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EVIDENCE AGAINST BROAD ABSORPTION LINES IN THE X-RAY–BRIGHT QUASAR PG 1416−129

PAUL J. GREEN,[1] THOMAS L. ALDCROFT,[2] AND SMITA MATHUR[3]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
AND
NORBERT SCHARTEL[4]
European Space Agency, *IUE* Observatory, P.O. Box 50727, E-28080 Madrid, Spain; Affiliated to the Astrophysics Division, Space Science Department, European Space Research and Technology Centre
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ABSTRACT

Recent results from the *ROSAT* All-Sky Survey and from deep *ROSAT* pointings reveal that broad absorption line quasars (BALQSOs) are weak in the soft X-ray bandpass ($\alpha_{ox} > 1.8$) in comparison to QSOs with normal OUV spectra ($\overline{\alpha_{ox}} = 1.4$). One glaring exception appeared to be the nearby BALQSO PG 1416−129, which is a bright *ROSAT* source showing no evidence for intrinsic soft X-ray absorption. We present here our new *HST* Faint Object Spectrograph (FOS) spectrum of PG 1416−129, in which we find no evidence for BALs. We show that the features resulting in the original BAL classification, based on *IUE* spectra, were probably spurious. On the basis of UV, X-ray, and optical evidence, we conclude that PG 1416−129 is not now, and has never been, a BALQSO. Our result suggests that weak soft X-ray emission is a defining characteristic of true BALQSOs. If BALQSOs indeed harbor normal intrinsic spectral energy distributions, their observed soft X-ray weakness is most likely the result of absorption. The ubiquitous occurrence of weak soft X-ray emission with UV absorption (BALs) thus suggests absorbers in each energy regime that are physically associated, if not identical.

Subject headings: quasars: absorption lines — quasars: individual (PG 1416−129) — ultraviolet: galaxies — X-rays: galaxies

1. INTRODUCTION

Broad absorption lines (BALs) are seen in about 10%–15% of optically selected QSOs and only among the radio-quiet (RQ) QSO population (Stocke et al. 1992). The optical/UV spectra show deep, wide absorption troughs, displaced to the blue of their corresponding emission lines (most often in the high ionization transitions of C IV, Si IV, N V, and O VI), which are suspected to result from a line of sight passing through highly ionized, high column density absorbing clouds outside the broad emission-line region (BELR). These clouds flow outward from the nuclear region at speeds up to 0.1–0.2 *c*. Low BAL cloud covering factors and the absence of emission lines at the high velocities observed in BALQSOs, along with the similarity of emission-line and continuum properties of BALQSOs and non-BALQSOs (Hamann, Korista, & Morris 1993; Weymann et al. 1991), suggest that all RQ QSOs (which in turn comprise ∼90% of all QSOs) have BAL clouds. Thus BALQSOs are by no means exotic, but rather represent a privileged line of sight toward the active galactic nucleus (AGN) that probes clouds that are very near, or cospatial with, the BELR.

The absorbing columns (e.g., $N_H \sim 10^{19}$ to 10^{20}) inferred for BAL clouds from the OUV data (Hamann et al. 1993; Turnshek 1988) are such that a priori one expects very little soft X-ray absorption ($\tau \ll 1$). However, Green et al. (1995) and Green & Mathur (1996, hereafter GM96) recently demonstrated that, when compared to normal RQ QSOs, BALQSOs are weak in the soft X-ray bandpass. If BALQSOs harbor normal intrinsic spectral energy distributions (SEDs), their soft X-ray weakness is most likely the result of absorption. Although this remains to be proven for BALQSOs as a class, strong X-ray absorption of a normal power-law continuum is clearly observed in the *ASCA* spectrum of the prototype BALQSO PHL 5200 ($N_H^{intr} \sim 10^{23}$; Mathur, Elvis, & Singh 1995).

