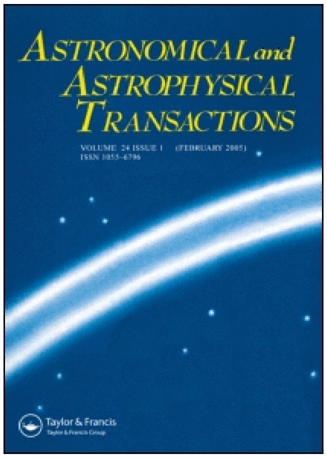

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VARIABILITY OF ACTIVE GALACTIC NUCLEI FROM THE OPTICAL TO X-RAY REGIONS

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Some of the progress in understanding the variability of active galactic nuclei (AGNs) from the optical to X-ray regions is reviewed. Although, where there is a clear correlation between variations in the two regions, the optical radiation lags the X-rays, simple reprocessing of the X-ray radiation to produce significant amounts of longer-wavelength continua seems to be ruled out. In a couple of objects where there has been correlated X-ray and optical variability, the amplitude of the optical variability has exceeded the amplitude of the X-ray variability. We suggest that the factor linking the X-ray and optical regions might not be irradiation, but accelerated particles striking matter (as in activity in the solar chromosphere). The diversity in optical–X-ray relationships at different times in the same object, and between different objects, could be explained by evolving differences in local geometry, and by changing directions of motion relative to our line of sight. Linear shot-noise models of the variability are ruled out; instead there must be large-scale organization of variability. Variability occurs on light-crossing timescales rather than viscous timescales and this probably rules out the standard Shakura–Sunyaev accretion disc. Instead, we believe that the main energy generation mechanism is probably electromagnetic. The overall average continuum shape appears to be the same in both radio-loud and radio-quiet AGNs, strongly suggesting a similar origin to the continua. Radio-loud and radio-quiet AGNs have quite similar optical variability properties, and this suggests a common variability mechanism. Beaming effects could be significant in all types of AGN. Despite their extreme X-ray variability properties, our observations show that narrow-line Seyfert 1 (NLS1) galaxies do not show extreme optical variability, and that their optical variability properties could well be similar to those of non-NLS1 galaxies.

Keywords: Active galactic nuclei; X-ray variability; Optical variability; Narrow-line Seyfert 1 galaxies; Accretion discs

1 OVERVIEW

The topic of variability of active galactic nuclei (AGNs) is very large, and the space available here does not permit a thorough review of this topic, which in recent years has generated hundreds of papers and much international collaboration. We therefore just give a brief, and necessarily selective, review of a little of the history, a listing of what we consider to be some of the important questions to be answered, a report on some recent work that we have been involved in, comments on a few results that we think worth noting, our current feelings on what we think variability has been telling us, and some suggestions for future

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collaborations. For a longer general review of AGN variability see Ulrich et al. (1997). For an earlier review of X-ray variability alone up to circa 1992 see Mushotzky et al. (1993).

2 EARLY HISTORY

Probably all AGNs vary at all wavelengths, and this variability has been recognized for a long time. In fact, optical variability was discovered before the true nature of AGNs was appreciated. In 1956, A. Deutsch at the Pulkova Observatory reported that the magnitude of the nucleus of NGC 5548 appeared to vary by about a magnitude. At the time it was believed that the continuous optical emission from the nuclei of galaxies was entirely due to the emission from many millions to billions of stars; so, apart from perhaps the occasional supernova explosion, detecting real optical variations was considered to be impossible, and therefore little serious attention was paid to Deutsch's report. A few years later, while compiling photoelectric measurements during preparation of the first Reference Catalog of Bright Galaxies (de Vaucouleurs and de Vaucouleurs, 1964), Antoinette de Vaucouleurs independently noticed that fluctuations in the photoelectric magnitudes of NGC 3516, NGC 4051, and NGC 4151 obtained in 1958 significantly exceeded the normal photometric errors (see discussion given by de Vaucouleurs and de Vaucouleurs (1968)).

The exciting modern era of AGN studies begins with the identification of the first high-luminosity AGNs (Schmidt, 1963). Even before Schmidt's discovery that the so-called 'quasistellar objects' were at high red shift, Kurochkin (1963) had searched for variability of 3C 273 on archival plates taken from the Sternberg Astronomical Institute (SAI). Sharov and Efimov (1963) discovered that 3C 273 varied by a magnitude of 0.7 over the period 1896–1960 on SAI archival plates. Special plates they took in the spring of 1962 revealed smaller variations with amplitudes of 0.2–0.3 magnitude, lasting a few days. Matthews and Sandage (1963) discovered from observations they had made going back to 1960 that 3C 48 varied by more than 0.4 magnitude in the V band over a 13 month period.

Smith and Hoffleit (1963a,b) studied the variability of 3C 273 over the period 1887–1963 using over 600 plates from Harvard plate archives. They found evidence for a 10 year cycle with a peak-to-peak amplitude of around 0.4 magnitude and 'occasional flashes' of up to a magnitude 'lasting about a week'.

Only a couple of years later, Dent (1965) discovered variations in the radio flux in flat-spectrum sources.

Less than a decade after the discovery of optical variability of AGNs, X-ray variability was discovered from observations made by the OSO-7, Uhuru and Copernicus satellites (Davidson et al., 1975; Winkler and White, 1975).

3 VARIABILITY BASICS: SINGLE-WAVEBAND VARIABILITY

If we first consider just one waveband, then perhaps the most fundamental questions are as follows:

(i) How much does the output vary?
(ii) How rapidly does it vary?

The answers to both questions tell us fundamental things about the region or regions of the AGN producing the observed emission.

The amplitude of variability gives us an idea of the relative importance of variability. It tells us how much the emission from the varying region varies and/or what fraction of the output is contributed by the varying region. A couple of stellar examples will illustrate this. In a supernova explosion the observed luminosity varies enormously. This tells us that the varying region dominates the observed emission and the mechanism responsible for the variability of this region is the main energy production mechanism. On the other hand, the optical variability of our Sun on a timescale of minutes to days is very small. Therefore the variations either come from small regions, or the whole Sun is only varying by a very small amount. In either case the variability of the Sun on short timescales is mostly irrelevant for understanding the fundamental mechanism producing the bulk of the Sun's radiation in the optical region. In the radio and X-ray spectral regions the Sun is highly variable, however, and this variability does tell us important information about the regions producing optical and X-ray emission.

The timescale Δt of variability gives information about the rate at which the region varies and it gives an upper limit to the ratio of the size L of the region to the velocity v at which changes propagate. This timescale is

$$\Delta t \sim \frac{L}{v}.$$

If one knows the speed at which the changes propagate, then Δt gives the approximate size of the varying region. Alternatively, if one independently knows the size of the varying region, then Δt provides the speed at which the changes propagate.

One obviously important speed is the speed of light, $c = 3 \times 10^5$ km s^{-1}. With only a few exceptions a region cannot vary on a timescale shorter than the light-crossing timescale $\Delta t \sim L/c$. One scenario in which this limit can be violated is when there is external irradiation of a region. If the re-emitting region is perpendicular both to the irradiation and to the observer, then there is no limit on how large the region can be. Another important scenario is when the emitting region is moving relativistically towards the observer. The radiation is then preferentially beamed towards the observer. This is important for BL Lac objects and blazars (Blandford and Rees, 1978).

