Ultrasoft Narrow-Line Seyfert 1 Galaxies: What Physical Parameter Ultimately Drives the Structure and Kinematics of Their Broad Line Regions?

W. N. Brandt

Department of Astronomy, The Pennsylvania State University, University Park, PA 16802

Th. Boller

Max-Planck-Institut für Extraterrestrische Physik, 85740 Garching, Germany

Abstract. Recent X-ray observations have greatly advanced the study of ultrasoft Narrow-Line Seyfert 1 galaxies and have revealed strikingly clear correlations between optical emission line properties and the shape of the X-ray continuum. In particular, the strength of the soft X-ray excess relative to the hard X-ray power law appears to be directly related to the 'primary eigenvector' of Boroson & Green. Ultrasoft Narrow-Line Seyfert 1s lie toward one extreme of the primary eigenvector, and their extreme X-ray spectral, X-ray variability and optical emission line properties suggest that they have extremal values of a primary physical parameter. We discuss efforts to identify this parameter and the observational evidence that it is the fraction of the Eddington rate at which the supermassive black hole is accreting.

1. Narrow-Line Seyfert 1s: An Extreme of Seyfert Activity

Many Seyfert galaxies and QSOs show highly-luminous and variable soft X-ray excess emission from their black hole regions. There is moderately good evidence that this emission is the high-energy tail of the 'Big Blue Bump' (BBB) that rises through the optical and ultraviolet. Together, the BBB and soft excess dominate the bolometric luminosity and provide the primary source of energy for the strong, broad emission lines that were the focus of this conference.

Clear relations are now apparent between the strength of the soft X-ray excess (relative to the underlying X-ray power law) and the FWHM of the optical Balmer lines, particularly Hβ (e.g. Boller, Brandt & Fink 1996; Laor et al. 1997). This is shown in Fig. 1a, where the photon index from a power-law fit to *ROSAT* data is used as a first-order way to quantify the relative strengths of the soft excess and power law. All of the Seyferts/QSOs with the strongest and hottest soft X-ray excesses are Narrow-Line Seyfert 1 class galaxies (NLS1). NLS1 have relatively narrow Balmer lines with FWHM of only 500–2000 km s^{-1}, and their interesting optical properties have been known for many years (e.g. Bergeron & Kunth 1980; Gaskell 1985; Osterbrock & Pogge 1985; Halpern &

