We describe how recent X-ray surveys have led to advances in the understanding of ultrasoft narrow-line Seyfert 1 galaxies. The number of known ultrasoft narrow-line Seyfert 1s has increased greatly in recent years due to X-ray surveys, and it is now possible to obtain high quality 0.1–10 keV spectral and variability measurements for a large number of these galaxies. We generalize some of the correlations between X-ray properties and optical emission line properties, focusing on how the ROSAT band spectral slope appears to be directly connected to the Boroson & Green (1992) primary eigenvector. We discuss how ultrasoft narrow-line Seyfert 1s may well have extremal values of a primary physical parameter, and we describe new projects that should further improve our understanding of these extreme representatives of Seyfert activity.

Key words: galaxies: Seyfert – galaxies: active – X-rays: galaxies.

AAA subject classification: Narrow-line Seyfert 1 galaxies (NLS1)

1. Ultrasoft Narrow-Line Seyfert 1s: New Objects and Quality X-ray Measurements

While Seyfert 1 type galaxies with extremely strong soft X-ray excess components (relative to their hard X-ray power-law components) had been identified as a class based on data from Einstein and earlier X-ray satellites (e.g. Córdova et al. 1992; Puchnarewicz et al. 1992), observations with ROSAT, ASCA and SAX have revolutionized the study of these galaxies. First of all, ROSAT has vastly increased the number of ultrasoft Seyferts known. At least 50 new ultrasoft Seyferts have been found using ROSAT data (one of the largest catalogs of new ultrasoft Seyferts is presented by Grupe 1996), and more are being discovered each month. Many of these are bright and suitable for detailed follow-up studies at X-ray and other wavelengths. The best available estimates suggest that there are > ∼ 1000 ultrasoft Seyferts in the ROSAT all-sky survey (RASS) above a flux level of 5 × 10^{-13} erg cm^{-2} s^{-1}, so new ultrasoft Seyfert identifications should continue for some time.

ROSAT, ASCA and SAX observations have also greatly improved the quality of the X-ray data available for ultrasoft Seyferts. Precise measurements of their 0.1–10 keV spectral and variability properties are now possible. Comparisons of these precise X-ray measurements with data at other wavelengths has lead to the discovery of strikingly clear relations between the X-ray properties of Seyferts and QSO and their optical emission line properties (e.g. Boller, Brandt & Fink 1996, hereafter BBF96; Laor et al. 1997, hereafter L97). Most notably, the FWHM of the optical Hβ line appears to be anticorrelated with the slope of the ROSAT band X-ray continuum (which serves as a measure of the strength of the soft X-ray excess compared to the power law). All of the softest Seyfert 1s known appear to be ‘narrow-line’ Seyfert 1s (hereafter NLS1; e.g. Osterbrock & Pogge 1985) with typical Hβ FWHM in the range 500–2000 km s^{-1}. Ultrasoft NLS1 lie at one extreme of the aforementioned anticorrelation, and they are sometimes called ‘I Zwicky 1’ type objects after one of the most famous NLS1. Other relations between X-ray properties and optical emission line properties have also been found (see BBF96, L97 and references therein), and we will describe these within a generalized framework in the next section.

2. Generalizing the Correlations Between X-ray Emission and Optical Emission Lines

Boroson & Green (1992a, hereafter BG92a) have used a principal component analysis (PCA) to identify a fascinating cluster of QSO optical emission line properties that vary together in a highly coordinated manner, the
Fig. 1: QSO optical emission line and X-ray properties versus the value of the BG92a primary eigenvector. The QSO in these plots are those from BG92a, and the X-ray measurements have been taken from L97. This plot is similar to that presented in BG92b, although the direct correlations of the X-ray data with the primary eigenvector are shown here for the first time. Solid dots are radio-quiet QSO, open triangles are core-dominated radio-loud QSO, and open circles are lobe-dominated radio-loud QSO. In the upper right corner of each panel we state the region of the QSO being probed by the quantity along the corresponding ordinate, and we note that size scales ranging from hundreds of parsecs to tens of Schwarzschild radii have correlated properties. In particular, it is clear that the property driving the eigenvector can strongly affect the appearance of the luminous and rapidly variable X-ray emission from the black hole region (within $\sim 50$ Schwarzschild radii of the black hole itself). In the lower left panel we have not plotted the QSO PG 1001+054 because its ROSAT photon index has a very large error bar (although the position of this QSO does agree well with the pictured trend). Also in this panel we note that the outlying open triangle is 3C273, which has a time-variable photon index at ROSAT energies. This may well be due to time-variable ionized absorption (see Guainazzi & Piro 1997), and 3C273 also has some blazar-like characteristics. In the lower right panel the two outlying solid dots are ‘X-ray weak QSO’ (see L97 for discussion). Following section 4 of Kellermann et al. (1994), we take PG 1211+143 to be radio-quiet.
‘primary eigenvector’ of their PCA. The relevant properties include Fe II strength, [O iii] strength, Hβ FWHM and Hβ asymmetry [see the top four panels of Fig. 1; for the Hβ asymmetry panel, Hβ lines that have excess light in their blue (red) wings are positive (negative)]. BG92a and Boroson (1992) use the [O iii] emission to argue that the property driving the eigenvector cannot be orientation. They also note that radio-loud QSO tend to lie toward the positive extreme of the eigenvector and suggest that the property driving the eigenvector is linked to the radio ‘volume control’ of QSO. NLS1 lie toward the negative extreme of the eigenvector.

