AGN WATCH CONTINUUM MONITORING OF RADIO-QUIET AND RADIO-LOUD AGN

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ABSTRACT

The International AGN Watch has monitored a number of radio-quiet and radio-loud Active Galactic Nuclei – the most luminous objects in the universe. We present a review of the main observational results from the continuum monitoring campaigns, concentrating on those which aim to quantify the simultaneous ultraviolet to X-ray variability characteristics. These data provide strong constraints on the proposed continuum emission mechanisms. The AGN Watch campaigns have made extensive use of a wide variety of both ground- and space-based multi-waveband observational facilities, and we stress that long-term simultaneous access to the entire electromagnetic spectrum is essential if further progress is to be made.

THE INTERNATIONAL AGN WATCH

In the late 1980's an informal consortium of about 100 astronomers was formed to obtain large, high-quality multi-waveband data for investigation of the continuum and emission-line variability characteristics of Active Galactic Nuclei (AGN). The consortium was formed in response to the realization that small groups were unlikely to obtain large amounts of observing time, and would face great practical difficulty in both coordinating observations over many months and rapidly reducing data from numerous ground-based and orbiting observatories. The AGN Watch exists to obtain such data and rapidly place them in the public domain. Smaller collaborations, drawn from both inside and outside AGN Watch, can then use these data to place firm constraints on the seemingly ever-growing list of proposed AGN models. Here we summarize the continuum monitoring campaigns. The emission-line monitoring is presented elsewhere (*e.g.* Peterson, these proceedings).

CONTINUUM MONITORING OF SEYFERT 1 GALAXIES

The AGN watch has conducted campaigns on 7 AGN to date. The object names, wavebands covered and publications in which the original data can be found are given in Table 1. The initial campaigns concentrated on UV (1150–3200Å) and optical monitoring using IUE and numerous ground-based telescopes. More recently the campaigns have been expanded to the EUV, X-ray and γ-ray wavebands to investigate the photoionizing continuum in detail, and to the IR to investigate the properties of hot dust and the putative dense molecular torus around the nucleus.

Table 1. AGN Watch Continuum Monitoring Campaigns

Object	Waveband (facility)	Data Publications
NGC5548	UV & Optical (IUE)	Clavel *et al.* (1991) (Paper I)
	Optical (Ground-based)	Peterson *et al.* (1991) (Paper II)
		Peterson *et al.* (1992) (Paper III)
		Dietrich *et al.* (1993) (Paper IV)
		Peterson *et al.* (1994) (Paper VII)
	UV (HST) & Optical (Ground-based)	Korista *et al.* (1995) (Paper VIII)
	EUV (EUVE)	Marshall *et al.* (1997)
NGC3783	UV & Optical (IUE)	Reichert *et al.* (1994) (Paper V)
	Optical (Ground-based)	Stirpe *et al.* (1994) (Paper VI)
NGC4151	UV (IUE)	Crenshaw *et al.* (1996)
	Optical (Ground-based)	Kaspi *et al.* (1996)
	X-ray (ROSAT/ASCA) & γ-Ray (CGRO)	Warwick *et al.* (1996)
		Edelson *et al.* (1996)
Fairall 9	UV (IUE)	Rodríguez-Pascual *et al.* (1997)
	Optical (Ground-based)	Santos-Lleó *et al.* (in prep.)
3C390.3	UV (IUE)	O'Brien *et al.* (in prep.)
	Optical (ground-based)	Dietrich *et al.* (in prep.)
	X-ray (ROSAT/ASCA)	Leighly *et al.* (1997)
	Radio (MERLIN)	Leighly *et al.* (in prep.)
NGC7469	UV (IUE/HST) & X-ray (XTE)	Campaign June–July 1996
Mrk279	IR (ISO) & Optical (Ground-based)	Campaign 1996–1997

UV and Optical Continuum Variability

The individual UV and optical continuum variability characteristics of the AGN monitored by AGN Watch are discussed in detail in the publications listed in Table 1. The principal results are:

(i) The radio-quiet objects show both long- and short-term UV/optical continuum variability. No evidence has been found for periodic behaviour. The continuum typically varies by less than a factor of two on long (weeks – months) timescales, with the variability amplitude rapidly decreasing towards shorter timescales. This trend can be quantified in terms of a fluctuation power density spectrum (PDS), in which the power $P(f) \propto f^{\alpha}$ where f is the temporal frequency. The observed PDS spectral index α is about -2 in the UV for NGC5548 (Krolik *et al.*, 1991) and -2.5 for NGC4151 (Edelson *et al.*, 1996). There is no indication of any high-frequency cutoff in the UV/optical PDS – significant variability is seen down to the temporal sampling limit, which for NGC4151 is only a few hours. Such high sampling rates correspond to the light-crossing time of a few tens of Schwarzschild radii around a $\sim 10^7$ $M_\odot$ black-hole. At low temporal frequencies (corresponding to a year or so) the PDS must turn-over to be consistent with the long-term variability trends.