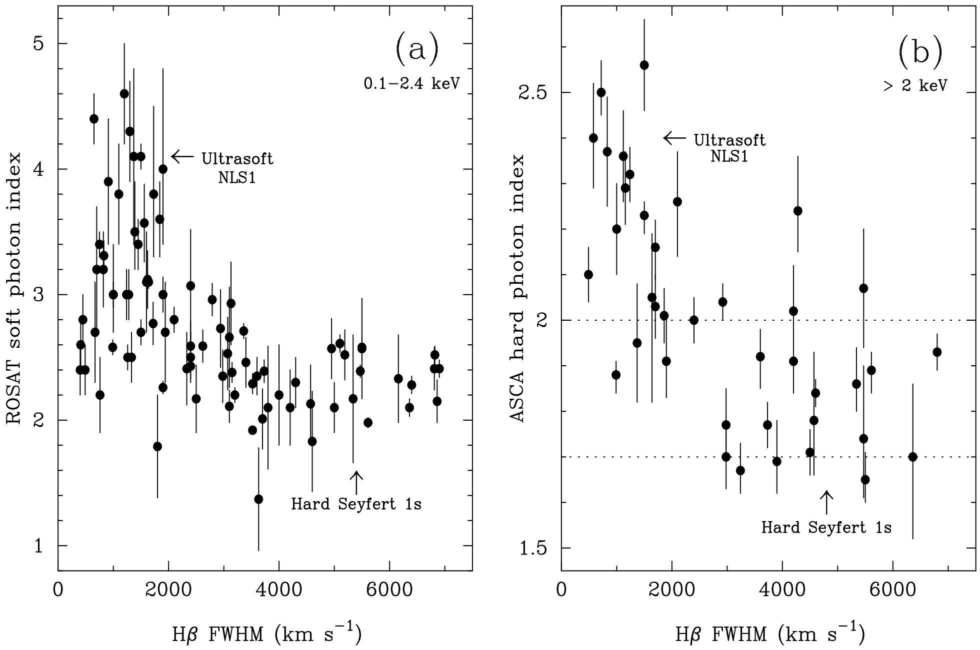

Figure 1. Relations between X-ray continuum shape and Hβ FWHM for Seyfert 1 galaxies and QSOs. **(a)** *ROSAT* photon index from a power-law fit versus Hβ FWHM. In this band (0.1–2.4 keV), both the soft X-ray excess and the underlying power law contribute to the spectrum (compare with Fig. 3). The photon index serves to quantify the relative strengths of these two components. Note the generally steep NLS1 spectra and the apparent absence of objects with both steep soft X-ray slopes and Hβ FWHM larger than $\approx$ 2000 km s^{-1}. **(b)** *ASCA* hard X-ray photon index versus Hβ FWHM (note that the ordinate scale is smaller than in the left hand panel). This diagram has been constructed using only data above 2 keV, and hence only the underlying power law contributes to the spectrum (again compare with Fig. 3). The horizontal dotted lines show the 'canonical' range of Seyfert 1 photon indices. Note that many ultrasoft NLS1 have hard photon indices that lie above the 'canonical' range of 1.7–2.0. This shows that there is substantially more 2–10 keV continuum diversity than was previously recognized.

Oke 1987). For example, NLS1 are prototypical emitters of strong optical Fe II emission, and they often have relatively weak [O III] emission. Due to their strong soft X-ray emission, NLS1 are found in abundance in soft X-ray-selected surveys (e.g. Puchnarewicz et al. 1992; Grupe et al. 1998). They comprise a significant ($\sim$ 20–30%) but often overlooked part of the Seyfert/QSO population.

NLS1 do not appear to form a distinct class but are instead connected to the 'standard' broad-line Seyfert 1s through a continuum of properties (e.g. Goodrich 1989). In particular, NLS1 lie toward one extreme of the strong set of optical emission line correlations studied by Boroson & Green (1992a; hereafter