Two other speeds of particular interest are the orbital speed $v_{orb} \sim (GM/R)^{1/2}$ and the sound speed $v_s \sim (kT/m)^{1/2}$. The orbital speed depends on the distance from the black hole and the mass of the black hole, but the fastest observed speeds of the Doppler-broadened Fe Kα lines are about 3.6×10^4 km s^{-1} (Fabian et al., 2000). The sound speed is about $20T_4^{1/2}$ km s^{-1} where $T_4 = T/10^4$ K; so

$$c > v_{orb} \gg v_s.$$

One very important size is the Schwarzschild radius $R_S = 2GM/c^2$. For the approximately $10^8 M_\odot$ black hole in a bright AGN this is about 10^{14} cm; so the relevant timescale is about 1 h. The Eddington limit

$$L_{Edd} = 1.3 \times 10^{38} \frac{M}{M_\odot} \text{erg s}^{-1}$$

gives a relationship between M and the luminosity L, if the accretion rate is at the Eddington limit, and hence it also give a relationship between R_S and L, and thus between a minimum timescale t_{min} of variability and L because the timescale of variability must not be less than the light crossing time of the Schwarzchild radius. This minimum variability timescale in seconds is given by

$$\log t_{\min} = \log L - 43.1,$$

where L is in ergs per second (Elliot and Shapiro, 1974).

4 THE TIME-AVERAGED SPECTRAL ENERGY DISTRIBUTION

The time-averaged spectral energy distribution (SED) over the X-ray to optical region is remarkably similar for AGNs of different radio types and luminosities. The apparent differences are mostly due to differences in the reddening (Gaskell et al., 2003b). Despite much work over several decades, the origin of the shape of the SED is not understood and this lack of understanding is one of the largest gaps in our knowledge of how AGNs work.

Broadly speaking, the overall continuum shape from the far infrared (IR) to the X-ray region can be characterized very roughly by a power law

$$F_\nu \propto \nu^{-1}.$$

The SED of AGNs is strikingly different from the SED of a star. A stellar SED is effectively a black body; the SED of an AGN is certainly not.

An explanation of the shape of the SED must also be consistent with the variability properties. Despite our poor understanding of the details of how the continuum is produced, the application of simple theoretical considerations to the observed time-averaged continuum gives us important information.

If we take the observed SED to be a sum of black bodies at different temperatures, then we can obtain a relationship between temperature and area (and hence size). The X-ray emission comes from a region several R_S across (light hours for a $10^8 M_\odot$ black hole) while there can be major contributions to the IR emission from a region thousands of R_S across (up to hundreds of light days).

5 FUNDAMENTAL QUESTIONS

Probably the most fundamental AGN question is: how is the energy produced? Since most, but not all, of this energy is seen as electromagnetic radiation, this question becomes: how are the different continua produced? A question that then follows is: are the various continua related?

We believe that variability probably poses the greatest challenge to understanding how AGNs work. A theory not only must explain the steady-state spectrum of an AGN but also must be able to explain how and why the continua vary.

Some more specific observational questions concerning variability include the following.

(i) What is the amplitude of variability in the various wavebands?
(ii) How are the amplitudes related to the timescales (power density spectrum (PDS))?
(iii) What are the timescales of variability? What are the shortest timescales? What are the longest timescales? Are there preferred timescales?
(iv) Is variability periodic?

(v) Is there evidence for nonlinear behaviour?
(vi) Are the variations chaotic?
(vii) How is variability of the various continua related?
(viii) How does the variability in various wavebands vary with luminosity?
(ix) Are mean variability properties the same for different classes of AGN (e.g. radio-loud and radio-quiet; face on and edge on; narrow-line Seyfert 1 (NLS1 and broad-line Seyfert 1 (BLS1) galaxies))?
(x) Do AGNs of the same class have the same variability properties (i.e. do quasars have different personalities)?
(xi) Can the variability properties of an AGN change with time (are AGNs moody)?

6 OPTICAL AND ULTRAVIOLET VARIABILITY

6.1 The Optical-Ultraviolet Amplitude is Large

It is important to recognize that optical and ultraviolet (UV) variability is enormous! It is enormous in both a relative and an absolute sense. In a typical AGN the annual mean in the V band will typically vary by a few tenths of a magnitude. Even variations of a few hundredths of a magnitude (something we find in essentially every AGN that we look at) mean that for a $10^{45}\,\mathrm{erg\,s^{-1}}$ AGN the energy equivalent of about 10^{10} solar luminosities is switching on and off! The variations are also enormous in a relative sense. In Fairall 9 the UV continuum varied by a factor of over 30 in 180 days (Recondo-Gonzalez et al., 1997). The UV continuum of NGC 4151 varied by a similar factor over a couple of years (Ulrich et al., 1997). So clearly, with these enormous factors in the variability, we are dealing with a massive change in the fundamental energy generation mechanism, not some additional superficial phenomenon.

6.2 The Ultraviolet–Optical Continuum Varies as a Unit

Another important factor to recognize is that the UV and optical continuum varies as a unit. As has been noted above, there is little if any change in the shape of the X-ray to optical spectral energy distribution while the luminosity varies from object to object by many orders of magnitudes. This would lead us to suspect that the spectral energy distribution might be the same in a given object as it varies, and this is indeed the case. Although the shape of the optical–UV continuum always appears to 'harden' when an AGN brightens, in Fairall 9 the optical spectral shape remained unchanged while the intensity increased by a factor of 20 (Lub and de Ruiter, 1992).

While to a first approximation one can think of the UV–optical continuum varying as a unit, we shall see below that there are now some cases where there are lags across the spectral region, and there is also some evidence that the energy distribution of outbursts varies (Doroshenko et al., 2001).

6.3 Timescale of Optical–Ultraviolet Variability

After the amplitude of variability, which tells us whether variability is energetically important or not, probably the most important factor is the timescale of variability.

On the longest timescales our knowledge is limited by how far back the observations go. For 3C 273 we have photographs going back to the 1880s (Smith and Hoffleit, 1963a,b). We have observations of NGC 4151 from 1906 to the present (Lyutyi and Oknyanskij, 1987). In both cases there is considerable variability, and we would have been unaware of the greatest outbursts without the historical record. In both cases also there is variability on the timescales of decades. In NGC 4151 there is variation on the longest timescale with a 80 year ‘period’. There are also quasiperiodic variations on timescales of years to a decade or so. We shall discuss the important question of possible periodicities below. The long timescale variations are of large amplitude. Because of starlight contamination, the real amplitude will certainly be larger than it appears to be in the optical region.

Variations on shorter timescales have smaller amplitudes (see discussion of the PDS below) and are therefore harder to detect. This is an area where modern high-precision photometry has much to contribute. X-ray variability on timescales as short as less than an hour is commonly observed in some objects. Similarly rapid (intranight) optical variability (sometimes called ‘microvariability’) is well established in optically violently variable (OVV) objects. Jang and Miller (1997) found intranight variability to be more common in radio-loud AGNs than in radio-quiet AGNs. There have been conflicting reports of microvariability in Seyfert galaxies. Because of the difficulty of measuring microvariability, observational errors might be contributing to some differences in reports, but Merkulova (2000, 2002) concluded that intranight variability is really transient in character and manifests itself with different probabilities for different galaxies.