(ii) The variability amplitude decreases towards longer wavelengths, indicating a hardening of the UV/optical continuum when brighter. This relation is difficult to quantify due to contamination by starlight and weak broad emission lines at optical wavelengths, although a correction was applied for this when thought significant. For NGC5548, NGC3783 and Fairall 9 the continuum at 1350Å varies

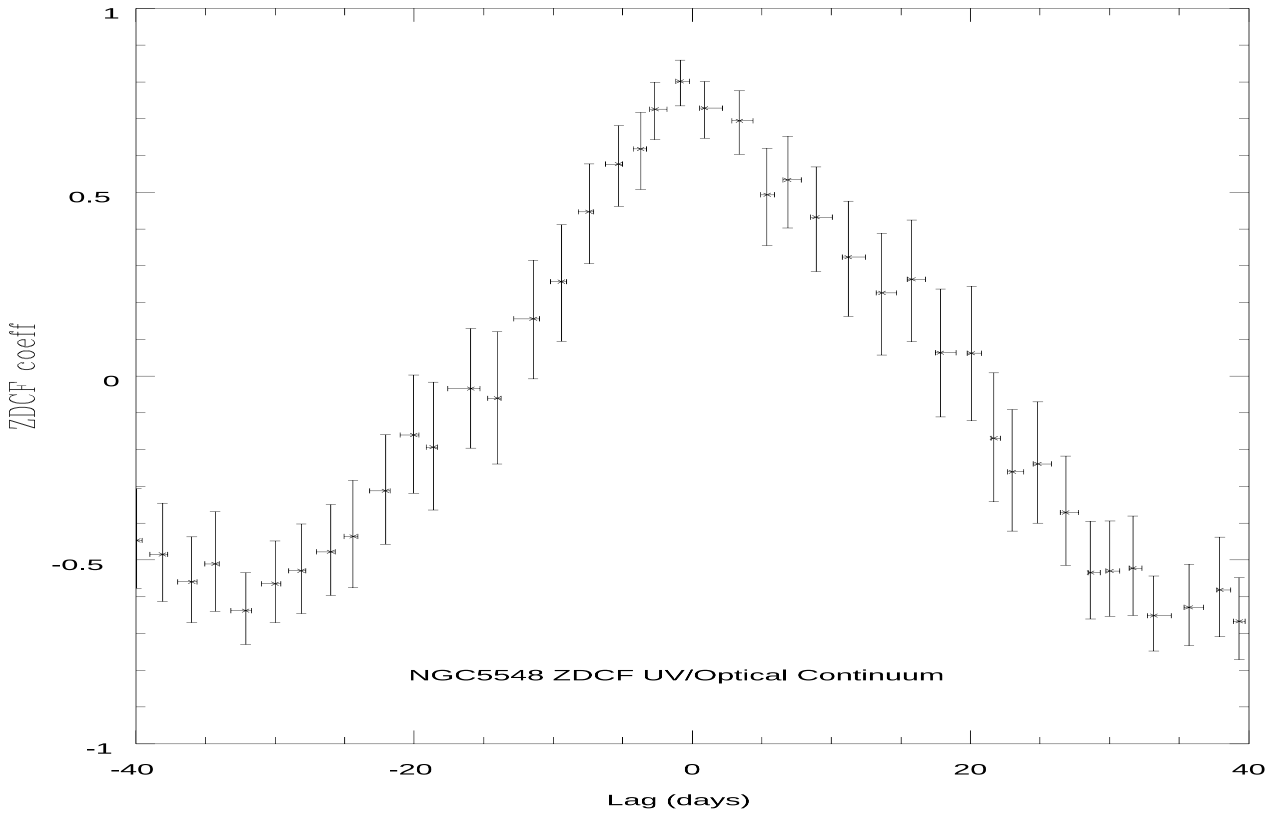

Figure 1: NGC5548 ZDCF computed between 1350 and 5100Å using data from Korista *et al.* (1995).

by a factor of about 3 more than at 5100Å (Reichert *et al.*, 1994; Korista *et al.*, 1995; Santos-Lleo *et al.*, 1996). For NGC4151 the factor is higher (6–7). No such trend was seen in the intensive multi-waveband study of the BL Lac object PKS 2155−304 (Edelson *et al.* 1995).