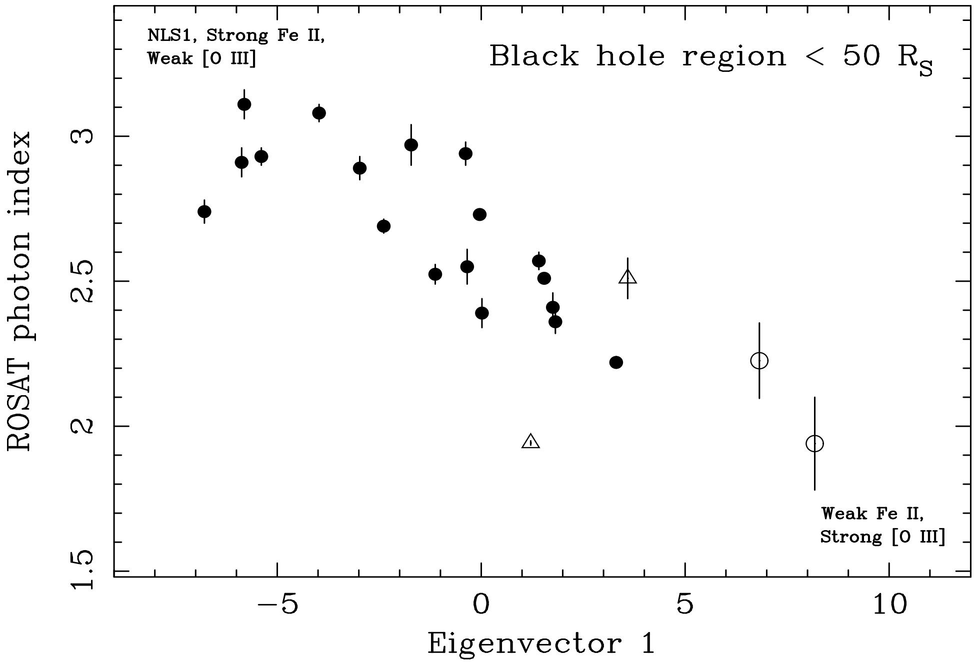

Figure 2. *ROSAT*-band (0.1–2.4 keV) photon index versus the value of the BG92 primary eigenvector for the PG QSOs from Laor et al. (1997). This figure should be compared with fig. 2 of Boroson & Green (1992b). Solid dots are radio-quiet QSOs, open triangles are core-dominated radio-loud QSOs, and open circles are lobe-dominated radio-loud QSOs. A Spearman rank-order test gives a Spearman $r_{\rm S}$ value of -0.834, which is significant with over 99.9% confidence. This correlation is substantially stronger than and probably responsible for the effect discussed by Corbin (1993). The one outlying open triangle is 3C273, which appears to have a time-variable spectral shape and ionized absorption.

BG92). These correlations emerged as the 'primary eigenvector' of the Principal Component Analysis (PCA) performed by BG92, and they relate Balmer line width/shape, Fe II emission and [O III] emission. The primary eigenvector represents the *strongest* set of optical emission line correlations found among QSOs, and several ultraviolet line properties also appear to be connected with the primary eigenvector (e.g. Wills et al. 1998). BG92 suggested that their primary eigenvector was 'driven' by an important, underlying physical parameter, and they speculated that this parameter might be the fraction of the Eddington rate at which the supermassive black hole is accreting ($\dot{M}/\dot{M}_{\rm Edd}$).

As expected from the discussion above, the *ROSAT*-band spectral slope also shows a remarkably strong correlation with the BG92 primary eigenvector (see Fig. 2). In fact, it appears that *ROSAT* spectral slope correlates more tightly with the primary eigenvector than with any of the individual optical emission line properties used to define the eigenvector (see Brandt & Boller 1998 for details). Since the highly-luminous and rapidly-variable X-ray emission

