ELEMENTAL ABUNDANCES IN QSOS:
Star Formation and Galactic Nuclear Evolution at High Redshifts

Fred Hamann
Department of Astronomy, University of Florida, 211 Bryant Space Sciences Center, Gainesville, FL 32611-2055; hamann@astro.ufl.edu (current)
and
Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, CA 92093-0424

Gary Ferland
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055; gary@pa.uky.edu
and
Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON, Canada, M5S 3H8

KEY WORDS: quasars, metallicity, emission lines, absorption lines, cosmology
Shortened Title: ELEMENTAL ABUNDANCES IN QSOS
ABSTRACT

Quasar (or QSO) elemental abundances provide unique probes of high-redshift star formation and galaxy evolution. There is growing evidence from both the emission and intrinsic absorption lines that QSO environments have roughly solar or higher metallicities out to redshifts >4. The range is not well known, but solar to a few times solar appears to be typical. There is also evidence for higher metallicities in more luminous objects, and for generally enhanced N/C and Fe/α abundances compared to solar ratios.

These results identify QSOs with vigorous, high-redshift star formation – consistent with the early evolution of massive galactic nuclei or dense proto-galactic clumps. However, the QSOs offer new constraints. For example, 1) most of the enrichment and star formation must occur before the QSOs “turn on” or become observable, on time scales of ≤1 Gyr at least at the highest redshifts. 2) The tentative result for enhanced Fe/α suggests that the first local star formation began at least ∼1 Gyr prior to the QSO epoch. 3) The star formation must ultimately be extensive in order to reach high metallicities, i.e. a substantial fraction of the local gas must be converted into stars and stellar remnants. The exact fraction depends on the shape of the initial mass function (IMF). 4) The highest derived metallicities require IMFs that are weighted slightly more toward massive stars than the in solar neighborhood. 5) High metallicities also require deep gravitational potentials. By analogy with the well-known mass–metallicity relation among low-redshift galaxies, metal-rich QSOs should reside in galaxies (or proto-galaxies) that are minimally as massive (or as tightly bound) as our own Milky Way.
Contents

1 Introduction 5

2 Emission Line Diagnostics 7
  2.1 Overview .................................................. 7
  2.2 Origin of the Broad Emission Lines ...................... 7
  2.3 Strategies for Abundance Work ......................... 9
  2.4 Basics of Abundance Analysis .......................... 9
    2.4.1 Collisionally-Excited Lines ....................... 9
    2.4.2 Recombination Lines ................................ 10
    2.4.3 Deriving Abundance Ratios ....................... 10
  2.5 Photoionization Simulations ............................. 12
    2.5.1 Parameters of Photoionization Equilibrium ....... 12
    2.5.2 A Computed Structure ................................ 12
    2.5.3 An Example: the CIV $\lambda$1549 Equivalent Width .... 13
    2.5.4 Line Dependence on Continuum Shape ............. 13
    2.5.5 Line Dependence on Abundances ................... 14
  2.6 Abundance Diagnostics and Results ...................... 15
    2.6.1 Intercombination Lines ............................. 15
    2.6.2 Permitted Lines ..................................... 16
    2.6.3 NV/HeII and NV/CIV ................................ 16
    2.6.4 FeII/MgII ........................................... 19

3 Absorption Line Diagnostics 19
  3.1 Overview: Types of Absorption Lines .................. 19
    3.1.1 Broad Absorption Lines (BALs) .................... 20
    3.1.2 Narrow Absorption Lines (NALs) .................... 20
  3.2 General Abundance Analysis ............................ 21
    3.2.1 Ionization Ambiguities ............................ 24
    3.2.2 Column Densities and Partial Coverage .......... 24
  3.3 Broad Absorption Line Results ........................ 27
    3.3.1 Uncertainties and Conclusions ................... 28
  3.4 Narrow Absorption Line Results ........................ 29
    3.4.1 Uncertainties and Conclusions ................... 30

4 General Abundance Summary 31
5 Enrichment Scenarios

5.1 Occam’s Razor: The Case for Normal Galactic Chemical Evolution . . . . 31

6 More Insights from Galactic Chemical Evolution

6.1 The Galactic Mass-Metallicity Relation . . . . . . . . . . . . . . . . . . . . 33
6.2 Specific Abundance Predictions . . . . . . . . . . . . . . . . . . . . . . . . . 33
6.3 Fe/α as a Clock . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
6.4 Nitrogen Abundances . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 35

7 Implications of QSO Abundances

7.1 High-Redshift Star Formation . . . . . . . . . . . . . . . . . . . . . . . . . . . 35
7.2 Fe/α: Timescales and Cosmology . . . . . . . . . . . . . . . . . . . . . . . . . 36
7.3 Comparisons to Other Results . . . . . . . . . . . . . . . . . . . . . . . . . . . 36

8 Future Prospects

9 Literature Cited
1. Introduction

Quasi-stellar objects (QSOs or quasars) are valuable probes of the high-redshift Universe (Schneider 1998). Their most distant representatives are now measurable out to redshifts of $z \sim 5$ (Schneider, Schmidt & Gunn 1991, Sloan Digital Sky Survey press release 1998). In Big Bang cosmologies, these redshifts correspond to times when the Universe itself was just $\sim 1$ Gyr old (see Fig. 1).

![Redshift versus age of the Universe in Big Bang cosmologies.](image)

Fig. 1 — Redshift versus age of the Universe in Big Bang cosmologies. The three solid curves correspond to $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0$ with $\Omega_M = 0, 0.3$ or 1. The dotted curve corresponds to $\Omega_M = 0.7$ and $\Omega_M = 0.3$. The “error” bars show the range of ages possible for $H_0$ between 50 and 80 km s$^{-1}$ Mpc$^{-1}$ (see Carroll & Press 1992).

Understanding the elemental abundances in these distant, early-epoch environments is a major goal of quasar research. Some of the first spectroscopic studies noted simply that quasar environments contain the usual array of “metals” (elements C, N, O and heavier) produced by stellar nucleosynthesis (Shklovskii 1965, Burbidge & Burbidge 1967). More quantitative estimates of the abundances came later from theoretical work on the broad emission lines, culminating in the important review by Davidson & Netzer (1979 — hereafter DN79, also Baldwin & Netzer 1978, Shields 1976). Those studies inferred solar or slightly higher metal abundances, with large uncertainties. The past two decades have seen considerable progress. Today we have a better theoretical understanding of quasar environments, and greater abilities to both observe and model a range of abundance diagnostics.
We also have renewed motivation from the growing evidence that links quasars to galaxies. See, for example, Kormendy et al. (1998), Magorrian et al. (1998) for black hole–host galaxy mass correlations, Chatzichristou, Vanderriest & Jaffe (1999), Hines et al. (1999), McLeod, Rieke & Storrie-Lombardi (1999), Boyce, Disney & Bleaken (1999), McLure et al. (1998), Aretxaga, Terlevich & Boyle (1998), Carballo et al. (1998), Bahcall et al. (1997), Miller, Tran & Sheinis (1996), McLeod & Rieke (1995) for direct observations of QSO hosts, Cavaliere & Vittorini (1998), Shaver et al. (1998), Terlevich & Boyle (1993), Boyle & Terlevich (1998), Osmer (1998) for arguments based on QSO number-density evolution, McCarthy (1993), Saikia & Kulkarni (1998), Haas et al. (1998), Brotherton et al. (1998a) for radio galaxy–radio quasar unification schemes, and Turner (1991), Haehnelt & Rees (1993), Loeb & Rasio (1994), Katz et al. (1994), Haehnelt, Natarajan & Rees (1998), Haiman & Loeb (1998), Taniguchi, Ikeuchi & Shioya (1999) for theoretical links between QSOs and galaxy evolution. If quasars reside, as expected, in galactic nuclei or dense proto-galactic clumps, their abundances could yield unique constraints on the evolution of those environments. For example, quasar abundances can indirectly probe the star formation that came before QSOs, possibly the first stars forming in massive collapsed structures after the Big Bang. Other studies of high-redshift galaxies and metal enrichment, involving, for example, the “Lyman-break” objects (Steidel et al. 1998, Connolly et al. 1997) or the damped-Lyα or Lyα “forest” absorbers in QSO spectra (Pettini et al. 1997, Lu, Sargent & Barlow 1998, Rauch 1998), probe more extended structures. The quasar results should therefore provide an important piece to the overall puzzle of high-redshift star formation and galaxy evolution.

Here we review the status and implications of quasar abundance work. We regret that many interesting related topics must be excluded; in particular, we will consider the quasars themselves to be simply light sources surrounded by emitting and absorbing gas. We discuss three abundance diagnostics that are readily observable in QSOs at all redshifts: the broad emission lines (BELs), the broad absorption lines (BALs) and the intrinsic narrow absorption lines (NALs). We include just these “intrinsic” spectral features to probe the abundances near QSO engines — excluding measures of the extended host galaxies, nearby cluster galaxies or cosmologically intervening gas. We begin with separate discussions of each abundance probe (§§2–3), followed by a summary of the overall results (§4). We then consider the plausible enrichment schemes, making a case for normal chemical evolution by stars in galactic nuclei (§5). Within that scheme, we use results from galactic studies (§6) to derive further implications of the QSO abundances (§7). We close with a brief outline for future work (§8).

In several sections below we will present results of photoionization calculations performed with the numerical code Cloudy (version 90.05, Ferland et al. 1998). This code is freely available on the world wide web [http://www.pa.uky.edu/~gary/cloudy/]. Finally, we will define solar abundances according to the meteoritic results in Grevesse & Anders (1989).
2. Emission Line Diagnostics

2.1. Overview

Quasars are surprisingly alike in their emission-line spectra (Osmer & Shields 1999 and refs. therein); for example, the range of intensity ratios is far less than in galactic nebulae. Figure 2 shows a composite UV spectrum that is fairly typical of QSOs without strong BALs. The object-to-object similarities span the full range of QSO redshifts, $0.1 \lesssim z \lesssim 5$, more than 4 orders of magnitude in luminosity, and billions of years in cosmological look-back time. The emission lines are either insensitive to the metal abundances, or QSOs have similar abundances across enormous ranges in other parameters. We will argue that the truth involves a bit of both explanations.

We will focus on the BELs in the rest-frame UV because they are present and relatively easy to measure in all QSOs at all redshifts. Furthermore, unlike the narrow emission lines, there is no ambiguity about their close physical connection to QSO engines (DN79).

![Normalized mean spectrum of 13 QSOs at $z > 4$](image)

Fig. 2 — Normalized mean spectrum of 13 QSOs at $z > 4$ (from Shields et al. 1997). Prominent BELs are labeled.

2.2. Origin of the Broad Emission Lines

Quasar emission-line research is an example of the “inverse problem” in astrophysics. We know the answer — the observed spectrum of a quasar, and we are trying to understand the question — the conditions that created it. Any model of the line-forming regions will have uncertainties related to uniqueness, but these can be minimized by considering the
astrophysical context and by limiting the models to essential properties. The essential properties of the BEL region (BELR) are as follows:

1) The BELR is photoionized. The main evidence for photoionization is that the emission-line spectra change in response to changes in the continuum, with lag-times corresponding to characteristic radii of the BELR (Peterson 1993). The shape of the ionizing continuum is a fundamental parameter and is in itself an area of active research (e.g. Zheng et al. 1997; Korista, Baldwin & Ferland 1997a, Brunner et al. 1997, Laor 1998). We will present calculations using simple power-laws between 1 µm and 100 keV, and describe results that do not depend strongly on the continuum shape.

2) The BELR spans a range of distances from the central object. The line variability or “reverberation” studies just mentioned find different lag-times for different ions. Highly ionized species tend to lie closer to the continuum source. Overall, the radial distances scale with luminosity, such that \( R \approx 0.1(L/10^{46}\text{ergs s}^{-1})^{1/2}\) pc is a typical value (Peterson 1993).

3) The BELR has a wide range of densities and ionization states. The range in ionization follows simply from the lines detected, from OI \( \lambda 1303 \) to at least NeVIII \( \lambda 774 \) (Hamann et al. 1998). The range in density comes mainly from the estimated radii and photoionization theory (e.g. Ferland et al. 1992). Clouds with densities from \( 10^8 \) to \( >10^{12} \) cm\(^{-3} \) may be present. Any given object could have a broad mixture of BELR properties (Baldwin et al. 1995, 1996).

4) The BELR probably has large column densities. Large columns, typically \( N_H \gtrsim 10^{23} \) cm\(^{-2} \), were originally used in BELR simulations to produce a wide range of ionizations in single clouds (Kwan & Krolick 1981 — hereafter KK81, Ferland & Persson 1989). These large columns might not apply globally because we now know that different lines form in different regions. In our calculations below, we will truncate the clouds at the hydrogen recombination front, with the result that different clouds/calculations can have different total column densities. However, the truncation depths are in all cases large enough to include the full emission regions of the relevant lines.

5) Thermal velocities within clouds are believed to dominate the local line broadening and radiative transfer. The observed line-widths are thus due entirely to bulk motions of the gas. This issue is important because i) continuum photoexcitation (“pumping”) can overwhelm other excitation processes if the local line broadening (e.g. micro-turbulence) is large, and ii) the line optical depths and thus photon escape probabilities (see below) vary inversely with the amount of line broadening. The interplay between these factors makes it hard to predict the behavior of a given line without explicit calculations. Shields, Ferland & Peterson (1995) plot some examples for the particular case of low column density clouds. One argument against significant micro-turbulence involves the Ly\( \alpha /H\beta \) intensity ratio. Simple recombination theory predicts a ratio of about 34 (Osterbrock 1989 — hereafter O89) while the observed value is far smaller, closer to 10 (Baldwin 1977a). This discrepancy is worsened by micro-turbulence (Ferland 1999). The solution probably

\[ \text{We use the term “cloud” loosely, referring to some localized part of the BELR but not favoring any particular model or geometry (see Arav et al. 1998, Mathews & Capriotti 1985).} \]
requires severely trapped Lyα photons resulting from large optical depths at thermal line
widths (see also Netzer et al. 1995).

2.3. Strategies for Abundance Work.

There is much that is unknown about QSO line-forming regions. We do not, for
easy, have a clear picture of the overall geometry or the spatial variations of key
parameters; but we do not need this information for abundance work. The emission
lines from photoionized clouds are controlled fundamentally by the energy balance and
microphysics. The strategy for abundance studies is to identify line ratios that have
significant abundance sensitivities and minimal dependences on other unknown or uncertain
parameters. For example, we can minimize the sensitivity to large-scale geometric effects
by comparing lines that form as much as possible in the same gas. Detailed simulations
are often needed to identify useful line ratios and quantify their parameter sensitivities.
Simple analytic expressions can be used for some applications and they can help, in any
case, provide physical insight into the emission-line behaviors.

Below we review some of the basic principles of photoionization and emission-line
formation. See O89 and Mihalas (1978) for further reviews, Davison & Netzer (1979 —
hereafter DN79), KK81, Ferland & Shields 1985, and Netzer (1990 — hereafter N90) for
applications to QSOs, and Ferland et al. (1998) for more on the numerical simulations and
input atomic data.

