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A Chandra Snapshot Survey of Broad Absorption Line Quasars

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Abstract. The profound soft X-ray silence of quasars that show broad absorption lines (BALs) in their optical/UV spectra has been reasonably attributed to large column densities of absorbing material intrinsic to the quasar. However, estimates of the absorbing column have been founded on many assumptions, the most important being that the strength and spectrum of the underlying X-ray emission is identical to that of the more typical non-BAL QSOs. Solid proof of both the existence of an absorber, and the presumed similarity of the underlying spectral energy distribution have been lacking, except by analogy to quasars with weaker optical/UV absorbers. From a Chandra snapshot of 10 optically bright BALQSOs, we show that the X-ray spectral energy distributions of typical high ionization BALQSOs, both the underlying power-law slope and the X-ray to optical flux ratio, are affected by strong intrinsic absorption, and that their underlying X-ray emission is consistent with non-BAL QSOs. By contrast, removal of the best-fit absorption column detected in the high ionization BALQSOs still leaves the 4 low-ionization BALQSOs in our sample as unusually X-ray faint for their optical luminosities.

1. Introduction

Quasars are immensely powerful and complicated structures, yet so distant as to appear faint and pointlike. So their study to date is mostly informed by spectroscopy. But quasar optical/UV emission line spectra are almost certainly subject to a profound averaging process, or maybe a Darwinian selection whereby clouds in the best position to radiate efficiently dominate the emission spectrum (e.g., Baldwin et al. 1995). Absorption lines caused by material intrinsic to quasars probably hold greater promise for revealing the conditions near the supermassive black holes. The velocity and ionization structure of the absorbers can be studied with spectra of adequate signal-to-noise ratio and resolution, if the absorption is not too complex or saturated. Regardless, some of us prefer to study the messiest, most spectacular cases, the broad absorption lines (BALs). Since BALQSOs host strong absorbing clouds flowing outward from the nucleus along our line of sight with velocities of 5,000 up to $\sim 50,000$km/s, their phenomenology is both rich and extreme.

While the intrinsic absorbing columns inferred from the UV BALs ($N_H^{intr} \sim 10^{20-21}\mathrm{cm}^{-2}$; Korista et al. 1992) appear low enough that we would have expected very little X-ray absorption, BALQSOs instead proved virtually undetectable in soft X-rays (Green et al. 1995; Green & Mathur 1996). We could nevertheless derive the implied X-ray absorbing columns by assuming that BALQSOs are "normal underneath", i.e. have intrinsic luminosities and spectral energy distributions (SEDs) similar to non-BALQSOs, particularly the optical-to-X-ray ratio parameterized by $\alpha_{\rm ox}$[1] and X-ray continuum photon index Γ. The large implied X-ray columns mean that the UV BALs sample an ionization state that holds for just a tiny fraction of the absorbing material - increasing the estimates of the mass outflow rate by 2 to 3 orders of magnitude. Outflows must then represent a significant component of the QSO energy budget. But the crucial assumption that BALQSOs are normal underneath has eluded verification.

We therefore proposed for Chandra Cycle 1 time to image a sample of optically bright BALQSOs with the Advanced CCD Imaging Spectrometer (ACIS). Our goal was to survey a representative sample of BALQSOs with short exposure times so that we might test the absorption scenario, and identify some most X-ray bright BALQSOs for further followup. Chandra is well-suited to these goals due to its $\sim 1''$ point-response profile and low background, which provide excellent sensitivity that extends into the more penetrating hard X-ray bandpass.

2. Observations

We compiled a list of QSOs with unmistakably strong *bona fide* BALs and magnitudes (usually B or m_{pg}) brighter than 17th. We calculated our proposed Chandra exposure times to result in a detection for each source, making the usual assumptions outlined above. The resulting sample spans redshifts from 0.1 to 2.4, and a wide range of BALQSO phenomena (Green et al. 2001). Four QSOs with low-ionization BALs (loBALs) are included, which also show broad absorption in lower ionization lines of Mg II or Fe II. LoBAL QSOs are reddened and tend to have particularly high polarization (Schmidt & Hines 1999). All 10 sources were observed between 1999-Dec-30 and 2000-May-15 using the back-illuminated S3 chip of the Advanced CCD Imaging Spectrometer (ACIS) on board Chandra.

[1] $\alpha_{\rm ox}$ is the slope of a hypothetical power-law from 2500 Å to 2 keV; $\alpha_{\rm ox} = 0.384 \log(\frac{L_{2500\text{Å}}}{L_{2\rm keV}})$.