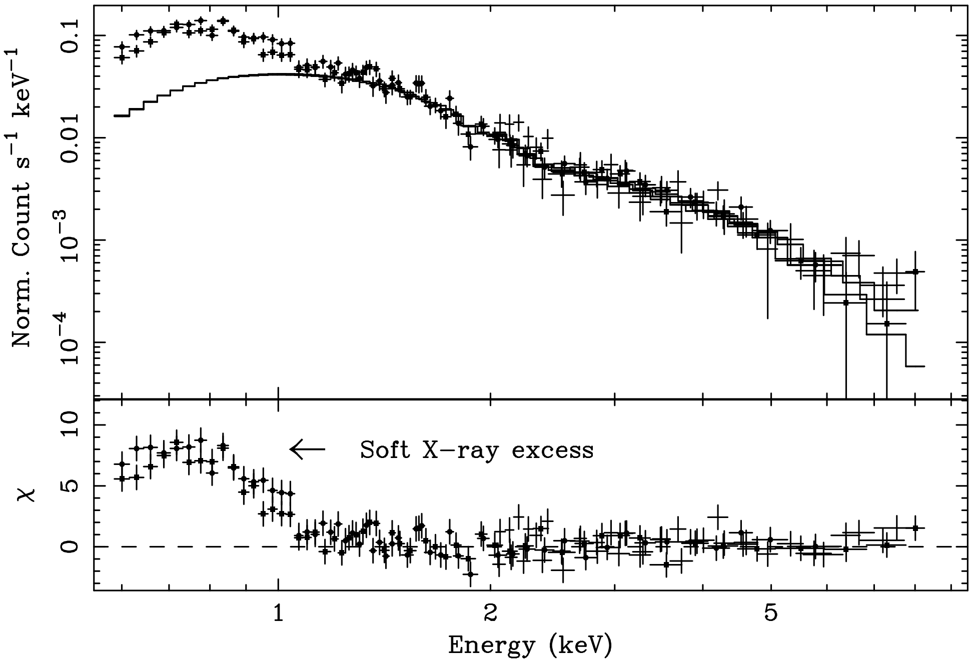

Figure 3. *ASCA* spectra of the ultrasoft NLS1 H 0707–495. A power-law model has been fit to the data above 2 keV and extrapolated downward in energy to show the systematic deviations from the model at low energies. Note the prominent soft X-ray excess emission that dominates the spectrum below $\approx$ 1.1 keV. This emission is even stronger at energies below the *ASCA* band. The ordinate for the lower panel (labeled χ) shows the fit residuals in terms of σ with error bars of size one.

is thought to be formed within $\sim$ 50 Schwarzschild radii ($50R_{\rm S}$) of the supermassive black hole, the correlation suggests that the physical parameter driving the eigenvector also ultimately originates within $\sim 50R_{\rm S}$. A compact origin is certainly expected if $\dot{M}/\dot{M}_{\rm Edd}$ drives the eigenvector, but it is not proper proof of this hypothesis. One would like to find compelling evidence that clinches the $\dot{M}/\dot{M}_{\rm Edd}$ interpretation, since this would be an important advance:

- We would gain a way to gauge the primary driver of these accretion-powered sources.
- We would determine the root cause of the extreme X-ray spectral and variability properties of ultrasoft NLS1.
- We would isolate one of the main effects shaping the structure and kinematics of the Broad Line Region (BLR) and Narrow Line Region (NLR).

While compelling evidence has not yet been found, it is clear that research directed towards this goal is driving our theoretical understanding of Seyferts and QSOs more generally. In the rest of this article, we will describe some of the progress that has been made and briefly examine future prospects.

2. Optical Emission Line Properties

The most notable optical property of ultrasoft NLS1 is their narrow Balmer lines, and these can be plausibly explained in terms of a model which postulates high $\dot{M}/\dot{M}_{\rm Edd}$ (e.g. Boller, Brandt & Fink 1996; Laor et al. 1997). The basic assumptions of this model are that (1) the motions of the BLR clouds are virialized in the gravitational potential of the central black hole and (2) the size of the BLR is primarily a function of luminosity (perhaps due to the sublimation of dust). Consider a set of QSOs that have similar luminosities and hence have BLRs of about the same size. The objects of this set with higher $L/L_{\rm Edd}$ will have smaller-mass black holes. Hence the virialized motions of their BLR clouds will have smaller velocity and their BLR lines will be narrower (see section 4.7 of Laor et al. 1997 for the corresponding equations).

While this basic picture admittedly lacks the details present in more sophisticated models of the BLR, it does demonstrate that there is a plausible connection between Balmer line width and $\dot{M}/\dot{M}_{\rm Edd}$. If one also takes into account the shape of the ionizing continuum, this further enlarges the relative sizes of the BLRs of ultrasoft NLS1 and strengthens the dependence on $\dot{M}/\dot{M}_{\rm Edd}$ (see Wandel 1997). The currently available observations of optical line variability appear to be consistent with the basic picture outlined above (see Giannuzzo et al. 1998).

It is more difficult at present to state a direct, simple reason why strong optical Fe II emission and weak [O III] emission should arise when $\dot{M}/\dot{M}_{\rm Edd}$ is large. However, some suggestions have been put forward (e.g. Boroson & Green 1992b) and need further investigation. We briefly return to the topic of Fe II below when describing the power-law X-ray continua of ultrasoft NLS1.

3. Broad-Band X-ray Continua

The X-ray luminosities of most ultrasoft NLS1 appear to be dominated by the emission from the strong and hot ($\gtrsim$100 eV) soft X-ray excess. This component can dominate their X-ray spectra up to $\approx$ 1.5 keV, and it can be acceptably modeled (at least in a statistical sense) using blackbodies or multi-temperature accretion disk models. The spectral character of this radiation should reflect the structure, temperature and dynamics of the inner accretion disk. However, current observational limitations have hindered the precision testing of physical models for the soft excess. These limitations should be removed over the next few years with the launches of the next generation of X-ray observatories.