2.4. Basics of Abundance Analysis

2.4.1. Collisionally-Excited Lines

Collisionally-excited lines form by the internal excitation of an ion following electron
impact. Their emissivities, or energy released per unit volume and time, follow from the
statistical equilibrium of the energy levels. For example, the equilibrium (detailed balance)
equation for a 2-level atom is,

\[ n_l n_e q_{lu} = n_u (\beta A_{ul} + n_e q_{ul}) \quad [\text{cm}^{-3} \text{s}^{-1}] \] (1)

where \( n_e \) is the electron density, \( \beta \) is the probability for line photons escaping the local
region \( (0 \leq \beta \leq 1) \), \( A_{ul} \) is the spontaneous decay rate, \( n_u \) and \( n_l \) are the number densities
in the upper and lower states, and \( q_{lu} \) and \( q_{ul} \) are the upward and downward collisional
rate coefficients, respectively. Note that \( \beta \sim \tau^{-1} \) when \( \tau \gg 1 \), where \( \tau \) is the line-center
optical depth (Frisch 1984). For most applications the ions are mainly in their ground
state and \( n_l \) is approximately the ionic density. The line emissivity is,

\[ \epsilon_{coll} = n_u \beta A_{ul} h \nu_o = n_l \beta A_{ul} h \nu_o \left( \frac{n_e q_{lu}}{\beta A_{ul} + n_e q_{ul}} \right) \quad [\text{ergs cm}^{-3} \text{s}^{-1}] \] (2)

where \( \nu_o \) is the line frequency. This emissivity has a strong temperature dependence
because \( q_{ul} \propto T^{-1/2} \) and \( (q_{lu}/q_{ul}) = (g_u/g_l) \exp (-h \nu_o/kT) \), where \( g_u \) and \( g_l \) are the
statistical weights. In the high density limit we have,

\[ \epsilon_{\text{coll}} = n_l \beta A_{ul} h \nu_o \frac{g_l}{g_u} \exp \left( -\frac{h \nu_o}{kT} \right) \]  

(3)

and the levels are said to be “thermalized.” Line thermalization, where \( \epsilon_{\text{coll}} \) no longer depends on the transition strength, additionally requires \( \tau \gg 1 \). (\( A_{ul} \) and \( \tau \) are both proportional to the oscillator strength, which therefore drops out of the factor \( \beta A_{ul} \approx A_{ul}/\tau \) in Eqn. 3 if \( \tau \gg 1 \).) At low densities we have,

\[ \epsilon_{\text{coll}} = n_l n_e q_{ul} h \nu_o \propto n_l n_e T^{-1/2} \exp \left( -\frac{h \nu_o}{kT} \right) \]  

(4)

Note that \( \epsilon_{\text{coll}} \) scales here like the density squared, compared to the linear dependence in Equation 3. The critical density, \( n_{\text{crit}} \), between these two limits is the density where the two terms in the denominator of Equation 2 are equal,

\[ n_{\text{crit}} = \beta A_{ul} \approx A_{ul} \frac{\tau q_{ul}}{\tau q_{ul}} \]  

(5)

where the approximate relation holds only if \( \tau \gg 1 \). Physically \( n_{\text{crit}} \) is the density where the upper level is as likely to be de-excited by collisions as by radiative decays. Note that significant optical depths have the effect of lowering \( n_{\text{crit}} \). Also note that transitions with very different oscillator strengths (but similar collision strengths) will have similar \( n_{\text{crit}} \) in the limit \( \tau \gg 1 \) (because \( A_{ul}/\tau \) is independent of oscillator strength).

### 2.4.2. Recombination Lines

The most prominent recombination lines belong to HI, HeI and HeII, with HI Ly\( \alpha \) being typically strongest. These lines form by the capture of free electrons into excited states, followed by radiative decays to lower states. In the simplest case, where every photon escapes freely and competing processes are unimportant, the emissivity is,

\[ \epsilon_{\text{rec}} = n_i n_e \alpha_{\text{rad}} h \nu_o \propto n_i n_e T^{-1} \quad [\text{ergs cm}^{-3} \text{ s}^{-1}] \]  

(6)

where \( \alpha_{\text{rad}} \) is the radiative recombination coefficient into the upper energy state and \( n_i \) is the number density of parent ions. The temperature dependence is approximate and derives from \( \alpha_{\text{rad}} \) (see O89).

### 2.4.3. Deriving Abundance Ratios

These two types of lines can be combined to form three types of ratios for abundance analysis. The general idea is that for any element \( a \) in ion stage \( i \), the observed line intensity, \( I(a_i) \), is proportional to the density in that ion, \( n(a_i) \), times a function of the overall gas density and temperature, \( F(a_i, T, n) \), such that \( I(a_i) = n(a_i) F(a_i, T, n) \). The ionic abundance ratios are then given by,

\[ \frac{n(a_i)}{n(b_j)} = \frac{I(a_i) F(b_j, T, n)}{I(b_j) F(a_i, T, n)} \]  

(7)
Abundance studies require line pairs for which the ratio of the two functions \( F \) is nearly constant or has limiting behaviors that still allow for abundance constraints. The last step is to convert the ionic abundances into elemental abundances, which we express logarithmically relative to solar ratios as:

\[
\frac{a}{b} = \log \left( \frac{n(a_i)}{n(b_j)} \right) + \log \left( \frac{f(b_j)}{f(a_i)} \right) + \log \left( \frac{b}{a} \right) \odot
\]

where \( f(a_i) \) is the fraction of element \( a \) in ion stage \( i \), etc. The middle term on the right hand side is the ionization correction (IC), which can be deduced from numerical simulations or set to zero (in the log) based on the similarity of the species (Peimbert 1967). Another strategy is to compare summed combinations of lines from different ion stages so that IC tends to zero on average (Davidson 1977).

Ratios of pure recombination lines are simplest because they are least sensitive to the temperature and density. In principle, we could derive the He/H abundance from these ratios. However, in practice, all of the strong HI and HeI recombination lines in QSOs, most notably Ly\( \alpha \), are affected by collisions and thermalization effects. Moreover, because H\( \Pi \), He\(+\) and He\(+^2\) have different ionization energies, they need not be co-spatial in the BELR and their levels of ionization depend on the different numbers of photons available to produce each ion (Williams 1971). As a result, the H and He recombination spectra are most useful as indicators of the shape of the ionizing continuum (e.g. Korista et al. 1997a). We do not expect substantial deviations from solar He/H abundances anyway, based on normal galactic chemical evolution, and the BEL data are grossly consistent with that expectation.

The second possible ratio involves collisional to recombination lines. These ratios have strong temperature dependences (compare Eqns. 3 and 4 to Eqn. 6). Nonetheless, they can still be used for abundance work if the temperature sensitivities are quantified by explicit calculations. For example, there is an upper limit on the line ratio NV \( \lambda 1240/\text{HeII } \lambda 1640 \) related to the maximum temperature attained in photoionized BELRs. That upper limit sets a firm lower limit on the N/He abundance (§2.6.3 below).

The last ratio, and the one most often used, involves two collisionally-excited lines. Roughly a dozen collisionally-excited BELs are routinely measured in the UV spectra of quasars, so there are a variety of possibilities. The ideal collisionally-excited line pair would have similar excitation energies, so their ratio has a small \( h\Delta\nu_0/kT \) and thus a small temperature dependence (Eqns. 3 and 4). Similar values of \( n_{\text{crit}} \) and similar ionization energies further minimize the sensitivities to density and BELR structure. Well-chosen ratios that meet these criteria can sometimes provide abundance estimates without recourse to detailed simulations (e.g. Shields 1976, §2.6.1 below)

---

\(1\)Our notation here is based on the usual definition of logarithmic abundances normalized to solar ratios, \([a/b] \equiv \log(a/b) - \log(a/b) \odot\).
2.5. Photoionization Simulations

A photoionized cloud is essentially a large-scale fluorescence problem. Energy comes into the cloud via continuum radiation, is converted into kinetic energy by the photo-ejection of electrons, and then leaves the cloud by various emission processes – mainly line radiation. The lines are thus the primary coolants; their total intensity depends on energy conservation and not at all on particular cloud properties.

In general situations, e.g. dense environments like BELRs, individual line strengths can be governed by a number of competing processes and by feedback related to the cloud structure and energy balance. Detailed calculations are needed to simultaneously consider a complex network of coupled processes. Here we describe some basic results for the line formation and ionization structure in realistic BELR clouds.

2.5.1. Parameters of Photoionization Equilibrium

The fundamental parameters in photoionization simulations are the shape and intensity of the ionizing continuum, and the gas’ space density, column density, and chemical composition. The flux of hydrogen-ionizing photons at the illuminated face of a cloud is,

$$\Phi(H) \equiv \int_{\nu_{LL}}^{\infty} \frac{f_\nu}{h\nu} d\nu \text{ [photons cm}^{-2} \text{s}^{-1}]$$

where $f_\nu$ is the energy flux density and $\nu_{LL}$ is the frequency corresponding to 1 Ryd. A dimensionless ionization parameter $U \equiv \Phi(H)/cn_H$ is often used instead, where $c$ is the speed of light and $n_H$ is the total hydrogen density ($H_0^+ + H^+$). $U$ is proportional to the level of ionization and has the advantage of stressing homology relations between clouds with the same $U$ but different $\Phi(H)$ and $n_H$. This simplification is appropriate if we are interested in just the gross ionization structure or in emission lines that are not collisionally suppressed. More generally, we can use either $\Phi(H)$ or $U$ as long as the density is also specified.

2.5.2. A Computed Structure

Figure 3 shows the ionization structure of a typical BELR cloud photoionized by a power-law spectrum with $\alpha = -1.5$, where $f_\nu \propto \nu^\alpha$. The hydrogen recombination front occurs at a depth of $\sim 10^{12}$ cm, while the $He^{+2}$–$He^+$ front is near $10^{11}$ cm. Note that there is significant ionization beyond the nominal $H^0$–$H^+$ front, due to penetrating X-rays and Balmer continuum photoionizations out of the $n = 2$ level in $H^0$ (KK81). Some important low-ionization lines like FeII form in that region. The ionization fractions in plots like Figure 3 help us identify ions, such as O$^{+5}$, N$^{+4}$ and He$^{+2}$, that are roughly co-spatial and thus good candidates for abundance comparisons.

XXXXXX INSERT FIGURE HERE XXXXXX

Fig. 3 — Ionization structure for a nominal BELR cloud with $n_H = 10^{10}$ cm$^{-3}$, log $U = -1.5$ and solar abundances.
2.5.3. An Example: the CIV λ1549 Equivalent Width

CIV λ1549 is one of the strongest collisionally-excited lines in quasar spectra. The left panel of Figure 4 shows how its predicted equivalent width changes with the density \(n_H\) and ionizing flux \(\Phi(H)\), see Korista et al. 1997b for many more similar plots). Powerful selection effects are clearly at work; the line radiates efficiently over just a narrow range of parameters. Varying \(\Phi(H)\) is equivalent to moving the cloud closer or farther from the continuum source. The line is weak at large values of \(\Phi(H)\), because carbon is too highly ionized, and at low values of \(\Phi(H)\), because carbon is too neutral. The line strength also changes with the gas density. When the density is above \(n_{\text{crit}}\), the line is collisionally suppressed and other permitted lines take over the cooling. When the density is low, the line weakens as the many forbidden and semi-forbidden lines become efficient coolants and the gas temperature declines. The line is most prominent at \(n_H \approx 10^{10} \text{ cm}^{-3}\) and \(\log U \approx -1.5\), which are the canonical BELR parameters deduced over twenty years ago from analysis of the CIV emission (DN79).

![Fig. 4 — Predicted equivalent width (EW) of CIV λ1549 as a function of the cloud density, \(n_H\), and incident ionizing flux, \(\Phi(H)\). The equivalent width here is dimensionless (line flux/\(\nu_o f_\nu_o\) in the continuum) and applies for the hypothetical case of global covering factor unity. Flux ratios for NV λ1240/HeII λ1640 and NV/CIV are also shown. Other parameters are the same as Fig. 3.](image)

It is important to remember that these selection effects exist whenever we observe an emission line. Baldwin et al. (1995) showed that a typical quasar BEL spectrum might result simply from selection effects operating in BELRs with a wide range of cloud properties (e.g. density and distance from the QSO). Numerical simulations can identify pairs of lines with similar selection behaviors so that their ratios are insensitive to the ranges or specific values of the parameters.

2.5.4. Line Dependence on Continuum Shape

Figure 5 shows a series of calculations using different incident spectral shapes. The actual shape of the ionizing continua in QSOs is a complicated issue, but the UV to X-ray slopes are roughly consistent with \(\alpha \sim -1.5\), near the center of the range shown (see Laor 1998, Korista et al. 1997a for recent discussions). The results in Figure 5 mainly reflect the conservation of energy in the cloud. Harder spectra (less negative \(\alpha\)) provide more heating per photoionization, leading to higher temperatures. The increased heating requires more line cooling via collisionally-excited lines like CIV. The ratio of a collisionally-excited line to a recombination line, such as CIV/Ly\(\alpha\), is proportional to the cooling per recombination or equivalently the heating per photoionization (DN79). Such ratios therefore have a strong continuum-shape dependence. The strengths of collisionally-excited lines relative to the adjacent continuum (i.e. their equivalent widths) also depend on the spectral slope.
because of the temperature sensitivity and because the continuum below the lines might be very different from that controlling the ionization. Ratios of collisionally-excited lines, such as NV/CIV, can similarly depend on the spectral shape if their ionization or excitation energies are different. In dense BELRs, these simple behaviors can be moderated by other effects. For example, the Ly$\alpha$ equivalent width increases with spectral hardening at fixed $U$ (Fig. 5) because it has a significant collisional (temperature-sensitive) contribution.

**Figure 5** — Predicted line flux ratios, gas temperatures ($T_4 = T/10^4$ K in the O$^{+2}$ zone, i.e. weighted by the O$^{+2}$ fraction), and dimensionless equivalent widths in Ly$\alpha$ (EW, as in Fig. 4) are plotted for clouds photoionized by different power law spectra. Other parameters are the same as Fig. 3. The lines are CIII $\lambda$977, NIII $\lambda$991, OVI $\lambda$1034, NV $\lambda$1240, CIV $\lambda$1549, HeII $\lambda$1640, OIII $\lambda$1664, NII $\lambda$1750 and CIII $\lambda$1909.

### 2.5.5. Line Dependence on Abundances

The left-hand panel of Figure 6 shows a series of calculations for clouds with different metallicities, $Z$ (scaled from solar and preserving solar ratios). The strengths of the collisionally-excited lines relative to Ly$\alpha$ change little with $Z$. In particular, CIV/Ly$\alpha$ varies negligibly for $0.1 \lesssim Z \lesssim 30 Z_{\odot}$ (see also Hamann & Ferland 1993a, hereafter HF93a). We have already noted that these ratios are more sensitive to the continuum shape (§2.5.4). Their lack of sensitivity to $Z$ can be traced to feedback in the energy balance. As the metal abundances grow, the line cooling increases. The growing metallicities, which might otherwise increase the metal line strengths, are thus balanced in real clouds by lower temperatures — with the result that the total metal line flux stays constant. This feedback is especially important for strong lines, like CIV, that by themselves control a large fraction of the cooling. Weak lines respond better to abundance changes. At low metallicities ($Z \lesssim 0.02 Z_{\odot}$) none of the metal lines are important coolants and their overall strengths do scale with $Z$.

Another factor in the line behaviors at high $Z$ is the increasing bound-free continuum absorption by metal ions. The metals absorb a larger fraction of the far-UV flux at high $Z$, such that the H and He recombination lines become somewhat weaker. This effect dominates the high-$Z$ rise in OVI/HeII and NV/HeII in Figure 6.

