Correlated X-ray and Optical Variability in X-ray Binaries

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Abstract. It has long been known that X-ray and optical/UV variability in active X-ray binaries is sometimes correlated. The expectation has been that this arises from rapid reprocessing of X-rays into longer wavelength photons, and hence that the lags between the bandpasses can be used to reconstruct an echo-map of the binary, revealing the geometry and spatial scale of reprocessing sites. I will review how this can be done, what can be learned, and what progress has been made with real data. In addition, an interesting twist to the story has emerged in the form of correlated variability that does not seem associated with reprocessing. This extends to very short timescales, includes quasi-periodic behavior, and may be associated with optical synchrotron emission from a jet. Finally, contrary to expectations we have recently discovered that similar correlations are seen even in an ostensibly ‘quiescent’ object allowing similar analyses of reprocessing effects.

1. Introduction

X-ray binaries, and more specifically the Low Mass X-ray Binaries (LMXBs) that are the focus of this review, are variable objects. This is a universal characteristic seen from the radio through optical to X-rays and γ-rays. The X-ray variability is usually dominated by instabilities in the accretion flow. X-rays irradiate the outer accretion disk and companion star, resulting in reprocessed optical and UV radiation which is expected to be imprinted with the same variability as the X-ray signal is. An important difference, however, is that the optical and X-rays originate from a volume of significant spatial extent, resulting in light travel time delays between the X-rays and the reprocessed emission. It is then possible to infer information about the geometry and scale of the reprocessing region from the lags measured between X-ray and optical/UV variability; this technique is known as reverberation or echo-mapping, as the reprocessed light behaves as an echo.

In this work we will review the concepts underlying the echo-mapping technique and the successes achieved in applying it to LMXBs to date. Surprisingly the technique is applicable not only in the most X-ray luminous systems but in at least one quiescent black hole as well. In attempting to apply the technique it has also emerged that not all optical/UV correlations arise in reprocessing at all.
We will briefly consider an alternative kind of correlations that may originate in optical/UV synchrotron emission from a jet.

2. The Echo-Mapping Technique

Echo or reverberation mapping are not uniquely applied to X-ray binaries. Much of the development and application of the technique has been for active galactic nuclei (AGN); see for example [Peterson & Horne (2005)] for a recent review of the AGN problem and [O’Brien et al. (2002)] for the application to X-ray binaries. The key idea is that optical (or UV) variability, in either lines or continuum, is induced by reprocessing of X-ray variability, but lagged by light travel times within the system. Each reprocessing point can be thought of as responding to X-rays with a \( \delta \) function response at a delay time determined by the path difference between direct and reprocessed emission. The total optical response is then the sum of lagged responses from all the reprocessing elements. For a \( \delta \) function variation in the X-rays the optical response is then termed the transfer function, and measures how strong the response is as a function of the delay, effectively encoding information about the reprocessing geometry. For real lightcurves, the optical lightcurve can be modeled as a convolution of the X-ray lightcurve with the transfer function.

Several assumptions are inherent in this description. It is assumed that the optical responds linearly to the X-rays, or at least that a non-linear response can be linearized for small perturbations. It is also implicit that the X-rays originate from a point source, or at least a region much smaller in spatial extent than the reprocessing region. Finally to determine geometric information it is necessary that the lags be geometric in origin; significant reprocessing times would compromise this, and will be discussed in the next section.

2.1. Geometrical modeling of the response

In the case of X-ray binaries we have a clearer expectation of the reprocessing geometry than in AGN. We anticipate reprocessing from the accretion disk around the compact object, possibly enhanced at a bulge where material feeds into the disk from the companion star. We also might expect some reprocessing from the heated inner face of the companion star. [O’Brien et al. (2002)] modeled the reprocessing geometry to predict transfer functions for a variety of binary parameters. An example as a function of orbital phase is shown in Fig. 1. Simplicistically one expects two components. The disk will extend from zero lag to \( r_{\text{disk}}(1 + \sin i) \) where \( r_{\text{disk}} \) is the disk radius in light seconds and \( i \) the binary inclination. Within this range the shape of the response is strongly sensitive to the inclination and somewhat less so to the degree of disk flaring. The response from the companion star approximately oscillates within the range \( a(1 \pm \sin i) \) over the course of the binary orbit, where \( a \) is the binary separation in light seconds. The strength and width of the companion response is a strong function of the mass ratio and disk thickness (which determines how much of the companion is shielded). One of the great appeals of applying echo-mapping to X-ray binaries is that with phase-resolved observations of the companion echo over the orbit, one could measure both \( a \) and \( i \) independently of other techniques and assumptions.
2.2. Empirical descriptions of the response

