How Massive are BALQSO Winds?

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Abstract. We are involved in a program to derive properties of broad absorption line (BAL) winds in quasars using combined UV and X-ray observations. A major obstacle is large uncertainties in the derived BAL column densities because of partial coverage of the background light source. In this preliminary report, we circumnavigate those uncertainties by making a simple assumption—that the relative metal abundances are roughly solar. In this case, the P\textsc{iv} λλ1549,1551 multiplet should have at least 500 times lower optical depth than C\textsc{iv} λλ1549,1551. Nonetheless, a P\textsc{v} BAL is present in at least half of the well-measured BALQSOs we studied. We conclude that the strong lines of abundant species like C\textsc{iv} are typically very optically thick. The total BAL column densities are $N_H \gtrsim 10^{22}$ cm$^{-2}$ (for solar overall metallicity), and they might be comparable to the X-ray absorbers, of order $10^{23}$ cm$^{-2}$, if the BAL gas is sufficiently ionized. If the column densities in outflowing BAL gas are, in fact, as large as the X-ray absorbers, it would present a serious challenge to models of radiatively-driven BAL winds.

1. Introduction

Broad absorption lines (BALs) in quasar spectra identify a dynamic but still mysterious component quasar environments. These features clearly form in high velocity winds from the central engines, with maximum speeds of typically 10,000 km s$^{-1}$ to 30,000 km s$^{-1}$, but many fundamental questions remain. For example, what are the total absorbing column densities? Recent X-ray studies have shown that the columns are typically large, in the range $N_H \approx 10^{23}$ to $10^{24}$ cm$^{-2}$, but how much of that column density is actually outflowing with the UV absorption-line gas? Are the flows radiatively accelerated? What is the geometry, location and "launch radius" of the flows, e.g., with respect to the accretion disk and emission line regions? What are the mass loss rates? What are the elemental abundances, ionizations, space densities, volume filling factors, etc. of the absorbing gas?

The most fundamental source of uncertainty (and confusion) in the analysis of BAL winds is the column densities. For a fully resolved absorption line that completely covers the emission source(s) along our line(s) of sight, the measured flux across the line profile, $F_v$, depends on the optical depth profile, $\tau_v$, by, $F_v = F_c e^{-\tau_v}$, where $F_c$ is the "continuum" flux (which may include line emission). This relationship ignores scattered/emitted flux from the absorbing region itself, but that contribution is generally considered to be small for BAL winds with small global covering factors ($\Omega/4\pi \ll 1$, cf. Hamann et al. 1993). The column density in the measured ion is then, $N_{\text{ion}} \propto \int \tau_v dv$. This analysis applied to the usual UV BALs, such as Ly$\alpha$, N\textsc{iv} λλ1238,1242, Si\textsc{iv} λλ1393,1404 and C\textsc{iv} λλ1549,1551, yields total column densities of typically $10^{19} \lesssim N_H \lesssim 10^{20}$ cm$^{-2}$ — much lower than those mentioned above based on X-ray observations. More surprisingly, this analysis leads to bizarre elemental abundance ratios, such as, $\text{[Si/C]} > 0.5$ and $\text{[C/H]} \approx 1$ to 2 (where $[x/y] = \log(x/y) - \log(x/y)_\odot$). The surprising detections of P\textsc{v} λλ1118,1128 BALs in sources imply $[P/C] \gtrsim 1.6$ (see Turnshek 1988, Junkkarinen et al. 1997, Hamann et al. 1993, Hamann 1998, and reference therein).

How can we understand these strange abundances and reconcile the vastly different UV and X-ray column densities? One very reasonable possibility is that the UV and X-ray absorbers are distinct. The large column density of X-ray absorbing gas might not be outflowing along with the BAL wind. Perhaps it is more or less stationary in the quasar rest frame, and the BAL gas is accelerated at larger radii downstream from the X-ray absorber (e.g., Murray et al. 1995). This situation could explain vastly different UV and X-ray absorbing columns, but it cannot explain the strange abundance ratios.

Another possibility is that the analysis of the BALs outlined above is simply incorrect (or incomplete). In particular, there is growing evidence that BAL column densities are underestimated by this analysis because of partial coverage of the background light source(s). There is unabsorbed flux filling in the bottoms of BAL troughs, and so the line profiles are not simply related to the optical depth by, $F_v = F_c e^{-\tau_v}$. Direct evidence for partial coverage in BALs has come from comparisons of line pairs in one BALQSO (Arav et al. 199x). Indirect evidence comes from...
flat-bottomed troughs that do not reach zero intensity, and from the growing numbers of intrinsic “mini-BALs” and narrow absorption lines (NALs) whose resolved doublet ratios (e.g., in C iv) frequently require partial coverage (Hamann et al. 1997, Barlow, Hamann & Sargent 1997, Arav et al. 1999, Telfer et al. 1998). Changes in the percent polarization across BAL profiles (e.g., Schmidt & Hines 1999) might also indicate partial coverage, in this case because of reflected continuum and/or line emission.