The Green et al. (1995) sample of 36 BALQSOs was chosen from a large uniformly selected QSO sample (the LBQS), as observed during the *ROSAT* All-Sky Survey (RASS). Although the short (∼600 s) exposure times of the RASS meant that the upper limits (for 35 of the 36 QSOs) were not very sensitive, by stacking the X-ray data, they were able to show that their uniform BALQSO sample was X-ray quiet at the 99.5% significance level compared to carefully chosen comparison RQ QSO samples.

Then, using deep pointed observations from the *ROSAT* PSPC, GM96 confirmed that BALQSOs are weak in the soft X-ray bandpass in comparison to RQ QSOs with normal OUV spectra. Nine out of 12 reputed BALQSOs in their sample were not detected by *ROSAT*, the deep pointings generally yielding $\alpha_{ox} > 1.8$. A comparison sample of 10 similar RQ QSOs (from Laor et al. 1994, hereafter L94) without BALs yielded a sample mean[5] of $\overline{\alpha_{ox}} = 1.45 \pm 0.08$.

[1] pgreen@cfa.harvard.edu.
[2] taldcroft@cfa.harvard.edu.
[3] smathur@cfa.harvard.edu.
[4] nrs@encina.vilspa.esa.es.

[5] The value of α_{ox} is known to increase with l_{opt} (Wilkes et al. 1994; Avni, Worrall, & Morgan 1995; Green et al. 1995). However, the difference in α_{ox} between the L94 sample and the GM96 BALs is much more than can be attributed to the difference in their mean optical luminosities (see discussion in § 7).

If indeed the central continuum source of BALQSOs is similar to that of other QSOs, as argued above, the intrinsic absorbing columns required to explain the observed soft X-ray deficit ($N_H^{intr} > 2 \times 10^{22}$ cm^{-2}) must be at least 100 times higher than those inferred from the UV data alone. In contrast, the non-BAL sample shows no evidence at all for absorption. Of the three remaining BALQSOs in GM96, 0312−555 was too distant for an interesting lower limit to α_{ox}. In a 58 ks summed exposure, the BALQSO 1246−057 was detected, yielding $\alpha_{ox} = 1.98$, and $N_H^{intr} \sim 10^{23}$ cm^{-2}. Only one QSO, PG 1416−129, was X-ray bright, with a value of $\alpha_{ox} = 1.4$ typical of non-BALQSOs.

That all BALQSOs but PG 1416−129 have large α_{ox} indeed suggests some physical connection between the UV and X-ray absorption, assuming similar intrinsic SEDs. However, if PG 1416−129 is a bona fide BALQSO, although it would be uniquely well suited for observational tests of absorber models, it would refute the hypothesis that highly ionized UV absorbers in BALQSOs are also responsible for their X-ray silence. If instead a high-quality UV spectrum reveals only associated absorption (narrow optical and ultraviolet absorption lines within the profiles of their broad emission lines), that model may stand. There are strong hints that a continuous distribution of UV/X-ray absorbing properties may exist between "associated absorbers" and BALs; PG 1416−129 might just be a "missing link."

Techniques have recently been developed that simultaneously exploit UV and X-ray spectra of QSOs with narrower line, associated absorbers to constrain the allowed ranges of the absorbing cloud conditions through detailed photoionization modeling (e.g., 3C 351, 3C 212, NGC 5548, NGC 3516; Mathur 1994; Mathur et al. 1994; Mathur, Elvis, & Wilkes 1995; Mathur, Wilkes, & Aldcroft 1997). Although these UV/X-ray techniques have shown that consistent physical conditions for both the UV and soft X-ray absorbers can in many instances be derived, there is still debate on whether they are physically associated (e.g., Kriss et al. 1996a, 1996b). An application of these techniques to BALQSOs may eventually provide stronger constraints on BAL clouds, but the weakness of BALQSOs in the soft X-ray regime makes this a daunting task.