The right-hand panel in Figure 6 shows the same line ratios as before, but in this case nitrogen is scaled such that N/H $\propto Z^2$ (where N/H is solar at $Z = Z_{\odot}$). This selective scaling is based on the expected secondary nucleosynthesis of nitrogen (§6 below). Shields (1976) noted that this abundance pattern should occur in QSOs by analogy with its direct observation in galactic HII regions. Figure 6 shows that it leads to a strong metallicity dependence for line ratios involving nitrogen. This strong dependence is possible because the N lines do not control the cooling.
2.6. Abundance Diagnostics and Results

2.6.1. Intercombination Lines

Shields (1976) proposed using various collisionally-excited intercombination (semi-forbidden) lines to derive metal-to-metal abundance ratios in QSOs. He emphasized the strengths of NIII $\lambda 1750$ and NIV $\lambda 1486$ compared to OIII $\lambda 1664$, CIII $\lambda 1909$ and CIV $\lambda 1549$ as potential diagnostics of the overall metallicity. As noted above, the metallicity dependence stems from the expected $Z^2$ scaling of N via secondary nucleosynthesis (also §6 below). Shields selected lines with similar ionization and excitation energies, so that their ratios are insensitive to the uncertain temperature, ionization and geometry. Comparisons with the measured line ratios in QSOs (see also Davidson 1977, Baldwin & Netzer 1978, DN79, Osmer 1980, Uomoto 1984) suggested that N/C and N/O are often solar or higher, consistent with solar or higher metallicities. Gaskell, Shields & Wampler (1981) extended this analysis to SiIII $\lambda 1892$ and other lines to show that the refractory elements cannot be substantially depleted by dust in BELRs.

One drawback of the intercombination lines is that most of them are weak and therefore difficult (or impossible) to measure. Nonetheless, the best recent measurements (Wills et al. 1995, Laor et al. 1995, Boyle 1990, Baldwin et al. 1996) support the earlier results. It is now possible to gather even more data for these lines at a range of redshifts. A note of caution is that the strong feature generally attributed to CIII $\lambda 1909$ can have large contributions from other lines (Laor et al. 1995, 1997, Baldwin et al. 1996), so that ratios like NIII]/CIII] might systematically underestimate N/C if line blending is not accounted for.

A more serious concern is that the early theoretical work did not consider the range of high densities now believed to be present in the BELR (§2.2). The intercombination lines probably form at or near their critical densities (typically $3 \times 10^9$ to $10^{11}$ cm$^{-3}$ for $\beta = 1$ in Eqn. 5). Lines with different $n_{krit}$ could have different degrees of collisional suppression. (For example, the calculated results using $n_e \approx n_H = 10^{10}$ cm$^{-3}$ in Figs. 5 and 6 favor large NIII]/CIII] at a given N/C abundance because CIII] is collisionally suppressed above its $n_{krit} \approx 3 \times 10^9$ cm$^{-3}$.) If there is a range of densities, lines with different $n_{krit}$ might form in different regions (even if they have similar ionizations), leading to a geometry dependence. Nonetheless, line ratios involving similar $n_{krit}$ and similar sensitivities to other parameters, such as NIII]/OIII], could still be robust abundance indicators when they are measurable. More theoretical work is needed to explore the parameter sensitivities and selection effects that can influence these lines in complex BELRs.
2.6.2. Permitted Lines

There are several possibilities for abundance diagnostics among the permitted UV lines. Figure 6 shows that NIII $\lambda 991$/CIII $\lambda 977$ and NV $\lambda 1240$/CIV $\lambda 1549$ should be good tracers of N/C. Another possibility is NV/HeII $\lambda 1640$, or perhaps NV/(CIV+OVI $\lambda 1034$). The NV, OVI and HeII lines form in overlapping regions (Fig. 3), as do NIII and CIII, so their flux ratios should be insensitive to the global BELR structure. Also, as noted above, the N lines are not important coolants and thus responsive to abundance changes. There are practical problems with most of these lines, however; NV is blended with Ly$\alpha$, CIII, NIII and HeII are weak, and CIII, NIII and OVI lie in the “forest” of intervening Ly$\alpha$ absorption lines. Nonetheless, improvements in the quality of data (for example, high resolution and high signal-to-noise spectra in the Ly$\alpha$ forest) are permitting increasingly accurate measurements of these lines in large QSO samples.

2.6.3. NV/HeII and NV/CIV

Some of the first studies of large QSO samples noted that NV $\lambda 1240$ is often stronger than predicted by photoionization models using solar abundances (Osmer & Smith 1976 and 1977). The NV/HeII and NV/CIV ratios have since received particular attention as abundance diagnostics (Hamann & Ferland 1992, HF93a, Hamann & Ferland 1993b — hereafter HF93b, and Ferland et al. 1996 — hereafter F96). Figure 7 shows the measured ratios in these lines for QSOs at different redshifts (from HF93b and Hamann et al. 1997a, with some new data and modifications based mainly on Wills et al. 1995 and Baldwin et al. 1996). NV/HeII is the ratio of a collisional to recombination line, with the expected strong temperature dependence (§2.4). Calculations similar to (but more exhaustive than) those shown in Figures 4–6, indicate that NV/HeII reaches a maximum value linked to the maximum temperature in photoionized clouds (F96). The maximum NV/HeII ratio is $\sim 2$–3 for solar N/He abundances, depending on how “hard” a continuum shape one considers realistic for QSOs. (Beware that the highest ratios in Fig. 4 occur for parameters where both lines are growing weak, cf. the EW(CIV) plot or Korista et al. 1997b.) Nominal BELR parameters predict NV/HeII near unity for solar N/He (Figs. 4–6). These predictions fall well below most of the measured ratios (Fig. 7), implying that QSOs typically have super-solar N/He. The ad hoc (high) temperatures that would be needed to explain the observed NV/HeII ratios with solar N/He are inconsistent with photoionization equilibrium, and would lead to strong far-UV emission lines. The fact that these far-UV line strengths are not seen sets an upper limit on the temperature and supports the result for super-solar N/He (F96).

The NV/CIV lines are collisionally excited with similar energies, so the temperature dependence is smaller than NV/HeII. Nominal BELR parameters predict NV/CIV of order 0.1 for solar N/C (Figs. 4–6, also HF93a,b). Comparisons with the data in Figure 7 thus indicate super-solar N/C for most QSOs.

The two NV ratios together therefore imply that 1) quasar metallicities are often solar or higher, especially in high redshift, high luminosity objects, and 2) nitrogen (e.g. N/C) is typically enhanced compared to solar ratios (F96, HF93a,b). The conclusion for enhanced N/C is based largely on NV/CIV, but we note that the scaling of $N \propto Z^2$ leads
to self-consistent estimates of $Z$ based on NV/HeII and NV/CIV (Fig. 7). The actual $Z$ values are uncertain, but the main point is that many observed ratios require $Z \gtrsim Z_\odot$. Figures 6 and 7 combined suggest that the nominal metallicity range is $1 \lesssim Z \lesssim 10 Z_\odot$ for standard photoionization parameters and $N \propto Z^2$.

![Graphs showing NV/HeII and NV/CIV flux ratios versus redshift and continuum luminosity.](image)

Fig. 7 — Measured NV/HeII and NV/CIV flux ratios versus redshift (left panels) and continuum luminosity (right). The upper and lower ranges might be undersampled (especially for NV/HeII at redshifts $>1$) because limits on weak lines (e.g. HeII) were often not available from the literature. The two asterisks in each panel represent mean values measured by Osmer et al. (1994) for “high” and “low” luminosity QSOs at redshift $>3$. The solid curves are predictions based on chemical evolution models (discussed in §6 below).

HF93b noted that the observed NV ratios tend to be higher in more luminous sources (Fig. 7). Most BELs exhibit the well-known “Baldwin effect,” that is, lower equivalent widths at higher luminosities (Baldwin 1977b). This effect is well established in CIV and appears to be even stronger in OVI (Zheng et al. 1995, Kinney, Rivolo & Koratkar 1990, Osmer & Shields 1999). Surprisingly, NV does not show this effect (Osmer et al. 1994, Laor et al. 1995, Francis & Koratkar 1995) even though its ionization is intermediate between CIV and OVI and its electron structure is identical. We proposed that the peculiar NV behavior is due to generally higher metallicities and more enhanced N abundances.
in more luminous QSOs. The recent theoretical study of the Baldwin effect by Korista, Baldwin & Ferland (1998) gives quantitative support to that conclusion. In §7 we will argue that this proposed metallicity–luminosity trend in QSOs could naturally result from a mass–metallicity correlation among their host galaxies.

The abundance results based on NV have been questioned by Turnshek et al. (1988, 1996) and Krolik & Voit (1998), who argue that the NV BEL forms largely by resonance scattering in an outflowing BAL region. NV might be selectively enhanced by this mechanism because it can scatter both the continuum and the underlying Lyα emission line. However, explicit calculations of the line scattering (Hamann, Korista & Morris 1993, Hamann & Korista 1996, Hamann, Korista & Ferland 1999a) do not support this scenario. For example, 1) the amount of NV scattering estimated by Krolik & Voit (1998) is too large by a factor of ~3 on average, because BALRs do not generally have the right velocity/optical depth structure to scatter all of the incident Lyα photons. In particular, NV BALs are not usually black across the Lyα emission line. 2) It is difficult for NV ions in high-velocity BAL winds to scatter Lyα photons into simple emission profiles with observed half-widths of typically 2000 to 2500 km s\(^{-1}\). For example, isotropic scattering of the Lyα flux would produce BEL half-widths of ~6000 km s\(^{-1}\) (the velocity separation between the NV and Lyα lines). Anisotropic scattering (e.g. in BALRs with equatorial or bipolar geometries) would lead to strong orientation effects and systematically broader BEL profiles in BAL versus non-BAL QSOs. These differences are not observed (Weymann et al. 1991). 3) It is not clear why, in individual spectra, the NV emission profiles should closely resemble those of other BELs if the former is produced by scattering in a high-velocity BAL wind while the latter are collisionally excited in a separate region (i.e. the usual BELR — whose velocity field is not mostly radial based on the reverberation studies, Türler & Courvoisier 1997, Korista et al. 1995). Finally, 4) large scattering contributions to NV would minimally require much larger global BALR covering factors (the fraction of the sky covered by the BALR as seen from the central QSO) than expected from their observed detection frequency in (randomly oriented) QSO samples. Goodrich (1997) and Krolik & Voit (1998) argue that larger global covering factors could occur, but that issue is not settled.

Another concern is that complex BELR geometries might cause the NV/HeII and NV/CIV abundance indicators to fail — but they would fail in opposite directions. Specifically, clouds that are truncated at different physical depths (see Fig. 3) could produce strong HeII with little or no NV and CIV emission, or strong HeII and NV with little or no CIV. For a given abundance set, this type of truncation could therefore either lower the observed NV/HeII ratio or increase NV/CIV. Comparing the data to simulations that do not take truncation into account (Figs. 4–6) might then lead to underestimated N/He abundances or overestimated N/C. However, we have already shown that these two line ratios yield similar metallicities when compared to the non-truncated simulations, so we are not likely being mislead by complex BELR geometries. Moreover, the NV/HeII ratio provides in any case a secure lower limit on N/He.
2.6.4. FeII/MgII

The broad FeII emission lines pose unique problems because the atomic physics is complex and many blended lines contribute to the spectrum, particularly at the wavelengths $\sim 2000-3000$ Å and $\sim 4500-5500$ Å. Nonetheless, FeII is worth the effort because a delay of $\sim 1$ Gyr in the Fe enrichment, relative to $\alpha$ elements such as O, Mg or Si, might provide a “clock” for constraining the ages of QSOs and the epoch of their first star formation (see §§6–7 below, also HF93b).

A series of important papers on FeII emission (Osterbrock 1977, Phillips 1977, 1978, Grandi 1981) culminated with Wills & Netzer (1983) and Wills, Netzer & Wills (1985, hereafter WNW). They performed sophisticated calculations showing that the large observed FeII fluxes, e.g. FeII(UV)/MgII $\lambda 2799$, require that either Fe is several times overabundant (compared to solar ratios) or some unknown process dominates the FeII excitation. One process that might selectively enhance FeII emission is photoexcitation by Lyα photons (Johansson & Jordan 1984). The absorption of Lyα radiation can pump electrons from the lower (metastable) energy levels of Fe$^+$ into specific high-energy states, leading to fluorescent cascades. WNW discounted this mechanism because it appeared insignificant in their simulations, but Penston (1987) noted that Lyα pumping is known to be important in some emission-line stars, such as the symbiotic star RR Tel, and therefore might be important in QSOs. More recent FeII simulations using better atomic data and exploring a wider range of physical conditions (Sigut & Pradhan 1998, Verner et al. 1999) suggest that Lyα can be important in some circumstances, but it is not yet clear if those circumstances occur significantly in QSOs.

Recent observations have renewed interest in this question by showing that the FeII(UV)/MgII emission fluxes can be larger than the WNW predictions even at $z > 4$, with the tentative conclusion that Fe/Mg is at least solar (and thus the objects are at least $\sim 1$ Gyr old, Taniguchi et al. 1997, Yoshii, Tsujimoto & Kawara 1998, Thompson, Hill & Elston 1999 and refs. therein). New theoretical efforts, such as Sigut & Pradhan (1998) and Verner et al. (1999), are needed to test these conclusions and quantify the uncertainties. However, a better way to measure Fe/$\alpha$ might be with the intrinsic NALs (see below).

3. Absorption Line Diagnostics

3.1. Overview: Types of Absorption Lines

Quasar absorption lines can have a variety of intrinsic or cosmologically intervening origins. We exclude from our discussion the damped-Lyα absorbers and the “forest” of many narrow Lyα systems with weak or absent metal lines because they form in cosmologically intervening gas (Rauch 1998). The remaining metal-line systems can be divided into two classes according to their broad or narrow profiles. This division is a gross simplification, but still useful because it distinguishes the clearly intrinsic broad lines from the many others of uncertain origin. Here we briefly characterize the two (broad and narrow) line types.
3.1.1. Broad Absorption Lines (BALs)

Broad absorption lines are blueshifted with respect to the emission lines and have velocity widths of at least a few thousand \( \text{km s}^{-1} \) (for example, Fig. 8). They appear in 10 to 15\% of optically-selected QSOs and clearly identify high-velocity winds from the central engines. The precise location of the absorbing gas is unknown, but there is little doubt that it is intrinsic — originating within at least a few tens of parsecs from the QSOs. See recent work by Weymann et al. (1991), Barlow et al. (1992), Korista et al. (1993), Hamann et al. (1993), Voit, Weymann & Korista (1993), Murray et al. (1995), Arav (1996), Turnshek et al. (1997), Brotherton et al. (1998b), and the reviews by Turnshek (1988, 1994), Weymann, Turnshek & Christianen (1985) and Weymann (1994, 1997).

![Graph showing spectral lines and absorption features](image)

**Fig. 8** — Spectrum of the BALQSO PG 1254+047 (emission redshift \( z_e = 1.01 \)) with emission lines labeled across the top and possible BALs marked below at redshifts corresponding to the 3 deepest minima in the CIV trough. Not all of the labeled lines are detected. The smooth dotted curve is a power-law continuum fit extrapolated to short wavelengths (from Hamann 1998).

3.1.2. Narrow Absorption Lines (NALs)

A practical definition of NALs would limit their full widths at half minimum (FWHMs) to less than the velocity separation of important doublets (e.g., <500 km s\(^{-1}\) for CIV, <1930 km s\(^{-1}\) for SiIV or <960 km s\(^{-1}\) for NV), because it is our ability to resolve these doublets that makes their analysis fundamentally different from the BALs (§3.2.2 below).

NALs can form in a variety of locations, ranging from very near QSOs, as in ejecta like the BALs, to unrelated gas or galaxies at cosmological distances (Weymann et al. 1979). It is not yet known what fraction of NALs at any velocity shift meet our definition of intrinsic (§1). Several studies have noted a statistical excess of NALs within a few thousand km s\(^{-1}\) of the emission redshifts. These are the so-called “associated” or \( z_a \approx z_e \) absorbers (with
redshifts close to the emission redshift, Weymann et al. 1979 and 1981, Young et al. 1982, Foltz et al. 1986 and 1988, Anderson et al. 1987). Their strengths and frequency of occurrence appear to correlate with the QSO luminosities or radio properties, suggesting some physical relationship (also Möller et al. 1994, Aldcroft, Bechtold & Elvis 1994, Wills et al. 1995, Barthel, Tytler & Vestergaard 1997). These correlations may extend to NALs at blueshifts of 30,000 km s\(^{-1}\) or more (Richards & York 1998). Nonetheless, we might expect a larger fraction of intrinsic NALs nearer the emission redshift and, if they are ejected from QSOs, they should appear at \(z_a < z_e\) rather than \(z_a > z_e\).

