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Optical and X-ray Variability of AGNs

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Abstract. I present new comparisons of AGN optical, UV, and X-ray variations. These reveal complex relationships between the different passbands that can change with time in a given object. While there is evidence from several objects that X-ray and optical activity levels are correlated on long timescales, variations on shorter timescales can occur independently. It is proposed that the combination of correlated and uncorrelated short-timescale variability is a consequence of anisotropic high-energy emission. It is also argued that the correlation between X-ray and optical variability on long timescales must be due to a common underlying factor and not to reprocessing of X-ray radiation.

1. Introduction

Lyuty (1978) showed that the X-ray and optical continuum fluxes of NGC 415 tracked one another on a timescale of months. The general expectation until fairly recently has been that the X-ray and optical would correlate with each other (e.g., Collin-Souffrin 1991). However, in recent years there have been various cases where the X-rays have *not* correlated with the optical. The most interesting of these has been NGC 3516 (Maoz et al. 2002). Here I give some results of our optical/X-ray monitoring of three very different AGNs and propose a mechanism to explain the curious combination of correlated and uncorrelated optical and X-ray variability seen in AGNs.

1.1. NGC 5548 – a Typical Broad-Line Seyfert 1

In 1998 we carried out a short *RXTE/ASCA/EUVE*/optical observing campaign (Chiang et al. 2000; Dietrich et al. 2001). During this campaign the *EUVE* flux led all other passbands. The *RXTE* PCA 2–10 keV flux lagged the *EUVE* by 0.39 ± 0.05 days. The *ASCA* SIS 0.5–1 keV flux lagged the *EUVE* by 0.15 ± 0.03 days. Combining the delays for all optical passbands in Dietrich et al. (2001) we find the optical lagging the *EUVE* by 0.2 ± 0.2 days. However, while the optical and *EUVE* show the same trend over our 30 day monitoring period, during our most intensive 5 days of simultaneous monitoring the detailed agreement is poor. The correlated flux variability between the X-ray and EUV fluxes in 1998 could be merely fortuitous. Haba et al. (2003) give an example of where there is a factor of two dip in the EUV flux over a few hours while the *ASCA* X-ray flux remains constant.

Uttley et al. (2003, see also these proceedings) have shown that there is a good correlation on a long ($>$ one month) timescale between the hard (2–10 keV) X-ray flux and the optical flux, as had been found for NGC 4151 by Lyuty

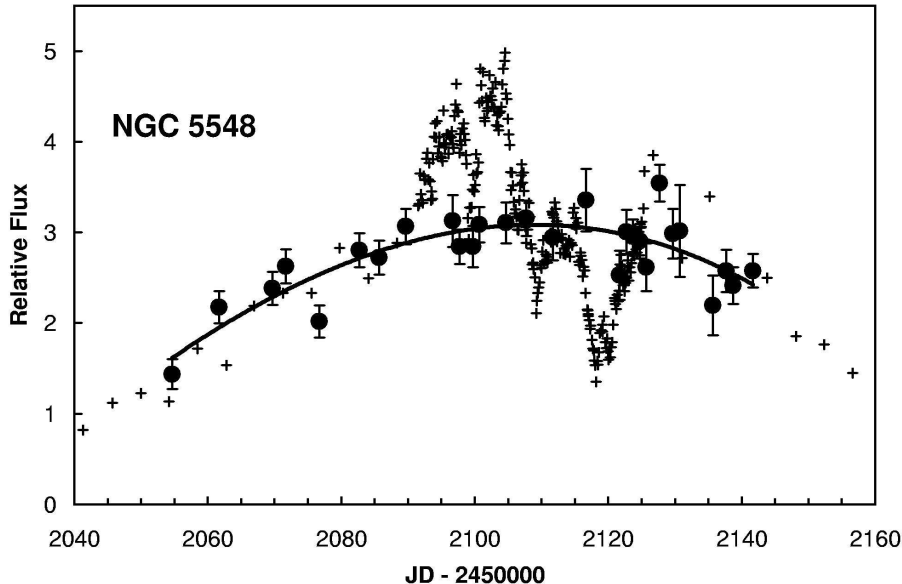


Figure 1. A comparison of the optical and X-ray variability of NGC 5548 over a three-month period in 2001. The *RXTE* 2–10 keV flux is shown by small crosses, and University of Nebraska V-band photometry (corrected for the host galaxy flux) is given by the solid circles with error bars.

