X-ray Spectroscopy of BAL and Mini-BAL QSOs

S. C. Gallagher, W. N. Brandt, G. Chartas, & G. P. Garmire

The Pennsylvania State University, Department of Astronomy & Astrophysics, 525 Davey Laboratory, University Park, PA 16802

Abstract. BAL QSOs are notoriously faint X-ray sources, presumably due to extreme intrinsic absorption. However, several objects have begun to appear through the obscuration with recent X-ray observations by Chandra and ASCA. Where enough counts are present for X-ray spectroscopy, the signatures of absorption are clear. The evidence is also mounting that the absorbers are more complicated than previous simple models assumed; current absorber models need to be extended to the high-luminosity, high-velocity, and high-ionization regime appropriate for BAL QSOs.

1. Introduction

Since the first surveys with ROSAT, BAL QSOs have been known to be faint soft X-ray sources compared to their optical fluxes (Kopko, Turnshek, & Espey 1994; Green & Mathur 1996). Given the extreme absorption evident in the ultraviolet, this soft X-ray faintness was assumed to result from intrinsic absorption. Based on this model, the intrinsic column densities required to suppress the X-ray flux, assuming a normal QSO spectral energy distribution, were found to be $\gtrsim 5 \times 10^{22} \text{ cm}^{-2}$ (Green & Mathur 1996). Due to the 2–10 keV response of its detectors, a subsequent ASCA survey was able to raise this lower limit by an order of magnitude for some objects, to $\gtrsim 5 \times 10^{23} \text{ cm}^{-2}$ (Gallagher et al. 1999).

In all of these studies, the premise of an underlying typical QSO spectral energy distribution and X-ray continuum was maintained. The strong correlation found by Brandt, Laor, & Wills (2000) between $C^\text{iv}$ absorption equivalent width (EW) and faintness in soft X-rays further supported this assumption.

ASCA observations of individual BAL QSOs such as PHL 5200 (Mathur, Elvis, & Singh 1995) and Mrk 231 (Iwasawa 1999; Turner 1999) provided suggestive evidence that intrinsic absorption was in fact to blame for X-ray faintness. However, limited photon statistics precluded a definitive diagnosis. The observation of PG 2112+059 with ASCA on 1999 Oct 30 provided the first solid evidence for intrinsic X-ray absorption in a BAL QSO.

2. X-ray Spectroscopy of a BAL QSO: PG 2112+059

PG 2112+059 is one of the most luminous low-redshift Palomar-Green QSOs with $M_V = -27.3$. Ultraviolet spectroscopy with HST clearly revealed broad, shallow $C^\text{iv}$ absorption (Jannuzi et al. 1998) with EW of 19Å (Brandt et
Table 1. Basic Properties of BAL and Mini-BAL QSOs\(^a\)

| Name                   | \(R\) | \(z\) | Intrinsic \(N_H\) \((10^{22}\text{ cm}^{-2})\) | \(f_{\text{cov}}\) | \(F_{2-10\text{ keV}}\) \((10^{-14}\text{ erg cm}^{-2}\text{s}^{-1})\) |
|------------------------|-------|-------|-----------------------------------------------|---------------------|-----------------------------------------------|
| APM 08279+5255\(^d\)  | 15.2  | 3.87  | \(7.0^{+2.6}_{-2.2}\)                         |                     | 41                                            |
| RX J0911.4+0551\(^d,e\)| 18.0  | 2.80  | \(19^{+4.28}_{-1.18}\)                        | 0.71^{+0.20}_{-0.39} | 5.8                                           |
| PG 1115+080\(^d,e\)   | 15.8  | 1.72  | \(3.8^{+2.5}_{-2.2}\)                         | 0.64^{+0.11}_{-0.16} | 30                                            |
| PG 2112+059            | 15.4  | 0.457 | \(1.1^{+0.5}_{-0.4}\)                         |                     | 75                                            |

\(^a\)X-ray errors given are for 90\% confidence taking all parameters except normalization to be of interest. \(^b\)Covering fraction is only provided when partial-covering absorption models provided a better fit to the data than simple neutral absorption. \(^c\)Flux measured in the 2–10 keV band from the best-fitting X-ray spectral model. \(^d\)Gravitational lens system. The listed optical magnitude is for the brightest image, and the X-ray spectral information is for all images combined. \(^e\)Mini-BAL QSO, see § 3.2. \(^f\)B magnitude.