6.4 Power Density Spectra

The PDS $P(f)$ potentially contains information about the nature of variability. For example, a ‘shot-noise model’ where variations arise from a stochastic series of independent overlapping events will produce a so-called ‘red-noise’ power spectrum of the form

$$P(f) \propto f^{-\alpha}$$

with $\alpha \approx 2$, which becomes ‘white noise’ with $\alpha = 0$ for low frequencies. Red noise is characteristic of many astrophysical and terrestrial systems. Many processes in nature produce so-called ‘1/f noise’ (Bak, 1996).

Kunkel (1967) using 100 day bins found that, for 3C 273, $\alpha \approx 2$ from 0.12 to 1.83 cycles year^{-1}. Collier and Peterson (2001) found that on timescales $\tau \approx$ 5–60 days, the mean UV and optical PDSs for 13 AGNs are equivalent. The combined UV–optical PDS has $\alpha = 2.13$. For sources with measured X-ray PDS indices, they found that the optical–UV and X-ray PDSs are indistinguishable. They present evidence that higher-mass systems have larger characteristic timescales.

6.5 Variations are Logarithmic

Optical astronomers almost invariably plot the brightness of AGNs in magnitudes. In a magnitude plot, the light curves of AGNs look symmetric both under time reversal and if the magnitude scale is inverted. The distribution of magnitudes is roughly normal; so the distribution of fluxes must therefore be roughly log-normal. Lyutyi and Oknyanskij (1987) made the important discovery that there was a linear relationship between the variations ΔF_U in the U-band flux and the U-band flux F_U itself for NGC 4151. This suggested that the amplitude of optical variability was directly proportional to the optical flux of the AGN. We shall show below that both log-normality of variations and a linear relationship between flux and variability also hold for X-ray variations.

6.6 No True Periodic Variations

A wide range of phenomena in astronomy are periodic (orbits, pulsations, etc.) and these periods provide important physical information about the systems they arise in. As soon as AGN variability was discovered, an obvious question to ask was: are the variations periodic? Smith and Hoffleit (1963a,b) reported a 10 year cycle in 3C 273, but Kunkel (1967) reported that there were 'no outstanding periodicities'. For NGC 4151, Lyutyi and Oknyanskij (1987) discussed of quasiperiods of tens of days, about 4, about 14, and about 80 years, but found no true periods for more than a few cycles. Longo et al. (1996) similarly found no evidence for periodicities.

Mention must be made of the BL Lac object OJ 287. Its long-term light curve, assembled from data accumulated over a century, shows nine nearly evenly spaced outbursts (Kidger, 2000). Owing to the uneven sampling, an exact value for the period cannot be determined, although the average seems to be about 11 years. However, there is predictive power to this finding, as the next maximum should occur in 2006, if the periodicity is real.

7 X-RAY VARIATIONS

7.1 X-rays Vary Greatly

It has long been appreciated that the amplitude of X-ray variability is large. Terrell (1986) found variations of at least an order of magnitude in the Vela 5B light curve of Cen A going back to 1969. The most spectacular cases of variability are seen in so-called NLS1 galaxies (see below). For example, during 30 day monitoring of IRAS 13224-3809, Boller et al. (1997) found five giant-amplitude 'flares', the largest with an amplitude of 60. In this object there is no evidence for a non-variable component (Gaskell, 2003). As with UV and optical variations, we can say that the variations represent changes in the fundamental energy mechanism.

7.2 X-rays Vary Rapidly

Variations in the X-ray region are more rapid than optical–UV variations of similar amplitude. In IRAS 13224-3809, for example, there was a factor of 2 variation in about 20 min (Boller et al., 1997). PHL 1092 has shown a flux increase of a factor of almost 4 in less than an hour. If these sorts of observed change are interpreted as changes in isotropic flux, they imply radiative efficiencies that exceed the maximum that can be achieved from a rotating black hole. This suggests that the emission is not isotropic and there is boosting due to relativistic motions (see Boller and Brandt (1999) for details). Certainly the regions varying must be within $15R_S$ or (less likely) be smaller regions further out. The important thing to note is that variations are taking place on a light-crossing timescale and not a viscous timescale. This probably rules out the standard accretion disc model of Shakura and Sunyaev (1973, 1976).

7.3 Soft X-rays Vary the Most

The most impressive X-ray variations, such as those mentioned in the previous section, occur in the soft X-rays. The soft component was found to vary the most in several studies of Seyfert 1 galaxies (Nandra et al., 1997; Turner et al., 1999; Markowitz and Edelson, 2001). This could be due to the presence of a softer continuum emission component that varies more strongly than a harder component or to a non-constant single component that becomes softer as the source becomes brighter. In NLS1 galaxies the fractional variability is independent of the waveband (Edelson et al., 2002). This could be because the hard component is relatively weak in NLS1 galaxies.

7.4 X-ray Power Density Spectra

Considerable effort has been put into determining X-ray PDSs. EXOSAT data showed that X-ray variability is scale-invariant 'red noise' from timescales of minutes to days (Lawrence et al., 1987; McHardy and Czerny, 1987). Lawrence and Papadakis (1993) found that the PDS had a mean power law index $\alpha \approx 1.55$ and pointed out that this mean slope is inconsistent with both standard shot-noise processes and traditional '1/f noise'. This sort of PDS was noted to be similar to PDSs of galactic black-hole X-ray binaries, although on a much longer timescale. This naturally raises the possibility that there could be similarities in the processes causing variability and this led to the search for other similarities in the PDSs.

Edelson and Nandra (1999) obtained a high-quality PDS for NGC 3516, which showed a progressive flattening of the power-law slope from 1.74 at short timescales to 0.73 at longer timescales. This gave a characteristic variability timescale corresponding to a cut-off temporal frequency of about a month. This is about six orders of magnitude longer than is seen in stellar mass galactic black-hole sources and thus suggested that the timescale scales with the mass. Similar breaks in the PDS have been found in a number of other objects, but Uttley et al. (2002) found no low-frequency break in NGC 5548.

7.5 X-ray Variations are Logarithmic

Just as Lyutyi and Oknyanskij (1987) discovered that optical variability is proportional to the mean optical flux level, Uttley and McHardy (2001) similarly discovered that the X-ray variability of the stellar mass black hole Cyg X-1 and the accreting millisecond pulsar SAX J1808.4-3658 was linearly related to the flux level. They also suggested that AGNs could show a similar relationship but they were only able to compare pairs of states of slightly different mean luminosities in three AGNs. Gaskell (2003) showed that there is indeed a linear relationship between X-ray variability and X-ray flux (Fig. 1) and argued that this flux-dependent behaviour of the variability rules out linear shot-noise models. Vaughan et al. (2003) found a similar relationship for MCG-6-30-15.

As noted above, optical light curves are approximately log-normal. Gaskell (2003) showed that for IRAS 13224-3809 the large variations in both the soft X-ray flux observed by ROSAT and the hard X-ray flux observed later by ASCA can be well fitted by a two-parameter log-normal distribution (Fig. 2).

Although at first glance the variations of the ASCA light curve for IRAS 13224-3809 appear to exhibit non-stationary behaviour with quiescent low states and more active flaring high states, our results show that the multiplicative variance is constant. Monte Carlo simulations of constant σ_{mult} give excellent matches to the observed X-ray light curve without the need to invoke special low and high states. This supports a picture in which the long-term variability is fundamental.

