HEAVY ELEMENTS IN QSOS: STAR FORMATION AND GALAXY EVOLUTION AT HIGH REDSHIFTS

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ABSTRACT

Intrinsic emission and absorption lines of QSOs provide several independent probes of the metal abundances in QSO environments. They indicate that the metallicities are typically solar or higher out to redshifts $z > 4$. These results support models of galaxy evolution where galactic nuclei, or dense condensations that later become galactic nuclei, form stars and evolve quickly at redshifts higher than the QSOs themselves.

1. Introduction

Measuring the heavy-element abundances near QSOs can provide unique constraints on high-redshift star formation and galaxy evolution. In particular, QSO abundances reflect the evolution characteristics of galactic nuclei or dense proto-galactic condensations at high redshifts – perhaps involving the first generations of stars formed after the Big Bang. The QSO results will therefore complement other studies of high-redshift galaxies that probe more extended structures and/or rely on very different data and analyses techniques. Combining the QSO abundance work with the other studies, involving, for example, the "Lyman-break" galaxies and damped-Lyα absorbers, should yield a more complete picture of star formation and galaxy evolution at early epochs.

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 intrinsic narrow absorption lines (NALs). Each of these probes has its own theoretical and observational uncertainties, so it is essential to consider as many of them as possible. I am now involved in several projects to examine a wide range of abundance 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.

2. Results

BELs. The broad emission lines have a major advantage in that they can be measured and compared in large samples of QSOs using using moderate resolution spectra. Line ratios involving nitrogen are particularly valuable as tracers of the chemical enrichment because N is selectively enhanced by "secondary" processing in stellar populations (increasing roughly as Z^2 for at least $Z \gtrsim 0.2Z_\odot$; see 10,19). Hamann & Ferland (9,10,4) used extensive photoionization calculations to show that the broad emission-line ratio NV $\lambda1240$/HeII $\lambda1640$ provides lower limits on the N/He abundances. This abundance sensitivity occurs because the NV and HeII lines form together within the He^{++} zone; NV can be relatively weak for some nebular parameters (e.g. gas density, ionizing flux and continuum shape, etc.), but it is not possible to produce large NV/HeII ratios without increasing N/He. The same calculations show that NV/CIV $\lambda1549$ can be an indicator of N/C.

Applying this analysis to observed NV/HeII and NV/CIV ratios in QSOs (see also 8), together with simple considerations from galactic chemical evoltuion, indicates that 1) QSOs out to $z > 4$ typically have solar or higher metallicities, 2) the stellar initial mass function favors massive stars (slightly) more than in the solar neighborhood, and 3) the enrichment timescales are $\lesssim$1 Gyr for at least the $z > 4$ sources (if $\Omega_o \approx 1$). Similar evolution characteristics have been inferred from the old stellar populations in present-day elliptical galaxies and spiral bulges; vigorous star formation in those environments should produce gas-phase abundances above solar at early cosmological epochs. (The present-day stellar populations represent an integral over all previous gas-phase abundances and therefore have lower *average* metallicities.) There is also a trend in the NV line ratios suggesting that more luminous QSOs have higher metal abundances (10, 13). If QSO luminosities are tied to the mass of their host galaxies (eg. 12), this tentative luminosity-metallicity trend could derive from a mass-metallicity relation among QSO hosts that is analogous (or identical) to the well-known relationship in nearby galaxies.

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

$$\left[\frac{a}{b}\right] \;=\; \log\left(\frac{N(a_i)}{N(b_j)}\right) \;+\; \log\left(\frac{f(b_j)}{f(a_i)}\right) \;+\; \log\left(\frac{b}{a}\right)_\odot \tag{1}$$

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 states i and j. Ideally, one has abundance-independent constraints on the ionization fractions from the column densities of different ions of the same element. Otherwise, we can also constrain the ionization by comparing column densities in different elements, with some assumption about their relative abundance. If there is a range of ionization states or a complete lack measured constraints (eg. if only HI and CIV lines are measured), it is still possible to use minimum ionization correction factors to derive minimum metal-to-hydrogen abundance ratios. Hamann (5) plotted theoretical correction factors for a wide variety of circumstances.