If PG 1416−129 is a true BALQSO, its relative X-ray brightness and proximity to earth (PG 1416−129, at $z = 0.129$, has a redshift lower than any confirmed BALQSO) would provide a uniquely accessible object for detailed X-ray/UV studies of high column density absorbers near the central engine of a QSO. At the same time, PG 1416−129 provides a litmus test for the hypothesis that BALQSOs are X-ray quiet as a class. We were thus led to examine its UV spectrum more carefully, as described below: is PG 1416−129 a true BALQSO?

2. *IUE* SPECTRA OF PG 1416−129

The BAL classification for PG 1416−129 was originally awarded by Turnshek & Grillmair (1986), based on a single *IUE* spectrum (SWP8916), and propagated in a number of subsequent papers (e.g., Ulrich 1988; de Kool & Meurs 1994; Staubert & Maisack 1996). That spectrum appears to show some evidence for what might be broad absorption in any of C IV, Si IV, or Lyα. Blueward of C IV in particular, there are possible absorption troughs that span more than 2000 km s^{-1}, extending as far as about 20,000 km s^{-1} from the line center. However, the combination of Si IV broad emission with a spurious flux spike near 1665 Å might merely combine to give that impression. In addition, a narrow absorption trough appears to bisect the C IV emission just redward of the line core, but no similar absorption is seen in Lyα.

Since then, three other *IUE* spectra have been obtained. A log of these observations is presented, along with continuum flux and W_λ measurements for the C IV emission line, in Table 1. We believe that none of these spectra show BALs. Neither does an average spectrum, whether weighted by signal-to-noise ratio (SNR) or not (e.g., see the optimally extracted and co-added spectrum of PG 1416−129 from Lanzetta, Turnshek, & Sandoval 1993). However, an SNR-weighted sum of the *IUE* spectra is dominated by SWP33030 (see § 3), which shows features blueward of C IV that could only optimistically be interpreted as BALs. An examination of reference spectra showing camera artifacts in *IUE* SWP spectra (Crenshaw, Norman, & Bruegman 1990) is revealing. Although the strengths, both relative and absolute, of camera artifacts can vary, the strongest spike for point sources is generally at 1663 Å, blueward of the C IV emission line in PG 1416−129. Other spurious features, like those near 1700 Å, probably contributed to the original BAL classification.

The unusual (and possibly variable) nature of the putative BALs in PG 1416−129, together with its X-ray brightness, led us to seek another UV spectrum, this time using the *HST*. None of the artifacts just discussed are

TABLE 1

BASIC DATA ON UV SPECTRA OF PG 1416L−129

Image	Date	Exposure (s)	f_{1450}[a] ($10-15$ ergs cm^{-2} s^{-1} Hz^{-1})	f_{1625}[a] ($10-15$ ergs cm^{-2} s^{-1} Hz^{-1})	W_λ(C IV)[b] (Å rest)
			IUE		
SWP08916	1980 May 04	8700	6.58 ± 3.49	7.20 ± 1.56	158 ± 14
SWP16763	1982 Apr 14	1680	13.2 ± 12.8	11.8 ± 5.55	<108
SWP33030	1988 Mar 03	24900	4.53 ± 2.62	4.68 ± 0.64	126 ± 18
SWP45019	1988 Jun 27	24900	1.62 ± 1.37	1.74 ± 0.51	96 ± 18
			HST		
Y3DB0103T......	1996 Aug 23	940	2.49 ± 1.77	3.39 ± 1.46	182 ± 14

[a] Mean (observed frame) continuum fluxes, measured at the (rest) wavelength indicated, in bins of 50 Å (also rest).

[b] Emission line equivalent width.