(1978). Peterson et al. (2000) found that the optical and X-ray fluxes of NGC 4051 were also correlated on similar long timescales. Even for NGC 3516, there is a correlation of the X-ray and optical fluxes from year to year. Interestingly, for NGC 5548, Uttley et al. find that the long-term optical amplitude is slightly *greater* than the X-ray amplitude.

In July of 2001 we carried out intensive monitoring of NGC 5548 (Gaskell, Klimek et al. in preparation) in conjunction with intensive *RXTE* monitoring. Observational details are as in Klimek, Gaskell, & Hedrick (2004). In Fig. 1 we show the host-galaxy-subtracted Nebraska V-band photometry compared with the *RXTE* 2–10 keV fluxes. It can be seen that while the general trend of the optical variations (shown by the smooth curve) agrees with the long-term trend of the X-rays (and, interestingly, with no detectable lag), there are major short-term X-ray events (a “flare” and an “anti-flare”) that are *completely absent* in the optical light curve.

1.2. The NLS1 Ark 564

Ark 564 is our best-studied Narrow-Line Seyfert 1 (NLS1). Fig. 2 shows the results of our simultaneous *ASCA*, *HST*, and optical monitoring of the narrow-line Seyfert 1 galaxy Ark 564. The 1 keV *ASCA* data are a 0.3-day running average taken from the observations reported in Turner et al. (2001) and Edelson et al. (2002). The $\lambda 1365$ UV fluxes are from Collier et al. (2001), and the optical photometry from Shemmer et al. (2001). It can be seen that there are numer-

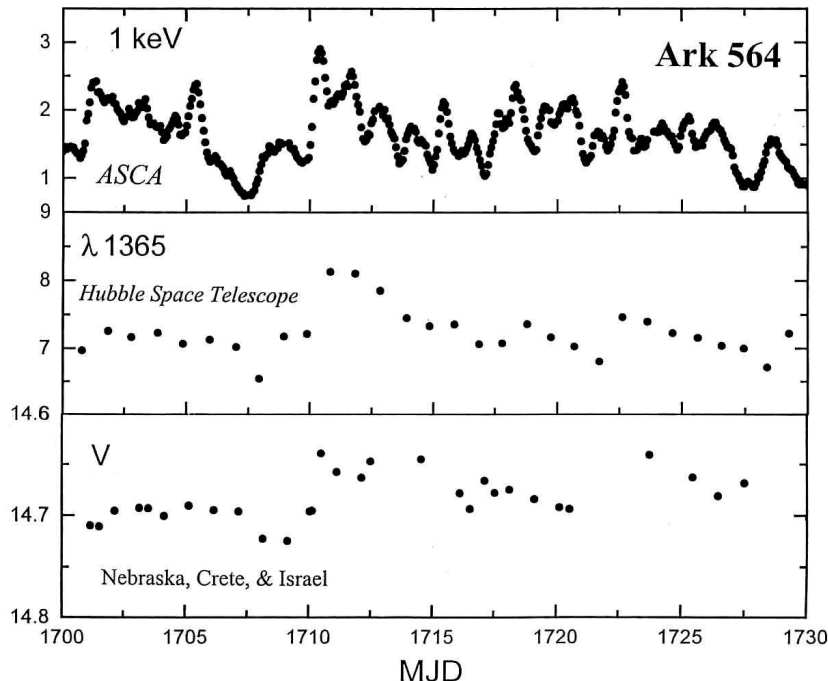


Figure 2. X-ray, UV, and optical variability of Ark 564. The top panel shows 0.3-day running average 1 keV *ASCA* fluxes, the middle panel *HST* $\lambda 1365$ UV fluxes, and the bottom panel V-band magnitudes (with no host galaxy correction) from the University of Nebraska, Skinakas Observatory (Crete), and Wise Observatory (Israel).

ous X-ray events on sub-day timescales and some of the largest of these have lower-amplitude UV and optical events following them by ~ 1.5 days.