A log-normal distribution of X-ray fluxes suggests that the emitting regions could have a log-normal size distribution or the energies could have a log-normal distribution.

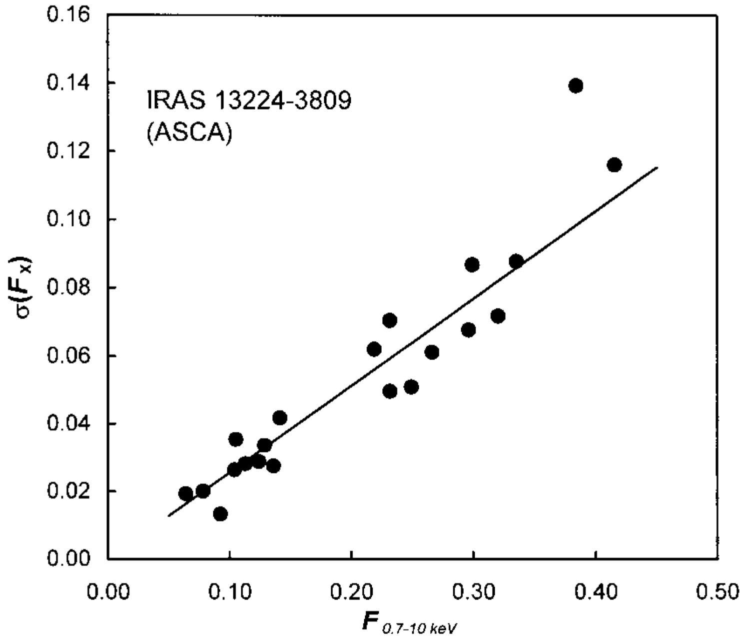

FIGURE 1 The standard deviations versus the mean count rate in half-day bins for IRAS 13224-3809 (from Gaskell, 2003). Both axes are in ASCA counts over the 0.7–10 keV energy range. The fit line is $\sigma(F_X) = 0.256F_X$.

7.6 Lags Between X-ray Bands

For NGC 5548 and MCG-6-30-15, the hard X-rays lag the soft X-rays (Chiang et al., 2000; Reynolds, 2000; Vaughan et al., 2003). This lag is very small, much less than an hour for MCG-6-30-15. Any hard or soft X-ray lags in Ark 564 and Ton S180 were too small to measure (Edelson et al., 2002). Edelson et al. (2002) found that, while there was a tight correlation between hard and soft X-ray bands on short timescales, the ratio of hard to soft X-rays showed long-term changes.

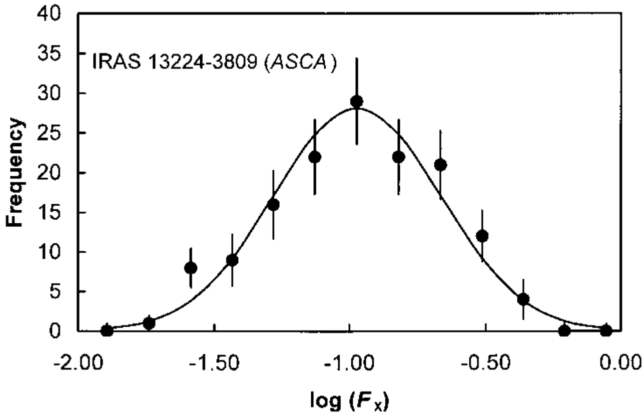

FIGURE 2 The frequency distribution of the logarithms of the ASCA count rates over 5 ks intervals (from Gaskell, (2003). The curve is a Gaussian of standard deviation 0.435 dex.

8 RELATIONSHIP BETWEEN X-RAY AND OPTICAL CONTINUA

Because of the large amplitude and rapidity of X-ray variability it has been commonly considered to be the driving variability of AGNs, but is this really so?

There are two models that venture to explain the AGN processes producing lags. In one model, the UV–optical bands observed are the result of reprocessed X-rays. The primary X-rays heat the cooler matter, perhaps lying in the disc or torus, which then re-radiates the reprocessed radiation. In this case, the prediction is that the optical radiation follows the X-rays. In another model, the X-rays are Comptonized UV–optical photons. In this scenario, a corona of relativistic electrons Comptonizes the UV–optical radiation, thereby producing X-rays. This model predicts that the X-rays follow the UV–optical emission.

While each model has its own specific prediction, the observational results have been unclear or insufficient to rule out any theory. The first lag comparison was made by Lyutyi (1978) who found that X-ray variability, while correlated with optical variability on both long and short timescales, has a greater amplitude and shorter timescale. He found that the optical band may have lagged that of the X-rays. Since then many researchers have used simultaneous observations in different wavebands to search for any kind of lag between two spectrum regimes. A range of results have been found for various objects. For example, Done et al. (1990) showed that there was very little optical variability (less than 1%) on timescales of days in NGC 4051 and no apparent correlation with the much larger amplitude X-ray variability. On a longer timescale, Peterson et al. (2000) suggested that the optical and X-ray light curves for NGC 4051 were correlated on timescales of months to

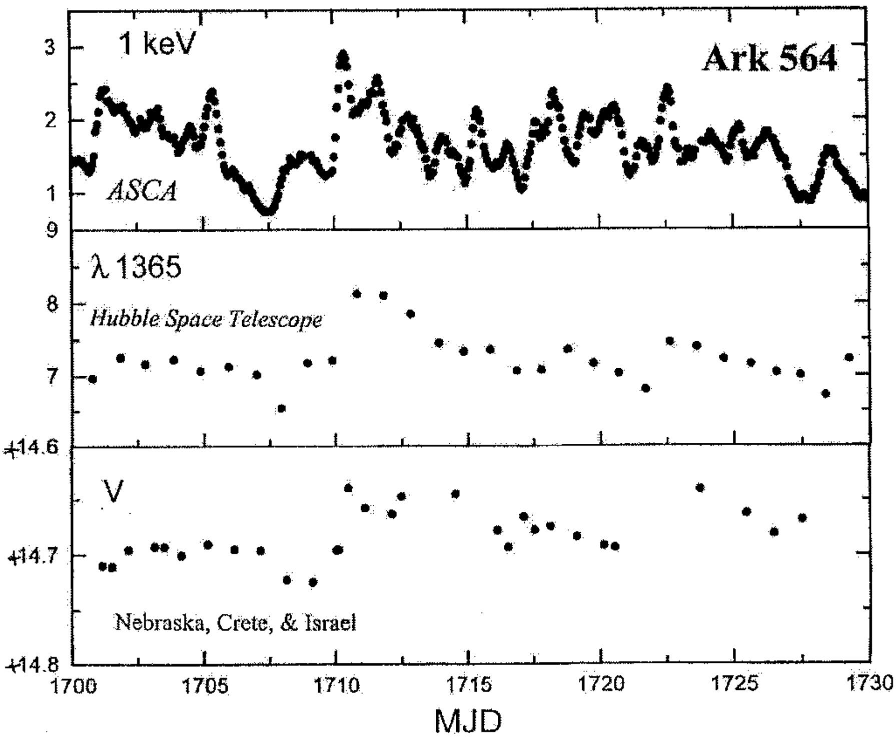

FIGURE 3 Multiple-waveband light curves of Ark 564. Data from Shemmer et al. (2001) and Gaskell et al. (2003a).