(iii) No clear time-delay or lag has been found between the continuum variations in the UV/optical. For NGC5548, NGC3783, NGC4151 and Fairall 9 the lags derived using a variety of cross-correlation techniques are consistent with zero. An example result for NGC5548 using HST (1350Å) and ground-based optical (5100Å) data is shown in Figure 1, computed by the ZDCF method (Alexander 1997). The optical continuum lags the UV by < 0.8 days, consistent with the 1.2 day limit derived by Korista *et al.* (1995) using other methods. Similarly, Edelson *et al.* (1996) derived a lag of < 1 day between 1275 and 5125Å for NGC4151, and Reichert *et al.* (1994) find a lag of < 2 days between 1460 and 5000Å for NGC3783. The upper limits on the lags between the various UV continuum bands are somewhat smaller (*e.g.* < 0.15 days for NGC4151).

The latter result is perhaps the most important and has been the subject of intensive observational and theoretical study during the last few years. The individual limits depend in part on the actual sampling rate of the light-curves, which in hindsight were too low for some of the early campaigns. Increasing the sampling rate has been one of the prime drivers behind the more recent campaigns. The NGC5548 HST campaign achieved 1 day sampling for 39 days. The NGC4151 IUE campaign achieved ≈ 70 minute sampling for 9.3 days. The recent NGC7469 IUE campaign achieved an average rate of ~ 5 hours for ~ 50 days. The observing time requirements of such campaigns severely limit the number of AGN which can be monitored without access to dedicated monitoring facilities.

UV, EUV, X-ray and γ-ray Continuum Variability

The IUE and HST campaigns provide information on the UV continuum (> 1150Å), but the need to probe shorter wavelengths is clear. The high-energy continuum is where a substantial, perhaps dominant, fraction of the bolometric luminosity emerges and is believed to be the continuum photoionizing the emission-line gas. Monitoring the high-energy continuum is more difficult due to the limited availability of observing facilities and their usually lower sensitivity compared to the UV/optical. However, the AGN Watch has successfully conducted several recent campaigns to investigate in particular the relation between the UV/optical and EUV/X-ray/γ-ray continua.

NGC5548. Following the discovery of simultaneous UV/optical continuum variability in NGC5548 (Clavel *et al.*, 1991), another consortium monitored the object with IUE and Ginga (Clavel *et al.*, 1992). They found a strong correlation between the UV and hard (2–10 keV) X-ray continua during 1989–90, the variations occurring simultaneously with a formal limit on any lag of ± 6 days. They noted, however, that there are other epochs when the UV appears stronger than expected from the correlation observed in 1989–90. This behaviour strongly suggests that more than one continuum emission mechanism contributes significantly in the UV and optical wavebands in NGC5548.

During the intensive HST, IUE and ground-based campaign on NGC5548 in 1993, AGN Watch also performed an EUVE monitoring campaign (Marshall *et al.*, 1997). The deep survey imaging detector light-curve indicates large, rapid variability in the 50–100Å band. The EUV continuum varied by a factor of four over a few days and by a factor of two in less than a day. In the most intensively sampled period which overlaps with the HST campaign, the EUV continuum has a variability amplitude twice that of the UV at 1350Å, but they vary simultaneously to within < 0.25 days. The short overlap in time (8 days) of these campaigns preclude a search for long lags, but taken at face value these results extend the UV and optical continuum correlations noted above into the EUV – the variability amplitude increases towards shorter wavelengths and there is no detectable wavelength-dependent lag. Marshall *et al.* note that similar, but even larger, EUV relative to UV variations were also seen in Mrk478 (Marshall *et al.*, 1995).

NGC4151. The AGN watch performed it's most comprehensive monitoring campaign up to that date in December 1993 on the low luminosity Seyfert 1 galaxy, NGC4151. This object has been the subject of many studies, but the new campaign uniquely obtained quasi-simultaneous data covering more than 5 decades in energy during a 10 day period. This campaign is described in detail in these proceedings by Edelson, so only the conclusions will be given here.