Several tests have been developed to help identify intrinsic NALs, including 1) time-variable line strengths, 2) multiplet ratios that imply partial line-of-sight coverage of the background light source(s), 3) high gas densities inferred from excited-state absorption lines, and 4) well-resolved line profiles that are smooth and broad compared to both thermal line widths and to the velocity dispersions expected in intervening clouds (e.g. Bahcall, Sargent & Schmidt 1967, Williams et al. 1975, Young et al. 1982, Barlow & Sargent 1997, Hamann et al. 1997b – hereafter H97b, Hamann et al. 1997c, Petitjean & Srianand 1999, Ganguly et al. 1999, and refs. therein). These criteria might not be definitive individually, but they sometimes appear in combination.

Figure 9 shows a \(z_a \approx z_e\) NAL system that is clearly intrinsic based on time-variable line strengths, partial line-of-sight coverage and relatively broad profiles. High metallicities might be another indicator of intrinsic absorption (§3.4 below), but that criterion would bias abundance studies; we would like to determine the intrinsic versus intervening nature independent of the abundances. The other (non-abundance) tests indicate that intrinsic NALs can have velocity shifts out to \(\sim 24,000\) km s\(^{-1}\) and a wide range of FWHMs down to \(\lesssim 30\) km s\(^{-1}\). See the references above and the reviews of \(z_a \approx z_e\) systems by Weymann et al. (1981) and Foltz et al. (1988).

### 3.2. General Abundance Analysis

Abundance estimates from absorption lines are, in principle, more straightforward than for emission lines because the absorption strengths are not sensitive to the temperatures or space densities. Moreover, absorption lines yield direct measures of the column densities in different ions. We need only apply appropriate ionization corrections to convert the column densities into relative abundances. For example, the abundance ratio of any two elements \(a\) and \(b\) can be written,

\[
\left[ \frac{a}{b} \right] = \log \left( \frac{N(a_i)}{N(b_j)} \right) + \log \left( \frac{f(b_j)}{f(a_i)} \right) + \log \left( \frac{b}{a} \right)_{\odot} \tag{10}
\]

which is identical to Equation 8 except that the \(N\) here are the column densities. Once again we define the ionization correction as \(IC \equiv \log(f(b_j)/f(a_i))\). Abundance studies would ideally compare lines with similar ionizations to minimize \(IC\) and reduce the sensitivity to potentially complex geometries. Unfortunately, the lines available often require significant ionization corrections. In particular, we are often forced to compare highly-ionized metals (such as CIV) to HI (Ly\(\alpha\)) to derive the metallicity. We must therefore use ionization models.
The usual assumption is that the gas is photoionized by the QSO continuum flux. Collisional ionization would lead to lower derived metallicities because it creates less HI (and more HII) for a given level of ionization in the metals (cf. Figs. 4 and 5 in Hamann et al. 1995, also Turnshek et al. 1996). However, collisional ionization has been generally dismissed for BAL regions (BALRs) because 1) it would be energetically hard to maintain, 2) it would produce excessive amounts of line emission (because of the much higher temperatures), and 3) it is hard to reconcile with the observed simultaneous variabilities in BAL troughs across a wide range of velocities (Weymann et al. 1985, Junkkarinen et al. 1987, Barlow 1993). In contrast, the strong radiative flux known to be present in QSOs
provides a natural ionization source. We will assume that photoionization dominates in both BALRs and intrinsic NALRs.

Fig. 10 — Ionization fractions in optically thin clouds photoionized at different $U$ by a power-law spectrum with $\alpha = -1.5$. The HI fraction appears across the top. The curves for the metal ions are labeled above or below their peaks whenever possible. The notation here is HI = H$^0$, CIV = C$^{+3}$, etc.

Estimates of $IC$ generally come from plots like Figure 10, which shows the ionization fractions of HI and various metal ions $M_i$ in photoionized clouds (see §2.5 and Ferland et al. 1998 for general descriptions of the calculations). Ideally, we would compare column densities in different ions of the same element to obtain abundance-independent constraints on the ionization and thus $IC$. Otherwise, column densities in different elements can also constrain $IC$ with assumptions about the relative abundances. Note that the results in Figure 10 are not sensitive to the particular abundances used the calculations (in this case solar), so the figure is useful for general abundance/ionization estimates (see Hamann 1997 — hereafter H97). The model clouds are optically thin in the ionizing UV continuum, which means that gradients in the ionization are negligible across the cloud and the
ionization fractions do not depend on the total column densities. This simplification appears to be appropriate for most intrinsic absorption line systems (based on their measured column densities), although shielding by many far-UV BALs might affect the ionization structure downstream in BALRs (Korista et al. 1996, Turnshek 1997, H97). Also, systems with low-ionization lines like FeII or MgII can be optically thick at the HI Lyman edge (Bergeron & Stańńska 1986, Voit et al. 1993, Wampler, Chugai & Petitjean 1995) and may require calculations with specific column densities that match the data.

### 3.2.1. Ionization Ambiguities

The main theoretical uncertainties involve the shape of the ionizing spectrum, the frequent lack of ionization constraints (too few lines measured), and the possibility of inhomogeneous (multi-zone) absorbing media. H97 addressed these issues by calculating IC values for a wide range of conditions in photoionized clouds. He noted that, whenever there is or might be a multi-zone with a range of ionizations, we can still make conservatively low estimates of the metal-to-hydrogen abundance ratios by assuming each metal line forms where that ion is most favored — that is, at the peak of its ionization fraction $f(M_i)$ in Figure 10. We can also place firm lower limits on the metal-to-hydrogen ratios by adopting the minimum values of IC, which correspond to minima in the $f$(HI)/$f$(M_i) ratios (see also Bergeron & Stańńska 1986). The lower limits are robust, even though they come from 1-zone calculations, because different or additional zones can only mean that larger IC values are appropriate for the data. Figure 11 plots several minimum metal-to-hydrogen ICs for optically thin clouds photoionized by different power-law spectra. The results in this plot simply get added to the logarithmic column density ratios (Eqn. 10) to derive minimum metallicities. Note that some important metal-to-metal ratios also have minimum IC values, such as PV/CIV and FeII/MgII (Hamann 1998, Hamann et al. 1999b).

### 3.2.2. Column Densities and Partial Coverage

The final critical issue is deriving accurate column densities from the absorption troughs. In the simplest case, the line optical depths are related to the observed intensities by,

$$I_v = I_o \exp(-\tau_v)$$

where $I_v$ and $I_o$ are the observed and intrinsic (unabsorbed) intensities, respectively, and $\tau_v$ is the line optical depth, at each velocity shift $v$. The column densities follow from the optical depths by,

$$N = \frac{m_e c}{\pi e^2 f \lambda_o} \int \tau_v \, dv$$
Fig. 11 — Minimum metal ion to HI ionization corrections (IC) normalized to solar abundances (the last two terms in Eqn. 10) are plotted for optically thin clouds photoionized by power-law spectra with different indices (α). The notation is the same as Fig. 10. The curves have been shifted vertically by +1 for OVI, by −2 for PV, and by −1 for AlII and AlIII. The curves for nitrogen ions are dash-dot.

where \( f \) is the oscillator strength and \( \lambda_o \) is the laboratory wavelength of the line. Column density derivations can involve line profile fitting or direct integration over the observed profiles (via Eqns. 11 and 12, Junkkarinen \textit{et al.} 1983, Grillmair & Turnshek 1987, Korista \textit{et al.} 1992, Savage & Sembach 1991, Jenkins 1996, Arav \textit{et al.} 1999 — henceforth A99). Very optically thick lines are not useful because the inferred values of \( \tau_v \) are far too sensitive to uncertainties in \( I_o \). In other cases, the analysis might still be compromised by 1) unresolved absorption-line components or 2) unabsorbed flux that fills in the bottoms of the observed troughs. If either of these possibilities occurs, the derived optical depths and column densities become lower limits and the derived abundances become incorrect. Errors from the first possibility can always be reduced or avoided by higher resolution spectroscopy.
Fig. 12 — Schematic showing possible “partial coverage” geometries. Partial line-of-sight coverage occurs when light rays like C, which pass through absorption-line clouds (indicated by filled ellipsoids), are combined with rays like A, B or D, which do not. Ray A represents reflected light from a putative scattering region. Ray B simply misses the absorption-line region. Ray D passes through the nominal absorbing zone but suffers no absorption because the region is porous.

The second possibility, of filled-in absorption troughs, is actually an asset for identifying intrinsic NALs (§3.1). We will refer to this filling-in generally as “partial coverage” of the background emission source. Figure 12 shows several geometries that might produce partial coverage and filled-in troughs. When partial coverage occurs, the observed intensities depend on both the optical depth and the line-of-sight coverage fraction, $C_f$, at each velocity,

$$I_v = (1 - C_f) I_o + C_f I_o \exp(-\tau_v)$$

where $0 \leq C_f \leq 1$ and the first term on the right side is the unabsorbed (or uncovered) contribution. Measured absorption lines can thus be shallow even when the true optical depths are large. In the limit $\tau_v \gg 1$, we have,

$$C_f = 1 - \frac{I_v}{I_o}$$

Outside of that limit, we can compare lines whose true optical depth ratios are fixed by atomic physics, such as the HI Lyman lines or doublets like CIV $\lambda\lambda 1548,1550$, SiIV $\lambda\lambda 1394,1403$, etc., to determine uniquely both the coverage fractions and the true optical depths across the line profiles (H97b, Barlow & Sargent 1997, A99, Srianand & Shankaranarayanan 1999, Ganguly et al. 1999). For example, a little algebra shows that for doublets with true optical depth ratios of $\sim 2$ (as in CIV, SiIV, etc.) the coverage fraction at each absorption velocity is,

$$C_f = \frac{I_2^2 - 2I_1 + 1}{I_2 - 2I_1 + 1}$$

where $I_1$ and $I_2$ are the observed line intensities, normalized by $I_o$, at the same velocity in the weaker and stronger line troughs, respectively. The corresponding line optical depths are $\tau_2 = 2\tau_1$ and,

$$\tau_1 = \ln\left(\frac{C_f}{I_1 + C_f - 1}\right)$$

It is a major strength of the NALs that we can resolve key multiplet lines and use this analysis to measure the coverage fractions and thus derive reliable column densities and

---

3The situation can be potentially more complicated if the absorber itself is a source of emission. The analysis discussed below remains the same, however.
abundances. It is a great weakness of the BALs that this analysis is usually not possible because the lines are blended. We will argue below that BAL studies so far have been seriously compromised by unaccounted for partial-coverage effects.

The only drawback of partial coverage for the NALs is that there might be a range of coverage fractions in multi-zone absorbing media. There is already evidence in some cases for coverage fractions that differ between ions or change with velocity across the line profiles (Barlow & Sargent 1997, Barlow, Hamann & Sargent 1997, H97b). Variations in $C_f$ with velocity can always be dealt with by analyzing limited velocity intervals in the line profiles (see also Arav 1997). But one can imagine complex geometries where ionization-dependent coverage fractions would jeopardize the simple analysis described above, in particular for comparisons between high and low ionization species like CIV and HI. Abundance ratios based on disparate species like these might require specific models of the ionization-dependent coverage. On the other hand, this worst-case scenario is not known to occur, and there is no reason to believe it would lead to generally overestimated metallicities anyway.

3.3. Broad Absorption Line Results

One common characteristic of BAL spectra is that the metallic resonance lines like CIV $\lambda 1548,1951$, SiIV $\lambda 1394,1403$, NV $\lambda 1239,1243$ and OVI $\lambda 1032,1038$ are typically strong (deep) compared to Ly$\alpha$ (e.g. Fig. 8). This result, and the fact that low-ionization lines like MgII $\lambda 2796,2804$ and FeII (UV) are usually absent, indicates that the BALR ionization is generally high (Turnshek 1984, Weymann et al. 1981,1985). However, quantitative studies of the ionization have repeatedly failed to explain the measured line strengths with solar abundances. These difficulties were first noted by Junkkarinen (1980) and Turnshek (1981, also Weymann & Foltz 1983), who showed that photoionization models with power-law ionizing spectra and solar abundances underpredict the metal ions, especially SiIV, by large factors relative to HI. A straightforward conclusion is that the metallicities are well above solar. Turnshek (1986, 1988) and Turnshek et al. (1987) estimated metal abundances (C/H) of 10 to 100 times solar, and provided tentative evidence for some extreme metal-to-metal abundance ratios such as P/C $\gtrsim 100$ times solar.

Better data in the past ten years have done nothing to change these startling results (e.g. Turnshek et al. 1996). The early concerns about unresolved line components (Junkkarinen et al. 1987, Kwan 1990) have gone away, thanks to spectroscopy with the Keck 10 m telescope at resolutions ($\sim 7$ km s$^{-1}$) close to the thermal speeds (Barlow & Junkkarinen 1994, Junkkarinen 1998). The previously tentative detections of PV $\lambda 1118,1128$ absorption, which led to the large P/C abundance estimates, have now been confirmed in two objects by excellent wavelength coincidences, by the predicted weakness of nearby lines like FeIII $\lambda 1122$, and in one case by the probable presence of PIV $\lambda 951$ absorption (Junkkarinen et al. 1997, Hamann 1998, Fig. 8). The commonality of PV absorption is not yet known (see also Korista et al. 1992, Turnshek et al. 1996), but its relative strength in just the two cases is surprising because the solar P/C ratio is only $\sim 0.001$.

More complex theoretical analyses, considering a range of ionizing spectral shapes or
multiple ionization zones, also do not change the main result for metallicities and P/C ratios well above solar (Weymann et al. 1985, Turnshek et al. 1987, 1996 and 1997, Korista et al. 1996). H97 used the analysis in §3.2 to determine how high the abundances must be given the measured column densities and a photoionized BALR. He showed that average BALR column densities require \([\text{C/H}]\) and \([\text{N/H}] > 0\) and \([\text{Si/H}] > 1.0\) for any range of ionizations and reasonable spectral shapes. The conservatively low (but not quite minimum) values of \(IC\) indicate \([\text{C/H}]\) and \([\text{N/H}] \gtrsim 1.0\) and \([\text{Si/H}] \gtrsim 1.7\). The results for individual BAL systems can be much higher. In PG1254+047 (Fig. 8, Hamann 1998) the inferred minimum abundances are \([\text{C/H}]\) and \([\text{N/H}] \gtrsim 1.0\), \([\text{Si/H}] \gtrsim 1.8\) and \([\text{P/C}] \gtrsim 2.2\).

However, we will now argue that all these BAL abundance results are incorrect, because partial coverage effects have led to generally underestimated column densities.

3.3.1. Uncertainties and Conclusions

There is now direct evidence for partial coverage in some BALQSOs based on widely separated lines of the same ion (A99) and resolved doublets in several narrow BALs and BAL components (Telfer et al. 1999, Barlow & Junkkarinen 1994, Wampler et al. 1995, Korista et al. 1992 — confirmed by Junkkarinen 1998). Although most this evidence applies to narrow features, it is noteworthy that there are no counterexamples to our knowledge — where narrow line components associated with BALs indicate complete coverage (also Junkkarinen 1998).

