Observational Similarities and Potential Connections Between Luminous Ultrasoft NLS1s and BALQSOs

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Abstract

Luminous ultrasoft NLS1s and low-ionization BALQSOs share many properties, and they both represent important extremes of the active galaxy phenomenon. We briefly discuss their observational similarities as well as potential physical connections between them, concentrating on the X-ray point of view. We present several ways by which potential connections might be further tested.

Key words: galaxies: active; QSOs: general; X-rays: galaxies

1 Introduction

It is clear from the papers presented at this workshop that studies of ultrasoft Narrow-Line Seyfert 1 galaxies (NLS1s) have undergone exciting growth over the past few years. Progress has been made defining their phenomenological properties; NLS1s show extreme spectral shapes and variability at a variety of wavelengths (e.g., X-ray, optical and radio). While a solid physical understanding of the origin of their extreme properties has not yet emerged, they are plausibly objects with high values of the mass accretion rate relative to the Eddington rate ($\dot{M}/\dot{M}_{\rm Edd}$).

In this paper, we will briefly discuss potential connections between luminous NLS1s and Broad Absorption Line QSOs (BALQSOs), concentrating on the X-ray point of view. We will informally advocate such connections to the greatest extent possible in an attempt to stimulate further work in this area. In the X-ray band, even the basic phenomenological properties of BALQSOs are poorly known (see §2). Because of their low X-ray fluxes, the present observations do not allow one to draw a characteristic X-ray spectral energy distribution for a BALQSO. However, with the advent of the new generation of X-ray observatories, one hopes that X-ray studies of BALQSOs will undergo exciting growth in the coming decade comparable to that achieved for NLS1s in the past few years.

2 X-rays from Broad Absorption Line QSOs

Most luminous QSOs are thought to have BAL outflows which comprise a major part of the nuclear environment (e.g., Weymann 1997, hereafter W97). Furthermore, the BAL phenomenon has interesting connections with the 'radio volume control' of QSOs (e.g., §4 of Becker et al. 2000 and references therein), and BAL outflows may clear gas from QSO host galaxies and thereby affect star formation and QSO fueling over cosmic timescales (e.g., Fabian 1999). With X-rays, one would like to study the BAL wind in absorption to determine properties such as its column density, ionization state, abundances, and covering factor. One would also like to probe the nuclear geometry (e.g., using the iron Kα line and X-ray variability) and determine if BALQSOs have normal QSO X-ray continua underlying their absorption.

Studies with *ROSAT*, *ASCA*, and *BeppoSAX* have established that BALQSOs are very weak emitters in the 0.1–2.0 keV band, and that with a few notable exceptions they are also weak when studied with more penetrating 2–10 keV X-rays (e.g., Green & Mathur 1996; Gallagher et al. 1999; Mathur et al. 2000; see Brandt et al. 2000 for a review). The higher detection fraction obtained in hard X-rays ($\approx 50\%$) is generally consistent with the presence of heavy internal X-ray absorption. If BALQSOs have normal underlying QSO X-ray continua, then large column densities of $\gtrsim 5 \times 10^{23}$ cm^{-2} are required to extinguish the X-ray emission in several cases (see Figure 1). These large X-ray column densities have important physical implications. For example, if the X-ray absorption occurs in gas at a distance $\gtrsim 3 \times 10^{16}$ cm outflowing with a significant fraction of the terminal velocity measured from the UV BALs, large mass outflow rates ($\dot{M}_{\rm outflow} \gtrsim 5$ M$_\odot$ yr^{-1}; $\dot{M}_{\rm outflow} \gtrsim \dot{M}_{\rm accrete}$) and kinetic luminosities ($L_{\rm kinetic} \gtrsim L_{\rm ionizing}$) are derived. While these can be reduced if the X-ray and UV absorbers in BALQSOs differ, the possibility of such powerful outflows demands further study.