The UV/optical continuum variability characteristics are described above. The high-energy continuum variability measured using ROSAT, ASCA and CGRO is complex (Warwick *et al.*, 1996; Edelson *et al.*, 1996). The < 1 keV continuum did not vary significantly. The 1–2 keV continuum varied simultaneously with the UV continuum at 1275Å to within 0.3 days, but by a factor of 3 more in amplitude. Early in the campaign the 1–2 keV continuum increased by a factor of 1.45 in just 2 days. The 50–150 keV continuum varied with a similar amplitude to the UV, but there is no clear relation between the form of the γ-ray and low-energy light-curves.

A clear correlation was found between the 2-10 keV absorption corrected X-ray flux and the UV in 1993 (Warwick *et al.*, 1996), with a similar slope to that found in an earlier study using EXOSAT and IUE data by Perola *et al.* (1986). However, the normalization of the correlation is different, with a relatively stronger UV continuum in 1993 implying, as found for NGC5548, that another emission mechanism contributes significantly in the UV and optical wavebands.

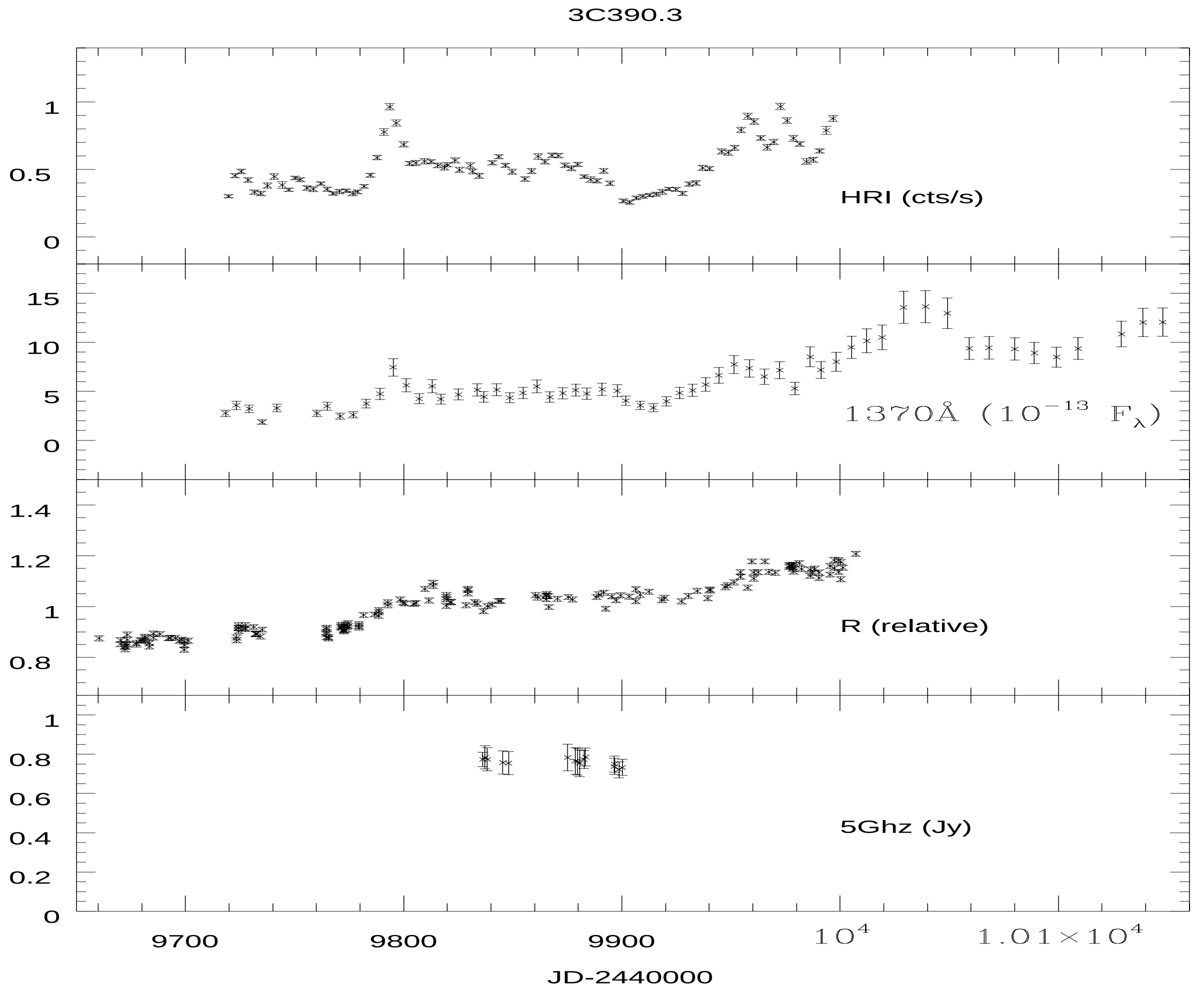

Figure 2: Continuum data for 3C390.3 in the X-ray (ROSAT/HRI), UV (IUE), R-band and Radio (MERLIN) obtained during the AGN Watch campaign in 1995–96.