Hamann (1998) argued that the surprisingly strong P v BALs are also evidence for partial coverage. The C iv and P v lines form under vary similar physical conditions and their ratio leads trivially to a lower limit on [P/C]. In the Sun, phosphorus is ~1000 times less abundant than carbon. With this abundance ratio, the optical depth in P v should be at least ~500 times less than C iv. Therefore, if the relative abundances are even close to solar, e.g. [P/C] ≈ 0, the P v line should not be present in BALQSO spectra unless C iv and other strong lines of abundant elements (such as O vi λ1031,1038) are very optically thick. The optical depths and column densities turn out to be much larger than one would generally derive from the naive analysis of BALs outlined above.

Below we discuss the implications of large column densities for BAL winds. We first summarize the findings from an ongoing study of a larger BALQSO sample (Junkkarinen 1999) might also indicate partial coverage, in this case because of reflected continuum and/or line emission.

Below we discuss the implications of large column densities for BAL winds. We first summarize the findings from a detailed analysis of UV + X-ray absorption in a particular BALQSO, PG 1254+047 (Hamann 1998, Sabra et al. 2001). Then we discuss some preliminary results from an ongoing study of a larger BALQSO sample (Junkkarinen et al. 2002).

2. Results for PG 1254+047

PG 1254+047 (z_em = 1.01) is particularly interesting because it has “detached” BAL troughs; in other words, there is no absorption near the quasar emission redshift (see Figure 1). The BALs identify a wind that intersects our line(s) of sight only at high blueshifted velocities, from roughly 15,000 to 27,000 km s\(^{-1}\). The strong X-ray absorption in this source (see below) must either be outflowing at the same high speeds as the BAL gas, or at rest (or at lower speeds) but producing no significant UV absorption lines. Either way, we have additional strong constraints on the nature of the BAL wind.

Hamann (1998) measured a P v BAL in PG 1254+047 whose strength compared to the C iv absorption suggests [P/C] \(\gtrsim 2.2\) by the analysis in §1 (assuming complete line-of-sight coverage). The data do not provide direct evidence for partial coverage. However, by making the reasonable assumption that the relative metal abundances are roughly solar (e.g. [P/C] \(\approx 0\)), Hamann (1998) used photoionization calculations to show that the line optical depths are much larger than one would infer simply from the depths of the observed troughs (§1). In particular, \(\tau_{\text{c}}(\text{C iv}) \gtrsim 25\) and \(\tau_{\text{e}}(\text{O vi}) \gtrsim 60\). The total column density needed to produce the measured P v is at least

![Fig. 1. Hubble Space Telescope spectrum of PG 1254+047 showing its detached BAL troughs. The BALs are labeled just above the spectrum, while the prominent broad emission lines are marked across the top. The measured flux has units 10\(^{-15}\) ergs/s/cm\(^2\)/Å. See Hamann (1998) for details.](image)

\[N_H \gtrsim 10^{22} \text{ cm}^{-2}\] if the overall metallicity is also solar. There is also a lower limit on the ionization parameter (i.e., the dimensionless ratio of hydrogen-ionizing photon to hydrogen particle densities at the illuminated face of the absorbing clouds) of \(\log U \gtrsim -0.6\), based on the absence of low-ionization BALs, such as Mg ii λ2796,2804. The total column density could be substantially larger if the gas is more highly ionized. In particular, the outflowing gas could have \(N_H \approx 10^{23} \text{ cm}^{-2}\) if \(\log U \approx 0.5\). The upper limit on the ionization and therefore the column density are unknown. Figure 7 in Hamann (1998) shows the permitted range of \(N_H\) values as a function of \(U\).

More recent Chandra X-ray observations by Sabra et al. (2001, see also Sabra & Hamann this proceedings) show that, like other BALQSOs, PG 1254+047 is also severely absorbed in soft X-rays. Sabra et al. derive a total column density in X-ray absorbing gas of \(N_H \approx 10^{23} \text{ cm}^{-2}\) if \(\log U \approx 0.5\). (It is not possible to simultaneously derive \(N_H\) and \(U\) from the existing X-ray spectrum with only ~47 counts; however, an ionized absorber does seem to fit the data better than a neutral one.) The important point here is that the total column density suppressing the X-rays is consistent with the heavily saturated BALs. How common is this result?

3. A Survey for P v in BALQSOs

To understand the frequency of P v absorption in BALQSOs, we have obtained rest-frame UV spectra for a small sample of 8 BALQSOs using the Hubble Space Telescope (HST, Junkkarinen et al. 2002). The sample con-
sists of bright sources with moderate redshifts (so P V λ1118,1128 is shifted into the HST wavelength range while avoiding severe contamination by the Lyα forest that would occur at higher redshifts). We also tried to select BALQSOs with relatively narrow line components, so that we can use the multiplet ratio λ1118/λ1128 in P V to diagnose directly the amount of saturation in these lines. To increase the sample size, we also include spectra from the HST archives of several other BALQSOs. Importantly, all of the spectra were obtained without any prejudice regarding the P V line strength. Finally, we have proposed to obtain X-ray spectra for some of the BALQSOs in this sample to compare directly their UV and X-ray absorbing properties.