At present, it has been possible to measure the intrinsic X-ray continuum shape well for only one 'bona-fide' BALQSO, PG 2112+059 ($z = 0.46$; Gallagher et al. 2000, in preparation; see Jannuzi et al. 1998 for the UV spectrum). This object is one of the most luminous PG QSOs at $z < 0.5$ with $M_{\rm V} = -27.3$. Our recent ASCA spectra show strong absorption below ≈ 2 keV, but the rest-frame 3–10 keV continuum appears relatively unaffected by absorption (see Figure 2). We measure a power-law photon index of $\Gamma_{3-10} = 1.94^{+0.23}_{-0.21}$ (90%

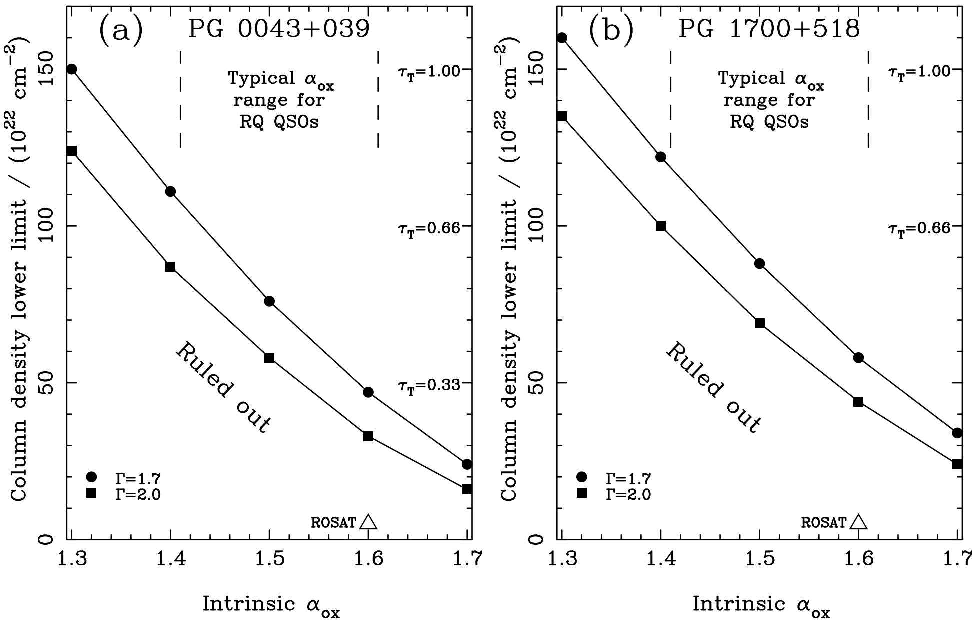

Fig. 1. Column density lower limits for (a) PG 0043+039 and (b) PG 1700+518 derived using *ASCA* SIS0 data. We show the inferred column density lower limit as a function of the intrinsic (i.e., absorption-corrected) value of $\alpha_{\rm ox}$ (the slope of a nominal power law connecting the rest-frame flux density at 2500 Å to that at 2 keV). The square data points are for an X-ray photon index of $\Gamma = 2.0$, and the circular dots are for an X-ray photon index of $\Gamma = 1.7$. The open triangle at $\alpha_{\rm ox} = 1.6$ illustrates the typical BALQSO column density lower limit found based on *ROSAT* data. The numbers along the right-hand sides of the panels show the Thomson optical depth of the corresponding column density. The column density lower limits shown in this plot are for absorption by neutral gas with solar abundances. Ionization of the gas can significantly raise the required column density. PG 0043+039 has many characteristics typical of low-ionization BALQSOs, but at present there is no convincing evidence for BALs due to low-ionization transitions (see Turnshek et al. 1994 for details). PG 1700+518 is a low-ionization BALQSO. From Gallagher et al. (1999).

confidence). This first detection of a typical power-law X-ray continuum for a BALQSO is reassuring and argues that BALQSOs indeed have normal X-ray power sources underneath their absorption.

3 Observational Comparison of NLS1s and BALQSOs

Several papers have qualitatively commented on observational similarities between NLS1s[1] and BALQSOs (e.g., Boroson & Meyers 1992, hereafter BM92; Brandt et al. 1997; Laor et al. 1997; Lawrence et al. 1997; Leighly et al. 1997).

