Elemental Abundances from Intrinsic QSO Emission and Absorption Lines

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Abstract. Several studies have shown that the column densities inferred from broad absorption lines (BALs) require extremely high metallicities and phosphorus overabundances – apparently in conflict with other abundance diagnostics. Here I use HST spectroscopy of the BALQSO PG 1254+047 to argue that the BALs abundance estimates are incorrect, because partial line-of-sight coverage of the continuum source(s) has led to gross underestimates of the line optical depths and column densities. I claim that the significant presence of P V λ1118,1128 absorption in this and other BALQSOs identifies the saturated absorption-line spectrum. This interpretation implies that the total column densities are at least ten times larger than previous estimates, namely log \( N_H (\text{cm}^{-2}) \) \( \gtrsim 22.0 \). The outflowing BAL gas, at velocities from \(-15,000\) to \(-27,000\) km s\(^{-1}\) in PG 1254+047, is therefore a strong candidate for the X-ray absorber in BALQSOs. If this high-column density outflow is radiately accelerated, it must originate \( \lesssim 0.1 \) pc from the QSO.

1. Introduction

Measurements of the elemental abundances in QSOs are important for understanding the physics and observable properties of the various emission/absorption regions. They can also provide valuable constrains on the extent and epoch of star formation in galactic nuclei. These constraints could be important complements to other studies of high-redshift galaxies (involving, for example, the “Lyman-break” galaxies or damped-Ly\( \alpha \) absorbers) that probe more extended structures and/or rely on very different data and techniques.

Three general, independent probes of QSO abundances are readily observable at all redshifts: the broad emission lines (BELs), the broad absorption lines (BALs) and the narrow associated (intrinsic) absorption lines (AALs). Each of these probes has its own theoretical and observational uncertainties, some of which might be unknown. It is therefore essential to consider as many abundance diagnostics as possible. I am now involved in several projects to examine a wide range of emission and absorption diagnostics in QSOs at different redshifts and luminosities. My principle collaborators are Drs. T. Barlow, F. Chaffee, G. Ferland, C. Foltz, V. Junkkarinen, K. Korista and J. Shields.

The most recent work on BEL abundances, based on the NV/HeII and NV/CIV line ratios (Hamann & Ferland 1992, 1993, Ferland et al. 1996), indi-
cates that the metallicities are typically solar or higher and nitrogen is selectively enhanced. There is also a significant trend in these line ratios suggesting higher metallicities in more luminous QSOs (see also Osmer et al. 1994 and Korista et al. 1998). Recent AAL studies based on high-resolution spectroscopy are in general agreement with the BELs, indicating typical metallicities from $\sim 1/2$ to a few times solar (see Petitjean et al. 1994, Hamann 1997, Tripp et al. 1996, 1997 and refs. therein).

The most surprising abundance results have come from studies of the BALs, where the strengths of the metal-lines compared to HI Ly$\alpha$ seem to require metallicities (for example Si/H) from 20 to $>100$ times solar (Turnshek et al. 1996; Hamann 1997). The secure detection of broad PV $\lambda\lambda 1118,1128$ absorption in one BALQSO, PG 0946+301 (Junkkarinen et al. 1997), and tentative detections in two others (Turnshek 1988; Korista et al. 1992), suggest further that phosphorus is highly overabundant, with P/C $> 60$ and P/H $>1000$ times solar (see also Hamann 1997). These abundances, particularly the high P/C, are not only in conflict with the other diagnostics but they are also incompatible with any enrichment scheme dominated by Types I or II supernovae or CNO-processed material from stellar envelopes. One possible explanation, suggested by Shields (1996), is that the BAL gas is selectively enriched by novae. Another possibility is that the BAL abundance estimates are incorrect. In this contribution I argue for the latter; the PV line has significant strength not because phosphorus is overabundant but because the stronger transitions are more optically thick than they appear. The true BAL abundances are unknown.

2. General Absorption Line Analysis

Absorption lines are, in principle, better abundance probes than the emission lines because their strengths relate directly to the ionic column densities along our line-of-sight. The abundance ratios for any two elements $a$ and $b$ simply scale with the column densities,

$$\left[ \frac{a}{b} \right] = \log \left( \frac{N(a)}{N(b)} \right) + \log \left( \frac{f(b)}{f(a)} \right) + \log \left( \frac{b}{a} \right) \odot$$

where $(b/a)\odot$ is the solar abundance ratio, and $N$ and $f$ are respectively the column densities and ionization fractions of elements $a$ and $b$ in ion stages $i$ and $j$. The corrections factors, $f(b)/f(a)$, are often uncertain because they depend on the poorly known ionization state of the absorber. Hamann (1997) calculated ionization fractions and correction factors for a wide range of one-zone absorbers in photoionization equilibrium with the QSO spectrum. Those calculations showed that the correction factors needed to derive metal-to-hydrogen abundance ratios, [M/H], from the column densities in HI and a metal ion $M_i$ have well-defined minima (at some particular level of ionization). Therefore, even if the absorber is complex and the ionization state(s) is(are) unknown, we can still use the minimum correction factors to place firm lower limits on the [M/H] ratios (see Hamann 1997 for details). The correction factors for some metal-to-metal abundance ratios also have well defined limits that provide further robust constraints. One example is the correction factor $f(CIV)/f(PV)$, whose minimum value provides lower limits on [P/C].
3. PV and the Problem with BAL Abundance Estimates