THE BROAD LINE RADIO GALAXY 3C390.3

To complement it's earlier campaigns on radio-quiet Seyfert 1 galaxies, the AGN Watch monitored the luminous Broad Line Radio Galaxy (BLRG) 3C390.3 during 1995–96. This classical FR II radio-galaxy is one of the nearest ($z = 0.056$) superluminal sources (Alef *et al.*, 1988). It displays a complex broad emission-line spectrum, particularly double-peaked Balmer lines usually taken as the signature of an accretion disk or bi-conical structure (*e.g.* Zheng *et al.*, 1991). These properties combined with a history of large amplitude continuum variations made it a prime candidate for intensive multi-waveband monitoring.

We obtained $\sim$ 1.5 ksec ROSAT HRI (0.1–2 keV) observations every 3 days for 9 months, IUE observations averaging every 6 days for 14 months, and numerous optical observations. A 3 month long radio campaign at 5 GHz using the MERLIN array was also undertaken halfway through the X-ray campaign. Unfortunately, the IUE campaign was terminated prematurely in March 1996 due to technical problems with the satellite. We note that 3C390.3 is a factor of 10–50 fainter in observed UV flux than the previously monitored Seyfert 1 galaxies, so even with longer integration times ($\sim$ 6 hours), the IUE spectra are of significantly lower quality than in the previous campaigns.

In addition only IUE/SWP spectra (1150–1950Å) were obtained so there is little constraint on the UV spectral shape. These multi-waveband data are currently being analysed, so only initial results will be presented here. The X-ray (HRI counts per second), UV (mean 1340–1400Å flux in 10^{-13} erg cm^{-2} s^{-1} Å^{-1}), R-band (relative flux converted from magnitudes) and 5Ghz (core flux in Jy) light-curves are shown in Figure 2, using data from Leighly *et al.* (1997), O'Brien *et al.* (in prep.) and Dietrich *et al.* (in prep.).

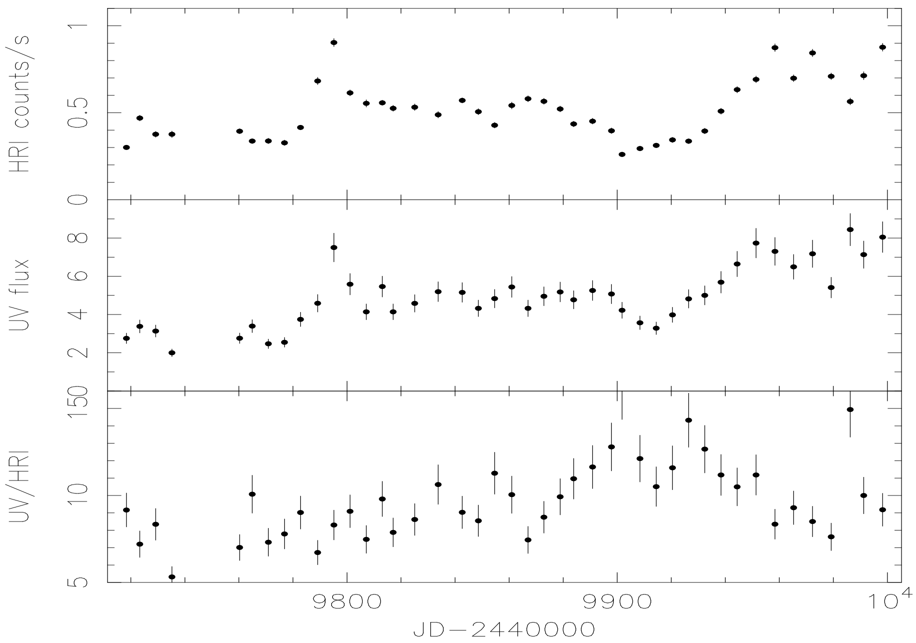

Figure 3: The UV and re-sampled HRI data for 3C390.3. HRI data in units of counts/s and UV in 10^{-13} erg cm^{-2} s^{-1} Å^{-1}. The UV/HRI ratio is shown in the lower box.

X-ray and UV Continuum Variability

The X-ray and UV light-curves indicate strong variability, with normalized variability amplitudes (NVA; Edelson *et al.* 1996) in the period of overlap of 0.32 and 0.31 respectively. The X-ray and UV light curves show a similar functional form and the cross-correlation function obtained using the ZDCF method gives a lag of less than 3 days, and is consistent with zero. The UV continuum at 1370Å and 1855Å also vary in phase. However, there are some differences in detail between the X-ray and UV continua. The X-ray flare at JD 2449795 and the low-state X-ray 'dip' beginning around JD 2449900 are less pronounced in the UV. This is shown more clearly in Figure 3, where the UV and X-ray (re-sampled to the UV temporal spacing) light-curves are plotted together with their ratio, which is higher during the X-ray dip.

The similar X-ray and UV NVA is in contrast to that observed for NGC4151, but is consistent with the NVA pattern observed in the BL Lac object PKS 2155−304. However, powerlaw spectral fitting to two ASCA spectra obtained during the HRI campaign on JD 2449732.5 and 2449842.5 show photon index variability (Leighly *et al.*, 1997). The X-ray spectrum became softer ($\Delta\Gamma \sim 0.1$) when the 2–10 keV flux increased by a factor of 1.5, a trend consistent with that generally seen from Seyfert 1 galaxies. The significant X-ray spectral variability implies that although the NVA is similar in the soft X-ray and UV wave-bands, they cannot arise from the same continuum component. There

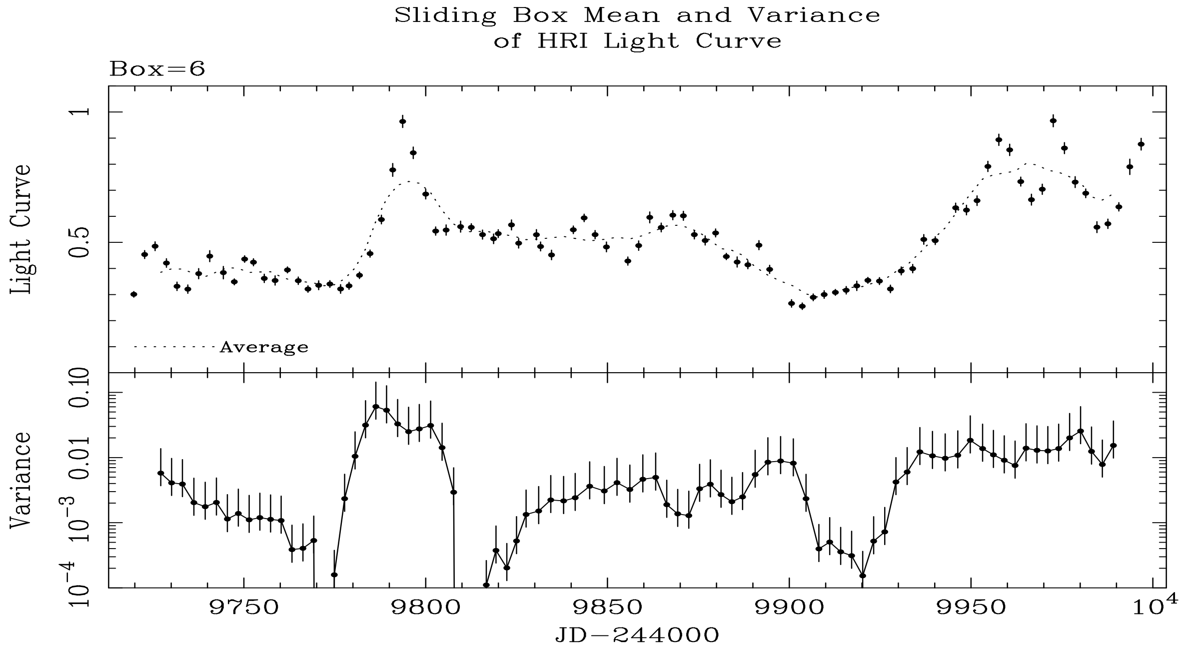

Figure 4: The HRI data for 3C390.3. The top curve shows the original data (counts/s). A sliding box-mean (box width 6) is superimposed as the dashed line whilst the lower curve shows the variance ((counts/s)^2) calculated over the same sliding box.

is no evidence for a soft X-ray excess component in the ASCA spectra, thus the ROSAT HRI data are sampling the X-ray powerlaw continuum component.