[1] The main interest here is in the majority of NLS1s that lie toward the strong Fe II, weak [O III] end of Boroson & Green (1992, hereafter BG92) eigenvector 1

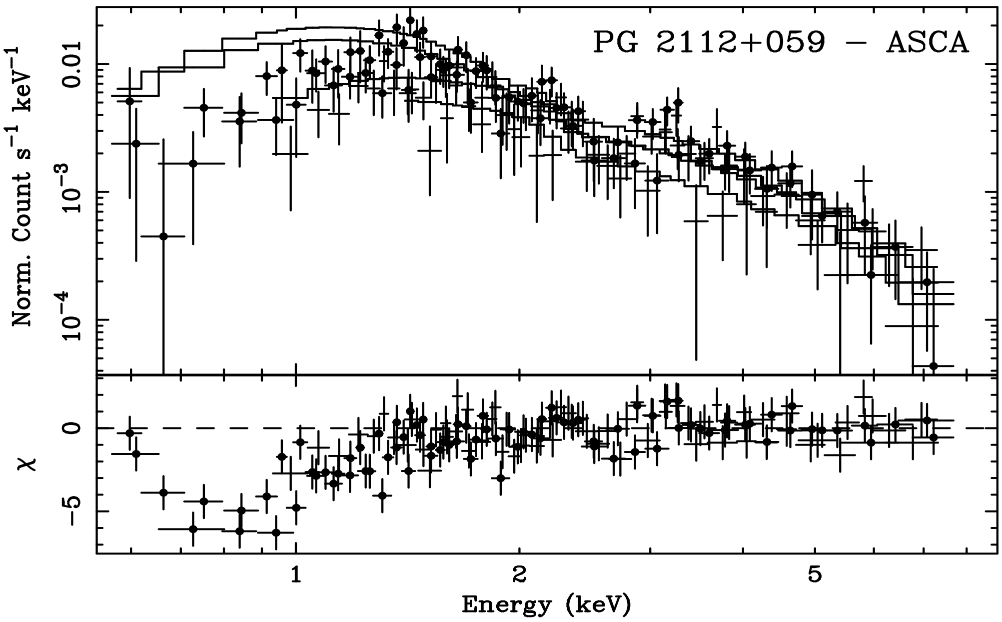

Fig. 2. ASCA SIS and GIS observed-frame spectra of the BALQSO PG 2112+059. A power-law model has been fit to the data above 2 keV and then extrapolated back to show the deviations at low energies. The ordinate for the lower panel (labeled χ) shows the fit residuals in terms of σ with error bars of size one. Note the systematic absorption residuals at low energies. From Gallagher et al. (2000, in preparation).

Two demographic facts must immediately be considered: (1) NLS1-type objects are found over a wide range of luminosity ranging from low-luminosity Seyferts such as NGC 4051 to luminous QSOs such as PHL 1092, while BALs are seen only in luminous QSOs, and (2) most and perhaps all QSOs have BAL regions while most QSOs do not show the characteristic 'NLS1' properties. The first suggests that only the luminous NLS1s may be unified with BALQSOs, and the rest of this paper shall focus on such objects. Fact 2 is double-edged: while it is implausible to try to unify *all* BALQSOs and luminous NLS1s, it appears that there must be *some* connection between them. The objective is then to identify the subset of BALQSOs that are the 'cousins' of luminous NLS1s.

Based on a comparison of Na I emission in I Zwicky 1 and BALQSOs, BM92 suggested that "I Zwicky 1 is a promising candidate for a Mg II BALQSO in which our line of sight does not pass through a BAL cloud." Low-ionization BALQSOs, showing absorption by species such as Mg II and Al III, comprise 10–15% of the BALQSO population and often have reddened continua and extremely weak [O III] emission (e.g., Weymann et al. 1991, hereafter W91; BM92; Sprayberry & Foltz 1992). They are thought to have large amounts of relatively cool gas and dust in their nuclei, and they are sometimes postulated

(i.e., the 'I Zwicky 1 objects'). We use the term 'NLS1s' loosely to refer to such objects.

Table 1
Selected Multiwavelength Properties of NLS1s and Low-Ionzation BALQSOs

Property	NLS1s	Low-Ionization BALQSOs
[O III] luminosity	Low	Low (BM92; Turnshek et al. 1997)
Optical Fe II/Hβ	Large	Large* (BM92; Lawrence et al. 1997)
Balmer line asymmetry	Strong blue wings	Strong blue wings (BM92)
Hβ FWHM	Small	See the text of §3 (BM92)
Radio loudness	Generally quiet	Generally quiet (W97; Becker et al. 2000)
Far-infrared luminosity	Generally high	Generally high (Low et al. 1989; W91)

* The low-ionization BALQSOs also have stronger UV Fe II emission than non-BALQSOs (W91).

to be young, recently activated QSOs. It appears that low-ionization BALQSOs have larger BAL-region covering factors ($f_{\rm c,BAL}$) than typical BALQSOs (e.g., BM92; Turnshek et al. 1997).