O'Brien et al. (2002) did apply their model to real data, and we will discuss their results in due course. Many echo-mapping studies use more pragmatic, and less model-dependent approaches. Ideally one would take high quality X-ray and optical lightcurves and deconvolve them to directly determine the shape of the transfer function. This is the basis of the maximum entropy echo-mapping technique (Horne 1994) in which a maximum entropy regularization method is used to suppress the problem of fitting the noise. Unfortunately for many X-ray binary datasets, this technique has proved of limited value. This is because of the much shorter timescales involved than in AGN, resulting in lower signal-to-noise data. Typically one finds that the transfer function is not well constrained in detail, and the response one recovers is very sensitive to the assumptions made.

An alternative and simpler approach has thus been developed in which a very simple functional form is adopted for the transfer function, either a rectangular response (Pedersen et al. 1982) or a Gaussian (Hynes et al. 1998). Both are introduced as approximations to the response rather than for a physically motivated region, and amount to the assumption that the data only constrain the mean lag and the amount of smearing. The Gaussian formulation essentially yields the first two moments of the delay distribution.
An even simpler, but widely used approach is to measure the cross-correlation of the two datasets. This yields a mean lag but no information about the smearing, and considerable care should be taken in interpreting the results of a cross-correlation analysis (Koen 2003).

3. Reprocessing physics

3.1. Energy dependent reprocessing

The response of an atmosphere, whether that of the disk or companion star, is highly sensitive to the energy of incident photons, and hence to the irradiating spectrum. The primary energy absorption mechanism will be photoabsorption, by K or L shell electrons of carbon, nitrogen, or oxygen below the iron edge (∼ 7 keV), and by iron above that. Photoabsorption cross-sections are a steep function of energy, so low energy photons will be absorbed in the upper layers of the atmosphere, while higher energies will penetrate progressively deeper. Above ∼ 10 keV photoabsorption cross-sections become small enough that Compton scattering begins to take over as the dominant source of X-ray opacity. Some of the higher energy photons will diffuse deeper into the atmosphere due to scattering, but others will be scattered back out depositing only a small fraction of their energy. At higher energies this Compton reflection becomes increasingly likely resulting in a high X-ray albedo and low reprocessing efficiency.

These effects divide the response into three regimes. At less than a few keV, photons are photo-absorbed at low optical depths and can be expected to produce an X-ray heated corona above the disk. The reprocessed spectrum will not be efficiently thermalized and may include a significant emission line component. At intermediate energies, up to ∼ 10 keV, photons penetrate deeper into the photosphere before being absorbed, resulting in absorption at moderate optical depths. In this case reprocessed optical and UV photons will undergo multiple scatterings before diffusing out of the atmosphere and a thermalized spectrum, closer to a black body, is expected. Finally above 10 keV, photons will increasingly tend to be Compton reflected rather than photo-absorbed, and less efficient reprocessing occurs.

It is worth remarking that type-I X-ray bursts, to be discussed in more detail subsequently, provide an ideal X-ray spectrum to observe thermal reprocessing. The typical 1–3 keV black body spectrum outputs most of its energy in the intermediate regime described above, resulting in an efficient thermalized response. Softer photons can be expected to produce some lines as well, and harder ones to result in a Compton reflected burst (see Ballantyne 2004 and references therein.)

3.2. Reprocessing times

We have thus far discussed only lags due to global light travel times within the system. Local delays in reprocessing the X-rays might also be expected, from two sources. The first are diffusion times, essentially local turbulent light travel times as reprocessed photons undergo a random walk to escape from the atmosphere. The second are finite times associated with each interaction of a photon with an atom or ion.
Diffusion times are expected to be the dominant of the two. These were briefly considered in the specific case of X-ray bursts by Pedersen et al. (1982) who estimated that the typical diffusion time will always be less than 0.6 s, small compared to light travel times within the binary. Cominsky, London, & Klein (1987) examined the problem more rigorously, calculating time-dependent responses of a hot stellar atmosphere to an X-ray burst, including the effect of the burst on the atmospheric temperature structure and opacities. Their results were in agreement with those of Pedersen et al. (1982), and they found that 50% of the reprocessed light is expected within just 0.2 s, but that there was also a very extended tail to the response up to 10 s. Their calculations also considered harder irradiation and cooler atmospheres, finding that both would increase the diffusion timescale significantly (see also McGowan, Charles, O'Donoghue, & Smale (2003)). Thus while reprocessing times are of marginal significance in considering burst reprocessing, they may be of more importance for other applications where further investigation is needed.