There are several interesting points to note. First, the UV and optical track each other well. Second, the UV and optical variability was of much lower amplitude than the X-ray variability. (After host galaxy correction, the optical and UV amplitudes are probably similar.) Third, as with NGC 5548, there were X-ray events with no optical counterparts (notably the short flare at JD 2451706).

1.3. The Broad-Line Radio Galaxy 3C 390.3

3C 390.3 is our best-studied radio galaxy. Radio galaxies lie at the opposite end of the eigenvector 1 from NLS1s. Fig. 3 shows the results of our simultaneous soft X-ray, UV, and optical monitoring. The *ROSAT* 0.1 – 2 keV fluxes are from Leighly et al. (1997), the *IUE* $\lambda 1370$ UV fluxes are based on O’Brien et al. (1998), and V-band fluxes have been derived with scalings and corrections from Dietrich et al. (1998). 3C 390.3 has a substantial (and as yet undetermined) host galaxy contribution. To emphasize the optical variations we have subtracted an arbitrary constant flux.

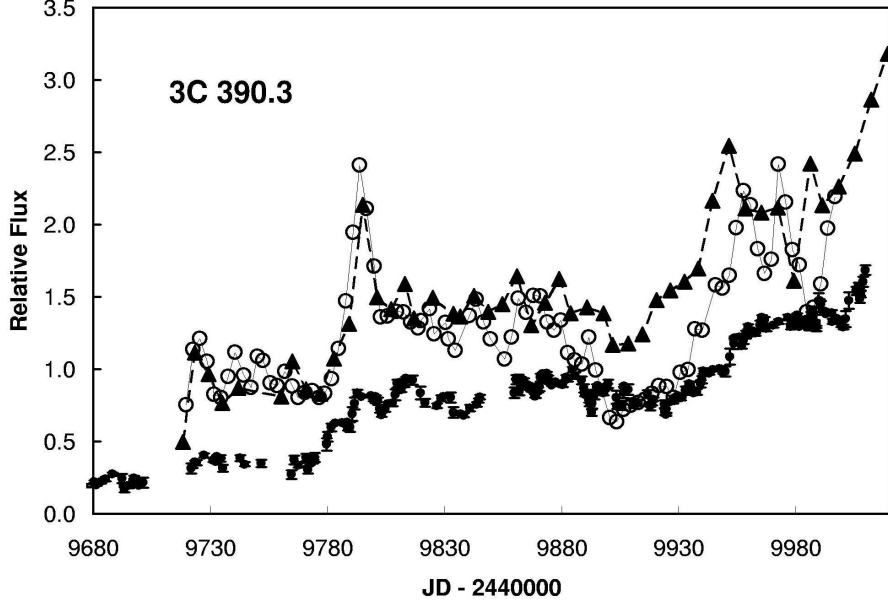


Figure 3. X-ray, UV, and optical fluxes of 3C 390.3. The open circles are 0.1 – 2 keV *ROSAT* HRI fluxes; the black triangles are *IUE* $\lambda 1370$ UV fluxes, and the small black circles with error bars are V-band fluxes. Scale factors have been chosen for plotting convenience, and an arbitrary constant has been subtracted from the V-band fluxes.

Fig. 3 shows a number of interesting things. The strong soft X-ray flare at JD 2449795 is followed only two days later by a $\lambda 1370$ UV flare that closely matches it in amplitude and duration, yet in the optical almost nothing happens! The same seems to be true for a smaller flare at JD 2449724. However, a pair of similarly strong soft X-ray flares at JDs 2449957 and 2449972 not only lack optical counterparts, but also lack UV counterparts.