A central issue in using NALs for abundance work is understanding the location of the absorbing gas. Some of the so-called "associated" (or $z_a \approx z_e$) absorbers might reside very near the QSOs, perhaps in outflows similar to BALs, but others could form in the extended halo of the host galaxy or in cosmologically intervening gas. Every system must be examined individually. Several empirical tests have been developed to help identify NAL systems that are truly intrinsic to QSO environments, for example 1) time-variable line strengths, 2) multiplet ratios that imply partial line-of-sight coverage of the background light source(s), and 3) well-resolved line profiles that are smooth and broad compared to thermal line widths (see 7, 3 and references therein).

I am in the midst of a program to identify intrinsic NALs and measure there abundances. In all three bonafide intrinsic systems studied so far, the metallicity is solar or higher (see 7, 8). This result agrees with the few other known cases of intrinsic NALs (14, 20) and with the preponderance of $Z \gtrsim Z_\odot$ results for general $z_a \approx z_e$ systems of uncertain origin (5,17,15,16).

BALs. The most surprising abundance results have come from studies of the BALs, where the strengths of the metal-lines compared to HI Lyα seem to require metallicities (for example Si/H) from 20 to >100 times solar (18,5). The secure detections of broad PV $\lambda\lambda$1118,1128 absorption in two BALQSOs (11,6), and tentative detections in two others, suggest further that phosphorus is highly overabundant, with P/C > 60 and P/H >1000 times solar (see also 5). 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.

Another possibility is that the BAL abundance estimates are simply incorrect. Hamann (6) 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 Lyα, $\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 Lyα 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 (2, 21) and intrinsic NALs (3, 5, 7 and refs. therein). Partial coverage has also been inferred from spectropolarimetry of BALQSOs. We cannot measure the coverage fractions from multiplet ratios in most BALs, but I claim that the significant strength of PV absorption signifies partial coverage and large line optical depths. Strong support for this interpretation comes from the only known NAL system with PV absorption, where the resolved doublets clearly indicate large optical depths and partial coverage in lines such as CIV, NV and SiIV (1).

Thus, the true BAL abundances are unknown. I am presently involved in a program to obtain spectra of BALQSOs across a wide range of rest UV wavelengths. Our goals are to 1) determine the general strength and frequency of PV absorption in BALQSOs, and 2) see if some BAL systems or some portions of BAL profiles (the high-velocity wings?) might still be useful for abundance studies.

3. Summary and Discussion

In spite of the null results from BALs, a consensus is emerging from the BELs and intrinsic NALs for typically solar or higher metallicities in high-redshift QSOs. These results support models of galaxy evolution wherein vigorous star formation in galactic nuclei, or dense proto-galactic condensations, produces super-solar gas-phase metallicities at redshifts >4. High metal abundances are a signature of deep gravitational potentials and thus *massive* galaxies or proto-galaxies because only they can retain their gas long enough against the building thermal pressures from supernova explosions. The enriched gas might ultimately be ejected from the galaxy, consumed by the black hole, or diluted by subsequent infall, but the evidence for early-epoch high-Z gas remains in the stars today. In particular, the mean stellar metallicities in the cores of nearby massive galaxies are typically $\sim$1 to 3 $Z_\odot$. The individual stars are distributed about these means with metallicities reflecting the gas-phase abundance at the time of their formation. Only the most recently formed stars at any epoch have metallicities as high as that in the gas. Simple chemical evolution models indicate that the gas-phase abundances in galactic nuclei should be $\sim$2 to 3 times larger than the stellar means, e.g. $\sim$2 to 9 $Z_\odot$ near the end of the star-forming epoch (see 10, 5 and references therein). Therefore, metallicities in the range $2 \lesssim Z \lesssim 9$ $Z_\odot$ can be *expected* in QSOs as long as considerable star formation and enrichment occurs before the QSOs "turn on" or become observable.

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