4. Type I X-ray Bursts

4.1. Historical observations

Type-I X-ray bursts are thermonuclear explosions on the surface of a neutron star in an LMXB (Strohmayer & Bildsten 2004). They represent an enormous increase in the X-ray flux, a factor of twenty or more, rising on a timescale of a few seconds. From these characteristics, together with the optimal spectrum as already discussed, it should be clear that X-ray bursts are an ideal echo-mapping probe. Hence it is using these events that some of the first echo-mapping experiments were performed, and the most convincing results have been obtained.

Reprocessed optical bursts were discovered in the late 1970’s in the LMXBs 4U 1735–444 and Ser X-1 (Grindlay et al. 1978; McClintock et al. 1979; Hackwell et al. 1979). The optical flux was found to rise by nearly a factor of two and lag a few seconds behind the X-rays. It was immediately appreciated that the optical flux was several orders of magnitude to high to be due to direct emission from the neutron star surface, and hence that the brightening must be due to reprocessing of X-rays by the much larger projected area of the accretion disk and/or companion star. The 2.8 s lag in 4U 1735–444 (McClintock et al. 1979) supported this interpretation, being consistent with the expected light travel time delays in this short-period binary.

Subsequent efforts focused on a number of coordinated campaigns to observe another LMXB 4U 1636–536 (Pedersen et al. 1982; Lawrence et al. 1983; Matsuoka et al. 1984; Turner et al. 1985; Truemper et al. 1985). These campaigns yielded a total of twelve simultaneous bursts from this system. Lags were found to be in the range 0–4 s with evidence that the variation in the lags was a real effect and not due to measurement error (Matsuoka et al. 1984). In one burst (Truemper et al. 1985) the optical rise-time was clearly longer than that of the X-rays, suggesting significant light-travel time smearing of a few seconds, but in most cases the data quality were insufficient, allowing only an upper limit on the smearing timescale.
The large amplitudes of X-ray bursts provide additional information not available when variability is a small perturbation. Observations never record the bolometric luminosity, but always a bandpass-limited one. Consequently the observed reprocessed lightcurve depends on the spectral evolution as the reprocessor cools. Shorter wavelengths are sensitive to hotter material, they are expected to decay more rapidly, and hence multicolor observations provide some temperature sensitivity. This is not a subtle effect, and the early observations indicate the reprocessor temperature typically doubles during a burst. The best considered case was analyzed by Lawrence et al. (1983), who found the reprocessor temperature rising from 25,000 K to 50,000 K at the peak of outburst. All of the early observations were constrained not only by data quality, however, but by the limitations of optical data (UBV photometry at best) in constraining such high temperatures precisely.

In the time since these studies were performed, substantial steps forward have been made both in X-ray sensitivity, most notably by RXTE, and in the quality of optical data. The replacement of photomultipliers with CCDs was initially a hindrance to this work, as high time-resolutions were not available, but the advent of fast CCD systems has allowed enormous improvements in optical data quality exploiting higher quantum efficiencies and two-dimensional detectors. This is exemplified by simultaneous observations of a burst in GS 1826–24 (Kong et al. 2000). The higher quality of these observations allowed determination of both a lag of $\sim 3$ s and a dispersion of $\sim 3$ s, in spite of the source being fainter than 4U 1636–536 at both X-ray and optical wavelengths. These observations make it clear that the accretion disk must play a major part in reprocessing of X-ray bursts, as might be expected. The large dispersions seen by Truemper et al. (1985) and Kong et al. (2000), and rapid onset of optical response, cannot arise from the companion star alone.