There is also circumstantial evidence for partial coverage in BAL systems. Namely, 1) spectropolarimetry indicates that BAL troughs can be filled in by polarized flux (probably from an extended scattering region) that is not covered by the BALR (Fig. 12, Goodrich & Miller 1995, Cohen et al. 1995, Hines & Wills 1995, Schmidt & Hines 1999). 2) Some BAL systems have a wide range of lines with suspiciously similar strengths or flat-bottom troughs that do not reach zero intensity (Arav 1997). 3) Voit et al. (1993) made a strong case for low-ionization BALRs being optically thick at the Lyman limit, which implies large optical depths in Lyα, yet the Lyα troughs are not generally black in these systems. 4) The larger column densities that follow assuming partial coverage and saturated BALs \((N_H \gtrsim 10^{22} \text{ cm}^{-2})\), Hamann 1998) are consistent with the large absorbing columns inferred from X-ray observations of BALQSOs (Green & Mathur 1996, Green et al. 1997, Gallagher et al. 1999).

More indirect evidence comes from the abundance results themselves. Voit (1997) noted that the derived overabundances tend to be greater for rare elements like P than for common elements like C. This is precisely what would occur if line saturation is not taken into account. The surprising detections of PV might actually be a signature of line saturation (and partial coverage) in strong lines like CIV, rather than extreme abundances (Hamann 1998). This assertion is supported by the one known NAL system with PV \(\lambda\lambda 1118,1128\) absorption, where the doublet ratios in CIV, NV and SiIV clearly indicate \(\tau \gg 1\) (Barlow et al. 1997, Barlow 1998).

We conclude that BAL column densities have been generally underestimated and the true BALR abundances are not known. Observed differences between BAL profiles that resemble simple optical depth effects are probably caused by a mixture of ionization,
coverage fraction and optical depth differences in complex, multi-zone BALRs. This
collection paints a grim picture for BAL abundance work, but it might still be possible to
derive accurate column densities and therefore abundances for some BALQSOs or some
portions of BAL profiles (Wampler et al. 1995, Turnshek 1997, A99). Most needed are
spectra at shorter rest-frame wavelengths to measure widely separated lines of the same
ion and thereby diagnose the coverage fractions and true optical depths (§3.2.2, Arav 1997,
A99).

3.4. Narrow Absorption Line Results

In contrast to the BALs, intrinsic NALs might be the best abundance probes we
have for QSO environments. Resolved measurements of NAL multiplets allow us to
measure both the coverage fractions and true column densities (§3.2.2). The NALs also
allow separate measurements of important lines that are often blended in BAL systems,
such as NV λ1239,1243–Lyα, OVI λ1032,1038–Lyβ and many others. We therefore have
potentially many more constraints on both the ionization and abundances.

Early NAL studies did not have the quality of data needed to derive column densit
ies and abundances, but several groups noted a tendency for larger NV/CIV line strength
ratios in za ≈ ze systems compared to za ≪ ze (Weymann et al. 1981, Hartquist & Snijders
1982, Bergeron & Kunth 1983, Morris et al. 1986, Bergeron & Boissé 1986). This trend is
probably not due simply to higher ionization in za ≈ ze absorbers, because recent studies
show that za ≪ ze systems typically have strong OVI lines and therefore considerable
high-ionization gas; NV appears to be weak relative to both CIV and OVI at za ≪ ze (Lu &
Savage 1993, Bergeron et al. 1994, Burles & Tytler 1996, Kirkman & Tytler 1997, Savage,
Tripp & Lu 1998). The lower NV/OVI and NV/CIV line ratios at za ≪ ze could be caused
by an underabundance of nitrogen (relative to solar ratios) in metal-poor intervening
gas (Bergeron et al. 1994, Hamann et al. 1997d, Kirkman & Tytler 1997). This would
be the classic abundance pattern involving secondary nitrogen (Vila-Costas & Edmunds
1993). Relatively higher N abundances and thus stronger NV absorption lines should occur
naturally in metal-rich environments near QSOs (see §§6–7 below).

The first explicit estimates of za ≈ ze metallicities were by Wampler et al. (1993),
Möller et al. (1994), Petitjean et al. (1994) and Savaglio et al. (1994) for QSOs at redshifts
of roughly 2 to 4. These studies found that za ≈ ze systems often have Z ≳ Z⊙, which is
at least an order of magnitude larger than the za ≪ ze systems measured in the same data.
Several of the metal-rich za ≈ ze systems have doublet ratios implying partial coverage and
thus, very likely, an intrinsic origin (Wampler et al. 1993, Petitjean et al. 1994). The
location of the other za ≈ ze absorbers is not known, but Petitjean et al. (1994) noted a
marked change from [C/H] ≲ −1 to [C/H] ≳ 0 at a blueshift of ~15,000 km s−1 relative to
the emission lines. If high abundances occur only in intrinsic systems, then these results
suggest that most za ≈ ze NALs are intrinsic (also Möller et al. 1994).

More recent studies support these findings. Petitjean & Srianand (1999) measured
Z ≳ Z⊙ and [N/C] > 0 in an intrinsic (partial coverage) za ≈ ze absorber. For za ≈ ze
systems of unknown origin, Savage et al. (1998) estimated roughly solar metallicities and
Tripp et al. (1997) obtained [N/C] ≳ 0.1 and, very conservatively, [C/H] ≳ −0.8. (The
lower limit on [C/H] for the latter system is −0.2 when more likely ionizing spectral shapes are used in the calculations.) Savaglio et al. (1997) revised the metallicities downward slightly from their 1994 paper to −1 < [C/H] < 0, based on better data. Those systems are of special interest because of their high redshift (\(z_a \approx 4.1\)). Wampler et al. (1996) estimated \(Z \sim 2 Z_\odot\) (based on a tentative detection of OI \(\lambda 1303\)) for the only other \(z_a \approx z_e\) systems studied so far at \(z > 4\).

H97, H97b and Hamann et al. (1995, 1997e, 1999b) used the analysis outlined in §3.2 to determine metallicities or establish lower limits for several \(z_a \approx z_e\) systems, including some mentioned above and some that are clearly intrinsic by the indicators in §3.1. The results generally confirm the previous estimates and show further that, even when there are no constraints on the ionization (for example, when only Lyα and CIV lines are measured), the column densities can still require \(Z \gtrsim Z_\odot\). A quick survey of those results suggests that bona fide intrinsic systems, and most others with \(Z \gtrsim 0.5 Z_\odot\), have [N/C] \(\gtrsim 0\).

### 3.4.1. Uncertainties and Conclusions

Most of the studies mentioned above would benefit from better data (higher signal-to-noise ratios and higher spectral resolutions) and more ionization constraints (wider wavelength coverage), but the frequent result for \(Z \gtrsim Z_\odot\) is convincing. Unlike the BALs, there are no obvious systematic effects that might lead to higher abundance estimates for \(z_a \approx z_e\) systems compared to \(z_a \ll z_e\). The possibility of ionization-dependent coverage fractions presents an uncertainty for those systems with partial coverage, but we do not expect that to cause systematic overestimates of the metallicities (§3.2.2). We conclude that most \(z_a \approx z_e\) NALs and, more importantly, all of the “confirmed” intrinsic systems, have \(Z \gtrsim 0.5 Z_\odot\) and usually \(Z \gtrsim Z_\odot\). The upper limits on \(Z\) are uncertain. The largest estimate for a well-measured system is \(Z \sim 10 Z_\odot\) (Petitjean et al. 1994), but those data are also consistent with metallicities as low as solar because of ionization uncertainties (H97). There are mixed and confusing reports in the literature regarding metal-to-metal abundance ratios, most notably N/C. In contrast to Franceschini & Gratton (1997), we find no tendency for sub-solar N/C in \(z_a \approx z_e\) systems. In fact, there is the general trend for stronger NV absorption at \(z_a \approx z_e\) compared to \(z_a \ll z_e\) systems, and the most reliable abundance data suggest solar or higher N/C ratios whenever \(Z \gtrsim Z_\odot\).

The only serious problem is in interpreting the abundance results for systems of unknown origin. High metallicities might correlate strongly with absorption near QSOs, but the metallicities cannot define the absorber’s location. For example, Tripp et al. (1996) estimated \(Z \gtrsim Z_\odot\) and [N/C] \(\gtrsim 0\) for a \(z_a \approx z_e\) system where the lack of excited-state absorption in CII∗ \(\lambda 1336\) (compared the measured CII \(\lambda 1335\)) implies that the density is low, \(\leq 7 \text{ cm}^{-3}\), and thus the distance from the QSO is large, \(\gtrsim 300\) kpc. (The relationship between density and distance follows from the flux requirements for photoionization, §2.5.1.) Super-solar metallicities at these large distances are surprising. At \(\gtrsim 300\) kpc from the QSO, we might have expected very low intergalactic or halo-like abundances. The solution might be that the absorbing gas was enriched much nearer the QSO and then ejected (Tripp et al. 1996).

Unfortunately, the excited-state lines used for density and distance estimates are not
generally available for \( z_a \approx z_e \) systems (because they have low ionization energies, e.g. CII* and SiII*). Of the six \( z_a \approx z_e \) absorbers known to be far (\( > 10 \) kpc) from QSOs based on these indicators, three of them clearly have \( z_a > z_e \) and are probably not intrinsic for that reason (Williams et al. 1975, Williams & Weymann 1976, Sargent et al. 1982, Morris et al. 1986, Barlow et al. 1997). Only one has a metallicity estimate — the system with \( Z \gtrsim Z_\odot \) at \( \gtrsim 300 \) kpc distance studied by Tripp et al. (1996).

4. General Abundance Summary

The main abundance results are as follows.

1) There is a growing consensus from the BELs and NALs for \( Z \gtrsim Z_\odot \) in QSOs out to \( z > 4 \). The upper limits on the metallicities are not well known, but none of the data require \( Z > 10 Z_\odot \). Solar to a few times solar appears to be typical. Based on very limited data, there is no evidence for a decline at the highest redshifts.

2) A trend in the NV/HeII and NV/CIV BEL ratios suggests that the metallicities are generally higher in more luminous QSOs.

3) The BELs and NALs both suggest that the relative nitrogen abundance (e.g. N/C and N/O) is typically solar or higher. We will argue below (§6) that this result corroborates the evidence for \( Z \gtrsim Z_\odot \) (because of the likely secondary origin of nitrogen at these metallicities).

4) There is tentative evidence for super-solar Fe/Mg abundances out to \( z > 4 \) based on the FeII/MgII BEL strengths. Again, based on limited data, there is no evidence for a decline in this ratio at the highest redshifts.

5) The extremely high metallicities and large P/C ratios derived so far from the BALs are probably incorrect. In further support of that conclusion, we note that BELR simulations using the nominally derived BAL abundances (including large enhancements in P and other odd-numbered elements like Al, Shields 1996) are inconsistent with observed BEL spectra (based on unpublished work in collaboration with G. Shields).

5. Enrichment Scenarios

Several scenarios have been proposed for the production of heavy elements near QSOs, including 1) the normal evolution of stellar populations in galactic nuclei (Hamann & Ferland 1992, HF93b), 2) central star clusters with enhanced supernova (and perhaps nova) rates due to mass accreted onto stars as they plunge through QSO accretion disks (Artimowitz, Lin & Wampler 1993), 3) star formation inside QSO accretion disks (Silk & Rees 1998, Collin 1998), and 4) nucleosynthesis without stars inside accretion disks (Jin, Arnett & Chakrabarti 1989, Kundt 1996).

5.1. Occam’s Razor: The Case for Normal Galactic Chemical Evolution

The first scenario listed above, for normal galactic chemical evolution, is most compelling because 1) it is the only one of these processes known to occur and 2) it is
sufficient to explain the QSO data. In particular, the stars in the centers of massive galaxies today are (mostly) old and metal rich (Bica, Arimoto & Alloin 1988, Bica, Alloin & Schmidt 1990, Gorgas, Efstathiou & Aragón Salamanca 1990, Bruzual et al. 1997, Vazdekis et al. 1997, Jablonka, Alloin & Bica 1992, Jablonka, Martin & Arimoto 1996, Feltzing & Gilmore 1998, Worthy, Faber & Gonzalez 1992, Kuntschner & Davies 1997, Sansom & Proctor 1998, Ortolani et al. 1996, Sil’chenko, Burenkov & Vlasyuk 1998, Idiart, de Freitas Pacheco, & Costa 1996, Fisher, Franx & Illingworth 1995, Bressan, Chiosi & Tantalo 1996). The exact ages are uncertain, but there is growing evidence for most of the star formation in massive spheroids (ellipticals and the bulges of large spiral galaxies) occurring at redshifts \( z \gtrsim 2–3 \), especially (but not only) for galaxies in clusters (see also Renzini 1998, Bernardi et al. 1998, Bruzual & Magris 1997, Ellis et al. 1997, Tantalo, Chiosi & Bressan 1998, Ivison et al. 1998, Kodama & Arimoto 1997, Ziegler & Bender 1997, Kauffmann 1996, Van Dokkum et al. 1998, Mushotzky & Loewenstein 1997 Spinrad et al. 1997, Sanford et al. 1998, Heap et al. 1998, Barger et al. 1998a,b). The star-forming (Lyman-break or Ly-α-emission) objects measured directly at \( z \gtrsim 3 \) might be galactic or proto-galactic nuclei in the throes of rapid evolution (Friaca & Terlevich 1999, Baugh et al. 1998, Steidel et al. 1998 and 1999, Connolly et al. 1997, Lowenthal et al. 1997, Trager et al. 1997, Hu, Cowie & McMahon 1998, Franx et al. 1997, Madau et al. 1996, Giavalisco, Steidel & Machetto 1996). These objects are more numerous than QSOs and some have been measured at \( z > 5 \) (Dey et al. 1998, Hu et al. 1998, Weymann et al. 1998), beyond the highest known QSO redshift of \( z \approx 5.0 \) (Sloan Digital Sky Survey press release 1998). On the theoretical side, recent cosmic-structure simulations show that proto-galactic condensations can form stars and reach solar or higher metallicities at \( z \gtrsim 6 \) (Gnedin & Ostriker 1997). Quasars might form in the most massive and most dense of these early-epoch star-forming environments (Turner 1991, Loeb 1993, Haehnelt & Rees 1993, Miralda-Escude & Rees 1997, Haehnelt et al. 1998, Spaans & Carollo 1997). They might also form preferentially in globally dense cluster environments, based on the higher detection rates of star-forming galaxies near high-\( z \) QSOs (Djorgovski 1998).

The gas in these environments might have been long ago ejected via galactic winds, consumed by central black holes or diluted by subsequent infall, but its signature remains in the old stars today. The mean stellar metallicities\(^4\) in the cores of massive low-redshift galaxies are typically \( \langle Z_{\text{stars}} \rangle \sim 1–3 \ Z_\odot \) (see refs. listed above). Individual stars are distributed about the mean with metallicities reflecting the gas-phase abundance at the time of their formation. If the interstellar gas is well-mixed and the abundances grow monotonically (as expected in simple enrichment schemes, §6), the gas-phase metallicity, \( Z_{\text{gas}} \), will always exceed \( \langle Z_{\text{stars}} \rangle \). Only the most recently formed stars will have metallicities as high as the gas. Therefore, the most metal-rich stars today should reveal the gas-phase abundances near the end of the last major star-forming epoch.