Luminous NLS1s and low-ionization BALQSOs appear to share many common properties, lending plausibility to a connection between them. These are listed in Table 1, where a few relevant references for the low-ionization BALQSO properties are also given. In several cases the low-ionization BALQSO properties have only been measured in small and statistically incomplete samples; better systematic studies are clearly needed so that one can reason armed with more than anecdotal evidence. Systematic Hβ FWHM measurements are in particular required. The four low-ionization BALQSOs in BM92 have Hβ FWHM of $\approx$ 2000–3000 km s^{-1}, fairly narrow for high luminosity objects. However, there also appear to be at least several low-ionization BALQSOs that have substantially broader Hβ FWHM of 4000–6000 km s^{-1} (e.g., McIntosh et al. 1999; M. Brotherton, private communication). While a few radio-loud NLS1s and low-ionization BALQSOs exist (e.g., Becker et al. 2000; Grupe et al. 2000), both classes are in general conspicuously radio quiet relative to Broad-Line Seyfert 1s and high-ionization BALQSOs.

Empirically, luminous NLS1s and low-ionization BALQSOs appear quite different in X-rays. Luminous NLS1s are strong emitters of soft X-rays while low-ionization BALQSOs are very weak in this band (see §2). However, this may just be due to absorption in low-ionization BALQSOs that prevents us from seeing the underlying X-ray continuum; the intrinsic X-ray continua of low-ionization BALQSOs could be very similar to those of NLS1s. If better data eventually show, for example, that many low-ionization BALQSOs have unusually steep X-ray power laws with photon indices of Γ = 2.0–2.5, this would strongly suggest a connection with luminous NLS1s (compare with

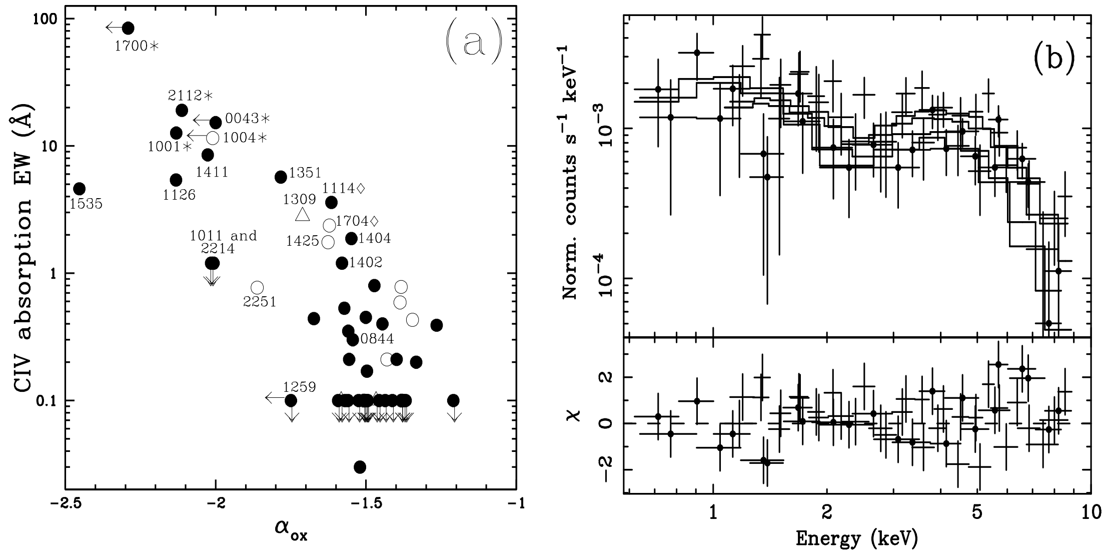

Fig. 3. (a) Plot of $\alpha_{\rm ox}$ versus C IV λ1549 absorption-line EW (in the rest frame) for the BG92 QSOs with UV coverage. Following BG92, solid dots are radio-quiet QSOs, open triangles are core-dominated radio-loud QSOs, and open circles are lobe-dominated radio-loud QSOs. Particularly interesting QSOs are labeled by the right ascension part of their name; note the extreme location of PG 1535+547. An asterisk to the right of an object's name indicates that it is a BALQSO or probable BALQSO, and a diamond indicates that it is known to have an X-ray warm absorber. From Brandt, Laor & Wills (2000). (b) ASCA SIS and GIS observed-frame spectra of PG 1535+547. A power-law model with absorption partially covering the X-ray continuum is shown and provides an acceptable fit to the data. The ordinate for the lower panel is as per Figure 2. From Gallagher et al. (2000, in preparation).