The $>$ 2 keV spectra of ultrasoft NLS1 were poorly studied until recently, largely due to the fact that few of these objects were detected in hard X-ray sky surveys. *ASCA* and *SAX* have allowed the first systematic studies of ultrasoft NLS1 in the 2–10 keV band. While their spectra do appear to 'break' to power laws above 2 keV (see Fig. 3, for example), these power laws show a wider range of slopes than has been seen among hard X-ray-selected type 1 objects (Brandt, Mathur & Elvis 1997; see Fig. 1b). Steep power-law photon indices of $\approx$ 2.0–2.6 appear to be fairly common for ultrasoft NLS1, and these directly demonstrate that there is substantially more 2–10 keV continuum diversity among Seyferts and QSOs than was previously recognized. The origin of this spectral diversity needs to be better understood. Since the hard X-ray power law is thought to be produced by the Compton upscattering of disk photons in an accretion disk corona, its photon index should provide information about the Thomson depth, temperature, and bulk motions of the corona. A steep 2–10 keV power law could arise as the result of a thinner corona (e.g. Poutanen, Krolik & Ryde 1997), a cooler corona (e.g. Pounds, Done & Osborne 1995), or a corona with large bulk motions (e.g. Ebisawa, Titarchuk & Chakrabarti 1996).

The strong soft X-ray components and steep power laws seen from many ultrasoft NLS1 are reminiscent of Galactic black hole candidates (GBHC) accreting in their ultrasoft high states. When GBHC make transitions to their high states, their hard photon indices increase from 1.5–2.0 to 2.0–2.5 (compare with Fig. 1b). If an analogy between high state GBHC and ultrasoft NLS1 is appropriate, then the steep power laws of ultrasoft NLS1 again suggest that these systems are accreting with relatively high $\dot{M}/\dot{M}_{\rm Edd}$.

The steep > 2 keV continua of ultrasoft NLS1 with strong optical Fe II emission also have implications for models of radiative Fe II formation. In the absence of any strong spectral flattening above the *ASCA* band, the total hard X-ray emission from these objects will be weak. This provides evidence against models of radiative Fe II formation that require strong hard X-ray emission such as the Compton-heating model of Collin-Souffrin, Hameury & Joly (1988). Other radiative heating models predict an anticorrelation between Fe II/Hβ and hard X-ray luminosity (see section 4 of Joly 1993 and references therein), and this appears to be what the currently available X-ray data suggest.

4. X-ray Variability

Strong variability in an ultrasoft NLS1 appears to have been first noted by Zwicky (1971), who commented on optical 'outbursts' in I Zwicky 1 due to 'implosive and explosive events.' He urged monitoring of this variability, and he would perhaps be happy to see that X-ray monitoring of ultrasoft NLS1 (also sometimes referred to as 'I Zwicky 1 objects') has recently proven quite fruitful.

Ultrasoft NLS1 generally (but not always) appear to exhibit the most extreme X-ray variability found among radio-quiet Seyferts/QSOs. For example, Boller et al. (1997) have discovered persistent, giant-amplitude (factors of 35–60) X-ray variability events from the ultrasoft NLS1 IRAS 13224–3809 (see Fig. 4; also see Otani, Kii & Miya 1996). The observed light curve consists of multiple strong flares interspersed among relatively quiescent periods, a characteristic of nonlinear variability (see Vio et al. 1992), and Boller et al. (1997) have demonstrated that the variability is in fact nonlinear.[1] This is physically important because it rules out the possibility that the variability is produced by the simple linear superposition of a large number of independent emission regions; rather the emission regions must interact in a nonlinear manner. Another impressive example of extreme X-ray variability has recently been provided by an 18-day HRI monitoring campaign on the highly-luminous NLS1-class QSO PHL 1092

[1]Nonlinear X-ray variability has also been seen in other ultrasoft NLS1 including PKS 0558–504 (Remillard et al. 1991) and NGC 4051 (Green, McHardy & Done 1998).