In the bulge of our own Galaxy, the nominal value of \( \langle Z_{\text{stars}} \rangle \) is \( 1 \ Z_\odot \) and the tail of the distribution reaches \( Z_{\text{stars}} \gtrsim 3 \ Z_\odot \), with even higher values obtaining near the Galactic center (Rich 1988 and 1990, Geisler & Friel 1992, McWilliam & Rich 1994, Minniti et al.\( ^{4}\))

\(^4\)It is worth noting here that, because of a significant time-delay in the iron enrichment, O/H and Mg/H are better measures of the overall “metallicity” than Fe/H (see §6 and Wheeler et al. 1989).
The gas-phase metallicity should therefore have been $Z_{\text{gas}} \gtrsim 3 Z_\odot$ after most of the Bulge star formation occurred. Simple chemical evolution models indicate more generally that $Z_{\text{gas}}$ should be $\sim 2$ to 3 times $\langle Z_{\text{stars}} \rangle$ in spheroidal systems like galactic nuclei (Searle & Zinn 1978, Tinsley 1980, Rich 1990, Edmunds 1992, de Fretas Pacheco 1996). Thus the observations of $\langle Z_{\text{stars}} \rangle \sim 1-3 Z_\odot$ suggest that gas with $Z_{\text{gas}} \sim 2-9 Z_\odot$ once existed in these environments. We might therefore expect to find $2 \lesssim Z \lesssim 9 Z_\odot$ in QSOs, as long as 1) most of the local star formation occurred before the QSOs “turned on” or became observable and 2) the metal-rich gas produced by that star formation was not substantially diluted or ejected. These expectations are consistent with the abundance estimates reported above (§4). More exotic enrichment schemes are therefore not needed to explain the QSO data.

6. More Insights from Galactic Chemical Evolution

If we assume that QSO environments were indeed enriched by normal stellar populations, then we can use the results from galactic abundance and chemical evolution studies to interpret the QSO data. Here we describe some relevant galactic results (see Wheeler, Sneden & Truran 1989 for a general review).

6.1. The Galactic Mass-Metallicity Relation

One important result from galaxy studies is the well-known mass–metallicity relationship among ellipticals and spiral bulges (Faber 1973, Faber et al. 1989, Bender, Burstein & Faber 1993, Zaritsky, Kennicutt & Huchra 1994, Jablonka et al. 1996, Coziol et al. 1997). This relationship is attributed to the action of galactic winds; massive galaxies reach higher metallicities because they have deeper gravitational potentials and are better able to retain their gas against the building thermal pressures from supernovae (Larson 1974, Arimoto & Yoshii 1987, Franx & Illingworth 1990). Low-mass systems eject their gas before high Z’s are attained. Quasar metallicities should be similarly tied to the gravitational binding energy of the local star-forming regions and, perhaps, to the total masses of their host galaxies (§7.1 below).

6.2. Specific Abundance Predictions

Another key result is the abundance behaviors of N and Fe relative to the $\alpha$ elements such as O, Mg and Si. HF93b constructed 1-zone infall models of galactic chemical evolution to illustrate these behaviors in different environments. Figure 13 plots the results for two scenarios at opposite extremes. Both use the same nucleosynthetic yields, but the “Giant Elliptical” model has much faster evolution rates and a flatter IMF (more favorable to high-mass stars) compared to the “Solar Neighborhood” (or spiral disk) case. The Giant Elliptical evolves passively (without further star formation) after $\sim 1$ Gyr because the gas is essentially exhausted. The parameters used in these calculations were based
on standard galactic infall models (e.g. Arimoto & Yoshii 1987, Matteucci & Tornambé 1987, Matteucci & Francois 1989, Matteucci & Brocato 1990, Köppen & Arimoto 1990). However, the results are only illustrative and not intended to match entire galaxies. For example, evolution like the Giant Elliptical model might occur in just the central cores of extreme high-mass galaxies (cf. Friaca & Terlevich 1998).

Fig. 13 — Logarithmic gas-phase abundance ratios normalized to solar for the two evolution models discussed in §6.2 (adapted from HF93b). Two scenarios for the N enrichment are shown (thin solid lines); one with secondary only and the other with secondary+primary (causing a plateau in N/O at low Z).

6.3. Fe/α as a Clock

At early times the abundance evolution is controlled by short-lived massive stars, mainly via type II supernovae (SN II’s). The α elements, such as O and Mg, come almost exclusively from these objects, but Fe has a large delayed contribution from type Ia supernovae (SN Ia’s) — whose precursors are believed to be intermediate mass stars in close binaries (Branch 1998). The predicted time delay is roughly 1 Gyr based on the IMF-weighted stellar lifetimes (Fig. 13, Greggio & Renzini 1983, Matteucci & Greggio 1986). The actual delay is uncertain, but recent estimates are in the range ~0.3 to 3 Gyr (Matteucci 1994, Yoshii, Tsujimoto & Nomoto 1996, Yoshii et al. 1998). Because this delay does not depend on any of the global evolution time scales (e.g. the star formation rate, etc.), Fe/α can serve as an absolute “clock” for constraining the ages of star-forming environments (Tinsley 1979, Thomas, Greggio & Bender 1998).

Observations of metal-poor Galactic stars suggest that the baseline value of [Fe/α] due to SN II’s alone is nominally −0.7 to −0.4 (Israelian, Garcia & Rebolo 1998, Nissen et al. 1994, King 1993, Gratton 1991, Magain 1989, Barbuy 1988, also de Freitas Pacheco 1996), which is slightly larger than the prediction in Figure 13. The subsequent increase caused by SN Ia’s is a factor of a few or more. Note that the increase in Fe/α should be larger in rapidly-evolving spheroidal systems because 1) by the time their SN Ia’s “turn on,” there
is relatively little gas left and each SN Ia has a greater effect, also 2) their rapid early star formation means that the SN Ia’s occurring later are more nearly synchronized. The net result can be substantially super-solar Fe/α in the gas (even though Fe/α is sub-solar in most stars).

6.4. Nitrogen Abundances

Nitrogen also exhibits a delayed enhancement, although not on a fixed time scale like Fe/α. Nitrogen’s selective behavior is due to secondary CNO nucleosynthesis, where N forms out of pre-existing C and O. Studies of galactic HII regions indicate that secondary processing dominates at metallicities above $\sim 0.2 Z_\odot$, resulting in N/O scaling like O/H (or N $\propto Z^2$) in that regime. At lower metallicities, primary N can be more important based on an observed plateau in [N/O] at roughly $-0.7$ (see Tinsley 1980, Vila-Costas & Edmunds 1993, Thurston, Edmunds & Henry 1996, Van Zee, Skillman & Salzer 1998, Kobulnicky & Skillman 1998, Thuan, Izotov & Lipovetsky 1995, Izotov & Thuan 1999, but see also Garnett 1990, Lu et al. 1998). The models in Figure 13 show two N/O behaviors, for secondary only and secondary+primary, where the latter has a low-Z plateau forced to match the HII region data. Notice that the secondary growth in N/O can be shifted down considerably from the simple theoretical relation [N/O] = [O/H] because of the delays related to stellar lifetimes. We therefore have a strong prediction, based on both observations and these simulations, that measured values of [N/O] $\gtrsim 0$ imply $Z \gtrsim Z_\odot$ — especially in fast-evolving spheroidal systems. This prediction was exploited above in the analysis of QSO BELs (§2.6, Shields 1976).

7. Implications of QSO Abundances

7.1. High-Redshift Star Formation

We can conclude from the previous sections that QSOs are associated with vigorous star formation, consistent with the early-epoch evolution of massive galactic nuclei or dense proto-galactic clumps (§5). However, QSO abundances provide new constraints. For example, the general result for $Z \gtrsim Z_\odot$ suggests that most of the enrichment and local star formation occurs before QSOs “turn on” or become observable. The enrichment times can be so short in principle (Fig. 13, HF93b) that the star formation might also be coeval with QSO formation. In any event, the enrichment times cannot be much longer that $\sim 1$ Gyr for at least the highest redshift objects (depending on the cosmology, Fig. 1).

If the QSO metallicities representative of a well-mixed interstellar medium, we can conclude further that the star formation was extensive. That is, a significant fraction of the initial gas must be converted into stars and stellar remnants to achieve $Z_{gas} \gtrsim Z_\odot$. The exact fraction depends on the IMF. A solar neighborhood IMF (Scalo 1990, as in the Solar Neighborhood model of §6) would lead to mass fractions in gas of only $\lesssim 15\%$ at $Z \sim Z_\odot$, and would not be able to produce $Z_{gas}$ above a few $Z_\odot$ at all. Flatter IMFs (favoring massive stars) could reach $Z_{gas} \gtrsim Z_\odot$ while consuming less of the gas. For example, the gas fraction corresponding to $Z_{gas} \sim Z_\odot$ in the Giant Elliptical model of §6.2 is nearly 70%.
Figure 7 in §2.6.3 illustrates the main star formation characteristics required by the QSO data. The solid curves on the right-hand side of that figure show theoretical BEL ratios from photoionization simulations that use nominal BELR parameters and abundances from the two chemical evolution models in Figure 13 (see HF93b for more details). The evolution is assumed to begin with the Big Bang and the conversion of time into redshift assumes a cosmology with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 1$ and $\Omega_\Lambda = 0$ (Fig. 1). The main results are that the Solar Neighborhood evolution is too slow and, in any case, does not reach high enough metallicities or nitrogen enhancements to match most of the high-redshift QSOs. Much shorter time scales and usually higher metallicities, as in the Giant Elliptical simulation, are needed.

A trend in the NV BELs suggests further that the metallicities are typically higher in more luminous QSOs (§2.6.3). That result needs confirmation, but it could result naturally from a mass–metallicity relationship among QSO host galaxies that is similar (or identical to) the well-known relation in low-redshift galaxies (§6, HF93b). By analogy with the galactic relation, the most luminous and metal-rich QSOs might reside in the most dense or massive host environments. This situation would be consistent with studies showing that QSO luminosities, QSO masses, and central black hole masses in galactic nuclei all appear to correlate with the mass of the surrounding galaxies (McLeod et al. 1999, McLeod & Rieke 1995, Bahcall et al. 1997, Magorrian et al. 1998, Laor 1998, also Haehnelt & Rees 1993). A direct application of the galactic mass-metallicity relation suggests that metal-rich QSOs reside in galaxies (or proto-galaxies) that are minimally as massive (or as tightly bound) as our own Milky Way.

### 7.2. Fe/α: Timescales and Cosmology

One of the most interesting predictions from galactic studies (§6) is that Fe/α ratios in QSOs might constrain the epoch of their first star formation and perhaps the cosmology. In particular, large Fe/α ratios (solar or higher) would suggest that the local stellar populations are at least $\sim 1$ Gyr old. At the highest QSO redshifts ($z \sim 5$), this age constraint would push the epoch of first star formation beyond the limits of current direct observation, to $z > 6$ (Fig. 1). The $\sim 1$ Gyr constraint would also be difficult to reconcile with $\Omega_M \approx 1$ in Big Bang cosmologies. Conversely, measurements of low Fe/α would suggest that the local stellar populations are younger than $\sim 1$ Gyr (although we could not rule out the possibility that only SN II's contributed to the enrichment for some reason). Some BEL studies have already suggested that Fe/α is above solar in $z > 4$ QSOs (§2.6.4).

### 7.3. Comparisons to Other Results

Quasar abundances should be viewed in the context of other measures of the metallicity and star formation at high redshifts. Damped-Lyα absorbers in QSO spectra, which probe lines of sight through large intervening galaxies (probably spiral disks, Prochaska & Wolfe 1998), have mean (gas-phase) metallicities of order 0.05 $Z_\odot$ at $z \gtrsim 2$ (Lu et al. 1996, Pettini et al. 1997, Lu, Sargent & Barlow 1998, Prochaska & Wolfe 1999). The Lyα forest absorbers, which presumably probe much more extended and tenuous inter-galactic
structures (Rauch 1998), typically have metallicities \(<0.01 Z_\odot\) at high redshifts (Rauch, Haehnelt & Steinmetz 1997, Songalia & Cowie 1996, Tytler \textit{et al.} 1995). The much higher metal abundances near QSOs are consistent with the rapid and more extensive evolution expected in dense environments (Gnedin & Ostriker 1997). Perhaps this evolution is similar to that occurring in the many star-forming objects that are now measured directly at redshifts comparable to, and greater than, the QSOs (see refs. in §5.1).

The detections of strong dust and molecular gas emissions from QSOs support the evidence from their high abundances that considerable local star formation preceded the QSO epoch. The dust and molecules, presumably manufactured by stars, appear even in QSOs at \(z \geq 4\) (Isaac \textit{et al.} 1994, Omont \textit{et al.} 1996, Guilloteau \textit{et al.} 1997).

8. Future Prospects

We now have the observational and theoretical abilities to test and dramatically extend all of the QSO abundance work discussed above. The most pressing needs are to 1) develop more independent abundance diagnostics, and 2) obtain more and better data to compare diagnostics in large QSO samples — spanning a range of redshifts, luminosities, radio properties, etc. Absorption line studies will benefit generally from higher spectral resolutions and wider wavelength coverage, providing more accurate column densities and more numerous constraints on the coverage fractions, ionizations and abundances (§3). BEL studies should include more of the weaker lines, such as OVI \(\lambda 1034\), CIII \(\lambda 977\), NIII \(\lambda 991\) and the intercombination lines, whenever possible (§2). Theoretical analysis of the FeII/MgII emission ratios, in particular, is needed to test the tentative conclusion for high Fe/Mg abundances. This and other BEL results should be tested further by examining the same lines (or same elements) in intrinsic NAL systems. The steady improvement in our observational capabilities at all wavelengths will provide many more diagnostic opportunities.

Below are some specific issues that new studies might address.

1) More data at high redshifts will constrain better the epoch and extent of early star formation associated with QSOs.

2) Reliable measurements of Fe/\(\alpha\) will further constrain the epoch of first star formation and, perhaps, the cosmology via the \(~1\) Gyr enrichment clock.

3) Better estimates of the metal-to-metal ratios generally will reveal more specifics of the star formation histories via comparisons to well-studied galactic environments and theoretical nucleosynthetic yields.

4) Abundances for QSOs spanning a wide range of luminosities and redshifts will isolate any evolutionary (redshift) trends and test the tentative luminosity–\(Z\) relationship. This relationship might prove to be a useful indicator of the total masses or densities of the local stellar populations by analogy with the mass–\(Z\) trend in nearby galaxies.

5) The range of QSO metallicities at a given redshift and luminosity will help constrain the extent of star formation occurring before QSOs turn on or become observable. Are there any low metallicity QSOs?

6) Combining the QSO abundances with direct imaging studies of their host galaxies
should test ideas about the chemical enrichment and help us interpret data at the highest redshifts where direct imaging is (so far) not possible. For example, are QSOs in large galaxies (e.g. giant ellipticals) more metal-rich than others?

7) Correlations between the abundances and other properties of QSOs, such as radio-loudness or UV–X-ray continuum shape, might reveal new environmental factors in the enrichment or systematic uncertainties in our abundance derivations.

8) Observations with wide wavelength coverage would allow us to compare abundances derived from the narrow emission lines (in the rest-frame optical) to BEL and NAL data in the same objects. These diverse diagnostics might provide crude abundance maps of QSO host galaxies.

9) How do QSO abundances compare to their low-redshift counterparts, the Seyfert galaxies and active galactic nuclei (AGNs)? Low-redshift metallicities might be less than the QSOs due to recent mergers or gaseous infall.