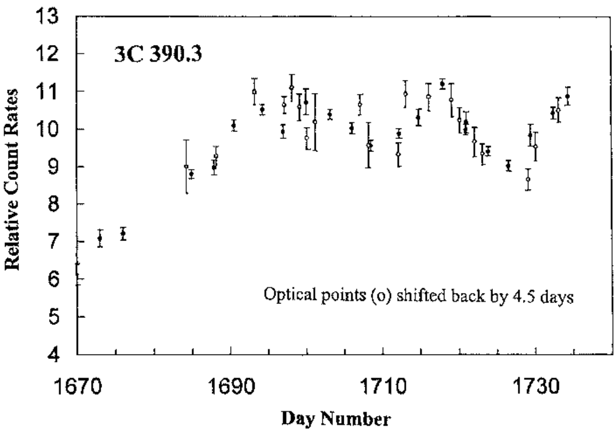

FIGURE 4 Simultaneous RXTE (•) and University of Nebraska optical (○) light curves for 3C 390.3 (Gaskell et al., 2003c). Note that no galaxy component has been subtracted from the V-band measurements and that the optical points have been shifted back by 4.5 days to emphasize the agreement with the X-ray light curve.

years. The conclusion from the International AGN Watch campaign focused on NGC 4151 (Edelson et al., 1996) was that there was no clear relationship between any of the wavebands. In studying NGC 3516 there was ‘no significant correlation or simple relationship’ (Edelson et al., 2000). However, in another study of NGC 7469, the X-rays actually seemed to follow the UV by about 5 days (Nandra et al., 2000). A 6 year study of the RXTE light curve of NGC 5548 (Uttley et al., 2003) showed that the X-ray light curve is strongly correlated with the optical light curve on long (about 1 year) timescales.

In a more recent international observing campaign targeting Ark 564 (Fig. 3), the optical band followed the X-rays by about 1.5 days (Shemmer et al., 2001; Gaskell et al., 2003a). For 3C 390.3 Gaskell et al. (2003c) found that the optical band lags the X-rays by 4.5 days (Fig. 4).

Clearly the area of X-ray correlations is one in which much more work is needed.

Uttley et al. (2003) found that the amplitude of the long-term optical variability in NGC 5548, after accounting for the host galaxy contribution, is larger than that of the X-ray variability. In our own study (Gaskell et al., 2003c) of the radio-loud AGN 3C 390.3 (see Fig. 4), we found that our optical fluxes show the same amplitude of variability even without allowing for host galaxy contamination. This means that the fractional amplitude of the daily optical variations is larger than the fractional amplitude for the X-ray observations. These results are of great importance because they rule out X-ray reprocessing as the main source of the optical–X-ray correlation.

9 WAVELENGTH-DEPENDENT LAGS IN THE ULTRAVIOLET–OPTICAL WAVEBAND

Lags across the UV–optical waveband are predicted by most models and have long been sought. Such a lag was convincingly found for the first time by Collier et al. (1998) in NGC 7469 (see also Kriss et al. 2000). The continuum at 7000 Å lagged the continuum at 1400 Å by about 1.5 days. Collier (2001) found a 1.4 day (rest-frame) lag across the optical passband for the gravitationally lensed quasar 0957+561. Recently, Oknyanskij et al. (2002) have found a similar delay across the optical passband in NGC 4151. Their result is very interesting because our earlier International AGN Watch campaign had put an upper limit on the UV–optical lag of less than 0.15 days (Edelson et al., 1996). This means that the geometry of the X-ray–optical emission regions has changed over a period of several years. Clearly more studies of more objects and repeated studies of objects are needed, and some such studies have been instigated as a joint campaign between a number of observatories in the former Soviet Union and the University of Nebraska.

It is important to note that the lags across the UV–optical region and the upper limits on such lags are on the light-crossing timescale. This means that whatever is causing the connection between different wavebands is propagating at close to the speed of light. This is commonly suggested to be external illumination, but, as noted elsewhere in this review, there are very serious problems with having all optical radiation arising from reprocessing. We therefore suggest that the linking factor might not be irradiation but accelerated particles striking matter, as happens in the solar chromosphere. Differences in local geometry, viewing angle and direction of motion relative to the line of sight could then explain the diversity of X-ray–optical relationships described in Section 8.

10 NONLINEARITY AND NON-STATIONARITY

One obvious way to try to explain the structure of light curves is by a linear superposition of discrete events. Such modelling has been attempted by Fahlman and Ulrych (1975, 1976), Scargle (1981) and others. However, there is much evidence that X-ray and optical light curves are both nonlinear and non-stationary. Angione and Smith (1985) pointed out that the 3C 273 light curves obtained by Smith (1965) and Terrell and Olsen (1970) 'scarcely seem to refer to the same object'. Vio et al. (1991) argued that the optical variations of 3C 345 are nonlinear and also non-stationary. A multifractal analysis performed by Longo et al. (1996) clearly indicated nonlinear intermittent behaviour in the long term (1910–1991) B-band light curve of NGC 4151. Leighly and O'Brien (1997) showed that the flares and quiescent periods in the light curve of 3C 390.3 suggest that its X-ray variability is nonlinear. The non-stationary character of the light curve could, however, be evidence that the variability power spectrum has not turned over at low frequencies. They suggested that the character of the variability is similar to that seen in Cygnus X-1, which has been explained by a reservoir or self-organized criticality model. Green et al. (1999) showed that NGC 4051 is also not statistically stationary on timescales of about 1 year. The non-stationarity and nonlinearity of light curves means that the power spectra do not adequately represent all the information contained in the light curve. Models in which the variability events are correlated rather than random are needed to describe the observed light curves. Gaskell (2003) pointed out that the log-normal nature of variability (see above) needs to be considered when evaluating stationarity. There is no evidence for IRAS 13224-3809 that the multiplicative variance is not stationary.

11 CHAOS?

A power-law PDS can theoretically arise from a chaotic system where global coherent variability is described by three or more nonlinear differential equations showing deterministic chaos. Such. However, Czerny and Lehto (1997) have analysed the EXOSAT light curves of eight AGNs and found no signs of deterministic chaos. In half the AGNs the variability is clearly of a stochastic nature, and in the other half the variability was not strong enough to determine its character, but stochastic variability was again favoured.

12 SELF-ORGANIZED CRITICALITY?

Vio et al. (1991) suggested that AGNs could be self-organized critical (SOC) systems, that is they become organized into a state where they are on the edge of instability. A pile of sand is a classic example of such an SOC system; the addition of a few grains of sand can cause a major avalanche. One of the signatures of an SOC system is that it produces power-law distributions (Bak, 1996). Negoro et al. (1995) argued that observational features in the light curve of Cygnus X-1 strongly suggest the presence of numerous reservoirs with different capacities for triggering X-ray fluctuations, a key assumption of the model based on the self-organized criticality. Xiong et al. (2000) have produced SOC models for accretion disc fluctuations. Their model can produce light curves and power spectra for the variability that agree with the range observed in optical and X-ray studies of AGN and X-ray binaries.

Despite the promise of SOC models we note that the log-normal flux distribution and the constancy of σ_{mult} (Gaskell, 2003) are incompatible with the power-law distribution of flaring amplitudes expected from simple SOC behavior. Takeuchi et al. (1995) offered a more detailed model that could fit the X-ray behaviour better.