Brandt, Mathur & Elvis 1997).[2]

It appears likely that absorbing gas capable of completely obscuring the intrinsic X-ray continuum is present in the nuclei of some NLS1s. A range of absorption strengths is already known to be present and is being extended to nearly BALQSO-level column densities with new observations. Several NLS1s are known to have X-ray warm absorbers (e.g., Brandt et al. 1997), and 'anomalous' absorption around 1 keV may be present in some NLS1s as well (e.g., Leighly et al. 1997). The 1 keV absorption features have been speculated to be associated with highly ionized gas ($N_{\rm H} \sim 2 \times 10^{21}$ cm^{-2}) flowing out of the nucleus at 0.2–0.3c. However, other explanations are also plausible (e.g., Nicastro, Fiore & Matt 1999), and the evidence requires substantial improvement. Heavier absorption still is known to be present in Mrk 507 (Iwasawa, Brandt & Fabian 1998) and the soft X-ray weak PG 1535+547 (Mrk 486;

[2] PG 2112+059, the only BALQSO with a measured X-ray continuum shape (see §2), does not have published spectral coverage of the key Mg II region for determining if it is a high-ionization or low-ionization BALQSO.

Gallagher et al. 2000, in preparation; also see Brandt, Laor & Wills 2000). The X-ray absorption in Mrk 507 is complex but appears to be mainly due to mildly ionized gas with a column density of $\approx (2\text{–}3)\times10^{21}$ cm^{-2}. Better UV spectra are now needed to search for UV absorption lines from this object. PG 1535+547 shows the heaviest X-ray absorption known in a NLS1; modeling it with neutral gas requires a column density of $\approx 1.2\times10^{23}$ cm^{-2} and a covering fraction of $\approx 90\%$ (see Figure 3). Unfortunately, the photon index of the underlying power law is poorly constrained at present ($\Gamma = 2.02^{+0.92}_{-0.95}$) due to limited photon statistics; spectra from *XMM* should reveal if the power law is unusually steep. The characteristics of the X-ray absorption are likely related to the observed UV absorption and high polarization (e.g., Smith et al. 1997), and the strength of the X-ray absorption is remarkable in a type 1 object. The derived column density is close to that seen for BALQSOs as well as the tori of some Seyfert 2 galaxies. In another example, based on a steep X-ray power-law continuum and strong variability, Iwasawa et al. (1996) have suggested that an obscured NLS1 nucleus may reside in the Seyfert 2 galaxy IRAS 18325–5926.

4 Physical Interpretation

X-ray studies of ultrasoft NLS1s suggest that they are characterized by extreme values of a primary physical parameter, probably $\dot{M}/\dot{M}_{\rm Edd}$ (e.g., Brandt & Boller 1999). Observations at optical and UV wavelengths have also revealed that NLS1s have large amounts of dense ($\sim 10^{11}$ cm^{-3}), low-ionization, line-emitting gas in their Broad Line Regions (BLRs; e.g., BG92; Wills et al. 1999; Kuraszkiewicz et al. 2000). However, the physical relation between high $\dot{M}/\dot{M}_{\rm Edd}$ and dense BLRs remains unclear. Wills et al. (1999) suggest that gas injected into the nucleus by starburst activity may lead to both high $\dot{M}/\dot{M}_{\rm Edd}$ and high BLR gas densities.

The most straightforward way to connect luminous NLS1s and low-ionization BALQSOs would be to postulate that both are characterized by high $\dot{M}/\dot{M}_{\rm Edd}$. It would then just be the presence or absence of BAL material along the line of sight that determines the classification of a given high $\dot{M}/\dot{M}_{\rm Edd}$ object. The amount of line-of-sight material could naturally be set by the nuclear orientation, although random fluctuations in the number of intervening BAL 'clouds' could perhaps also be relevant. The average value of $f_{\rm c,BAL}$ for high $\dot{M}/\dot{M}_{\rm Edd}$ objects would set the relative number densities of luminous NLS1s and low-ionization BALQSOs. While $\langle f_{\rm c,BAL}\rangle$ for high $\dot{M}/\dot{M}_{\rm Edd}$ objects could plausibly be as large as $\sim 50\%$ given likely selection effects against low-ionization BALQSOs (e.g., Goodrich 1997; Krolik & Voit 1998), a value much larger than this would probably overpredict the number of low-ionization BALQSOs relative to luminous NLS1s.