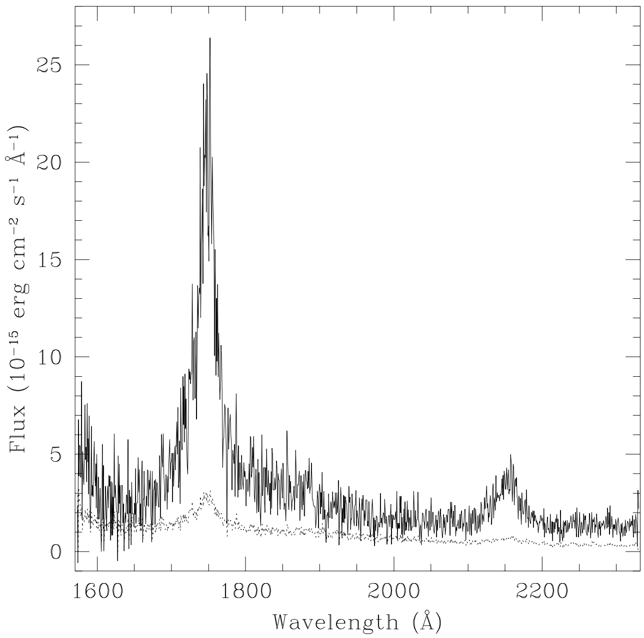

FIG. 1.—*HST* FOS spectrum of PG 1416−129 from 1996 August 23 (*solid line*), block averaged by two, with its associated error (*dashed line*). No evidence for either broad or narrow associated absorption is seen in the *HST* spectrum at C IV (1749 Å in the observed frame).

visible in our new *HST* spectrum, nor are any features reminiscent of BALs.

3. *HST* FOS OBSERVATIONS

On UT 1996 August 23, we obtained a 1 orbit (940 s) spectrum of PG 1416−129 with the Faint Object Spectrograph (FOS) on the *HST*, using a 0″.43 aperture and the G190H grating with the blue detector. We are aware of the scattered light problem in the FOS when observing at the shortest wavelengths (Rosa 1994). In our case, we would not expect a significant scattered light component because PG 1416−129 has a typical blue power-law continuum. Nevertheless, it is prudent to make certain that the FOS spectrum does not approach zero intensity blueward of C IV, as it appears to do in the spectrum of Turnshek & Grillmair (1986). We used the BSPEC program (Rosa 1994) to simulate the scattered red light in the FOS G190H bandpass. The input SED was derived from an optical spectrum of PG 1416−129 (kindly provided by B. Wilkes) that covers the range 3200–6000 Å. We find a negligible contribution from scattered light.

The full spectrum, with a noise spectrum underlaid, is shown as Figure 1. Given sufficient SNR, the spectral resolution ($R \approx 2000$) is adequate to measure narrow associated lines (NALs) and to resolve some of the velocity structure of broad lines. The FOS spectrum shows no evidence for absorption either narrow or broad. For narrow lines, we used the software described in Aldcroft, Bechtold, & Elvis (1994), which iteratively fits for the quasar continuum + emission-line profile and searches for narrow absorption lines that are significant at 4 σ confidence. Within 6000 km s^{-1} of the quasar C IV emission line, the strongest observed absorption line has a rest equivalent width of 1.7 Å, while the detection limit is 2.3 Å. For broad lines, it is more difficult to establish formal detection criteria because the dominant uncertainty is determination of the quasar continuum and emission-line profile. In the case of PG 1416−129, the FOS spectrum is clearly consistent with no BALs. The features which lent an impression of BALs to the *IUE* spectra are revealed to be noise spikes when the C IV region is contrasted between SWP33030 and the FOS spectrum in Figure 2.