13 NARROW-LINE SEYFERT 1 GALAXIES

NLS1 galaxies (Gaskell, 1984; Osterbrock and Pogge, 1985) are so called because the central engine with its surrounding dense gas can be seen directly, as in Seyfert 1 galaxies, but the permitted optical emission lines arising from gas (the broad-line region) are much narrower than in normal Seyfert 1 galaxies. NLS1 galaxies show the most extreme X-ray variability. Boller et al. (1996) showed that, as a class, NLS1 galaxies also have strong soft X-ray excesses and greater X-ray variability than would be expected for their luminosity. At a particular X-ray luminosity, the excess variance is typically an order of magnitude larger for NLS1 galaxies than for Seyfert 1 galaxies with broad optical lines (Leighly, 1999). IRAS 13224-3809 mentioned above is a NLS1 galaxy.

The enhanced excess variance exhibited by NLS1 galaxies can be interpreted as evidence that they are scaled-down versions of broad-line objects, having black-hole masses roughly an order of magnitude smaller and requiring an accretion rate an order of magnitude higher (Leighly, 1999). It is possible, however, that the X-ray variability of NLS1 galaxies has higher-amplitude flares than normal BLS1 (non-NLS1) galaxies and might be different.

Boller et al. (1996) showed that NLS1 galaxies have a strong soft X-ray excess and a steeper X-ray spectrum. The strength of the soft excess is correlated with the variability parameters, so that objects with strong soft excesses show higher amplitude variability (Leighly, 1999). It is important to understand why this is so.

Since NLS1 galaxies show extreme X-ray variability, it is reasonable to ask whether they also show extreme optical variability. Young et al. (1999) looked unsuccessfully for optical microvariability in the extremely X-ray variable AGN IRAS 13224-3809, but Miller et al. (2000) did find significant microvariability on one night for the same object.

We have carried out a long-term multiple-observatory international study of the variability of Ark 564 (Shemmer et al., 200l; Gaskell et al., 2003a). We have found a number of rapid events on intra night timescales that we have observed at more than one observatory. Some of the events correlate with X-ray events (see Fig. 4), but the optical fractional amplitudes are much less than the X-ray fractional amplitudes. It is hard to say whether such rapid low-amplitude events are also common in non-NLS1 galaxies because of the lack of a suitable control sample. Combining out observations with earlier data from Doroshenko we now have coverage of Ark 564 for over a decade a half (Gaskell, 2003b) and it shows long-term variations similar to non-NLS1 galaxies.

We have also completed a large-scale optical photometric study of additional NLS1 galaxies, searching for variability from intranight timescales to timescales of years (Klimek et al., 2003). Despite looking on approximately 40 nights, we have not detected significant intranight variability. We do not see the sort of 0.3 magnitude intranight variability that Miller et al. (2000) reported for IRAS 13224-3809. The lack of suitable control samples again makes it hard to say how the level of microvariability that we find compares with that of non-NLS1 galaxies, but we can confidently state the following.

(i) NLS1s do not show the sort of extreme variability in the optical that they show in the X-ray region.
(ii) The amplitudes of intranight optical variability for NLS1 galaxies are not significantly greater than for non-NLS1 galaxies.

On longer timescales the optical variability of NLS1 galaxies seems to be similar to that of non-NLS1 galaxies, but again the lack of a control group of non-NLS1 galaxies is a problem. We mention the lack of control group problem because studies of non-NLS1 galaxies have been biased towards objects that are known to vary. The effect of this bias needs to be evaluated. We need to know whether AGNs of the same class (e.g. radio-quiet non-NLS1 galaxies) have different personalities.

14 BEAMING

In this review we are intentionally avoiding known beamed sources such as BL Lacs and other OVV AGNs. There are definite differences between the variability properties of OVV and 'normal' AGNs (see the review by Ulrich et al. (1997)), especially in amplitude and timescale, but we do wonder whether these differences have been over-emphasized, particularly since OVV and non-OVV AGNs tend to be observed by different researchers and discussed at different meetings. If OVV light curves are appropriately scaled, it is not clear how different they are from non-OVV light curves. Since explaining the observed optical–X-ray amplitudes and correlations in non-OVV AGNs necessarily requires the transmission of large amounts of energy in relativistic particles, we suggest that beaming could well be a major factor in 'normal' AGNs. For example, the nonlinear intermittent behaviour found by Longo et al. (1996) in NGC 4151 led them to suggest that the physical mechanism responsible for the variability of NGC 4151 could be similar to the mechanism responsible for the variability of the OVV 3C 345.

15 DO RADIO-LOUD AND RADIO-QUIET AGNs VARY IN THE SAME WAY?

If there is beaming going on in non-OVV AGNs, then the AGNs most likely to be similar to OVV AGNs are radio-loud AGNs. This raises the question: do radio-loud and radio-quiet AGNs vary in the same way? We have pointed out above that after allowing for reddening and dust properties in AGNs (Gaskell et al., 2003b) the continua of radio-loud and radio-quiet AGNs appear to be very similar in the UV and the optical regions.

OVV AGNs are all radio-loud, and because their extreme variability is believed to be due to relativistic beaming (see previous section), this has led to a belief that radio-loud AGNs are more variable than radio-quiet AGNs. We believe, however, that apart from OVV AGNs there is little compelling evidence for this. The historical amplitudes of variability of the radio-loud AGN 3C 273 (which is sometimes classified as a blazar) are similar to those of well-studied radio-quiet Seyfert galaxies such as NGC 4151. We have given above examples of where the continuum of radio-quiet Seyfert galaxies has varied by a factor of over 20.

We have found that a recently discovered radio-quiet AGN, PDS 456 (Torres et al., 1997), surprisingly displays as much optical variability as a comparable radio-loud object. PDS 456 is the most luminous object in the 'local' Universe and is similar to the luminous quasars seen when the Universe was only 10–20% of its current age. Strongly X-ray variable (Reeves et al., 2000), this object is comparable in luminosity with 3C 273, the classic radio-loud bright nearby AGN. We found that the total range of optical variation in PDS 456 was 30% over a span of about 120 days. In comparison, 3C 273, a comparable radio-loud object, has a typical seasonal range roughly half of this at 16%. In fact, 75% of the seasons during which 3C 273 was observed have a variation range of less than PDS 456's 30%. On only one occasion in 30 years did 3C 273 vary as much as PDS 456.

This similarity of the variability of PDS 456 to 3C 273 suggests to us that the variability mechanisms of radio-loud and radio-quiet AGNs are the same. We intend to make further observational studies to investigate this.

16 VARIABILITY–LUMINOSITY DEPENDENCE

Paltani and Courvoisier (1997) looked at the luminosity dependence of variability in IUE spectra. The UV variability amplitude goes as $L^{-0.08}$ and they found that an index of -0.5 is definitely excluded. This luminosity dependence has no natural explanation in terms of discrete events.

Barr and Mushotsky (1986) showed that, in the X-ray region, the timescale of variability is correlated with the luminosity and Wandel and Mushotzky (1986) showed that there was a corresponding relationship between mass and the timescale of variability. The amplitude of X-ray variability of large samples of radio-quiet AGNs shows that the variability amplitude scales inversely with luminosity (Green et al., 1993; Lawrence and Papadakis, 1993; Nandra et al., 1997). For NLS1 galaxies, time series analysis shows that the excess variance from the NLS1 light curves is inversely correlated with their X-ray luminosity (Leighly, 1999). However, with a logarithmic slope of about -0.3, the dependence of the excess variance on luminosity is flat compared with broad-line objects and the expected value of -1 from simple models.