ACKNOWLEDGEMENTS
We are grateful to G Burbidge for his patience and encouragement. We also thank KT Korista and JC Shields for helpful comments on this manuscript, and TA Barlow, N Arav and VT Junkkarinen for useful discussions. GF thanks the Canadian Institute for Theoretical Astrophysics for their hospitality during a sabbatical year, and acknowledges support from the Natural Science and Engineering Research Council of Canada through CITA. The work of FH was supported by NASA grant NAG 5-3234. Research in nebular astrophysics at the University of Kentucky is supported by the NSF through grant 96-17083 and by NASA through its ATP (award NAG 5-4235) and LTSA programs.
9. Literature Cited

Aldcroft TL, bechtold J, Elvis M. 1994, Ap. J. Suppl. 93, 1
Anderson SF, Weymann RJ, Foltz CB, Chaffee FH. 1987, Astron. J. 94, 278
Arav N. 1996, Ap. J. 465, 617
Arav N. 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 208
Arav N, Barlow TA, Laor A, Sargent WLW, Blandford RD. 1998, MNRAS 297, 990
Arav N, Korista KT, de Kool M, Junkkarinen VT, Begelman MC. 1999, Ap. J. in press (A99)
Aretxaga I, Terlevich RJ, Boyle BJ. 1998, MNRAS 296, 643
Arimoto N Yoshii Y. 1987, Astron. Astrophys. 173, 23
Artymowicz P, Lin DNC, Wampler EJ. 1993, Ap. J. 409, 592
Bahcall JN, Kirhakos S, Saxe DH, Schneider DP. 1997, Ap. J. 479, 642
Bahcall JN, Sargent WLW, Schmidt M. 1967, Ap. J. 149, L11
Baldwin JA. 1977a, MNRAS 178, 67P
Baldwin JA. 1977b, Ap. J. 214, 679
Baldwin JA, & Netzer H. 1978, Ap. J. 226, 1
Baldwin JA, Ferland GJ, Korista KT, Carswell RF, Hamann F, et al. 1996, Ap. J. 461, 664
Baldwin JA, Ferland GJ, Korista KT, Verner D. 1995, Ap. J. 455, L119
Barbuy B. 1988, Astron. Astrophys. 191, 121
Barger AA, Aragon-Salamanca A, Smail I, Ellis RS, Couch WJ, et al. 1998a, Ap. J. 501, 522
Barger AA, Cowie LL, Trentham N, Fulton E, Hu EM, et al. 1998b, preprint [astro-ph/9809299]
Barlow TA. 1993, Ph.D. Dissertation, University of California – San Diego
Barlow TA. 1998, private comm.
Barlow TA, Hamann F, Sargent WLW. 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 13
Barlow TA, Junkkarinen VT. 1994, BAAS, 26, 1339
Barlow TA, Junkkarinen VT, Burbidge EM, Weymann RJ, Morris SL, et al. 1992, Ap. J. 397, 81
Barlow TA, Sargent WLW. 1997, Astron. J. 113, 136
Barthel PD, Tytler DR, Vestergaard M. 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 48
Baugh CM, Cole S, Frenk CS, Lacey CG. 1998, Ap. J. 498, 504
Bender R, Burstein D, Faber SM. 1993, Ap. J. 411, 153
Bergeron J, Boissé P. 1986, Astron. Astrophys. 168, 6
Bergeron J, Kunth D. 1983, MNRAS 205, 1053
Bergeron J, Petitjean P, Sargent WLW, Bahcall JN, Boksenberg A, et al. 1994, Ap. J. 436, 33
Bergeron J Stasi´nska G. 1986, Astron. Astrophys. 169, 1
Bernardi M, Renzini A, da Costa LN, Wegner G, Victoria M, et al. 1998, preprint [astro-ph/9810066]
Bica E, Alloin D, Schmidt AA. 1990, Astron. Astrophys. 228, 23
Bica E, Arimoto N, Alloin D. 1988, Astron. Astrophys. 202, 8

Boyce PJ, Disney MJ, Bleaken DG. 1999, MNRAS 302, 39

Boyle B. 1990, MNRAS 243, 231

Boyle BJ, Terlevich RJ. 1998, MNRAS 293, 49

Branch D. 1998, Annu. Rev. Astron. Astrophys. 36, 17

Bressan A, Chiosi C, Tantalo R. 1996, Astron. Astrophys. 311, 425

Brotherton MS, Van Breugel W, Smith RJ, Boyle BJ, Shanks T. 1998b, Ap. J. 505, 7

Brotherton MS, Wills BJ, Dey A, Van Breugal W, Antonucci R. 1998a, Ap. J. 501, 110

Brunner H, Mueller C, Friedrich P, Doerrter T, Staubert R, et al. 1997, Astron. Astrophys. 326, 885

Bruzual G, Barbuy B, Ortolani S, Bica E, Cuisinier F. 1997, Astron. J. 114, 1531

Bruzual G, Magris G. 1997, in the STScI Symp on the Hubble Deep Field, (astro-ph/9707154)

Burbidge G, Burbidge M. 1967, in Quasi-Stellar Objects, WH Freeman and Co.

Burles S, Tytler D. 1996, Ap. J. 460, 584

Carroll SM, Press WH. 1992, Annu. Rev. Astron. Astrophys. 30, 499

Carballo R, Sanchez SF, Gonzalas-Serrano JI, Benn CR, Vigotti M. 1998, Astron. J. 115, 1234

Castro S, Rich RM, McWilliam A, Ho LC, Spinrad H, et al. 1996, Astron. J. 111, 2439

Cavaliere A, Vittorini V. 1998, in The Young Universe, eds. S D’Odorico, A Fontana, E Giallongo, ASP Conf. Ser., 146, 28

Chatzichristou ET, Vanderriest C, Jaffe W. 1999, Astron. Astrophys. 343, 407

Cohen MH, Ogle PM, Tran HD, Vermeulen RC, Miller JS, et al. 1995, Ap. J. 448, L77

Collin S. 1998, preprint

Connolly AA, Szalay AS, Dickenson M, SubbaRao MU, Brunnler RJ. 1997, Ap. J. 468, L11

Cozial R, Contini T, Davoust E, Considère S. 1997, Ap. J. 481, L67

Davidson K. 1977, Ap. J. 218, 20

Davidson K, Netzer H. 1979, Rev. Mod. Phys., 51, 715, (DN79).

de Freitas Pacheco JA. 1996, MNRAS 278, 841

Dey A, Spinrad H, Stern D, Graham JR, Chaffee FH. 1998, Ap. J. 498, L93

Djorgovski SG. 1998, in Fundamental Parameters of Cosmology, ed. Y Giroud-Héraud, (Gif sur Yvette:Editions Frontières), in press

Edmunds MG. 1992, in Elements and the Cosmos, eds. MG Edmunds, R Terlevich, (Cambridge Univ. Press:New York), p.289

Ellis R, Smail I, Dressler A, Couch WJ, Oemler WJ, et al. 1997, Ap. J. 483, 582

Faber SM. 1973, Ap. J. 179, 423

Faber SM, Wegner G, Burstein D, Davies RL, Dressler A, et al. 1989, Ap. J. Suppl. 69, 763

Feltzing S, Gilmore G. 1998, in Galaxy Evolution: Connecting the Distant Universe with the Local Fossil Record, p. 71

Ferland GJ. 1999, in Quasars as Standard Candles for Cosmology, eds. J Baldwin, GJ Ferland, KT Korista, in press

Ferland GJ, Baldwin JA, Korista KT, Hamann F, Carswell RF, et al. 1996, Ap. J. 461, 683

