

First Search for an X-ray – Optical Reverberation Signal in an Ultraluminous X-ray Source

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ABSTRACT

Using simultaneous optical (VLT/FORS2) and X-ray (*XMM-Newton*) data of NGC 5408, we present the first ever attempt to search for a reverberation signal in an ultraluminous X-ray source (NGC 5408 X-1). The idea is similar to AGN broad line reverberation mapping where a lag measurement between the X-ray and the optical flux combined with a Keplerian velocity estimate should enable us to weigh the central compact object. We find that although NGC 5408 X-1's X-rays are variable on a timescale of a few hundred seconds (RMS of $9.0 \pm 0.5\%$), the optical emission does not show any statistically significant variations. We set a 3σ upper limit on the RMS optical variability of 3.3%. The ratio of the X-ray to the optical variability is an indicator of X-ray reprocessing efficiency. In X-ray binaries, this ratio is roughly 5. Assuming a similar ratio for NGC 5408 X-1, the expected RMS optical variability is $\approx 2\%$ which is still a factor of roughly two lower than what was possible with the VLT observations in this study. We find marginal evidence (3σ) for optical variability on a ~ 24 hour timescale. Our results demonstrate that such measurements can be made, but photometric conditions, low sky background levels and longer simultaneous observations will be required to reach the optical variability levels similar to X-ray binaries.

Subject headings: X-rays: binaries: Accretion disks: Methods: Data analysis

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1. Introduction

X-ray bright, off-nuclear point sources in nearby galaxies whose isotropic luminosities exceed the Eddington value of a $25 M_{\odot}$ black hole, i.e., $\gtrsim 3 \times 10^{39}$ ergs s^{-1} , are referred to as ultraluminous X-ray sources (ULXs). The main debate concerning these objects is whether they are stellar-mass black holes (mass range of 3-25 M_{\odot}) circumventing the Eddington limit via high accretion and/or emission (e.g., King et al. 2001; Körding et al. 2002; Begelman et al. 2002; Poutanen et al. 2007; Gladstone et al. 2009), or if they are powered by intermediate-mass black holes (IMBHs: mass range of a few 100-1000 M_{\odot}) accreting below the Eddington limit (e.g., Colbert & Mushotzky 1999; Miller et al. 2004, 2013). Recent studies suggest that ULXs are very likely an inhomogeneous sample of both stellar and intermediate-mass black holes (e.g., Farrell et al. 2009; Motch et al. 2014; Pasham et al. 2014, 2015; Mezcua et al. 2015); and in some rare cases may even be powered by neutron stars (Bachetti et al. 2014).

A straightforward way to solve the ULX mass problem is by measuring the dynamical masses of their compact objects. This involves identifying the compact object’s companion star (an optical counterpart) and Doppler tracking its radial velocity (using spectroscopic lines) from which one can extract the orbital period of the system and the companion’s radial velocity semi-amplitude. These two quantities can be combined to construct the so-called mass function, which would enable a lower limit on the black hole mass (see, for example, Soria et al. 1998 for relevant equations). Although very challenging, there have been a handful of such attempts that have succeeded in weighing stellar-mass black holes in ULXs (e.g., Liu et al. 2013; Motch et al. 2014; See, however, Roberts et al. 2011, Cseh et al. 2013, where the mass could not be tightly constrained). This method is difficult primarily because ULX optical counterparts are extragalactic, and hence faint with V-band magnitudes in the range of 22-24 (e.g., Tao et al. 2011; Gladstone et al. 2013). Extracting their optical spectra is not only challenging but also very expensive—requiring an 8-m class telescope (e.g., Cseh et al. 2013).

In the absence of dynamical mass constraints various indirect methods—that have been well-calibrated against stellar-mass black holes—have been used. For example, it is known in stellar-mass black hole systems that at a given X-ray energy spectral power-law index, the centroid frequency of the low-frequency quasi-periodic oscillation (QPO) scales inversely with the black hole mass (e.g., