X-ray dependencies on luminosity in AGN

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Abstract. Several X-ray properties of active galactic nuclei depend, or appear to depend, on their luminosity. It has long been suggested that $\alpha_{\text{ox}}$, the X-ray “loudness” decreases with luminosity. There never has been a satisfactory explanation of this observational claim, and the statistical soundness of the result has been disputed. The earliest systematic studies of the X-ray variability of AGN showed that these properties also depend on luminosity. In particular, the normalization of the power spectrum, or alternatively the variability amplitude, are anti-correlated with luminosity. Most recently, tentative evidence from Ginga for an X-ray Baldwin effect - a decrease in the Fe K$\alpha$ equivalent width with luminosity - has been confirmed and extended by ASCA. The new data show that the reduction in strength is accompanied by changes in profile. These results will be described and their interpretation discussed.

1. Introduction

Active Galactic Nuclei (AGN) are strong X-ray emitters. The apparent power-law nature of the X-ray continuum suggests a non-thermal radiation mechanism. This demands an energy-deposition process which is distinct and in addition to the thermal emission usually attributed to an accretion disk (e.g., Malkan & Sargent 1982). The X-ray continuum of AGN is rapidly variable, suggesting a very compact region close to the central black hole. Recent X-ray spectral observations have confirmed this, by detecting the relativistic signatures of the hole in the profile of the Fe K$\alpha$ line (Tanaka et al. 1995; Nandra et al. 1997). Gravitational and Doppler effects distort the profile of the line in a characteristic manner (Fabian et al. 1989; Laor 1991). The X-ray emission of AGN does not therefore merely invite explanation, but also offers an opportunity to examine the central engine in detail.

An increasing number of the X-ray properties of AGN have been found to be related to other parameters. For example, a menagerie of correlated optical properties (Boroson & Green 1992) appear also to be related to the X-ray emission (e.g. Boller, Brandt & Fink 1996; Lawrence et al. 1997; Laor et al. 1997). The origin of these correlations is currently the subject of intense study and speculation. Also, certain X-ray properties of AGN are correlated with luminosity. These relationships are likely to be of great relevance to the physics of AGN. Here, three X-ray properties of AGN which are, or appear to be, related to source luminosity will be discussed. Evidence exists that the following quantities decrease with luminosity:
• The X-ray “loudness”
• The amplitude of X-ray variability on a fixed time scale
• The equivalent width of the Fe Kα line

In the following sections, the evidence for and nature of these correlations will be reviewed and speculation made on their origin and sources of scatter. The prospects for improvement in the observational data and theoretical interpretations will also be explored. Thereafter, the correlations will be examined for suitability as cosmological calibrators.

2. The Correlations

2.1. X–ray “loudness”, $\alpha_{\text{ox}}$

Data from the Einstein Observatory gave the first indication that the X-ray emission of AGN was correlated with luminosity. Early observations showed that the ratio of the X-ray to the optical luminosity, $L_x/L_o$, of quasars depended on $L_o$ (Avni & Tananbaum 1982; Kriss & Canizares 1985). A convincing demonstration of this effect was given by Avni & Tananbaum (1986) who studied the PG sample of quasars and a number of other, more heterogeneously-defined samples. These workers showed that the spectral slope between 2500Å and 2 keV, $\alpha_{\text{ox}}$, increased with optical luminosity. This steepening of the slope implies that the X–ray emission gets relatively weaker as the optical luminosity increases. Their best estimate for the relationship between optical and X-ray luminosity was $L_x \propto L_o^{0.8}$. This correlation has also been observed in a larger IPC sample (Wilkes et al. 1994) and in a large ROSAT sample (Green et al. 1995), who found that $\alpha_{\text{ox}} \propto L_o^{-0.1}$.

The origin of the correlation The question of why the X-ray loudness might depend on the optical luminosity has never really been answered. Crudely, in the standard model, one might expect the $L_o$ to indicate the luminosity of the accretion disk. This would depend on the accretion rate, the mass of the black hole and the efficiency by which the disk converts the rest-mass energy of the accreting material into radiation. The broad-band X-ray luminosity, on the other hand, should also depend on the first two parameters but the relevant efficiency in this case is that of energy deposition into the X-ray producing particle distribution. $\alpha_{\text{ox}}$ may therefore be revealing something about the ratio of these efficiencies. There are, however, a number of other considerations which may confuse this naive interpretation.

First of all, most AGN samples exhibit a strong correlation of luminosity with redshift. Simple bandpass effects might therefore induce artificial correlations. This seems unlikely in the present case, as no correlation has generally been found between $\alpha_{\text{ox}}$ and red shift. There are also likely to be effects due to the disk inclination. The apparent luminosity of the disk depends on its orientation to the line-of-sight and if the X-ray luminosity does not, or has a different dependence, this could be responsible for the correlation. Another possibility is that X-ray absorption is more common in AGN with high optical luminosity, especially relevant as the Einstein Observatory IPC and ROSAT PSPC data are
Figure 1. Dependence of the normalized “excess variance” \( \sigma^2_{\text{RMS}} \), which measures the X-ray variability amplitude, versus X-ray luminosity. The data are for a sample of Seyfert galaxies and quasars observed by ASCA (Nandra et al. 1997a). There is a very strong anticorrelation, with an index of \( \sim -0.7 \). These data confirm the previous EXOSAT results.

In the soft X-ray band, this is not thought to be the case, indeed the opposite is anecdotally assumed, but no systematic studies have yet been undertaken. Conversely, optical reddening could be more common in low luminosity AGN. An even more depressing interpretation of the observed correlation is that it is due to a statistical effect. Yuan, Siebert & Brinkmann (1998) have used Monte-Carlo simulations to show that if the distribution of \( L_o \) has a higher dispersion than that of \( L_X \), an apparent anticorrelation between \( \alpha_{ox} \) and \( L_o \) can be observed without any physical reason.

**Sources of scatter** There is a lot of scatter in the \( L_X-\alpha_{ox} \) relation. While it was mentioned above that absorption might be the cause of the observed effect, if it were not, it could certainly be a cause of scatter. Hard X-ray selected samples, which should be less affected by absorption, show a wide range of absorption columns, covering several orders of magnitude in column density (Turner & Pounds 1989; Nandra & Pounds 1994). Such columns would have a dramatic effect on the soft X-ray flux and therefore the inferred luminosity.
Future prospects The results on $\alpha_{\text{ox}}$ have been established primarily with optically-selected AGN, using soft X–ray data. For the future, it would be interesting to see if the correlations held for the hard X-ray band, which is much less affected by absorption. It is also important to consider samples which have been selected in different ways. Further examination of both kinds of correlation may well be possible with ASCA, if large, well-selected samples are completed.

2.2. X-ray Variability parameters

It has long been suspected that higher-luminosity sources are, in some sense, “less variable” in the X-ray band. For example, Barr & Mushotzky (1986) correlated a measure of the source doubling time scale with luminosity and found a significant correlation. More convincing evidence for such a correlation came from EXOSAT observations (Lawrence and Papadakis, 1993; Green, McHardy & Lehto, 1993). The power density spectra (PDS) of the EXOSAT AGN was found to be consistent with a single form, but the amplitude showed a strong anticorrelation with the X-ray luminosity.

This result has been confirmed using ASCA data by Nandra et al. (1997a). The normalized “excess variance”, $\sigma_{\text{RMS}}$, of an ASCA sample of AGN is plotted against $L_X$ in Fig. 1. $\sigma_{\text{RMS}}$ is defined as the variance above that expected from the (Poissonian) errors in the data, normalized by the mean count rate. This quantity should, for a stationary PDS, represent the integral over the frequencies corresponding approximately to the length of the observation and the bin size. For a red-noise PDS, as observed in AGN, $\sigma_{\text{RMS}}^2$ depends on and increases with the observation length. The length of the ASCA observations was similar, however, and making accurate PDS estimates for data which is unevenly-sampled is notoriously difficult. It is therefore preferable to use this quantity, rather than attempt to estimate the PDS amplitude. The $\sigma_{\text{RMS}}^2$ anticorrelation found with ASCA depends on $L_X^{-0.71}$ (Table 1). Similar dependencies $L_X^{-0.68}$ and $L_X^{-0.55}$ were reported by Green et al. and Lawrence & Papadakis. The dependence is therefore much stronger than that of, e.g., $\alpha_{\text{ox}}$, or the UV Baldwin relations (Baldwin 1977).

The origin of the correlation Lawrence & Papadakis (1993) briefly discuss some possible origins of the correlation. The most obvious conclusion is that it is related to the source size, although one might then expect a $L_X^{-1}$ dependence. Bao & Abramowicz (1996) have suggested a model in which the X-ray variations are produced by hot-spots on a rotating accretion disc. In that model, $L_X$ depends on the inclination: more edge-on disks have lower luminosities due to projection effects. The variability is also enhanced due to increased relativistic effects. This models conflicts somewhat with observations of the Fe K$\alpha$ line, which suggest that in type 1 Seyfert galaxies the accretion disks are all observed close to face-on (Nandra et al. 1997b). It is, however, the only serious model which has been suggested so far to explain the correlation.

Sources of scatter Once again, it is clear that the correlation between the variability parameters and the luminosity is imperfect. One possibility is that the variability amplitude is also related to the so-called “eigenvector 1” of Boroson & Green (1992). Their work revealed a number of correlations between various
optical properties of AGN and some X-ray properties are also related. For example, narrow H$\beta$ emission, strong Fe II lines, steep soft X-ray spectra and large amplitude, rapid X-ray variability all seem to be found in the same objects, the so-called “narrow-line Seyfert 1 galaxies” (NLS1). A systematic study of NLS1 by ASCA (K. Leighly, priv. comm.) has revealed that, as a class, these sources also follow the $\sigma_{\text{RMS}}^2$ vs. $L_X$ relation, but with a higher overall variability amplitude. Some indication of this is shown in Fig. 1, which includes a NLS1 galaxy PG 1404+226, which clearly lies higher than the overall distribution. Thus it may be possible to attribute the bulk of the scatter in Fig. 1 to this other (but as yet unknown) parameter.

Future prospects X-ray variability data have, until now, been collected in a rather haphazard way, sometimes merely as a by-product of spectral studies. This is unfortunate, as it makes it much harder to perform detailed, systematic analysis. Also, the above correlations have only been established conclusively for the very brightest sources, which are predominantly low redshift, and on short time scales. Ideally, one would like to obtain data over as wide a range of time scales as possible, for as wide a range of luminosities as possible.

Medium-long time scale variability has been particularly neglected by X-ray studies, mainly as it appeared initially that the most rapid variations were the most interesting. This has not necessarily been borne out by observations, and several groups are now using the particular capabilities of RXTE to obtain variability information on time scales of months-to-years. Unfortunately, these experiments are rather time-consuming and difficult to schedule. First results, however, are promising. For example the PDS of NGC 3516, sampled from hours-to-months, shows evidence for a cutoff on long time scales (Edelson & Nandra 1998) which had been suspected in other other sources, but never measured explicitly (McHardy 1989; Papadakis & McHardy 1995). It is probable that this cutoff frequency is also related to the luminosity. Similar data on a large sample of objects is required to demonstrate this.

A further problem with rapid variability studies is that, mainly due to the correlation described, high luminosity sources show very small amplitudes of variability, which are consequently extremely difficult to detect. The solution to this lies not in more sensitive instrumentation, but rather in switching attention to longer time scales, where all sources show higher amplitudes of variability.

An exciting prospect for the future of long-time scale monitoring of AGN is the employment of lobster-eye optics for X-ray imaging (Angel 1979; for a recent review see Peele et al. 1998). The idea behind this technology is to provide an extremely large field-of-view (up to all-sky), with arc-minute imaging. The more ambitious lobster-eye mission concepts would be capable of monitoring 1000s of AGN simultaneously on time scales of days to years, covering a wide range of redshifts (Priedhorsky, Peele & Nugent 1996). With very uniform data over the right time scales for a large sample of AGN, such experiments offer the opportunity of revolutionizing our knowledge of X-ray variability.

2.3. Fe K$\alpha$ strength and profile
Iwasawa & Taniguchi (1993), based on data from Ginga, suggested that there may be an X-ray “Baldwin” effect, whereby the equivalent width (EW) of the Fe
Figure 2. Equivalent width of the Fe Kα emission lines versus $L_X$ for a sample of AGN observed by ASCA. The data are binned every decade of luminosity. Both the total EW and that of the narrow “core” reduce with $L_X$. Above $10^{45}$ erg s$^{-1}$ the core and total EWs are consistent, showing the lack of any broad, red wing in the data.

Kα line reduces with luminosity. This result has recently been confirmed with much higher significance with ASCA (Nandra et al. 1997c; Fig 2). As mentioned in the introduction, the Fe Kα lines in low-luminosity AGN are complex, with a core peaking close to 6.4 keV and a strong and very broad “red wing”. The top left panel of Fig. 3 shows the summed line profile for the sample of AGN presented by Nandra et al. (1997c), illustrating these features. This figure also illustrates the fact that the profile, as well as then strength of the Fe Kα line changes with luminosity. The bin with $10^{44} < L_X < 10^{45}$ shows a weakening of the line emission, especially at the core, and the the blue flux is relatively stronger. At $10^{45} < L_X < 10^{46}$ the red wing seems to have disappeared, and the core now occurs at an energy higher than 6.4 keV. The total flux is even weaker now. Above $10^{46}$ erg s$^{-1}$ there is no evidence for any line emission at all.