17 AN OVERALL PICTURE

Much work has been done researching AGN variability, and the field is far from slowing down. Many fundamental questions remain unanswered, and new questions keep arising the more that these objects are studied, but so far there is not enough evidence to pick out a winning AGN model, if indeed one even as yet exists. Conflicting findings, perhaps arising from poor sampling, or unusual 'moods' of objects, are observational reasons for this. On the theoretical side, no theory has so far been able to account for all the properties AGNs are observed to have.

We believe that a theory must explain the following:

(i) the rapidity of AGN variability;
(ii) that variability of AGNs is fundamental in that it is related to the main energy generation process;

(iii) that X-ray variability dominates energetically;
(iv) the relationship of the optical band to the X-rays: studies of this relationship tell us that the optical emission is not simple reprocessing, although reprocessing to some degree is probably going on; the complexity and variety of temporal relationships between the X-rays and the optical even in the same object needs to be explained;
(v) that the optical variabilities of radio-loud and radio-quiet AGNs are quite similar;
(vi) that it is hard to distinguish between beamed and non-beamed sources on the basis of many variability characteristics: this suggests that the mechanisms producing beamed and non-beamed variability are similar and perhaps the same.

Although we are far from having a complete theory, we believe that a new picture is emerging:

(a) We believe that the rapidity and amplitude of variability make the ‘standard’ model of a quasar powered by viscous dissipation in a relatively stable accretion disc untenable (Shakura and Sunyaev, 1973).
(b) We believe instead that electromagnetic processes must dominate. We suggest that the dominant process underlying all variability is relativistic flares.

18 CONCLUDING REMARKS: THE IMPORTANCE OF INTERNATIONAL COLLABORATION

In AGN research, the challenges faced by equipment limitations, weather and simply getting enough telescope time have contributed to the lack of quality optical (and IR) data that can solidly support or reject various theories. Uninterrupted continuous coverage of a range of AGN in all wavebands is desired but unrealistic. The closest that we can get to this ideal situation is through international collaborations and coordination with X-ray and UV observations during the operational lifetimes of orbiting astronomical satellites. It cannot be stressed enough how important these multinational observing campaigns have been and are for contributing to the needs of the astronomical and scientific world.

There are a number of practical issues that make collaborative efforts essential. Good sampling is needed in order to cover just about every type of timescale, including minutes, hours, days, weeks, months, years and even decades. For microvariability, which is on the smallest timescales of hours or less, the variations are of such low amplitude that systematic instrumental errors start to become a problem. In this case, independent confirmation by other observers strengthens the validity of the observations, thereby helping to remove the doubt surrounding the reality of any microvariability claim. In order to obtain full 24 h coverage of an object, we need observatories that are spread out in longitude. Additionally, having observers in different geographic locations is helpful in overcoming weather problems and also helps to overcome the problem that observers seldom get enough telescope time at any one observatory. The longest timescales require us to look at the different historical archives that observatories have built up.

Satellites can be taken for granted. They seem to stream down incessantly a wealth of data such that we cannot obtain from the ground. While satellites might seem to pump out invaluable data tirelessly, they do not live for ever. We need to be making the best use of all resources while they are available to us. For example, the Vela 5B satellite provided a good X-ray light curve of Cen A continuously on a daily basis from 1969 to 1979. Today, the RXTE satellite, for example, will only be in operation for a few more years. The finite lifetime of X-ray missions means that now is an important time to coordinate optical monitoring with the X-ray observations. RXTE is currently observing a number of AGNs for the long term, providing us the opportunity to build up a decent sized archive of simultaneous optical–X-ray data that can be used in correlation studies. There are other satellites to take advantage of, such as the Chandra, XMM-Newton, and INTEGRAL observatories.

In order to obtain the best optical coverage, observations need to be taken around the world through collaborations between as many researchers as possible. One of the sad things about the study of variability over the last couple of decades has been the inferiority of optical coverage compared with X-ray coverage. Almost no X-ray light curve has a comparable simultaneous optical light curve. Yet, optical data are much cheaper to obtain than the X-ray data! One X-ray point might cost US $10,000 or even much more, while the price of optical data can be as little as US $10 per point. We hope that this situation will be rectified in the future.

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References

Angione, R. J. and Smith, H. J., 1985, Astron J. 90, 2474.
Bak, P., 1996, How Nature Works: The Science of Self-Organized Criticality, Springer, New York.
Barr, P. and Mushotzky, R. F., 1986, Nature 320, 421.
Blandford, R. D. and Rees, M. J., 1978, In: A. M. Wolfe, (Ed.), Proceedings of the Pittsburgh Conference on BL Objects, University of Pittsburgh, Pittsburgh, p. 328.
Boller, T. H. and Brandt, W. N., 1999, In: Gaskell, C. M. et al., (Eds.), Structure and Kinematics of Quasar Broad Line Regions, ASP Conference Series, Vol. 175, Astronomical Society of the Pacific, San Francisco, California, p. 285.
Boller, T. H., Brandt, W. N., Fabian, A. C. and Fink, H., 1997, Mon. Not. R. Astron. Soc., 289, 393.
Boller, T. H., Brandt, W. N. and Fink, H., 1996, Astron. Astrophys. 305, 53.
Chiang, J., Reynolds, C., Blaes, O., Nowak, M., Murray, N., Madajski, G., Marshall, H. and Magdziarz, P., 2000, Astrophys. J. 528, 292.
Collier, S. J., 2001, Mon. Not. R. Astron. Soc. 325, 1527.
Collier, S. J. et al., 1998, Astrophys. J. 500, 162.
Collier, S. and Peterson, B. M., 2001, Astrophys. J. 555, 775.
Czerny, B. and Lehto, H. J., 1997, Mon. Not. R. Astron. Soc. 285, 365.
Davidson, P. J. N., Culhane, J. L., Mitchell, R. J. and Fabian, A. C., 1975, Astrophys. J. 196, L23.
Dent, W. A., 1965, Science 148, 1458.
de Vaucouleurs, G. and de Vaucouleurs, A., 1964, Reference Catalog of Bright Galaxies, University of Texas Monographs in Astronomy, University of Texas, Texas.
de Vaucouleurs, G. and de Vaucouleurs, A., 1968, Astron. J. 73, 858.
Done, C., Ward, M. J., Fabian, A. C., Kunieda, H., Tsuruta, S., Lawrence, A., Smith, M. G. and Wamsteker, W., 1990, Mon. Not. R. Astron. Soc. 243, 713.