The HST spectra are currently under analysis. Detection of the P V BALs can be hampered by blending with nearby lines, such as O VI and C III X977. Nonetheless, a preliminary review of the data indicates that broad P V absorption is present in at least 50% of the measured sources. With the assumption that P/C is roughly solar, we again note that the optical depths in P V should be at least 500 times lower than C IV. Our tentative conclusion is that saturation is common in the strong lines of abundant species, such as C IV, N V and O VI, and therefore, by analogy with PG 1254+047 above, the total column densities in BAL winds are frequently greater than 10^{22} cm^{-2}.

4. What Does this Imply for BAL Wind Dynamics?
Large column densities in outflowing BAL gas place strong constraints on wind models that employ radiative acceleration. The equation of motion for a radial wind emanating from a point source can be written as,
\[ \frac{vdv}{dr} = \frac{f_L L}{4\pi r^2 c \mu m_p N_H} - \frac{GM}{r^2} \]
where \( v \) is the wind velocity at radius \( r \), \( M \) is the central black hole mass, \( L \) is the quasar luminosity, and \( f_L \) is the fraction of the incident flux that is absorbed or scattered by the wind (along a given line of sight). Integrating this expression from an initial “launch” radius to infinity yields the terminal velocity:
\[ v_\infty \approx 9300 R_{0.1}^{-1/2} \left( \frac{f_{0.1} L_{46}}{N_{22}} - 0.1 M_S \right)^{1/2} \text{ km/s} \]
where \( R_{0.1} \) is the launch radius in units of 0.1 pc, \( f_{0.1} \) is the absorption fraction relative to 10%, \( L_{46} \) is the luminosity relative to 10^{46} ergs/s, \( N_{22} \) is the column density relative to 10^{22} cm^{-2}, and \( M_S \) is the black hole mass relative to \( 10^8 M_\odot \). \( L_{46} = 1 \) is the Eddington luminosity for a mass \( M_S \approx 1 \), and \( f_{0.1} \approx 1 \) should be roughly appropriate for normal high-ionization BALQSOs (Hamann 1998).

BAL winds with total column densities of order \( N_H \approx 10^{22} \text{ cm}^{-2} \) (\( N_{22} \approx 1 \)) should have no trouble reaching a typical terminal velocity of 15,000 to 20,000 km/s, as long as the launch radius is \( R \lesssim 10^{17} \text{ cm} \) (\( R_{0.1} \lesssim 0.3 \)). However, if the outflows have \( N_H \gtrsim 10^{23} \text{ cm}^{-2} \) (\( N_{22} \gtrsim 10 \)), which is comparable to the X-ray results and consistent with the measured BALs in PG 1254+047 (see above), then the radiative force might be too small to overcome gravity at any launch radius. A gas with \( f_{0.1} \approx 1 \) and this total column would remain gravitationally bound to the black hole. Even if we ignore gravity for a moment, the launch radius of a flow with \( N_H \gtrsim 10^{23} \text{ cm}^{-2} \) must be very small, \( R \lesssim 10^{16} \text{ cm} \), to reach the observed terminal velocities.

This small launch radius would not seem to be a problem, except that the BAL gas is supposed to reside outside of (at larger radii than) the broad emission line region (BELR). The main evidence for this statement comes from observations of N V BALs that clearly absorb the underlying Lyα BEL whenever wind material appears at the right flow velocity (\( \sim 5000 \text{ km/s} \)). In a small fraction of cases, where there is deep absorption setting in abruptly near the BEL rest velocity, it is again clear that the BAL wind absorbs both the continuum and broad line radiation. The radius of the Lyα and/or C IV BELR, \( R_{BELR} \), therefore sets a minimum radius for the observed BAL wind, \( R_{min} \), such that
\[ R_{min} \approx R_{BELR} \approx 0.05 L_{46}^{0.7} \text{ pc} \approx 10^{17} L_{46}^{0.7} \text{ cm} \]
where the estimate of \( R_{BELR} \) comes from variability studies (Kaspi et al. (2001)). We emphasize that this limit applies to the observed BAL wind radius because the launch radius might be smaller. Certainly in PG 1254+046 (and other BALQSOs with detached troughs), the wind is launched somewhere out of our line(s) of sight to the emission sources (requiring a non-radial velocity component – see the sketches in Ganguly et al. 2001 and Elvis 2000). By the time the wind intersects our sightline(s), it is already travelling at speeds \( \gtrsim 15,000 \text{ km/s} \). A similar situation explains the sources with deep BAL absorption near the rest velocity, in this case requiring a geometry where the highest observed wind speeds occur at the smallest radii. In any case, it is not really clear what plausible wind geometry could allow a launch radius that is 10 or more times smaller than the observed BAL region radius. Moreover, as we noted above, BAL winds with column densities of order \( 10^{23} \text{ cm}^{-2} \) might be gravitationally bound no matter the launch radius. If the outflowing column densities do prove to be this large, some other mechanism is likely contributing to the acceleration (e.g., Emmering et al. 1992).

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