A 21.1 ks \(\text{ROSAT}\) PSPC observation on 1991 Nov 15 detected PG 2112+059, unusual for a BAL QSO. A 31.9 ks \(\text{ASCA}\) observation provided \(\approx 2000\) counts in all four detectors, enough for spectroscopic analysis (described in detail in Gallagher et al. 2001).

To model the continuum, the data were fit above 3 keV (2 keV in the observed frame) with a power law. The resulting photon index, \(\Gamma = 1.94^{+0.23}_{-0.21}\), was consistent with those of typical radio-quiet QSOs (e.g., Reeves & Turner 2000). The power law was extrapolated back to the lowest energies in the \(\text{ASCA}\) bandpass to investigate potential intrinsic absorption (see Figure 1). The significant negative residuals are indicative of strong absorption, and the spectrum was subsequently fit with an intrinsic, neutral absorber with a column density, \(N_H \approx 10^{22}\text{ cm}^{-2}\). The structure in the residuals is suggestive of complexity in the absorption, but the signal-to-noise ratio was insufficient to investigate this fully.

This analysis of PG 2112+059 provided the first direct evidence of a normal X-ray continuum suffering from intrinsic absorption in a BAL QSO. In addition, correcting the X-ray flux for this absorption also demonstrated that this BAL QSO had an underlying spectral energy distribution typical of radio-quiet QSOs. Though PG 2112+059 has a high optical flux with \(B = 15.4\) , many of the optically brightest BAL QSOs have been undetected in \(\text{ASCA}\) observations of similar or greater exposure time. Notably, PG 0946+301 \((B = 16.0)\) was barely detected by \(\text{ASCA}\) with \(\approx 100\) ks (Mathur et al. 2000).

The launch of \(\text{Chandra}\) has opened a new era in X-ray observations of BAL QSOs. The low background and excellent spatial resolution allow \(\text{Chandra}\) to probe 2–10 keV fluxes approximately twice as faint as \(\text{ASCA}\) in \(\lesssim 1/4\) of the time.

3. Gravitationally Lensed QSOs with Broad Absorption

As part of a \(\text{Chandra}\) GTO program, gravitationally lensed QSOs were observed with ACIS-S3 to take advantage of the power of the High Resolution Mirror Assembly to resolve the individual lensed images. As an added benefit, several of
Figure 1. ASCA SIS and GIS observed-frame spectra of PG 2112+059 fitted with a power-law model above 2 keV, which has then been extrapolated back to lower energies. Note the significant negative residuals (lower panel) below \( \approx 2 \text{ keV} \) suggestive of a complex absorber.

these targets contain broad absorption lines. The magnifying effect of the lensing allows us to probe fainter intrinsic X-ray luminosities than would otherwise be possible, and these targets provided some of the best prospects for spectroscopic analysis. The X-ray spectral analysis for each object was done on all images combined to increase the signal-to-noise ratio, and the results are summarized in Table 1.

3.1. APM 08279+5255

Since its recent discovery in 1998, the BAL QSO APM 08279+5255 has inspired more than 20 publications. Its apparently incredible bolometric luminosity, which seemed to exceed \( 10^{15} L_\odot \), was found to be magnified by a factor of \( \gtrsim 40 \) by gravitational lensing (Irwin et al. 1998). On 2000 Oct 11, APM 08279+5255 was observed for 9.3 ks with the ACIS-S3 instrument. Chandra revealed this luminous QSO to be sufficiently bright for spectral analysis. A result similar to that obtained for PG 2112+059 was found: APM 08279+5255 showed a typical QSO continuum with the signature of strong absorption. The best-fitting model is comprised of a power law with \( 7 \times 10^{22} \text{ cm}^{-2} \) of neutral absorbing gas (see Figure 2). Increasing the complexity of the spectral model to include a partially covering or ionized absorber did not improve the fits. At such high redshift, \( z = 3.87 \), the diagnostics for such models have passed below the Chandra bandpass.