The long-term variability (see Fig. 4) shows additional interesting things. Here we give 24-day average fluxes. There is now more qualitative agreement in the shapes and relative amplitudes of the light curves. The smoothed optical curves seems to be always lagging the UV by about three weeks. Before JD 2449830 the UV seems to be closely following the soft X-rays. However, from JD 2449900 onwards a remarkable thing is happening: the UV is clearly *leading* the soft X-rays by ~ 1 week! The optical is also leading the X-rays (although probably lagging the UV). Looking at the shorter-term variability in Fig. 3, it can be seen that the increased activity that leads to the strong X-ray flare at JD 2449957 *begins in the UV*.

On the other hand, in subsequent monitoring of 3C 390.3 we find that our V-band flux appears to lag the *RXTE* 2–10 keV flux by ~ 4.5 days (see Fig. 4 of Gaskell & Klimek 2003), and the amplitude of the short-term optical variability exceeds the amplitude of the X-ray variability.

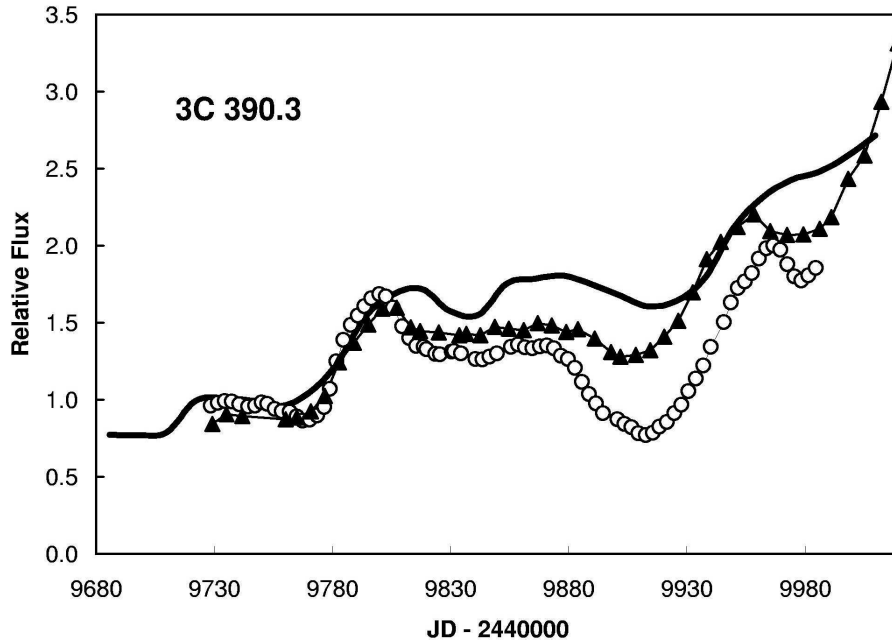


Figure 4. 24-day running average X-ray, UV, and optical fluxes for 3C 390.3. Open circles are 0.1 – 2 keV *ROSAT* HRI fluxes; black triangles are *IUE* $\lambda 1370$ UV fluxes, and the solid line is the V-band flux. The scale factors of the X-rays and UV are as in Fig. 3, but the optical observations have been arbitrarily re-scaled to roughly match the ranges of the X-ray and UV light curves.

2. Things to be Explained

The picture that emerges from these three objects (and others) is a complicated one. The following general statements can be made:

- (i) X-ray variability can be very rapid.
- (ii) Optical variability can sometimes be rapid too.
- (iii) For the very different AGNs NGC 4051, NGC 4151, NGC 5548, and 3C 390.3, the general level of activity in both the optical and X-ray regions is correlated on *long* timescales, and is probably of similar amplitude.
- (iv) Short-term variations of the X-ray and optical fluxes *can* be correlated.
- (v) Short-term variations in the X-ray and optical can also be *uncorrelated*.
- (vi) When the optical and X-ray fluxes are correlated, the lag of the optical is small.
- (vii) There is probably a preference for the EUV region to lead variability, but different signs of phase differences can be seen in the same object at different times.