3. Analysis

We performed spectral modeling for the six sources from with more than 20 counts. Since each source spectrum taken individually has insufficient counts to usefully constrain the intrinsic absorption or power-law spectral index, instead we *simultaneously* fitted all 6 spectra. Note that these brightest sources are all hiBAL QSOs, so the spectral parameters we derive may not apply to loBAL QSOs. We tested several source models. A single global power-law with an individual flux normalization for each QSO and ($z = 0$) absorption fixed to the Galactic value for each QSO (Model A) yields a hard photon index $\Gamma = 1.1 \pm 0.1$. At 99.7% (3σ) confidence, a better fit is achieved by allowing for a global intrinsic absorption column fixed at each quasar's redshift. The best-fit slope of Model (B) is $\Gamma = 1.44 \pm 0.23$, with intrinsic (rest-frame) absorption $N_H^{intr} = 6.5^{+4.5}_{-3.8} \times 10^{22}\,\mathrm{cm}^{-2}$. Inclusion of a *global* partial covering parameter C_f for the redshifted absorbers (Model C) further improves the fit, again at 99.5% confidence (F-test). The "composite" BALQSO has intrinsic (rest-frame) absorption $N_H^{intr} = 6.5^{+4.5}_{-3.8} \times 10^{22}\,\mathrm{cm}^{-2}$ covering 80^{+9}_{-17}% of the source, whose intrinsic power-law energy index $\Gamma = 1.80 \pm 0.35$. This final best fit model is plotted in Figure 1 over the summed spectrum.

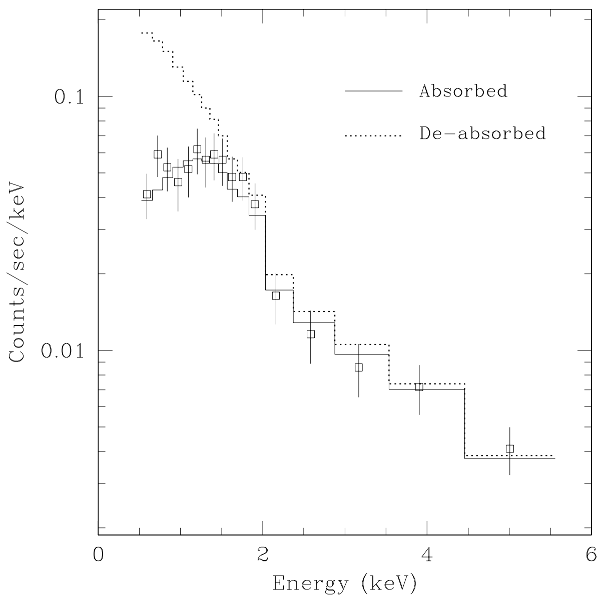

Figure 1. Summed Chandra X-ray spectrum for the BALQSOs with more than 20 counts. The sum of the all the individual source models is plotted over the merged event lists of all 6 objects. The solid line shows the global best-fit model (Model C). The dashed line shows the "de-absorbed" model spectrum, where the intrinsic absorption component is removed from Model C *after* fitting.

We note that one QSO represents 30% of the counts fitted, and that the next most dominant 20%. We therefore explored the suitability of the global fit for each QSO by thawing the power-law slope and amplitude in Model C and refitting individual QSOs. All the QSOs included in the simultaneous fit have power-law slopes and intrinsic columns consistent with the final global fits Model C except Q0254-334 with $\Gamma = 2.6 \pm 0.4$. Most likely, this QSO is not strongly absorbed in X-rays, but warrants further investigation. It represents about 15% of the counts in the global fit, and our conclusions are unchanged if we exclude it entirely.

Our most important result, which has never been demonstrated before for a representative sample of BALQSOs, is that the best-fit power-law index Γ for our BALQSO sample is entirely consistent with the (ASCA) mean for non-BAL radio quiet quasars of $\sim 1.89 \pm 0.05$ with dispersion $\sigma = 0.27 \pm 0.04$ (Reeves & Turner 2000; Vignali et al. 1999). Gallagher et al. (2001, and this volume) find similar results for PG2112+059, which appears to have weak BALs and perhaps the brightest flux of any BALQSO. Her current Chandra sample of BALQSOs should considerably further these studies.

4. Broadband Energy Distributions

Now that we have a *measured* mean spectral shape for hiBAL QSOs, for the first time we can calculate fluxes consistently using the best-fit model with the redshifted absorption component removed. This tells us what $\alpha_{\rm ox}$ values BALQSOs would have without their intrinsic absorption, since their (de-absorbed) intrinsic SEDs are well-characterized by the above slope. With the modeled intrinsic absorption removed, the high ionization BALQSOs in our sample fit reasonably well along the empirical trend of increasing α_{ox} (weakening X-ray emission) with increasing L_{opt}. On the other hand, the four low-ionization BALQSOs in our sample are extremely X-ray weak. Two are not detected at all (for which we assign 5 counts as an upper limit). Of the two loBAL QSOs that are detected, one is the most nearby object (at $z = 0.148$), and the other is a radio-intermediate BALQSO.