3.2. RX J0911.4+0551 and PG 1115+080

In contrast to APM 08279+5255, RX J0911.4+0551 and PG 1115+080 have luminosities more comparable to those of Seyfert 1 galaxies, and they are both properly classed as mini-BAL QSOs. Although the C\textsc{iv} absorption troughs are obviously broad (\( \Delta v \gtrsim 3000 \text{ km s}^{-1} \)), these objects do not formally meet the
Figure 2. *Chandra* ACIS-S3 spectrum of APM 08279+5255 fit with a power law above 5 keV (1 keV in the observed-frame) which has then been extrapolated back to lower energies. The high redshift of APM 08279+5255 has shifted the signatures of absorption almost completely out of the ACIS bandpass.

BAL QSO criteria of Weymann et al. (1991). With less extreme ultraviolet absorption, mini-BAL QSOs might be expected to be stronger X-ray sources than bona-fide BAL QSOs. In fact, the mini-BAL QSO PG 1411+442 was successfully observed with *ASCA*; spectral analysis indicated a substantial intrinsic absorber with a column density, $N_H \approx 10^{23}$ cm$^{-2}$, and an absorption covering fraction, $f_{\text{cov}} \approx 97\%$ (Brinkmann et al. 1999; Gallagher et al. 2001).

RX J0911.4+0551 was discovered as part of a program to identify bright *ROSAT* sources (Bade et al. 1997), though the 29.2 ks *Chandra* observation of 1999 Nov 2 showed it to be a factor of $\approx 8$ fainter than during the *ROSAT* All Sky Survey (Chartas et al. 2001). Spectral analysis revealed an X-ray continuum with a typical photon index overlaid with absorption. However, the absorption was not adequately modeled with neutral gas. The low-energy residuals from a power-law fit above rest-frame 5 keV suggested some complexity in the absorption such as would result from either a partially covering or an ionized absorber. Both models were significant improvements over the neutral absorber with the first model being slightly preferred (Chartas et al. 2001). The best-fitting intrinsic column density, $N_H = 2 \times 10^{23}$ cm$^{-2}$, is the largest of the four QSOs presented in this paper.

PG 1115+080 is notable for significant variability of the ultraviolet O\textsc{vi} emission and absorption lines (Michalitsianos, Oliversen, & Nichols 1996) as well as X-ray flux changes (Chartas 2000). This target has been observed with *Chandra* on two occasions, for 26.2 ks on 2000 Jun 2 and 9.7 ks on 2000 Nov 3. The data were analyzed following the procedure outlined above with a similar result as for RX J0911.4+0551; a partially covering absorber model with $N_H = 4 \times 10^{22}$ cm$^{-2}$ was preferred over neutral absorption. PG 1115+080 has fairly good photon statistics (see Figure 3), thus making it a good target for additional observations to investigate X-ray spectral variability.
4. General Picture and Conclusions

As the number of BAL QSOs detected with enough X-ray photons for spectral analysis grows, a consistent picture is beginning to emerge. The X-ray continua can be well modeled by power-law models with photon indices consistent with those of other radio-quiet QSOs, $\Gamma \approx 2$. In addition, correcting the X-ray spectra for absorption reveals normal ultraviolet-to-X-ray flux ratios, thus indicating that the underlying spectral energy distributions of BAL QSOs are not unusual. Both of these observations support the scenario whereby broad absorption line outflows are common components of the nuclear environments of radio-quiet QSOs.