Hamann (1998) recently examined the ionization, column densities and metal abundances in the BALQSO PG 1254+047. The BAL troughs in this object are detached, with velocities ranging from $-15,000$ to $-27,000$ km s$^{-1}$, but the spectrum (Fig. 1) appears in every other way typical of BALQSOs (cf. Weymann et al. 1991). Like most optically selected BALQSOs, this object has strong BALs in high-ionization species such as CIV, NV and OVI without absorption in MgII and other low-ionization lines. What makes this source particularly useful is its moderate redshift ($z_{\text{em}} \approx 1.01$), which allows us to measure the BALs at $\lambda \lesssim 1200$ Å in a relatively sparse “Ly$\alpha$ forest.” For example, broad absorption in the PV $\lambda\lambda 1118,1128$ doublet is unambiguously detected at the same outflow velocities as the stronger BALs (Fig. 1; see Hamann 1998 for a full discussion of the line identifications). The rarity of previous PV detections is probably due to the observational difficulties – namely, complex line blending or low signal-to-noise ratios across the PV wavelengths. (To my knowledge, there are no existing spectra of BALQSOs that can rule out PV absorption at a strength comparable to PG 1254+047.) Significant PV absorption might therefore be common in BALQSOs.

![Figure 1](image-url)  
*Figure 1. HST spectrum of the BALQSO, PG 1254+047. The Flux has units $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The emission lines are labeled at $z_{\text{em}} = 1.010$ across the top. The BALs are labeled at 3 redshifts corresponding to the 3 deepest minima in the CIV trough. The smooth dotted curve is a simple power-law fit to the continuum.*

Significant PV absorption is, in any case, surprising because phosphorus is nominally a rare element; in the sun the P/C abundance is $\sim 0.001$ while P/O is $\sim 0.0004$. Hamann (1998) used the analysis outlined in §2 to derive specific abundance constraints for PG 1254+047. A critical assumption in that analysis is that the measured BAL troughs accurately represent the run of optical depth.
versus velocity for each ion. With that assumption, the column densities follow by simple integration of the optical depth profiles. These column densities, combined with the minimum ionizations corrections (from Hamann 1997), imply extreme abundances, $[\text{C}/\text{H}] \gtrsim 1.0$, $[\text{Si}/\text{H}] \gtrsim 1.8$ and $[\text{P}/\text{C}] \gtrsim 2.2$.

However, Hamann (1998) argued that the PV BAL has a significant strength not because phosphorus is overabundant, but because the strong transitions like CIV, NV and OVI are much more optically thick than they appear. Explicit calculations of the line optical depths assuming solar relative abundances show that PV is the first weak line to appear as the stronger transitions become more saturated. The strength of the PV BAL in PG 1254+047 implies optical depths of, for example, $\gtrsim 6$ in Ly$\alpha$, $\gtrsim 25$ in CIV and $\gtrsim 80$ in OVI for solar relative abundances. These results indicate that the column densities derived from the measured troughs are gross underestimates and, consequently, the true abundances are unknown.

BALs like CIV, OVI and Ly$\alpha$ might be optically thick while not reaching zero intensity if the absorber covers just part of the continuum source(s). Furthermore, different optically thick lines can have different strengths and profiles if their coverage fractions differ. Note that coverage fraction differences between BALs (that mimic simple optical depth or ionization effects in observed spectra) can occur naturally if the absorbing regions have a range of ionization states or column densities. There is already direct evidence for partial coverage, and sometimes different coverage fractions in different lines, from the resolved multiplet ratios in the narrow components of some BALs (Barlow & Junkkarinen 1994, Wampler et al. 1995) and AALs (Barlow & Sargent 1997; Hamann et al. 1997; Hamann 1997 and refs. therein). Partial coverage has also been inferred from spectropolarimetry of BALQSOs (Cohen et al. 1995, Goodrich et al. 1995, Hines & Wills 1995). We cannot measure the coverage fractions from multiplet ratios in most BALs, but I claim that the PV line signifies partial coverage and large line optical depths. Strong support for this interpretation comes from the only known AAL system with PV absorption, where the resolved doublets clearly indicate large optical depths and partial coverage in lines such as CIV, NV and SiIV (Barlow et al. 1998).

4. Further Consequences of BAL Saturation

The calculations by Hamann (1998) also show that the PV BAL in PG 1254+047 requires a minimum total column density (in HI+HII) of $\log N_{\text{H}}(\text{cm}^{-2}) \gtrsim 22.0$ if the metallicity is roughly solar. The actual column density depends on the unknown ionization state (higher ionizations require larger total columns for a given PV absorption strength). Figure 2 shows the ranges of HI and total column densities consistent with the PG 1254+047 observations for photoionized clouds with different ionization parameters ($U \equiv$ the dimensionless ratio of hydrogen-ionizing photon to hydrogen particle densities at the illuminated face of the clouds). At each $U$, the column densities are bounded below by the minimum optical depth of $\tau \gtrsim 0.2$ in PV and above by the maximum optical depths in undetected low-ionization lines like MgII and AlIII (see Hamann 1998).