The *apparent* L_X of loBAL QSOs are so low that they are comparable to bright starburst galaxies. Since their broad emission lines betray the presence of an AGN, the minimum difference between our hiBAL and loBAL QSOs is $\Delta\alpha_{\rm ox} \sim 0.3$, could be due to additional absorption approaching $10^{24}{\rm cm}^{-2}$ in loBALs that is unaccounted for in our hiBAL spectral model. The decrease in polarization toward longer wavelengths in some loBALs suggests edge-on dust-scattering models where the scattered line of sight is less reddened, so that loBAL QSOs have been proposed as the *most* edge-on QSOs (Brotherton et al. 1997). On the other hand, loBAL QSOs may be nascent QSOs embedded in a dense, dusty star formation region (e.g., Voit, Weymann, & Korista 1993). The expected strong extinction has been seen (Sprayberry & Foltz 1992; Boroson & Meyers 1992), and could explain their low (1-2%) incidence in optically-selected samples. Deep, higher S/N X-ray spectroscopy of these objects should solidify their tie-in to hiBAL QSOs, and begin to clarify the relationship between merger/starburst activity and outflows in AGN.

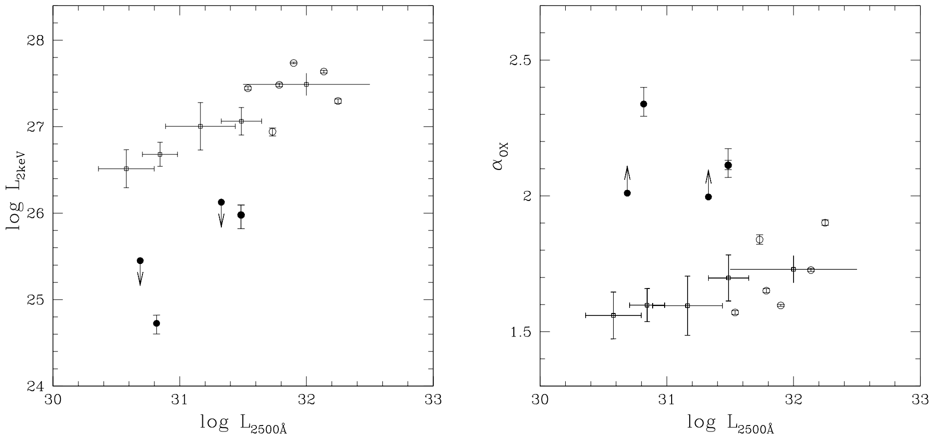

Figure 2. LEFT: The log of the monochromatic (2keV) X-ray luminosity plotted against the log of monochromatic 2500Å optical luminosity for quasars (both in units of ergs sec^{-1} Hz^{-1}). RIGHT: The optical to X-ray spectral slope α_{ox} (from 2500 Å to 2 keV), also plotted against log$L_{2500Å}$. In both panels, circles depict the 10 BALQSOs in our Chandra sample. Filled circles are those objects known to have low-ionization broad absorption lines (loBALs). Errorbars represent the poisson error in the counts. Arrows mark limits to X-ray luminosity in our Chandra exposures. The open boxes with error bars are means from co-added subsamples of radio-quiet LBQS QSOs observed in the ROSAT All Sky Survey (Green et al. 1995). The errorbars are the RMS dispersion of the QSOs in each bin. We also add one mean point at higher luminosity (log$L_{2500Å} > 31.5$) for ROSAT-observed radio-quiet QSOs from Yuan et al. (1998).

4.1. Orientation, Outburst, and Evolution

Most interpretations of the optical and UV observations imply that all QSOs host BAL clouds, at least for the more common high ionization BALs (hiBALs henceforth). This 'unification' picture is supported by (1) the covering factor of the BAL region (< 20% Hamann et al. 1993), (2) by the optical/UV emission lines and continuum slopes of hiBAL QSOs, remarkably similar to those of non-BALQSOs (Weymann et al. 1991), and (3) by the higher average polarization of BALQSOs (Schmidt & Hines 1999) and increase of polarization in the BAL troughs (Ogle et al. 1999).

An alternative or perhaps complementary approach to BALQSOs is that, rather than representing an orientation effect, they are in a phase of high accretion rate (outburst). If the BAL phase represents a high accretion rate period in a quasar's lifetime, than an intrinsic power-law steeper than that for non-BAL QSOs might be expected, by analogy to narrow line Seyferts and Galactic black hole candidate binary systems in outburst (Leighly 1999; Mathur et al. 2000). Our composite sample analysis does not support this, with the possible exception of Q0254-334. However, Mathur discusses one other such case PHL 5200 in this volume, and we consider the possibility open that both orientation *and* high accretion rate may contribute to the BAL phenomenon. The latter may affect the evolution of the observed space density of quasars, and is very sensitive to selection effects.

Higher accretion rates would tend to be associated with mergers, which in turn should be found more frequently at early cosmic times in a scenario of hierarchical structure formation. Thus a larger fraction of BALQSOsshould exist at higher redshifts. Hints abound that this may be the case (Maiolino et al. 2001; Chartas 2000). The detections presented here in relatively short Chandra exposures indicate that deep, large-area X-ray surveys with good sensitivity above 2keV should help find an increasing number of high-z BALQSOs.

It's important to note that naïve individual spectral fits to the few count X-ray spectra of BALQSOs yield hard spectral slopes such that especially at high redshifts, BALQSOs might represent a significant fraction of absorbed AGN postulated to contribute to the cosmic X-ray background.

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