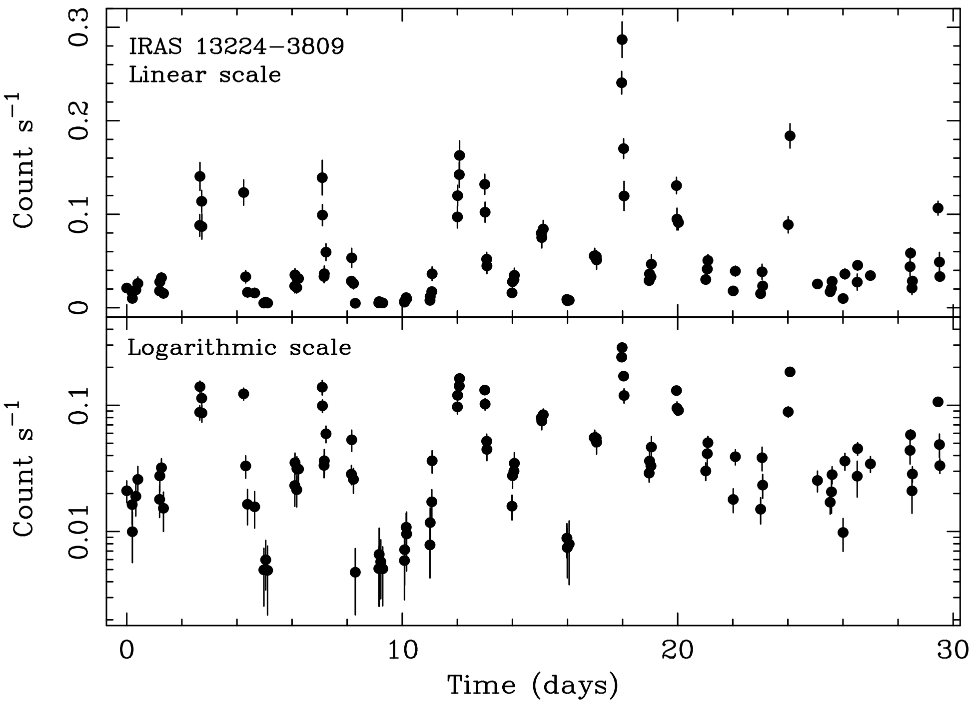

Figure 4. *ROSAT* HRI light curve for IRAS 13224–3809 obtained during a 30-day monitoring campaign in 1996 January–February. The light curve is shown with both linear and logarithmic scalings of the ordinate. By holding this book upside down (and perhaps using a mirror), you can judge if the 'logarithmic' light curve looks symmetric (see the question by Martin Gaskell in the discussion section).

(Brandt et al., in preparation). Based on reports of strong X-ray variability in a short *ROSAT* PSPC observation (e.g. Forster & Halpern 1996), we monitored PHL 1092 and found remarkably rapid and large-amplitude X-ray variability for such a luminous object (see Boller & Brandt 1998 for details). When 'efficiency limit' arguments (see Fabian 1979) are applied to the most rapid observed variability event, relativistic X-ray flux boosting appears to be implied. Finally, systematic studies of Seyfert/QSO variability (e.g. Green, McHardy & Lehto 1993; Fiore et al. 1998a) suggest that ultrasoft NLS1 as a class show enhanced X-ray variability over a wide range of timescales.

The cause of the extreme X-ray variability of ultrasoft NLS1 is not properly understood. Enhanced X-ray variability might again plausibly arise as the result of high $\dot{M}/\dot{M}_{\rm Edd}$,[2] but in this case there does not appear to be a direct, simple analogy with GBHC in their ultrasoft high states (see the response to Mike Eracleous in the discussion section). In addition, it is not obvious that a high

[2]At a fixed luminosity, black holes radiating at higher fractions of the Eddington rate will have lower masses. Lower mass black holes are thought to be associated with physically smaller emission regions that vary more rapidly.