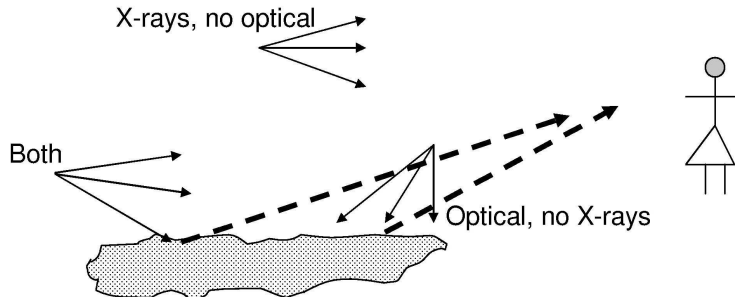


Figure 5. A schematic illustration of possible effects of directional emission of X-rays and high-energy particles on short-term X-ray and optical variability. The X-ray emission at the top happens to be towards the observer but mostly misses the reprocessing surface. The emission on the left is aimed towards the observer, but also hits a reprocessing surface and produces enhanced optical emission. The X-rays on the right are not directed at the observer, but do hit the reprocessing surface. The observer only sees the reprocessed radiation in this case.

3. An Anisotropic Emission Model

The frequent independence of the X-ray and optical variability on short timescales is puzzling given that sometimes the short-term variability *does* appear to be correlated. I want to conclude by suggesting a possible explanation of this. I believe that the rapid soft X-ray and EUV variability implies that the origin of the variability is *electromagnetic*, rather than arising primarily from gas dynamics. Electromagnetic phenomena propagate close to the speed of light, while gas-dynamical timescales (which tend to be of the order of the sound-crossing timescale) are much too long. It has already been suggested that the large amplitudes observed on short times in some cases could even require relativistic beaming (e.g., Boller et al. 1997; Reeves et al. 2002). An electromagnetic origin of variability is not unreasonable because, if one believes in energy equipartition, $E_{\text{magnetic}} \sim E_{\text{kinetic}}$.

What I want to draw attention to is that electromagnetic variability is *intrinsically anisotropic* – we see this in the outer layers of the sun all the time. This is true even if we are not seeing relativistic beaming, because particles are accelerated anisotropically. The intrinsic anisotropy implies that (a) we will not always have the emission aimed towards us, and (b) the emitted electromagnetic radiation or high-energy particles will not always hit a reprocessing medium. These two considerations result in the three possibilities that are sketched in Fig. 5 and described in the caption. Note that the heating is not necessarily arising from anisotropic X-ray or EUV emission, but, as with solar flares, it could arise from high-energy particles hitting the reprocessing medium.

This model offers an explanation of why short-term X-ray and optical variability are only sometimes correlated. The small X-ray optical lags that are seen are on the light-travel time + heating/cooling timescale. Because optical emission is more isotropic we see more optical events, but the larger number,

plus the smearing out of optical events, means that the optical amplitude will be smaller.

4. The Long-Term Relationship Between Optical and X-ray Variability

Although reprocessing of soft X-rays and EUV radiation into longer-wavelength emission fits in with the model just suggested to explain the varied short-term relationships between X-ray and optical variability, I think that reprocessing can be ruled out as the cause of *long-term* optical variability for at least three reasons: first, as shown above, UV and optical variability sometimes leads X-ray variability. Second, as noted by Uttley et al. (2003), in NGC 5548 the amplitude of optical variability exceeds that of the X-ray variability. A third reason is the lack of lag between the smoothed light curves. This means that the smoothing function extends to both positive and negative time, and hence that the activity in each wavelength region is correlated with the activity in the other wavelength region at a *later* time. To avoid violating causality the activity in the separate wavelength regions must both be driven by some independent slowly varying process. It has been shown elsewhere Gaskell (2004) that rapid variability depending on a slowly varying level of activity explains the proportionality of the variability to the mean flux level, explains the log-normal nature of X-ray variability, and produces light curves similar to those observed.

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