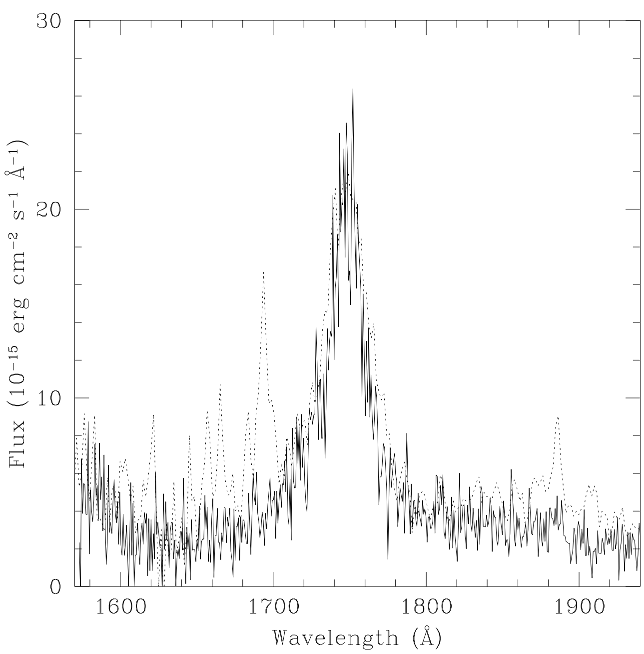

FIG. 2.—C IV region of our *HST* FOS spectrum of 1996 August 23 (*solid line*), and of the highest SNR *IUE* spectrum, SWP33030 from 1988 March 3 (*dashed line*). No evidence for BALs are seen in the *HST* spectrum. The overall line and continuum shape between the two spectra are similar (no normalization has been applied). Flux spikes at 1664 Å and 1694 Å in the *IUE* spectrum are probably spurious; one is a known artifact, and none of the other four UV spectra reproduce these lines.

4. VARIABILITY

There appears to be significant UV variability in PG 1416−129 between the epochs of the observations presented here. During the FOS and *IUE* observations (and from the *IUE* observing logs and the line-by-line spectra) the QSO was always well centered in the aperture. We thus believe the changes in flux to be intrinsic to the QSO, particularly because they are also accompanied by changes in emission-line equivalent width.

Is PG 1416−129 unusually variable? For comparison to published results from *IUE* spectra of a large sample of AGNs, we calculated the standard deviation in continuum flux $f_{50}(\lambda)$ for two 50 Å bins centered at (rest) wavelengths of 1450 and 1625 Å, as outlined in Paltani & Courvoisier (1994; hereafter PC94) (see Table 1). The normalized variability index from N epochs is calculated as

$$\sigma_f(\lambda) = \frac{\sqrt{(1/N-1)\sum_{i=1}^{N}[f_{50,i}(\lambda) - \overline{f_{50}}(\lambda)]^2}}{\overline{f_{50}}(\lambda)} ,$$

and it yields 0.813 and 0.681 at 1450 and 1625 Å, respectively, using all 5 UV spectra of PG 1416−129. At these wavelengths, the UV variability in RQ QSOs of similar luminosity to PG 1416−129, as observed by *IUE* is typically about 34% ± 14% (PC94). PG 1416−129 thus appears to be unusually variable, similar to about 15% of AGNs that vary by more than 50% [i.e., $\sigma_f(\lambda) > 0.5$; PC94].

In addition to UV continuum variability, the C IV emission-line flux and W_λ also changed significantly. There is no significant trend with time for either line or continuum and no correlation of continuum level with line W_λ (i.e., no Baldwin effect).

Is it possible that true BALs in PG 1416−129 weakened or disappeared? Absorption-line variability has been seen both in narrower associated absorbers and in BALQSOs (Koratkar et al. 1996; Barlow 1994). However, no published record exists of any absorption lines in BALQSOs completely disappearing. Rather, BAL variability is seen in about 15% of BALQSOs at the level of 20%–40% (Barlow 1994). Since BALs span a wide range in velocity, most models of BAL cloud outflows require either an ensemble of clouds along the line of sight or winds blown off the surface of the accretion disk (de Kool & Begelman 1995; Murray & Chiang 1995). In either case, only small fractional changes in total absorption column are expected. Thus, since no BALs are presently seen in this QSO, when combined with the other evidence presented here we conclude that there are not now, and never have been, BALs in PG 1416−129.