In the lower two panels of Fig. 1, we show correlations of ROSAT power-law photon index and 2 keV luminosity versus the BG92a primary eigenvector. A highly significant anticorrelation between ROSAT photon index and the eigenvector is apparent in the lower left panel. A Spearman rank-order correlation gives a Spearman $r_s$ value of $-0.834$, which is significant with over 99.9 per cent confidence (we use all 23 of the L97 QSO in this calculation). This anticorrelation is stronger than any of the L97 correlations/anticorrelations of X-ray properties with emission line widths and ratios, suggesting that it is more fundamental and supporting the idea that the eigenvector has an important physical meaning. We note that the ROSAT photon index was not used in the PCA calculation of the primary eigenvector, so the abscissa and ordinate in the lower left panel are independent quantities (this is not the case for the upper four panels but BG92a show that the correlations are not artificially induced in this manner). The energetically important and rapidly variable X-ray emission is thought to be formed within $\sim 50$ Schwarzschild radii ($R_S$) of the supermassive black hole itself. Thus it appears that the property which ultimately drives the eigenvector also originates within $\sim 50R_S$ (or at least can strongly influence the appearance of the X-ray emission from this region). We comment that PG QSO were selected by their UV excesses and most are relatively ‘clean’ systems in that they do not appear to have large amounts of intrinsic obscuration along the line of sight to the active core (although there are a few exceptions to this general rule). It appears unlikely that complex X-ray absorption effects are confusing the measurements of the X-ray continuum shape (see L97 for details of the ROSAT fits).

Corbin (1993) correlated the 2 keV X-ray luminosities of 55 PG QSO with their optical emission line properties from BG92a, and he argued that the 2 keV luminosity was linked to the BG92a primary eigenvector. We also see such a correlation in the lower right panel of Fig. 1 (it has a Spearman $r_s = 0.468$ corresponding to a correlation probability of 97.6 per cent). However, this correlation is significantly weaker than the one in the lower left panel, suggesting that the low 2 keV luminosities at the negative end of the eigenvector are only a secondary consequence of the steep X-ray slope (in agreement with L97; this remains true even if we exclude the two ‘X-ray weak QSO’). The 0.3 keV luminosity does not show a significant correlation with the BG92a primary eigenvector, consistent with the idea that the X-ray spectral shape, rather than the X-ray luminosity, is the primary quantity responsible for the X-ray correlations.

Inspection of Fig. 1 also makes it clear why soft X-ray surveys are very effective at finding new ultrasoft NLS1: soft X-ray selection will preferentially choose the steep X-ray spectrum Seyferts and QSO with negative values of the BG92a primary eigenvector. These Seyferts and QSO tend to have narrow Hβ FWHM as well as strong Fe II, weak [O iii] and blue asymmetric Hβ profiles.

3. Determining the Physical Parameter that Drives the Correlations

Ultrasoft NLS1 have extreme optical emission line properties and extreme X-ray properties. The fact that they persistently tend to lie at the ends of distributions of Seyfert quantities suggests that they may have extremal values of some important, underlying Seyfert physical parameter. BG92a argued that the parameter driving the eigenvector is not orientation but rather an intrinsic property. We have argued above that the parameter originates close to the supermassive black hole and can induce energetically important changes in the X-ray spectral energy distribution (these X-ray clues help to restrict the number of possibilities that must be considered for the driving parameter). It is unlikely that black hole mass is the sole driver of the correlations due to the fact that NLS1 characteristics are observed in sources spanning an extremely wide range of luminosity. However, the fraction of the Eddington rate at which the supermassive black hole is accreting (see BG92b) or the spin rate of the black hole might plausibly drive the correlations. If we can clearly determine the driving parameter this would be an important advance, since we would then be able to study the observational consequences of a difference in a primary driver of these accretion powered sources. We stress that the correlations discussed above are the strongest ones that emerge when large samples of Seyferts and QSO are systematically studied (that is, we are not trying to explain mere ‘2 per cent effects’).

How might one clearly determine the driving parameter? One possible avenue for progress is to carefully and systematically search for other properties that correlate with the BG92a eigenvector. Hard X-rays offer several properties that can be tested for correlation. The intrinsic hard X-ray continuum slope is one of the most basic and important of these, since it is thought to probe the temperature and Thomson depth of the accretion disk corona.
The currently available data suggest that there is a correlation with NLS1 having steeper intrinsic continuum slopes on average (Brandt, Mathur & Elvis 1997; although the correlation appears weaker than that in soft X-rays). Hard X-ray spectral slope measurements for NLS1 with strong optical Fe \text{II} emission will also help to constrain models of Fe \text{II} line formation (e.g. sect. 3.2 of Brandt et al. 1997 and references therein). Iron K line and Compton reflection continuum properties could also be checked for correlations. Some interesting iron K line results for ultrasoft NLS1 have already emerged (e.g. Comastri et al. 1997), but better data are needed before general conclusions can be drawn. X-ray variability, while often difficult to rigorously quantify, offers another promising set of properties that can be tested for correlation with the BG92a eigenvector. Several NLS1 have certainly shown dramatically rapid, large-amplitude and nonlinear X-ray variability (see Boller et al. 1997 for one of the most interesting examples and references; also see Fiore 1997).

Finally, it is important to check for loopholes in some of the argumentation that is often taken for granted. For example, [O \text{III}] emission has been used to argue against an orientation interpretation of the BG92a eigenvector (see above). However, the relevant arguments rely on the assumption that [O \text{III}] is an isotropic property. This common assumption has been called into question (e.g. Hes, Barthel & Fosbury 1993; Baker 1997). Measurements of [O \text{II}] emission, which has a lower ionization potential and critical density than [O \text{III}], would be useful for critically examining the orientation interpretation.

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