Confirming these generalizations will require additional, long spectroscopic observations of the brightest BAL QSOs. To complement this endeavor, large, exploratory surveys of well-defined samples of BAL QSOs will offer enough information to examine which multi-wavelength properties are related to the X-ray characteristics. As of yet, predicting which BAL QSOs will be productive targets for spectroscopic X-ray observations remains a black art. Connecting the X-ray properties, such as flux and coarse spectral shape, to properties in other spectral regimes will ultimately help us to understand the nature of the intrinsic absorption in the X-ray and ultraviolet. We have begun such a program in the Chandra Cycle 2 observing round with 18 BAL QSO targets from the Large Bright Quasar Survey, and the data that have arrived thus far are promising.

In terms of the column density of the absorbing gas, the best-fitting values range from $(1-20) \times 10^{22}$ cm$^{-2}$. Though relatively simple models can adequately explain the observations, the physical absorber in each system is likely to be complex. Partial-covering absorption models suggest that multiple lines of sight are present; the direct view suffers from heavy obscuration while a second, scattered line of sight could be clearer. In addition, if the X-ray absorbing gas is close to the nucleus and associated with the ultraviolet-absorbing gas, it must also be
highly ionized. In this case, the column density measurements can only be considered lower limits. Additionally, significant velocity dispersion of the absorber would increase the continuum opacity of bound-bound absorption lines, and thus further complicate determining an accurate value of the column density.

X-rays are powerful probes of the inner regions of BAL QSOs as they are sensitive to molecular, neutral, and partially ionized gas. Estimates of the absorption column density from X-ray observations (compared to ultraviolet spectral analysis) suggest that the bulk of the absorbing gas is more readily accessible in the high-energy regime. Thus, X-ray observations offer the greatest potential for determining the true mass outflow rate of QSOs. To constrain this value, a measure of the velocity structure of the X-ray absorbing gas is essential. To this end, a gratings observation with *XMM-Newton* of the X-ray brightest BAL QSO, PG 2112+059, offers the most promise.

**Acknowledgments.** This research was supported by NASA grant NAS8-38252, Principal Investigator, GPG. SCG also gratefully acknowledges NASA GSRP grant NGT5-50277.

**References**

Bade, N., Siebert, J., Lopez, S., Voges, W., & Reimers, D. 1997, A&A, 317, L13
Brandt, W. N., Laor, A., & Wills, B. J. 2000, ApJ, 528, 637
Brinkmann, W., Wang, T., Matsuoka, M., & Yuan, W. 1999, A&A, 345, 43
Chartas, G. 2000, ApJ, 531, 81
Chartas, G., Dai, X., Gallagher, S. C., Garmire, G. P., Bautz, M. W., Schechter, P. L., & Morgan, N. D. 2001, ApJ, in press
Gallagher, S. C., Brandt, W. N., Sambruna, R. M., Mathur, S., & Yamasaki, N. 1999, ApJ, 519, 549
Gallagher, S. C., Brandt, W. N., Laor, A., Elvis, M., Mathur, S., Wills, B. J., & Iyomoto, N. 2001, ApJ, 546, 795
Green, P. J. & Mathur, S. 1996, ApJ, 462, 637
Irwin, M. J., Ibata, R. A., Lewis, G. F., & Totten, E. J. 1998, ApJ, 505, 529
Iwasawa, K. 1999, MNRAS, 302, 96
Jannuzi, B. T., et al. 1998, ApJS, 118, 1
Kopko, M., Turnshek, D. A., & Espey, B. R. 1994, in IAU Symp. 159, Multi-Wavelength Continuum Emission of AGN, ed. T. Courvoisier & A. Blecha (Dordrecht: Kluwer), 450
Mathur, S., Elvis, M., & Singh, K. P. 1995, ApJ, 455, L9
Mathur, S. et al. 2000, ApJ, 533, L79
Michalitsianos, A. G., Oliversen, R. J., & Nichols, J. 1996, ApJ, 461, 593
Morgan, N. D., Chartas, G., Malm, M., Bautz, M. W., Jones, S. E., & Schecter, P. L., 2001, ApJ, submitted
Reeves, J. N. & Turner, M. J. L. 2000, MNRAS, 316, 234
Turner, T. J. 1999, ApJ, 511, 142
Weymann, R. J., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, ApJ, 373, 23