5. X-RAY & GAMMA-RAY OBSERVATIONS

PG 1416−129 was strongly detected both by *Einstein* and *ROSAT* in the soft X-ray bandpass, yielding consistent spectral fits typical of RQ QSOs. Wilkes & Elvis (1987) found a best-fit power-law slope $\alpha_E = 0.9^{+1.3}_{-0.6}(f_\nu \sim \nu^{-\alpha_E})$ with a neutral (cold) absorption column of $N_H = 1.2 \times 10^{21}$ cm^{-2} with the *Einstein* IPC (0.3–3.5 keV). A *ROSAT* (0.1–2.4 keV) observation in 1992 January yielded similar spectral results ($\alpha_E = 1.2 \pm 0.15$; de Kool & Meurs 1994), again with a cold absorbing column ($N_H = 7 \times 10^{20}$ cm^{-2}) entirely consistent with the measured 21 cm Galactic absorption. Assuming a warm (ionized) absorber, the best-fit spectrum yields $N_H < 2 \times 10^{21}$ cm^{-2}. Even this limit is far below those derived from deep *ROSAT* observations of bona fide BALQSOs presented in GM96.

Earlier hard X-ray results from *Ginga* (1988 February) showed a very flat spectrum between 2 and 20 keV ($\alpha_E \approx 0.1$; Williams et al. 1992), the hardest of all known AGNs. Since the flux at the low end was well matched to the later *ROSAT* fluxes, there was no evidence for variability.

PG 1416−129 varied at energies from 50–150 keV during (1994 September) OSSE observations (Staubert & Maisack 1996). A power-law fit at these energies is considerably steeper ($\alpha_E = 2.2 \pm 0.5$) than for most Seyfert galaxies (~ 1.2). If instead, the power-law slope is fixed at the *Ginga* value (whereby the normalization must have varied), a good fit to the OSSE data requires an exponential cutoff of *e*-folding energy 35 ± 10 keV, similar to many Seyfert galaxies.

Even though weakened soft X-ray emission suggestive of absorption is observed in every BALQSO to date, the exact physical relation between the UV and X-ray absorbers in BALQSOs is as yet unclear. It is thus not obvious whether large changes in BALs would result in concomitant changes in the emergent soft X-ray flux or spectral shape. However, we would expect to see stronger changes in soft X-rays, if any, than at the OSSE range. PG 1416−129 never showed any soft X-ray absorption, either before or after the *IUE* observations. We therefore view substantial variation in the BALs in this QSO as an unlikely explanation of the apparent discrepancy between the *IUE* and *HST* spectra.

6. IS PG 1416−129 A BALQSO?

It is clear from recent *HST* FOS spectra that PG 1416−129 currently shows no BALs. Although there are some features resembling BALs in the *IUE* spectra, we argue for a variety of reasons that PG 1416−129 never exhibited BALs.

From UV data, the *IUE* spectra show spikes more consistent with recognized artifacts, noise, and/or defects such as cosmic rays than with the smooth broad troughs normally seen in BALQSOs. These spikes vary rather conspicuously with time in the *IUE* spectra, but are not visible in our new *HST* FOS spectrum. Furthermore, based on observations of other BALQSOs, it is not likely that there were true BALs in PG 1416−129 that have since vanished.

All soft X-ray observations of PG 1416−129 are consistent with no intrinsic absorption either cold or warm. Furthermore, no substantial variability in either soft X-ray slope or normalization is observed, as might be expected if indeed an absorber showed substantial changes in column or ionization state.

Finally we consider optical emission lines. From a 1990 optical spectrum (Boroson & Green 1992), PG 1416−129 has somewhat weak Fe II λ4500 emission and average [O III]/Hβ, when compared to RQ QSOs of similar redshift. By contrast, BALQSOs typically have strong iron emission (Weymann et al. 1991), and small [O III]/Hβ (at least for low-ionization BALQSOs; Boroson & Meyers 1992). We also note from the *IUE* spectra of PG 1416−129 that N V emission is virtually undetectable, even as an asymmetry in the Lyα profile, while Junkkarinen, Burbidge, & Smith (1987) suggest that N V in BALQSOs is marginally stronger than in non-BALQSOs. As a caveat, some of these effects may depend on redshift and/or luminosity. Unfortunately, since PG 1416−129 is the lowest redshift (putative) BALQSO, no comparison samples of BALQSOs at similarly low redshift and luminosity exist.