### 4.2. Multiwavelength bursts from EXO 0748–676

The best dataset for the method yet obtained was obtained for EXO 0748–676 (Hynes et al. 2005; see also Hynes et al. 2004b). This brought together a number of threads from previous successful studies. Use of RXTE provided high quality X-ray coverage, while a fast CCD camera coupled to the large aperture of the Gemini-S telescope provided exquisite quality optical lightcurves. Four bursts were observed over two successive nights, providing some phase information, and one of these was also observed at high time-resolution in the far-UV by HST/STIS. The latter was a unique observation to date, providing far more sensitivity to high temperature responses than is possible with optical data alone, and also yielding a time-resolved UV spectrum, facilitating a direct test of the expectation that the reprocessed light should be close to a black body.

The burst recorded simultaneously in X-rays, optical, and UV is shown in Fig. 2. This was fitted with a model in which the X-ray burst (expressed as approximately bolometric irradiating luminosity) was convolved with a Gaussian transfer function to determine the bolometric reprocessed luminosity. This was then converted to $V$ and far-UV fluxes assuming that the reprocessor is a single-temperature black-body. This allows superb fit to optical and UV data, but at the expense of requiring renormalization between the bandpasses. The latter may indicate a source of excess optical reprocessed light from a cooler region
(such as the companion star) which does not contribute to the far-UV. The best fit parameters yield a mean lag of about 4 s and smearing width of 2.5 s (standard deviation). This would be consistent with a combination of emission from the disk and companion, but is too extended for the disk alone. The temperature evolution spans the range 18,500–35,200 K, comparable to previous measures, but more precisely constrained by the far-UV coverage. The far-UV burst spectrum is dominated by the continuum and is consistent with a slightly reddened 27,000 K black body (the flux-weighted average temperature from the light curve fit). This confirms that the reprocessed burst flux is quite effectively thermalized.

5. Flickering

While bursts provide an ideal signal for echo-mapping, they also have limitations. Not only are bursts not seen in black hole systems, but there are also neutron star LMXBs which do not burst (e.g. Sco X-1). Clearly we would like complementary echo mapping information about these systems. Furthermore, bursts are rather infrequent, with inter-burst intervals typically 2–10 hrs. Accumulating phase-coverage can therefore be extremely expensive. An alternative source of variability is provided by the flickering that seems a ubiquitous signature of accretion. While analysis of simultaneous X-ray and optical/UV flickering can potentially provide phase-resolved information in any system, this potential has
yet to be fully realized. It has been found that the optical response is rather weak, only a few percent at best. Consequently high signal-to-noise observations are needed to pick out a measurable correlation. Even then, success is typically only achieved when high levels of variability are present, with other datasets yielding a non-detection. For example, in the dataset discussed above on EXO 0748–676, high quality optical data were obtained, and correlated bursts were observed, yet no correlation is present between the inter-burst X-ray and optical lightcurves (other than orbital variations).

Consequently echo-mapping type analyses based on flickering have only been published for three objects (excluding XTE J1118+480 which will be described separately as a special case). The bright neutron star system Sco X-1 was observed by [Ilovaisky et al. 1980] and [Petro et al. 1981]. Both found correlations, with evidence for lags and substantial smearing of the response; [Petro et al. 1981] described the optical response as a low-pass filtered version of the X-rays, with variability on timescales \( \lesssim 20 \) s smoothed out. [McGowan, Charles, O'Donoghue, & Smale 2003] reanalyzed these datasets with the Gaussian transfer function method. In some cases no good fit could be obtained. The pair of lightcurves where the method did appear to succeed yielded a lag of 8.0±0.8 s and Gaussian dispersion of 8.6±1.3 s. For comparison, lags of up to 4–5 s are expected from the disk and 10 s from the companion star.

The primary focus of [McGowan, Charles, O'Donoghue, & Smale 2003] was LMC X-2, for which new optical and X-ray data were presented. A correlation was detected with the optical data clearly lagging significantly. Gaussian transfer function fitting yielded a lag of 18.6±7.3 s with respect to 2–10 keV X-rays and a Gaussian dispersion of 10.2±5.8 s. In the case of this system, interpretation is less clear as system parameters are not known. The orbital period is believed to be 8.2 hrs (see [McGowan, Charles, O'Donoghue, & Smale 2003] for discussion). If the compact object is a neutron star then we expect disk lags of 2–3 s and the secondary at 6 s. If it is a 10 M\( \odot \) black hole then disk and companion lags of 4–5 s and 11 s are expected respectively. Thus for both Sco X-1 and LMC X-2 there is marginal evidence for a response extending to later than expected from light travel times alone.