The 3C390.3 X-ray light-curve is uniquely well sampled on time-scales from days to months, and looks different to those obtained for AGN on shorter time-scales (*e.g.* McHardy and Czerny, 1987). The combination of flares interspersed among quiescent periods (see Figure 4) is evidence for non-linear behaviour (Leighly and O'Brien, 1997). Thus, the 3C390.3 X-ray light-curve probably cannot be modeled by a superposition of independent events, such as in shot-noise models associated with flares in the disk–corona, or spots on the disk modulated by rotation and gravitational effects (*e.g.* Abramowicz et al. 1991).

Optical Continuum Variability

The NVA is 0.10 for the R-band, and is slightly higher at V and lower at I (Dietrich *et al.*, in prep.). Thus, the trend of decreasing NVA with increasing wavelength seen in in the UV and optical for Seyfert 1 galaxies is also seen in 3C390.3. Formally the cross-correlation methods give a small lag of 3–9 days for the R-band relative to the UV or X-ray, but more careful analysis is required to investigate the significance of this result. The impression from Figure 2 is that the R-band light-curve is not simply a smeared-out version of the X-ray/UV. It does not show the early X-ray/UV flare or the long dip, yet follows some other trends closely, such as the increases around JD 2449800 and 2449940, albeit with lower amplitude.

Radio Variability

The 5 GHz radio flux showed no significant variability ($< 2\%$) during a period when the X-ray continuum varied by $\pm 20\%$ (NVA $= 0.13$). The simplest explanation is that the radio flux originates from a region much larger than the X-ray source. Thus, the X-ray variations need not be connected with the superluminal components seen at 5 GHz, which appear some 5 milli-arcseconds ($\sim$ 10pc) from the radio core (Alef *et al.*, 1988). One could argue that the X-ray/UV flare seen early in the campaign may be associated with a separate continuum component, possibly a relativistic jet. However, the reduction in X-ray variability before and after the flare (Figure 4) argues against this, as superimposing another variable component would be expected to increase the variability amplitude.

THEORETICAL IMPLICATIONS

The observational results summarized above, and in particularly those related to multi-waveband phase-delay and variability amplitude comparisons, comprise the best available data for these non-blazar AGN. Detailed comparisons between the observations and theoretical models are presented elsewhere, including several papers in these proceedings, but we note a few major points:

Accretion Disk Models

The lack of a detectable UV/optical continuum lag appears inconsistent with the predictions of standard accretion disk models in which the signal connecting parts of the disk emitting at different temperatures travels through the disk (*e.g.* Krolik *et al.* 1991). The derived upper-limits imply signal propagation speeds of $> 0.1c$, significantly faster than the local sound speed or photon diffusion rate. Edelson *et al.* (1996) propose a disk model for NGC4151 in which all the variable UV/optical emission comes from a small (< 0.1 light-day), hot inner region. This model predicts UV/optical lags and NVAs in agreement with the observations, but does not directly explain the simultaneous large-amplitude soft X-ray variations.

Reprocessing Models

The lack of a phase delay between the X-ray, UV and optical continua imply that the entire optical – X-ray continuum emission, and possibly the γ-ray, are closely inter-related. The hypothesis is that one band provides the 'seed photons' which are then 'reprocessed' by some mechanism to drive the emission in another. Which band provides the seed photons and which the reprocessed is a difficult problem, and feedback between the bands is also likely. However, the different proposed reprocessing mechanisms, such as thermal reprocessing of X-ray photons to UV/optical by an accretion disk or Thomson thick clouds, or Compton scattering of UV photons to X-ray by hot electrons around a disk predict different behaviour (*e.g.* Nandra, 1994). Simultaneous variability data should provide the cleanest test between the proposed mechanisms.