$\dot{M}/\dot{M}_{\rm Edd}$ would lead to a predilection for nonlinear flaring or the relativistic boosting of X-rays. There is an eerie similarity between the nonlinear flaring seen from ultrasoft NLS1 and that seen from many blazars, and some have even suggested that ultrasoft NLS1 may harbor small relativistic X-ray jets that intermittently undergo nonlinear flares (Green, McHardy & Done 1998). It is perhaps not a coincidence that sources with steep energy spectra are those most prone to relativistic variability enhancement when observed in a fixed energy band (see Boller et al. 1997 for a detailed discussion).

5. Spectral Features

The 6.40–6.97 keV iron Kα lines observed from type 1 Seyferts/QSOs are often associated with the innermost parts of accretion disks. Theoretical calculations generally predict that an accretion disk will become more highly ionized as $\dot{M}/\dot{M}_{\rm Edd}$ increases, and the ionization of iron should be detectable as an increase in the centroid energy of the iron Kα line. Unfortunately, current line measurements do not show a clear trend towards increasing iron ionization for ultrasoft NLS1. Some ultrasoft NLS1 do show evidence for ionized iron Kα lines, but others do not (e.g. Comastri et al. 1998). It is important to note, however, that iron line fitting is currently very difficult for ultrasoft NLS1. The photon statistics for the observed lines are limited, and as a result line fits can be degenerate and difficult to interpret. A more unified picture may well emerge based on observations with satellites such as *XMM*, *Astro-E* and *Constellation-X*.

Even less clear at present is the origin of the peculiar spectral residuals seen from 1.0–1.2 keV in some ultrasoft NLS1 (e.g. Brandt et al. 1994; Leighly et al. 1997; Fiore et al. 1998b; Turner, George & Nandra 1998). These can be statistically modeled using edges and/or lines, but standard ionized X-ray absorber models cannot produce edges/lines at the correct energies without also producing much stronger features at other energies which are not observed. Brandt et al. (1994) pointed out, with due caution, that the residuals could in principle be explained by Doppler blueshifted absorption from ionized oxygen (with a velocity of $\sim 0.3c$), and this possibility was explored in detail by Leighly et al. (1997) using *ASCA* data. Detailed modeling is difficult at present since the soft X-ray excess and hard power law are exchanging dominance of the spectrum near the energy where the putative features are observed. In addition, the sources with the residuals often show significant spectral variability and this can lead to confusion when spectra are binned using time intervals that include such variability. Another possibility is that at least some of these features arise from reflection off an ionized accretion disk, and as mentioned above an ionized accretion disk is expected for high $\dot{M}/\dot{M}_{\rm Edd}$. These features definitely need further study; they may well offer a new probe of the nuclear environment that has yet to be properly exploited.

6. Other Possible Drivers of the Primary Eigenvector

An alternative way to clinch the high $\dot{M}/\dot{M}_{\rm Edd}$ interpretation of the primary eigenvector would be to falsify all other plausible interpretations. Alternatively, one of the other interpretations might be proven correct! The two leading contenders at present suggest that the primary eigenvector is driven by (1) orientation of the nuclear region and (2) black hole spin.

BG92 argued that orientation of the nuclear region could not drive the primary eigenvector. However, their argument relies upon the assumption that [O III] emission is isotropic. This common assumption has recently been questioned (e.g. Hes, Barthel & Fosbury 1993; Baker 1997). Precise measurements of [O II] emission, which has a lower critical density and ionization potential than [O III], can better test whether the primary eigenvector might be driven by orientation. Some of the requisite observations have been made, and analysis will be performed soon.