Finally the black hole system GRO J1655–40 was observed simultaneously by HST and RXTE on several occasions. On one of these clear correlations were seen between rapid X-ray and optical variability ([Hynes et al. 1998]). These were repeatable across multiple independent pairs of lightcurves and implied lags of 10–20 s with smearing times of order 10 s. This system has well determined orbital parameters allowing direct comparison of the measured lags with expectations. At the orbital phase observed the companion star should have produced lags of over 40 s so is ruled out by causality. The lags measured are consistent with being dominated by the disk. An analysis using modeled binary transfer functions by [O'Brien et al. 2002] came to the same conclusion.

6. Echoes in Quiescence

Thus far we have only discussed echo-mapping experiments in the context of X-ray bright states. Although optical flickering is present in quiescent X-ray binaries (e.g. [Zurita, Casares, & Shahbaz 2003] [Hynes et al. 2003]), it has generally
been assumed that the X-rays are too faint to cause measureable reprocessing and that optical flickering arises from similar mechanisms as in cataclysmic variables, in the outer disk and/or stream-impact point. The highest quality optical observations reveal lightcurves clearly distinct from those of cataclysmic variables, however, calling this assumption into question. The strongest evidence against it came from spectroscopic observations of optical flares in the black hole system V404 Cyg (Hynes et al. 2002). Emission line flares exhibited the characteristic double-peaked profile of emission distributed across an accretion disk, leading to the speculation that they might be global events driven by irradiation rather than local magnetic reconnection events. This was strikingly confirmed by simultaneous X-ray and optical observations of the system demonstrating a clear correlation between the X-rays and both the optical line emission (which was again double-peaked) and the continuum (Hynes et al. 2004a). The flare timescales, and lags between X-rays and optical, are much shorter than the dynamical timescales in the disk regions implied by the line profile enhancements, indicating that only light travel timescales can couple these regions fast enough.

This discovery raises the possibility of applying echo-mapping (and even echo-tomography) to determine the geometry of the accretion flow in quiescent systems. Furthermore, the strong line response allows us to obtain kinematic information on the reprocessing site as well as light travel time diagnos-
Figure 4. Simultaneous quiescent lightcurves of the black hole system V404 Cyg at X-ray and optical wavelengths. Note the correlation between X-ray and optical variability. The lines must be formed through reprocessing, although the origin of the continuum remains unclear. From Hynes et al. (2004a).

Fundamental to echo-mapping is the assumption that correlated X-ray and optical/UV variability indicate reprocessing of the X-rays by relatively cool material. We should not take this for granted, however, and there are some observations which seriously challenge this assumption.

7. When is an Echo Not an Echo?

The first indication of difficulties came from fast optical observations of the black hole binary GX 339–4 (Motch, Ilovaisky, & Chevalier 1982; Motch et al.).
Dramatic optical variability was seen extending to extremely short timescales (10–20 ms), much shorter than the light travel timescales expected, or the smearing typically observed in other systems described above. Fabian et al. (1982) argued that the flares most likely originated cyclotron radiation, with a brightness temperature $\gtrsim 9 \times 10^8$ K. Correlations were seen in a short (96 s) simultaneous observation, but of a puzzling nature. The X-ray and optical were anti-correlated with optical dips apparently preceding the X-rays by 2.8 $\pm$ 1.6 s. The connection between X-ray and optical behavior was further reinforced by the presence of quasi-periodic oscillations at the same frequency in both energy bands. The brevity of the simultaneous observation, and the ambiguity in the lags introduced by quasi-periodic variability left this result tantalizing however.