The total column densities implied by Figure 2 are at least an order of magnitude larger than previous estimates from the BALs, but they are con-
sistent with the large absorbing columns derived from X-ray observations of BALQSOs (Mathur et al. 1995; Green & Mathur 1996). In particular, an X-ray absorber with log $N_{\text{H}}(\text{cm}^{-2}) \sim 23$ could produce the observed BAL spectrum if $+0.4 \lesssim \log U \lesssim +0.7$ in a simple one-zone medium. The outflowing BAL gas, at velocities from $-15,000$ to $-27,000$ km s$^{-1}$ in PG 1254+047, is therefore a strong candidate for the X-ray absorber in BALQSOs.

![Figure 2. Theoretical limits on $N_{\text{H}}$ (solid curves, left-hand scale) and $N_{\text{HI}}$ (dashed curves, right-hand scale) in the BAL region of PG 1254+047 for different ionization parameters, $U$, in photoionized clouds with solar abundances. The permitted values of $N_{\text{H}}$ and $N_{\text{HI}}$ lie between the two pairs of curves for $\log U \gtrsim -0.6$, as indicated by the arrows.]

While resolving an apparent discrepancy between the UV and X-ray data, higher column densities in the BAL region might cause serious problems for radiative acceleration. The terminal velocity of a radiatively driven BAL wind can be expressed as follows,

$$v_\infty \approx 32000 R_{0.1}^{\frac{1}{2}} \left( \frac{f_L L_{46}}{N_{22}} - 0.008 M_8 \right)^{\frac{1}{2}} \text{ km s}^{-1}$$  

(2)

where $R_{0.1}$ is the inner wind radius in units of 0.1 pc, $L_{46}$ is the QSO luminosity in units of $10^{46}$ ergs s$^{-1}$, $N_{22}$ is the total column density in $10^{22}$ cm$^{-2}$, $M_8$ is the central black hole mass relative to $10^8 M_\odot$, and $f_L$ is the fraction of the spectral energy distribution absorbed or scattered in the wind. $L_{46} \sim 1$ is the Eddington luminosity for $M_8 = 1$, and $R_{0.1} \sim 1$ is a nominal BEL region radius for $L_{46} = 1$ (cf. Peterson 1993). This equation holds strictly for open geometries, where the photons escaping one location in the BALR are not scattered or absorbed in another location. The line optical depth calculations by Hamann (1998) indicate that $f_L$ could be as large as a few tenths. Therefore, the large total column densities implied by the PV analysis (Fig. 2) can be radiatively driven to the observed velocities, but there are restrictions on the inner wind radius. For example, if the total column in outflowing gas is log $N_{\text{H}}(\text{cm}^{-2}) \sim 23$, the wind must arise from within $\sim 0.01$ pc of the QSO.
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Questions:

_M. Crenshaw:_ What covering factors do you get for the BALQSOs?

_F. Hamann:_ I claim that strong BALs like Lyα, CIV and OVI are very optically thick, so the observed depths of the troughs are direct measures of the coverage fractions. For example, from Figure 1 I estimate mean coverage fractions of $\sim 70\%$ in CIV and $\leq 50\%$ in Lyα (which is not clearly detected).

_B. Wilkes:_ If, as you suggest, the BAL gas is the X-ray absorber and this absorber does not cover completely the continuum source, then we would expect to see soft X-ray emission from the uncovered part of the continuum source. Do you know if this is consistent with the current X-ray data on BALQSOs?

_F. Hamann:_ I'm not sure we can perform that consistency check because different ions appear to have different coverage fractions. If the high-ionization gas is “fluffier” (more extended) than the low-ionization gas, OVII and OVIII, which might dominate the absorption in soft X-rays, could have complete coverage while ions like CIV are only partial. Furthermore, the UV and X-ray continuum sources could be spatially distinct, so coverage fractions derived from the UV lines might not be meaningful for the X-rays.

_N. Arav:_ Having UV BALs saturated without being black combined with strong X-ray absorption might be the signature of scattering of photons into the line of sight as opposed to partial coverage.

_F. Hamann:_ Perhaps. Note that I use the phrase “partial coverage” with the understanding that the “uncovered” continuum flux might come from an extended scattering region.

_M. Gaskell:_ Could you comment on the emission we will see from your optically thicker BAL clouds?

_F. Hamann:_ I have not calculated emission line fluxes from the BAL gas, but the typical high-column density BAL region I propose is highly ionized and optically thin at the HI Lyman edge (Fig. 2). This gas will not contribute significantly to low-ionization BELs such as MgII, but there might be some emission in high-ionization lines (depending on what the actual column densities and global covering factors are). In any case, I would expect emission lines from the BAL gas to present very broad and shallow profiles, especially in sources like PG 1254+047 where the BAL region appears exclusively at high outflow velocities (at least along our line of sight).