Seyfert 1 Galaxies. The X-ray spectral features seen in Seyfert 1 galaxies are consistent with those predicted by models in which X-ray photons are reprocessed by dense gas into UV and optical photons (Mushotzky, Done and Pounds 1993 and references therein). These features include an Fe Kα emission-line due to fluorescence and a hard (few tens of keV) X-ray 'tail' due to Compton reflection. Most of the incident X-ray energy, however, is absorbed by the gas and re-radiated thermally at UV/optical wavelengths determined by the effective temperature of the gas ($\sim 10^5$ K). The X-rays would therefore synchronise variability between the wave-bands, in agreement with the lack of observed phase-delay. In practice, several variations on the theme of disk-corona models or Thomson thick cloud models have been proposed, which by adjusting factors such as the patchiness of the disk-corona, the cloud covering factor and the Thomson optical depth of the gas can produce a variety of spectra. Even for the best studied source, NGC4151, a consensus has not yet been reached (*e.g.* Warwick *et al.* 1996; Poutanen *et al.* 1996; Zdziarski and Magdziarz 1996). The excess UV emission seen in NGC5548 and NGC4151 at some epochs must also be explained, for example by invoking significant intrinsic accretion disk emission due to viscous heating.

3C390.3. The X-ray/UV/optical continuum variability characteristics seen in 3C390.3 appear quite similar to those seen in the radio-quiet AGN, so the X-ray reprocessing model seems an attractive proposition for this object. A 1993 ASCA X-ray spectrum of 3C390.3 (Eracleous *et al.*, 1996) shows evidence for a broad Fe Kα line, believed to be evidence for X-ray reprocessing by gas near a black-hole (Tanaka *et al.*, 1995). Their ASCA GIS3 spectrum also show evidence for a hard X-ray tail, consistent with Compton reflection; however, calibration uncertainties could affect this result. Determining whether the difference in the relative NVA in the X-ray and UV between 3C390.3 and NGC4151 is related to NGC 4151 being in an unusually high UV state during the 1993 campaign, or reflects a more intrinsic difference requires more detailed study. The differences between the X-ray/UV/optical light-curves in 3C390.3 must also be explained.

FUTURE REQUIREMENTS

Despite much effort the kind of intensive multi-waveband campaigns discussed in this paper are few and far between. Much organizational effort is involved in conducting such campaigns over many weeks, requiring co-operation from schedulers and other observers as well as taking up valuable research time for many astronomers. The size of AGN watch is testament to these facts, and it is not a practical way to proceed over the long-term. In addition, very few AGN are monitored leading to poor statistics, made even worse by the knowledge that to gain observing time we must pre-select AGN known to be highly variable, which may introduce significant and unknown biases into the results. For the future there appear to be two approaches: (1) Multi-waveband facilities which allow simultaneous observations across a wide frequency range without requiring huge collaborations; (2) Robotic facilities, either ground- or space-based, which provide probably limited frequency access, but require little effort for scheduling.

An example of the first approach is the forthcoming ESA X-ray Multi-Mirror Observatory (XMM). XMM will not only carry a large X-ray (0.1–10 keV) telescope system but also a small (30cm), but sensitive, co-aligned UV/optical telescope – the Optical Monitor (XMM-OM). The XMM-OM will provide both broad-band filter and grism capability from 1500–6000Å. Thus, XMM will allow rapid, simultaneous X-ray and UV/optical monitoring of every AGN pointed at in guest-observer mode, and others in the surrounding field of view. For example, for a bright AGN such as 3C390.3 a 10 minute observation will give an $\approx 100\sigma$ detection in the X-ray and $\approx 50\sigma$ in the 1700–2300Å filter. X-ray and UV/optical grism spectra can also be obtained on longer timescales.

The second approach is already under-way for ground-based robotic telescopes. Exiting facilities are fairly small, but plans for 1-2m class facilities are well advanced (Parker 1996). In space one possible candidate is Lobster-eye, an all-sky, soft X-ray (0.5–2.4 keV) monitoring satellite (Priedhorsky *et al.*, 1996). This SMEX-class mission proposal uses advanced micro-channel plate technology to image a large sky area ($\sim 2\pi$ sr) simultaneously, spinning the satellite to get full coverage. The base-line study gives a daily 5σ detection limit of 2×10^{-12} erg cm^{-2} s^{-1}. This would result in daily observations of ~ 1000 AGN, with better sampling and/or quality for the brighter objects. Such X-ray light-curves, combined with data from other wave-bands, would totally revolutionise AGN continuum studies.

ACKNOWLEDGMENTS

We are grateful to Mathias Dietrich for the optical data of 3C390.3, Karen Wills for the MERLIN data and Tal Alexander for the ZDCF code. The AGN Watch also gratefully acknowledges the numerous observatory directors, schedulers and TACs whose facilities we have used.

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