There do not appear to be any compelling arguments against the possibility that black hole spin drives the primary eigenvector. BG92 noted that radio-loud QSOs fall towards one end of their primary eigenvector, and based on this they suggested that the parameter driving the eigenvector was largely responsible for the presence of radio emission (see fig. 2 of Boroson & Green 1992b). Black hole spin has also been discussed in connection with the radio-loudness 'volume control' (e.g. Wilson & Colbert 1995), with radio-loud QSOs being postulated to have the most rapidly spinning black holes. Since radio-loud QSOs and ultrasoft NLS1 lie at opposite ends of the primary eigenvector, a spin interpretation for the eigenvector would suggest that ultrasoft NLS1 have the slowest spinning black holes. However, it does not seem that a slowly spinning black hole would naturally explain the observed properties of ultrasoft NLS1. If anything, their hot soft X-ray components and extreme X-ray variability might suggest a rapidly spinning black hole (e.g. Cunningham 1975 and Boller et al. 1997). Observations of relativistic iron Kα lines with *XMM*, *Astro-E* and *Constellation-X* are needed to measure black hole spins and address this issue.

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Discussion

Mike Eracleous: You drew an analogy between the X-ray spectra of ultrasoft NLS1 and the X-ray spectra of Galactic black hole candidates (GBHC) in their ultrasoft high states. Can one draw a similar analogy between the variability properties of the two classes?

Niel Brandt: I am not aware of a direct, simple analogy and suspect that it will be difficult to construct one. The soft components of high-state GBHC show markedly reduced variability from the usual millisecond flickering, although they do vary on timescales of about a day. One might expect the supermassive analogs of high-state GBHC to be stable on timescales of thousands of years if the variability scales roughly with black hole mass. However, this is not observed to be the case; the soft components of many ultrasoft NLS1 show large-amplitude X-ray variability on timescales down to ~ 1000 s. So the timescale discrepancy here is a factor of $\sim 10^7$!

Some GBHC do have 'very high states' which show rapid variability. Ultrasoft NLS1 could perhaps be in states analogous to these, although this complication causes the analogy to lose some of its directness and simplicity.

Martin Gaskell: If you take an optical light curve plotted in magnitudes (i.e. on a logarithmic scale), you can turn it upside down and it looks the same. Your X-ray light curve for IRAS 13224–3809 was plotted with a linear scale. Would it be more symmetric if you plotted it with a logarithmic scale?

Niel Brandt: Please see Fig. 4 which can be used to judge this matter.

Greg Shields: Is the soft X-ray excess significantly better fit by a blackbody than by optically-thin thermal bremsstrahlung? How do you get a blackbody much hotter than the effective temperature?

Niel Brandt: For the ultrasoft NLS1 that I know best, a blackbody model does provide a statistically better fit than an optically-thin thermal bremsstrahlung model. Optically-thin thermal bremsstrahlung also appears unlikely based on *EUVE* results for the NLS1 Mrk 478 (Marshall et al. 1996). Finally, the arguments of Elvis et al. (1991) combined with the very rapid observed variability provide additional evidence against optically-thin thermal bremsstrahlung models. It is important to comment, however, that observational limitations currently hinder testing of all but the simplest spectral models for the soft X-ray excess. In addition, some objects appear to have soft X-ray excesses that are too broad to be fit by a single blackbody. These can be fit with a sum of blackbodies or a multi-temperature accretion disk model.

I do not have a compelling theoretical explanation for the high blackbody temperatures. All I can say is that, from an observational point of view, they appear to be present. The spectrum shown in Fig. 3, for example, gives a blackbody temperature of $\gtrsim 100$ eV. Relativistic effects and Compton scattering can raise the apparent temperature. However, it is not clear that these effects can produce the observed spectral form. Better soft excess spectra from missions such as *AXAF* and *XMM* are needed for precision model testing.

Amri Wandel: In order to constrain disk-corona models one would want to compare the relative variability of the soft and hard X-ray components. Have you tried to do such a comparison?

Niel Brandt: Detailed comparisons of this type are difficult at present since most current satellites do not provide simultaneous, precision constraints on both the soft and hard X-ray emission. The limited data currently available suggest that the soft emission generally shows larger-amplitude variability than the hard emission.