New light was shed on this behavior by the 2000 outburst of the black hole system XTE J1118+480. A much larger time-resolved database was accumulated on this object including both multi-epoch simultaneous X-ray/UV observations (Haswell et al. 2000, Hynes et al. 2003b) and independent X-ray/optical data (Kanbach, Straubmeier, Spruit, & Belloni 2001, Spruit & Kanbach 2002, Malzac, Belloni, Spruit, & Kanbach 2003). Large amplitude X-ray variability was present, and accompanied by correlated UV and optical variations. In this case a positive correlation with the optical/UV lagging the X-rays was clearly present leading to hopes that this would be an ideal echo-mapping dataset. There were serious problems with this interpretation, however. These were most pronounced in the optical data (Kanbach, Straubmeier, Spruit, & Belloni 2001) and included an optical auto-correlation function narrower than that seen in X-rays, and a cross-correlation function containing a marked “precognition dip” before the main peak. The latter could be interpreted in terms of optical dips leading X-ray flares by a few seconds, as suggested in GX 339–4, suggesting a common origin. Neither of these effects are expected in a reprocessing model. Light travel times should only act to smooth out optical responses, and hence broaden the optical auto-correlation function, and continuum responses (as considered here) should generally be positive. As in GX 339–4 the variability extended to very short timescales ($\lesssim 100$ ms) and hence Kanbach, Straubmeier, Spruit, & Belloni (2001) estimated a minimum brightness temperature of $2 \times 10^8$ K. They also suggested that the strange variability properties were the result of optical cyclosynchrotron emission. These properties become weaker at shorter wavelengths (Hynes et al. 2003a), as does the variability, as might be expected if the behavior originates from a very red source of emission like synchrotron.

Dominant synchrotron emission in this system was not uniquely suggested by the variability properties. The very flat UV to near-IR spectrum had previously been attributed to synchrotron emission (Hynes et al. 2000) and the broad-band spectral energy distribution has been successfully accounted for using a simple jet model (Markoff, Falcke, & Fender 2001). In the latter model, only the IR originates from flat-spectrum (self-absorbed) synchrotron, whereas the extension of the flat spectrum into the UV is explained as a coincidental combination of optically thin synchrotron and disk emission. The variability amplitudes define a rather different energy distribution to that seen in persistent light. The variability decreases from nearly 50% rms in the $K$ band to just a few percent in the far-UV (Hynes et al. 2003b). When these fractional amplitudes are converted into absolute flux units, the rms variability energy...
distribution defines a power-law with \( F_\nu \propto \nu^{-0.59} \), totally consistent with optically thin synchrotron. Furthermore, this power-law not only applies to the IR–UV variability, but extends to X-rays, and accounts for both the amplitude and energy dependence of X-ray variability. This implication of synchrotron X-ray emission remains controversial, but was also predicted by the jet model of Markoff, Falcke, & Fender (2001). Recently Malzac, Merloni, & Fabian (2004) have shown that it is also possible to reproduce the auto-correlation and cross-correlation function properties using a model in which a common magnetic reservoir drives both X-ray variations in an accretion flow (in this case assumed to be inverse Compton emission rather than synchrotron) and optical variability in a jet.

These arguments together provide strong evidence that a jet, or at least some kind of outflow, is responsible for much of the emission in XTE J1118+480 and for the correlated variability. By extension, the same interpretation may apply to other objects showing similar properties. GX 339–4 is of course a prime candidate, but it is also argued that jets may be dominant in quiescent black hole systems (Fender, Gallo, & Jonker 2003). It may thus be that the continuum component correlated with X-rays in V404 Cyg in quiescence actually arises from jet variability, rather than reprocessing as required to explain the line emission.

8. Conclusion

Correlated X-ray and optical/UV variability has now been widely, if not commonly, detected in X-ray binaries. The detections span the lowest luminosities to the highests and suggest a more complex origin than the simple reprocessing originally envisioned.

Reprocessing does appear to be responsible for reprocessed type I X-ray bursts, and for correlated flickering in luminous X-ray binaries. Typically these studies have shown that the disk appears to dominate the response, although in some cases the lags appear to lag for light travel times alone. Where a reprocessed spectrum has been obtained it is consistent with predominantly optically thick thermal reprocessing. The full potential of this technique has yet to be exploited, either through phase-resolved echo-tomography or through kinematically resolved emission line echo-mapping.

On the other hand, correlated variations in X-ray binaries in the low/hard state do not have the characteristics of reprocessed variability, and instead appear to originate in optical synchrotron emission, likely from a jet. Understanding the variability properties in the context of a jet model remains a topic of ongoing research, but this may prove a very valuable diagnostic of the disk-jet connection.

At the lowest luminosities, there is evidence that emission line variability in V404 Cyg in quiescence is dominated by reprocessing within the disk. The origin of continuum variability is less clear, and this might either be reprocessing, or synchrotron. For these systems the low X-ray brightnesses are a challenge that Chandra and XMM are barely adequate for, and full exploitation of echo-mapping in quiescence will likely require a larger throughput mission such as Constellation-X.
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