The origin of the correlation. The ASCA sample is not well-selected, and at least two important parameters are also correlated with the X-ray luminosity: the redshift and the radio-loudness. It is possible that, in fact, it is these which are related to the equivalent width of the Fe Kα line, rather than the luminosity. Conclusive proof requires larger and better-selected samples with data at higher
Figure 3. Mean line profiles (expressed as the ratio of the data to a local power-law model) of AGN observed by ASCA, split into several luminosity bins. The line strength and profile change above $L_x \sim 10^{44}$ erg s$^{-1}$, with a reduction in both the core and “red wing”. Above $10^{46}$ erg s$^{-1}$ there is no evidence for line emission at all.
signal-to-noise ratios. For the time being, however, it seems most likely that the luminosity is the primary parameter. Although radio-loudness could be an important factor in determining Fe Kα strength, for example if the X-rays are produced in a relativistic jet boosted away from the accretion disk, it is unlikely to be the sole source of the observed correlation, as it persists when only radio-quiet AGN are considered. Similarly, although the very highest-luminosity bin with no line emission contains only objects at very high redshift, there are clear changes in profile in the lower-luminosity bins, where the range of redshifts is very small.

If luminosity is indeed the important factor, an attractive explanation of the observed EW and profile variations is that the ionization state of the accretion disk increases with X-ray luminosity. This would be expected with a fixed size and density. As the ionizing radiation field becomes more intense, we would expect the iron atoms in the inner disk to become fully stripped, causing the “red wing” to disappear. Further out, high ionization species of iron would cause a peak at higher energies than the 6.4 keV expected for neutral iron. At extreme luminosities, iron in the X-ray illuminated part of the disk could become completely stripped, with no line emission being observed at all. If true, this suggests that higher-luminosity AGN have higher accretion rates.

Sources of scatter The ASCA data are of insufficient quality to determine whether or not there is significant scatter in the EW vs. \(L_x\) relation. From a theoretical perspective, one would expect scatter. For example, the equivalent width of the Fe Kα line is a strong function of disk inclination (e.g., George & Fabian 1991). The X-ray source and disk geometry - in particular the solid angle of the disk subtended at the X-ray source, is also related to the strength of the line. Further speculation, however, requires improved data.

Future prospects The emission lines in the low luminosity sources are reasonably well measured by ASCA, and although higher-resolution future missions such as ASTRO-E will improve these measurements dramatically, what is really required is to obtain reliable measurements and upper limits for the high luminosity sources. This requires an instrument with moderate resolution and high throughput, such as the XMM/EPIC. Observations of large quasar samples - preferably with well-defined selection criteria - will enable disentanglement of the various related parameters and show whether or not luminosity is indeed the driving force for the EW variations. One can also then search for scatter in the X-ray Baldwin relation and examine its origins.

3. The suitability of X-ray correlations for cosmology

A summary of the various correlations of X-ray properties with luminosity is given in Table 1. As this volume addresses the suitability of using QSO properties for cosmology, the usefulness of these X-ray relations is discussed here.

As can be seen from the Table, and a comparison with the traditional Baldwin relations, it can be seen that the X-ray dependencies with luminosity can be very strong. In particular both the variability amplitude and Fe Kα EW are very sharp functions of luminosity. This makes the relations more useful, as the data
do not have to be measured to so high an accuracy. The variability amplitude is perhaps most promising of the relationships to use to calibrate cosmological distances. Unfortunately, however, the relation is so strong that it has not yet been possible to measure any variability at all in the highest-luminosity (and therefore highest redshift) sources. As mentioned above, a serious lobster-eye experiment could change that. Fig. 1 does show scatter, but it is relatively small compared to the traditional Baldwin relation. Although the origin of the scatter is not understood it seems clear that at least some of it arises from “eigenvector 1” and an attempt could be made to correct for this scatter, using for example optical line width or soft X-ray slope.

### 4. Conclusions

The correlation of X-ray properties with luminosity can reveal much about the physics of AGN, particularly in the central regions. Their relevance to cosmology is, at this stage, less certain as high-quality data are only just beginning to emerge. Of the observed correlations, the most promising is that of variability amplitude. This quantity has a very steep dependence with luminosity and it may be possible to reduce the scatter in the relationship using optical or X-ray spectral data. All that remains is to assemble the necessary data, which may be feasible with future, all-sky monitoring experiments, such as lobster-eye optics.

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| Quantity   | Satellite | Dependence | Reference                        |
|------------|-----------|------------|----------------------------------|
| $\alpha_{ox}$ | Einstein  | $L^{-0.1}$  | Avni & Tananbaum (1986)          |
| $\alpha_{ox}$ | ROSAT    | $L$        | Green et al. (1995)              |
| $A_{PDS}$  | EXOSAT    | $L^{-0.5}$  | Lawrence & Papadakis (1993)      |
| $\sigma_{RMS}$ | ASCA    | $L^{-0.7}$  | Nandra et al. (1997a)            |
| EW (Fe K$\alpha$) | Ginga  | $L^{-0.2}$  | Iwasawa & Taniguchi (1993)      |
| EW (Fe K$\alpha$) | ASCA    | $L^{-0.2}$  | Nandra et al. (1997c)            |

Table 1. Summary of correlations
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