameters used in the photoionization simulations. The parameters used for this plot *nearly* maximize the line ratios at a given Z and may be typical of most QSOs (HF93). Baldwin et al. (1993) have shown that *truly* optimized parameters can just match the lower limits to the largest line ratios in Fig. 8 with $Z \sim 10\ Z_\odot$ (see Fig. 4 above). If the optimal parameters obtain generally, then lower Z's than Figure 8 suggests might apply. Nonetheless, even in the optimized case $Z \gg 1\ Z_\odot$ is required in many high redshift sources.

Another important result is that the line ratios, and thus metallicities, are typically larger at high redshift and high luminosity. In HF93 we suggest that the metallicities correlate with the masses of the QSOs and/or host galaxies. Thus there may be a mass-metallicity-redshift correlation among QSOs analogous to the well known mass-metallicity relation in nearby ellipticals (Pagel and Edmunds 1981; Vader 1986). This relationship among the ellipticals is believed to be caused by the influence of galactic winds driven by supernovae. High mass galaxies reach higher Z's because they are better able to retain the gas against the building thermal pressures. The correlation with redshift in the QSOs might result from the natural tendency to form denser and more massive systems at early epochs, when the mean density of the Universe was itself higher. In this sense, the mass-metallicity-redshift correlation is consistent with recent theories of quasar/galaxy formation that can fit the observed quasar luminosity function (Rees 1993; Haehnelt and Rees 1993). Unfortunately our models do not specify the total masses involved. Strictly speaking we are modeling only the evolution that effects the BLR – probably just the galaxy cores or bulges. Nonetheless, both models and observations of elliptical galaxies suggest that the highest Z's we infer at high redshift require the deep gravitational well of systems with total masses of $\sim 10^{12}\ M_\odot$ or more (Arimoto and Yoshii 1987; Bica, Arimoto, and Alloin 1988; Angeletti and Giannone 1990).

One of the initial goals of this work was to see whether the presence of heavy elements in high redshift quasars could constrain the cosmology. As discussed above, this is not the case for the light elements. Massive stars are able to build them up on short timescales, so that observations at redshift $\sim$10 would be needed before meaningful determinations can be made. However, accurate Fe abundances, e.g. Fe/O or Fe/Mg, offer the prospect of constraining both QSO ages and the cosmology at lower redshift. This is because Fe derives substantially from type Ia supernovae, which require the formation of a white dwarf in close intermediate mass binaries. The enrichment is dominated by the more numerous low mass systems with a mean timescale of $\sim$1 Gyr (see §3 and Fig. 7). It is possible to measure the intensities of iron lines over a wide range of redshifts, and it *may* be possible to observationally determine the redshift at which the lines weaken or "go away", due to the factor of $\sim$10 abundance drop predicted by our models. The age of the universe at that redshift might then be known.