Although the *HST* spectrum alone shows definitively that PG 1416−129 has no UV BALs, we take the *IUE*, *HST*, X-ray, and optical spectral evidence together to show that PG 1416−129 is not now, and has never been, a bona fide BALQSO.

7. DISCUSSION

GM96 compared their BALQSO sample to that of L94, who derived a mean α_{ox} of 1.45 ± 0.08 for 10 RQ QSOs. By contrast, the BALQSOs in GM96 have a formal mean $\overline{\alpha_{ox}} = 2.17 \pm 0.1$, including PG 1416−129. By removing PG 1416−129 from the BALQSO sample of GM96, we derive an overall sample mean α_{ox} of 2.24 ± 0.08. Note that this formal "mean" is derived via survival analysis and includes only one detection, at $\alpha_{ox} = 1.94$.

However, α_{ox} is known to depend on optical luminosity, and the BALQSO sample and the L94 samples have significantly different mean l_{opt} (31.5 ± 0.2 vs. 30.5 ± 0.1 in the log, respectively, with or without PG 1416−129). From larger samples (Wilkes et al. 1994; Avni et al. 1995), the expected mean α_{ox} values for the BALQSO and L94 samples are 1.64 ± 0.03 and 1.53 ± 0.02, based only their optical luminosities. The relationship derived in Green et al. (1995) from an even larger, complete, optically selected sample and different statistical techniques predicts a similarly significant ($\sim 3\ \sigma$) difference between two samples of normal RQ QSOs at these luminosities. The observed difference between the predicted mean value of α_{ox} at $\overline{\log l_{opt}} = 31.5$ and that observed for BALQSOs is thus ~ 0.6, about a 7 σ disparity.

PG 1416−129 might have been an outstanding exception that disproves the rule, if indeed it were a true BALQSO. An unabsorbed, X-ray bright BALQSO would be a direct challenge to some recent models that depict BALs as absorption of the nuclear continuum by entrained winds off an accretion disk (Murray & Chiang 1995). However, all bona fide BALQSOs have, upon close examination, been X-ray quiet, suggesting strong absorption in soft X-rays. Conversely, as we demonstrate here for one important case, it appears that QSOs with a normal ratio of optical to soft X-ray flux α_{ox} upon close examination will turn out not to be bona fide BALQSOs. Weak soft X-ray emission is a defining characteristic of BALQSOs.

The result that large α_{ox} is observed in BALQSOs for every case to date, together with the observation that intrinsic soft X-ray absorption is rare in optically selected QSOs (e.g., Laor et al. 1997), suggests that the UV and soft X-ray absorbers have nearly the same covering factor and occupy the same solid angle as seen from the QSO. This indicates that the UV and X-ray absorbers may be closely related, if not identical.

We note that true variability has been detected in UV BAL troughs: about 15% of BALQSOs show variability in the residual UV intensity (rather than in the velocity structure) at the $\sim$20%–40% level, indicating lower limits to column changes of about 10^{14} cm^{-2} (Smith & Penston 1988; Barlow et al. 1992; Barlow 1994). An ensuing change in the measured soft X-ray absorption, however, has not yet been observed. Although we here rule out PG 1416−129 from consideration as a BALQSO, a demonstration of correlated variability between BALs and soft X-ray flux would provide strong evidence that UV and soft X-ray absorbers are physically associated in true BALQSOs. Such studies present a daunting task for the current generation of X-ray telescopes, given the weak soft X-ray fluxes of BALQSOs, but would be feasible with the larger effective areas of the Advanced X-ray Astronomy Facility, X-ray Multimirror Mission, or future high-throughput X-ray spectroscopy missions. These UV/X-ray variability studies could also determine whether BAL variability is the result of a change in column density (e.g., due to motion of the absorber along the line of sight) or in ionization.

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