Ferland GJ, Korista KT, Verner DA, Ferguson JW, Kingdon JB, et al. 1998, PASP 110,
Ferland GJ, Persson SE. 1989, *Ap. J.* 347, 656
Ferland GJ, Peterson BM, Horne K, Welsch WF, Nahar SN. 1992, *Ap. J.* 387, 95
Ferland GJ, Shields GA. 1985, in Astrophysics of Active Galaxies and Quasi-Stellar Objects, ed. JS Miller, Univ. Sci. Books, p. 157
Fisher D, Franx M, Illingworth G. 1995, *Ap. J.* 448, 119
Foltz CB, Chaffee F, Weymann RJ, Anderson SF. 1988, in QSO Absorption Lines: Probing the Universe, eds. JC Blades, DA Turnshek, CA Norman (Cambridge: Cambridge Univ Press), p. 53
Foltz CB, Weymann RJ, Peterson BM, Sun L, Malkan MA, *et al.* 1986, *Ap. J.* 307, 504
Franceschini A, Gratton R. 1997, *MNRAS* 286, 235
Francis PJ, Koratkar A. 1995, *MNRAS* 274, 504
Franx M, Illingworth GD. 1990, *Ap. J.* 359, L41
Franx M, Illingworth GD, Kelson DD, Van Dokkum PG, Tran K. 1997, *Ap. J.* 486, 75
Friaca ACS, Terlevich RJ. 1998, *MNRAS* 298, 399
Friaca ACS, Terlevich RJ. 1999, *MNRAS* in press
Frisch H. 1984, in Methods in Radiative Transfer, ed. W Kalkofen (Cambridge: Cambridge Univ. Press), 65
Gallagher SC, Brandt WN, Sambruna RM, Mathur S, Yamasaki N. 1999, *Ap. J.* in press
Ganguly R, Eracleous M, Charlton JC, Churchill CW. 1999, *Astron. J.* in press
Garnett DR. 1990, *Ap. J.* 363, 142
Gaskell CM, Shields GA, and Wampler EJ. 1981, *Ap. J.* 249, 443
Geisler D, Friel DE. 1992, *Astron. J.* 104, 128
Giavalisco M, Steidel CC, Macchetto FD. 1996, *Ap. J.* 470, 189
Gnedin NY, Ostriker JP. 1997, *Ap. J.* 486, 581
Goodrich RW, Miller JS. 1995, *Ap. J.* 448, L73
Gorgas J, Efstanthiou G, Aragón Salamanca AA. 1990, *MNRAS* 245, 217
Grandi SA. 1981, *Ap. J.* 251, 451
Gratton RG. 1991, in Evolution of Stars: The Photospheric Abundance Connection, eds. G. Michaud, AV Tutukov, IAU Symp. 145, (Montreal:Univ. Montreal), 27
Green PJ, Aldcroft TL, Mathur S, Shartel N. 1997, *Ap. J.* 484, 135
Green PJ, Mathur S. 1996, *Ap. J.* 462, 637
Greggio L, and Renzini A. 1983 *Astron. Astrophys.* 118, 217
Grevesse N, Anders E. 1989, in Cosmic Abundances of Matter, AIP Conf. Proc. 183, ed. CI Waddington (New York:AIP), 1
Grillmair CJ, Turnshek DA. 1987, in QSO Absorption Lines: Probing the Universe, Poster Papers, eds. JC Blades, C Norman, DA Turnshek, p. 1
Guilloteau S, Omont A, McMahon RG, Cox P, Petitjean P. 1997, *Astron. Astrophys.* 328, L1
Haas M, Chini R, Maisenheimer K, Stickel M, Lemke D, *et al.* 1998, *Ap. J.* 503, L109
Haehnelt MG, Natarajan P, Rees MJ. 1998, *MNRAS* 300, 817
Haehnelt MG, Rees MJ. 1993, *MNRAS* 263, 168
Haiman Z, Loeb A. 1998, *Ap. J.* 503, 505
Hamann F. 1997, *Ap. J. Suppl.* 109, 279 (H97)
Hamann F. 1998, *Ap. J.* 500, 798
Hamann F, Barlow TA, Beaver EA, Burbidge EM, Cohen RD, et al. 1995, Ap. J. 443, 606
Hamann F, Barlow TA, Junkkarinen V. 1997c, Ap. J. 478, 87
Hamann F, Barlow TA, Cohen RD, Junkkarinen V, Burbidge EM. 1997b, Ap. J. 478, 80 (H97b)
Hamann F, Barlow TA, Cohen RD, Junkkarinen V, Burbidge EM. 1997e, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 187
Hamann F, Beaver EA, Cohen RD, Junkkarinen V, Lyons RW, et al. 1997d, Ap. J. 488, 155
Hamann F, Chaffee R, Weymann RJ, Barlow TA, Junkkarinen VT. 1999b, in prep.
Hamann F, Cohen RD, Shields JC, Burbidge EM, Junkkarinen VT, et al. 1998, ApJ, 496, 761
Hamann F, Ferland GJ. 1992, ApJL, 391, L53
Hamann F, Ferland GJ. 1993a, Rev. Mex. Astr. Astrof., 26, 53
Hamann F, Ferland GJ. 1993b, Ap. J. 418, 11, (HF93b)
Hamann F, Korista KT. 1996, Ap. J. 464, 158
Hamann F, Korista KT, Ferland GJ. 1999a, in prep.
Hamann F, Korista KT, Morris SL. 1993, Ap. J. 415, 541
Hamann F, Shields JC, Cohen RD, Junkkarinen VT, Burbidge EM. 1997a, in Emission Lines From Active Galaxies: New Methods and Techniques, IAU Col. 159, eds. BM Peterson, F-Z Cheng, AS Wilson, ASP Conf. Ser., 113, 96
Hartquist TW, Snijders MAJ. 1982, Nature, 299, 783
Heap SR, Brown TM, Hubeny I, Landsman W, Yi S, et al. 1998, Ap. J. 492, L131
Hines DC, Low FJ, Thompson RI, Weymann RJ, Storrie-Lombardi LJ. 1999, Ap. J. 512, 140
Hines DC, Wills BJ. 1995, Ap. J. 448, L69
Hu EM, Cowie LL, McMahon RG. 1998, Ap. J. 502, L99
Idiart TP, De Freitas Pacheco JA, Costa RDD. 1996, Astron. J. 112, 2541
Isaac KG, McMahon RG, Hills RE, Withington S. 1994, MNRAS 269, 28
Isotov YI, Thuan TX. 1999, Ap. J. in press
Israelian G, López RJG, Rebolo R. 1998, Ap. J. 507, 805
Ivison RJ, Dunlop JS, Hughes DH, Archibald EN, Stevens JA, et al. 1998, Ap. J. 494, 211
Jablonska P, Alloin D, Bica E. 1992, Astron. Astrophys. 260, 97
Jablonska P, Martin P, Arimoto N. 1996, Astron. J. 112, 1415
Johansson S, Jordan C. 1984, MNRAS 210, 239
Jenkins EB. 1996, Ap. J. 471, 292
Jin L, Arnett WD, Chakrabarti SK. 1989, Ap. J. 336, 572
Junkkarinen VT. 1980, Ph.D. Dissertation, University of California – San Diego
Junkkarinen VT. 1998, private comm.
Junkkarinen VT, Beaver EA, Burbidge EM, Cohen RC, Hamann F, et al. 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 220
Junkkarinen VT, Burbidge EM, Smith HE. 1983, Ap. J. 265, 51
Junkkarinen VT, Burbidge EM, Smith HE. 1987, Ap. J. 317, 460
Katz N, Quinn T, Bertchinger E, Gelb JM. 1994, MNRAS 270, L71
Kauffmann G. 1996, MNRAS 281, 487
King JR. 1993, *Astron. J.* 106, 1206
Kinney AL, Rivolo AR, Koratkar AR. 1990, *Ap. J.* 357, 338
Kirkman D, Tytler D. 1997, *Ap. J.* 489, L123
Kobulnicky HA, Skillman ED. 1998, *Ap. J.* 497, 601
Kodama T, Arimoto N. 1997, *Astron. Astrophys.* 320, 41
Köppen J, Arimoto N. 1990, *Astron. Astrophys.* 240, 22
Korista KT, Alloin D, Barr P, Clavel J, Cohen RD, *et al.* 1995, *Ap. J. Suppl.* 97, 285
Korista KT, Baldwin JA, Ferland GJ. 1998, *Ap. J.* 507, 24
Korista KT, Baldwin JA, Ferland GJ, Verner D. 1997b, *Ap. J. Suppl.* 108, 401
Korista KT, Ferland GJ, Baldwin BA. 1997a, *Ap. J.* 487, 555
Korista KT, Hamann F, Ferguson J, Ferland GJ. 1996, *Ap. J.* 461, 641
Korista KT, Voit GM, Morris SL, Weymann RJ. 1993, *Ap. J. Suppl.* 88, 357
Korista KT, Weymann RJ, Morris SL, Kopko M, Turnshek DA, *et al.* 1992, *Ap. J.* 401, 529
Kormendy J, Bender R, Evans AS, Richstone D. 1998, *Astron. J.* 115, 1823
Krolik J, Voit GM. 1998, *Ap. J.* 497, L5
Kundt W. 1996, *Astrophys. Sp. Sci.* 235, 319
Kundtschner H, Davies RL. 1997, *MNRAS* 295, L29
Kwan J. 1990, *Ap. J.* 353, 123
Kwan J, Krolik J. 1981, *Ap. J.* 250, 478, (KK81)
Laor A. 1998, in *Quasars as Standard Candles for Cosmology*, eds. J Baldwin, GJ Ferland, KT Korista, in press
Laor A, Bahcall JN, Jannuzi BT, Schneider DP, Green RF. 1995, *Ap. J. Suppl.* 99, 1
Laor A, Jannuzi BT, Green RF, Boroson TA. 1997, *Ap. J.* 489, 656
Larson RJ. 1974, *MNRAS* 169, 229
Loeb A. 1993, *Ap. J.* 404, L37
Loeb A, Rasio FA. 1994, *Ap. J.* 432, 52
Lowenthal JD, Koo DC, Guzman R, Gallego J, Phillips AC. 1997, *Ap. J.* 481, 673
Lu L, Sargent WLW, Barlow TA. 1998, *Astron. J.* 115, 55
Lu L, Sargent WLW, Barlow TA, Churchill CW, Vogt SS. 1996, *Ap. J. Suppl.* 107, 475
Lu L, Savage BD. 1993, *Ap. J.* 403, 127
Madau P, Ferguson HC, Dickenson ME, Giavalisco M, Steidel CC, *et al.* 1996, *MNRAS* 283, 1388
Magain P. 1989, *Astron. Astrophys.* 209, 211
Magorrian J, Tremaine S, Richstone D, Bender R, Bower G, *et al.* 1998, *Astron. J.* 115, 2285
Mathews WG, Capriotti ER. 1985, in *Astrophysics of Active Galaxies and Quasi-Stellar Objects*, ed. JS Miller, Univ. Sci. Books, p. 183
Matteucci F. 1994, *Astron. Astrophys.* 288, 57
Matteucci F, Brocato E. 1990, *Ap. J.* 365, 539
Matteucci F, Francois P. 1989, *MNRAS* 239, 885
Matteucci F, Greggio L. 1986, *Astron. Astrophys.* 154, 279
Matteucci F, Tornambè A. 1987. *Astron. Astrophys.* 185, 51
McCarthy PJ. 1993, *Annu. Rev. Astron. Astrophys.* 31, 639
McLeod KK, Rieke GH. 1995, *Ap. J.* 454, L77
McLeod KK, Rieke GH, Storrie-Lombardi L.J. 1999, Ap. J. 511, L67
McLure RJ, Dunlop JS, Kukula MJ, Baum SA, O'Dea CP, et al. 1998, preprint astro-ph/9809030
McWilliam A, Rich RM. 1994, Ap. J. Suppl. 91, 749
Mihalas D. 1978, Stellar Atmospheres, WH Freeman & Co., (San Francisco:Univ. Chicago Press)
Miller J, Tran H, Sheinis A. 1996, BAAS, 28, 1031
Minniti D, Olszewski EW, Liebert J, White SD, Hill JM, et al. 1995, MNRAS 277, 1293
Miralda-Escudé J, Rees MJ. 1997, Ap. J. 478, L57
Möller P, Jakobsen P, Perryman MAC. 1994, Astron. Astrophys. 287, 719
Morris SL, Weymann RJ, Foltz CB, Turnshek DA, Sheetman S, et al. 1986, Ap. J. 310, 40
Murray N, Chiang J, Grossman SA, Voit GM. 1995, Ap. J. 451, 498
Mushotzky RF, Loewenstein M. 1997, Ap. J. 481, L63
Netzer H. 1990, in Active Galactic Nuclei, eds. RD Blandford, H Netzer, L Waltjer, (Berlin:Springer), 57
Netzer H, Brotherton MS, Wills BJ, Han M, Baldwin JA, et al. 1995, 448, 27
Netzer H, Wills BJ. 1983, Ap. J. 275, 445
Nissen PE, Gustafsson B, Edvardsson B, Gilmore G. 1994, Astron. Astrophys. 285, 440
Omont A, Petitjean P, Guilloteau S, McMahon RG, Solomon PM. 1996, Nature, 382, 428
Ortolanı S, Renzini A, Gilmozzi R, Marconi G, Barbuy B, et al. 1996, in Formation of the Galactic Halo...Inside and Out, Eds. II Morrison, A Sarajedini, ASP Conf. Ser., 92, 96
Osmer PS. 1980, Ap. J. 237, 666
Osmer PS. 1998, in The Young Universe, eds. S D’Odorico, A Fontana, E Giallongo, ASP Conf. Ser., 146, 1
Osmer PS, Porter AC, Green RF. 1994, Ap. J. 436, 678
Osmer PS, Shields, JC. 1999, in Quasars as Standard Candles for Cosmology, eds. J Baldwin, GJ Ferland, KT Korista, in press
Osmer PS, Smith MG. 1976, Ap. J. 210, 276
Osmer PS, Smith MG. 1977, Ap. J. 213, 607
Osterbrock DE. 1977, Ap. J. 215, 733
Osterbrock DE. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, University Science Press
Peimbert M. 1967, Ap. J. 150, 825
Penston M. 1987, MNRAS 229, 1P
Peterson BM. 1993, PASP 105, 1084
Petitjean P, Rauch M, Carswell RF. 1994, Astron. Astrophys. 291, 29
Petitjean P, Srianand R. 1999, Astron. Astrophys. in press
Pettini M, King DL, Smith LJ, Hunstead RW. 1997, Ap. J. 486, 665
Phillips MM. 1977, Ap. J. 215, 746
Phillips MM. 1978, Ap. J. 226, 736
Prochaska JX, Wolfe AM. 1998, Ap. J. 507, 113
Prochaska JX, Wolfe AM. 1999, Ap. J. in press
Rauch M. 1998, Annu. Rev. Astron. Astrophys. 36, 267
Rauch M, Haehnelt MG, Steinmetz M. 1997, Ap. J. 481, 601
Renzini A. 1997, *Ap. J.* 488, 35
Renzini A. 1998, in The Young Universe, eds. S D’Odorico, A Fontana, E Giallongo, ASP Conf. Ser., 146, 298
Rich RM. 1988, *Astron. J.* 95, 828
Rich RM. 1990, *Ap. J.* 362, 604
Richards GT, York DG, Yanny B, Kollgaard RI, Laurent-Muehleisen SA, et al. 1999, *Ap. J.* in press
Saikia D, Kulkarni AR. 1998, *MNRAS* 298, L45
Sansom AE, Proctor RN. 1998, *MNRAS* 297, 953
Savage BD, Sembach KR. 1991, *Ap. J.* 379, 245
Savage BD, Tripp TM, Lu L. 1998, *Astron. J.* 115, 436
Savaglio S, Cristiani S, D’Odorico S, Fontana A, Giallong E, et al. 1997, *Astron. Astrophys.* 318, 347
Savaglio S, D’Odorico S, Mö ller P. 1994, *Astron. Astrophys.* 281, 331
Scalo JM. 1990, in Windows on Galaxies, eds. G Fabbiano, JS Gallagher, A Renzini, (Dordrecht:Kluwer Academic Publishers) p. 125
Schmidt GD, Hines DC. 1999, *Ap. J.* in press
Schneider DP. 1998, in Science with NGST, eds. EP Smith, A Koratkar, ASP Conf. Ser., 133, 106
Schneider DP, Schmidt M, and Gunn JE. 1991, *Astron. J.* 102, 837
Searle L, Zinn R. 1978, *Ap. J.* 225, 357
Shaver PA, Hook IM, Jackson CA, Wall JV, Kellerman KI. 1998, in Highly redshifted Radio Lines, eds. C Carilli, S Radford, K Menton, G. Langston, (PASP:San Francisco), in press
Shields GA. 1976, *Ap. J.* 204, 330
Shields GA. 1996, *Ap. J.* 461, L9
Shields JC, Ferland GJ, Peterson, BM. 1995, *Ap. J.* 441, 507
Shields JC, Hamann F, Foltz CB, Chaffee FH. 1997, in Emission Lines in Active Galaxies, eds. BM Peterson, F-Z Cheng, ASP Conf. Ser., 113, 118
Shklovskii IS. 1965, Sov. Astr., 8, 635
Sigut TAA, Pradhan AK. 1998, *Ap. J.* 499, L139
Sil’chenko OK, Burenkov AN, Vlasyuk VV. 1998, *Astron. Astrophys.* 337, 349
Silk J, Rees MJ. 1998, *Astron. Astrophys.* 331, L1
Songalia A, Cowie LL. 1996, *Astron. J.* 112, 335
Spaans M, Corollo CM. 1997, *Ap. J.* 482, L93
Spinrad H, Dey A, Stern D, Dunlop J, Peacock J, et al. 1997, *Ap. J.* 484, 581
Srianand R, Shankaranarayanan S. 1999, *Ap. J.* in press
Stanford SA, Eisenhardt PR, Dickenson M. 1998, *Ap. J.* 492, 461
Steidel CC, Adelberger KL, Dickenson M, Giavalisco M, Pettini M, et al. 1998, *Ap. J.* 492, 428
Steidel CC, Adelberger KL, Giavalisco M, Dickenson M, Pettini M. 1999, *Ap. J.* in press
Taniguchi Y, Arimoto N, Murayama T, Evans AS, Sanders DB, et al. 1997, in Quasar Hosts, eds. DL Clements, I Perez-Fournon, ESO-IAC Conf. Pro., p. 127
Taniguchi Y, Ikeuchi S, Shioya Y. 1999, *Ap. J.* 514, L12
Tantalo R, Chiosi C, Bressan A. 1998, *Astron. Astrophys.* 333, 419
Telfer RC, Kriss GA, Zheng W, Davidsen AF, Green RF. 1999, Ap. J. in press
Terndrup DM, Sadler EM, Rich RR. 1995, Astron. J. 110, 1774
Terlevich RJ, Boyle BJ. 1993, MNRAS 262, 491
Thomas D, Greggio L, & Bender R. 1998, MNRAS in press
Thompson KL, Hill GJ, Elston R. 1999, Ap. J. in press
Thuan TX, Izotov YI, Lipovetsky VA. 1995, Ap. J. 445, 108
Thurston TR, Edmunds MG, Henry RB. 1996, MNRAS 283, 990
Tiede GP, Frodl JA, Terndrup DM. 1995, Astron. J. 110, 2788
Tinsley B. 1979, Ap. J. 229, 1046
Tinsley B. 1980, Fund. of Cosmic Phys., 5, 287
Trager SC, Faber SM, Dressler A, Oemler A. 1997, Ap. J. 485, 92
Tripp TM, Lu L, Savage BD. 1996, Ap. J. Suppl. 102, 239
Tripp TM, Lu L, Savage BD. 1997, Ap. J. Suppl. 112, 1
T"urler M, Courvoisier TJ-L. 1997, Astron. Astrophys. 329, 863
Turner EL. 1991, Astron. J. 101, 5
Turnshek DA. 1981, Ph.D. Dissertation, University of Arizona
Turnshek DA. 1984, 280, 51
Turnshek DA. 1986, in Quasars, eds. G. Swarup, VK Kapahi, IAU Symp. No. 119, (Dordrecht: Reidel), p. 317
Turnshek DA, Briggs FH, Foltz CB, Grillmair CJ, Weymann RJ. 1987, in QSO Absorption Lines: Probing the Universe, Poster Papers, eds. JC Blades, C Norman, DA Turnshek, p. 1
Turnshek DA. 1988, in QSO Absorption Lines: Probing the Universe, eds. JC Blades, C Norman, DA Turnshek, (Cambridge: Cambridge Univ Press), p. 17
Turnshek DA. 1994, in QSO Asborption Lines, ed. G Meylan, (Springer-Verlag), p. 223
Turnshek DA. 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 193
Turnshek DA, Kopko M, Monier E, Noll D, Espey B, et al. 1996, Ap. J. 463, 110
Turnshek DA, Monier EM, Christopher JS, Espey BR. 1997, Ap. J. 476, 40
Tytler D, Fan XM, Burles S, Cottrell L, Davis C, et al. 1995, in QSO Absorption Lines, ed. G Meylan, (Garching:ESO), 289
Uomoto A. 1984, ApJ 284, 497
Van Dokkum PG, Franx M, Kelso DD, Illingworth GD. 1998, Ap. J. 504, L17
Van Zee L, Skillman ED, Salzer JJ. 1998, Ap. J. 497, L1
Vazdekis A, Peletier RF, Beckman JE, Casuso E. 1997, Ap. J. Suppl. 111, 203
Verner EM, Verner DA, Korista KT, Ferguson JW, Hamann F, et al. 1999, Ap. J. in press
Vila-Costas MB, Edmunds MG. 1993, MNRAS 265, 199
Voit GM, 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav, ASP Conf. Series, 128, 200
Voit GM, Weymann RJ, Korista KT. 1993, ApJ 413, 95
Wampler EJ, Bergeron J, Petitjean P. 1993, Astron. Astrophys. 273, 15
Wampler EJ, Chugai NN, Petitjean P. 1995, Ap. J. 443, 586
Warren SJ, Hewett PC, Osmer PS. 1994, Ap. J. 421, 412
Weymann RJ. 1994, in QSO Asborption Lines, ed. G Meylan, (Springer-Verlag), p. 213
Weymann RJ. 1997, in Mass Ejection From AGN, eds. R Weymann, I Shlosman, N Arav,
Weymann RJ, Foltz C. 1983, in Quasars and Gravitational Lenses, 24th Liege Int. Astronomy Coll., (Univ. de Liege:Belgium), p. 538

Weymann RJ, Turnshek DA, Christiansen WA. 1985, in Astrophysics of Active Galaxies and Quasi-Stellar Objects, ed. J Miller, (Mill Valley, CA: University Science Books), 185

Weymann RJ, Morris SL, Foltz CB, Hewett PC. 1991, Ap. J. 373, 23

Weymann RJ, Carswell RF, Smith MGA. 1981, Annu. Rev. Astron. Astrophys. 19, 41

Weymann RJ, Stern D, Bunker A, Spinrad H, Chaffee FH, et al. 1998, Ap. J. 505, L95

Weymann RJ, Williams RE, Peterson BM, Turnshek DA. 1979, Ap. J. 218, 619

Wheeler JC, Sneden C, Truran JW. 1989, Annu. Rev. Astron. Astrophys. 27, 279

Williams RE. 1971, Ap. J. 167, L27

Williams RE, Strittmatter PA, Carswell RF, Craine ER. 1975, Ap. J. 202, 296

Williams RE, Weymann RJ. 1976, Ap. J. 207, L143

Will BJ, Netzer H. 1983, Ap. J. 275, 445

Wills BJ, Netzer H, and Wills D. 1985, Ap. J. 288, 94

Wills BJ, Thompson KL, Han M, Netzer H, Wills D, et al. 1995, Ap. J. 447, 139

Worthey G, Faber SM, Gonzalez J. 1992, Ap. J. 398, 69

Yoshii Y, Tsujimoto T, Kawara K. 1998, Ap. J. 507, L113

Yoshii Y, Tsujimoto T, Nomoto K. 1996, Ap. J. 462, 266

Young P, Sargent WLW, and Boksenberg A. 1982, Ap. J. Suppl. 48, 455

Zaritsky D, Kennicutt RC, Huchra JP. 1994, Ap. J. 420, 87

Zheng W, Kriss GA, Davidsen AF. 1995, Ap. J. 440, 606

Zheng W, Kriss GA, Telfer RC, Grimes JP, Davidsen AF. 1997, Ap. J. 475, 469

Ziegler BL, Bender R. 1997, MNRAS 291, 527
Fig 3

Fig 4
Fig 5

Fig 6