The scenario of the previous paragraph has a couple of attractive features. First of all, the strong, high $f_{\rm c,BAL}$ outflows of low-ionization BALQSOs might well result from high $\dot{M}/\dot{M}_{\rm Edd}$. Accreting systems with high $\dot{M}/\dot{M}_{\rm Edd}$ have a greater ability to radiatively drive outflows due to their larger photon luminosities per unit gravitational mass. Furthermore, radiation-dominated analogues of advective inflow-outflow solutions may become important at high $\dot{M}/\dot{M}_{\rm Edd}$ (e.g., §5 of Blandford & Begelman 1999; Blandford & Begelman, in preparation). The scenario of the previous paragraph may also be able to explain why NLS1s have unusually dense BLRs without requiring a secondary agent, such as starburst activity. Some of the gas accelerated as a result of the high value of $\dot{M}/\dot{M}_{\rm Edd}$ is likely to end up in the BLR, where it can cool and increase the local density (see §8.2 of Brandt, Laor & Wills 2000).

If high-velocity outflows with large covering factors are present in the nuclei of all luminous active galaxies with high $\dot{M}/\dot{M}_{\rm Edd}$, one might hope to occasionally see 'occultations' when material moves through the line of sight. Such occultations have been seen in several high $\dot{M}/\dot{M}_{\rm Edd}$ X-ray binaries where they can cause dramatic X-ray variability, sometimes without strong spectral changes (e.g., Dower, Bradt & Morgan 1982; Brandt et al. 1996). An intriguing, speculative possibility is that *some* of the extreme X-ray variability seen in the most variable NLS1s is due to occultations. The large-amplitude variability seen in IRAS 13224–3809, for example, is difficult to explain as true luminosity changes on energetic grounds. An occultation model is able to explain the variability seen on a timescale of days provided the occulting material is quite thick and moves rapidly across the line of sight (Boller et al. 1997). While BAL winds are both thick and rapidly moving, they probably could not cause the variability because they originate too far from the nucleus. However, highly ionized material launched at smaller radii (e.g., the 'hitchhiking gas' of Murray et al. 1995) may be relevant.

5 Future Prospects for X-ray Studies

Observations with the new generation of X-ray observatories should be able to test some of the ideas discussed above. For example, systematic measurements of the X-ray continuum shapes of both high-ionization and low-ionization BALQSOs can test if low-ionization BALQSOs have unusually steep power-law continua with photon indices of $\Gamma = 2.0$–2.5. If they do, this would immediately suggest a connection with luminous NLS1s and high $\dot{M}/\dot{M}_{\rm Edd}$, and it is encouraging to see that some progress is now being made measuring BALQSO X-ray continua (see §2 and §3). Unusually strong X-ray variability from low-ionization BALQSOs would also suggest a connection with luminous NLS1s. Furthermore, high-quality X-ray and UV spectroscopy of moderately absorbed NLS1s should help to bridge the gap between unabsorbed NLS1s and the heavily absorbed BALQSOs. For at least one NLS1, PG 1535+547, the X-ray column density is comparable to that inferred for BALQSOs, and UV absorption is also present (see §3). The NLS1s with the strongest known absorption (e.g., Mrk 507 and PG 1535+547) unfortunately fall short of having QSO-level luminosities; hopefully more luminous examples will be found.

Finally, if low-ionization BALQSOs and luminous NLS1s are indeed related, one might hope to see 'transitions' between these two types of objects. These could occur due to abrupt changes in the flow geometry of the absorbing material. Strong changes in the absorption-line properties of some low-ionization BALQSOs have already been seen (e.g., Boroson et al. 1991; Junkkarinen, Cohen & Hamann 1999), although these appear to occur on fairly long timescales. Perhaps at the Y3K workshop on NLS1s there will be a celebration when Mrk 231 undergoes such a transition and ends up looking something like PHL 1092. This would be a sight to rival the Y2K launch of *XMM*!

6 Acknowledgments

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