Doroshenko, V. T., Lyuty, V. M., Bochkarev, N. G., Merkulova, N. I., Sergeev, S. G., Vlasyuk, V. V., Mikhailov, V. P., Spiridonova, O. I., Ezhkova, O. V., Grankin, K. N. and Mel'Nikov, S. Yu., 2001, Astron. Lett. 27, 691.
Edelson, R., et al., 1996, Astrophys. J. 470, 364.
Edelson, R., et al., 2000, Astrophys. J. 534, 180.
Edelson, R. and Nandra, K., 1999, Astrophys. J. 514, 682.
Edelson, R., Turner, T. J., Pounds, K., Vaughan, S., Markowitz, A., Marshall, H., Dobbie, P. and Warwick, R., 2002, Astrophys. J. 568, 610.
Elliot, J. L. and Shapiro, S. L., 1974, Astrophys. J. 192, L3.
Fabian, A. C., Iwasawa, K., Reynolds, C. S. and Young, A. J., 2000, PASP, 112, 1145.
Fahlman, G. and Ulrych, T., 1975, Astrophys. J. 201, 277.
Fahlman, G. and Ulrych, T., 1976, Astrophys. J. 209, 663.
Gaskell, C. M., 1984, Astrophys. Lett. 24, 43.
Gaskell, C. M., 2003, Astrophys. Lett. (submitted).
Gaskell, C. M., Doroshenko, V. T., Klimek, E. S., Campbell, J. S., Crowley, K. A., George, T. A., Goosmann, R. W., Grove, R., Hedrick, C. H., Hiller, M. E., Peterson, B. W. and Poulsen, M. A., 2003a (to be published).
Gaskell, C. M., Goosmann, R. W., Antonucci, R. and Whysong, D., 2003b, Astrophys. J. (submitted).
Gaskell, C. M., et al., 2003c (to be published).
Green, A. R., McHardy, I. M. and Lehto, H. J., 1993, MNRAS, 265, 664.
Green, A., McHardy, I. and Done, C., 1999, Mon. Not. R. Astron. Soc. 305, 309.
Jang, M. and Miller, H. R., 1997, Astron. J. 114, 565.
Kidger, M. R., 2000, Astron. J. 119, 2053.
Klimek, E. S., et al., 2003 (to be published).
Kriss, G. A., et al., 2000, Astrophys. J. 535, 58.
Kunkel, W. E., 1967, Astron. J. 72, 1341.
Kurochkin, N. G., 1963, Astron. Tsirk. 251, 1
Lawrence, A. and Papadakis, I., 1993, Astrophys. J. 414, L85.
Lawrence, A., Watson, M. G., Pounds, K. A. and Elvis, M., 1987, Nature 325, 694.
Leighly, K., 1999, Astrophys. J., Suppl. Ser. 125, 297.
Leighly, K. and O'Brien, P., 1997, Astrophys. J. Lett. 481, L15.
Longo, G., Vio, R., Paura, P., Provenzale, A. and Rifatto, A., 1996, Astron. Astrophys. 312, 424.
Lub, J. and Ruiter, H. R., 1992, Astron. Astrophys. 256, 33.
Lyutyi, V. M., 1978, Soviet Astron. Lett. 4, 267.
Lyutyi, V. M. and Oknyanskij, V. L., 1987, Soviet Astron. 64, 465.
Markowitz, A. and Edelson, R., 2001, Astrophys. J. 547, 684.
Matthews, T. A. and Sandage, A. R., 1963, Astrophys. J. 138, 30.
McHardy, I. M. and Czerny, B., 1987, Nature 325, 696.
Merkulova, N. I., 2000, Astron. J. 119, 631.
Merkulova, N. I., 2002, Astron. Astrophys. 387, 40.
Miller, H. R., Ferrara, E. C., McFarland, J. P., Wilson, J. W., Daya, A. B. and Fried, R. E., 2000, New Astron. Rev. 44, 539.
Mushotzky, R. F., Done, C. and Pounds, K. A., 1993, A. Rev. Astron. Astrophys. 31, 717.
Nandra, K., George, I., Mushotzky, R., Turner, T. J. and Yaqoob, T., 1997, Astrophys. J. 476, 70.
Nandra, K., et al., 2000, Astrophys. J. 544, 734.
Negoro, H., Kitamoto, S., Takeuchi, M., et al., 1995, Astrophys. J. Lett. 452, L49.
Oknyanskij, V. L., Horne, K., Lyuty, V. M., Sadakane, K., Honda, S. and Tanabe, S., 2002, In: Collin-Souffrin, S., Combes, F. and Shlosman, I. (Eds.), Active Galactic Nuclei: From Central Engine to Host Galaxy, ASP Conference Series, Vol. 290. Astronomical Society of the Pacific, San Francisco, California, p. 119.
Osterbrock, D. E. and Pogge, R. W., 1985, Astrophys. J. 297, 166.
Paltani, S. and Courvoisier, T., 1997, Astron. Astrophys. 323, 717.
Peterson, B. M., et al., 2000, Astrophys. J. 542, 161.
Recondo-Gonzalez, M. C., et al., 1997, Astron. Astrophys., Suppl. Ser. 121, 461.
Reeves, J. N., O'Brien, P. T., Vaughan, S., Law-Green, D., Ward, M., Simpson, C., Pounds, K. A. and Edelson, R., 2000, Mon. Not. R. Astron. Soc. 312, L17.
Reynolds, C. S., 2000, Astrophys. J. 533, 811.
Scargle, J. D., 1981, Astrophys. J., Suppl. Ser. 45, 1.
Schmidt, M., 1963, Nature 197, 1040.
Shakura, N. I. and Sunyaev, R. A., 1973, Astron. Astrophys. 24, 337.
Shakura, N. I. and Sunyaev, R. A., 1976, Mon. Not. R. Astron. Soc. 175, 613.
Sharov, A. S. and Efimov, Yu. N., 1963, Inf. Bull., Variable Stars No. 23.
Shemmer, et al., 2001, Astrophys. J. 561, 162.
Smith, H. J., 1965, In: Robinson, I., Schild, A. and Schucing, E. L. (Eds.), Quasi-stellar Sources and Gravitational Collapse. University of Chicago Press, Chicago, Illinois.
Smith, H. J. and Hoffleit, D., 1963a, Astron. J. 68, 292.
Smith, H. J. and Hoffleit, D., 1963b, 198, 650.
Takeuchi, M., Mineshinge, S. and Negoro, H., 1995, Publns Astron. Soc. Japan 47, 617.
Terrell, J., 1986, Astrophys. J. 300, 669.

Terrel, J. and Olsen, K., 1970, Astrophys. J. 161, 399.
Torres, C. A. O., Quast, G. R., Coziol, R., Jablonski, F., de la Reza and Lépine, J. R. D., 1997, Astrophys. J. 303, L19.
Turner, T. J., George, I., Nandra, K. and Turcan, D., 1999, Astrophys. J. 524, 667.
Ulrich, M.-H., Maraschi, L. and Urry, C. M., 1997, A. Rev. Astron. Astrophys. 35, 445.
Uttley, P., Edelson, R., McHary, I. M., Peterson, B. M. and Markowitz, A., 2003, Astrophys. J. 584, L53.
Uttley, P. and McHardy, I. M., 2001, Mon. Not. R. Astron. Soc. 323, L26.
Uttley, P., McHardy, I. M. and Papadakis, I., 2002, MNRAS, 332, 231.
Vaughan, S., Fabian, A. C. and Nandra, K., 2003, Mon. Not. R. Astron. Soc. 339, 1237.
Vio et al., 1991, Astrophys. J. 380, 351.
Wandel, A. and Mushotzky, R. F., 1986, Astrophys. J. 306, L61.
Winkler, P. F. and White, A. E., 1975, Astrophys. J. 199, L139.
Young, A. J., Crawford, C. S., Fabian, A. C., Brandt, W. N. and O'Brien, P. T., 1999, Mon. Not. R. Astron. Soc. 304, L46.
Xiong, Y., Wiita, P. and Bao, G., 2000, Publns Astron. Soc. Japan 52, 1097.