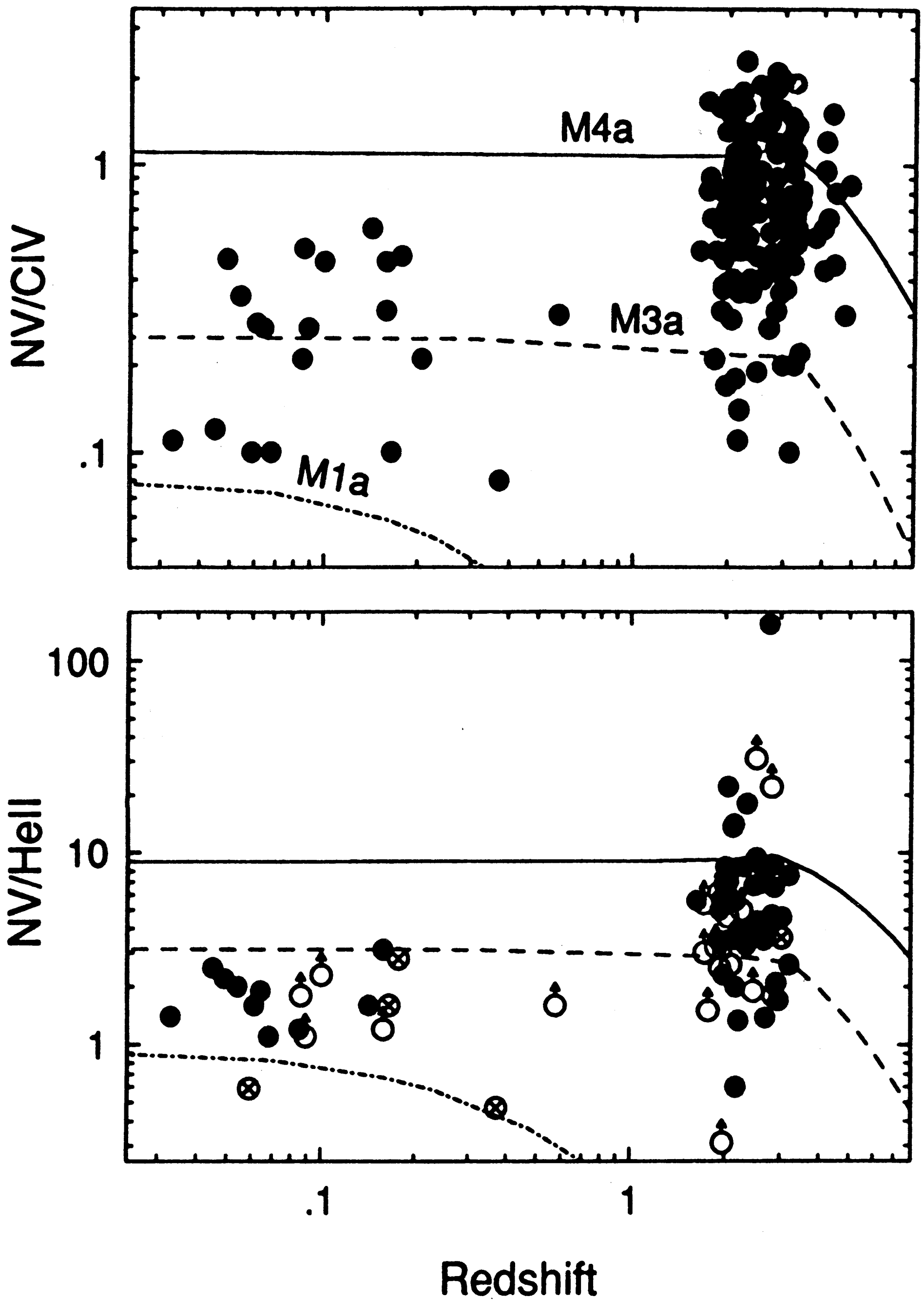

Figure 8. The data and evolution models are compared in plots of NV/CIV and NV/HeII vs. redshift.

V. CONCLUSIONS

Several conclusions may be drawn from the work we have outlined here.

• Metallicities of ~1 to ≳10 $Z_\odot$ are attained in < 1 Gyr in quasars. This rapid evolution to high Z's is xactly like that expected in the cores of massive galaxies. This further strengthens the circumstantial case ıat luminous quasars are associated with early stages in the formation of massive galaxies

- Higher metallicities occur in higher redshift, higher luminosity systems. This could be owing to a mass-metallicity-redshift relation that is analogous to the well known mass-metallicity trend in nearly elliptical galaxies. The correlation with redshift is consistent with recent studies suggesting that the higher mass quasars/galaxies form preferentially at high redshift.

- The high Z's we derive for the QSOs strongly suggests that there is a population of massive galaxies evolving rapidly at redshifts > 2, and that the QSO phenomenon occurs *after* these stars have created an enriched ISM.

- The formation of preferentially more massive stars is needed to reproduce metallicities as high as we infer in quasars. Low-mass stars tend to lock up gas and produce little enrichment of the surrounding ISM. The situation may be similar to that proposed for low redshift starburst galaxies, on entirely different grounds (Scalo 1990).

- The relative Fe enrichment is expected to be delayed by ~1 Gyr, independent of the star formation rate and the overall enrichment timescale. Therefore measurements of the Fe abundance (e.g., Fe/O or Fe/Mg) at high redshifts could constrain both the ages of quasars and the cosmology.

- The epoch of rapid chemical enrichment is predicted to end when the combined effects of many supernovae drives the ISM out of the galaxy. Could this blow-out be associated with the BALQSO phenomenon?

Fred Hamann acknowledges the receipt of a Columbus Fellowship at The Ohio State University and Gary Ferland thanks the NSF and NASA for support.

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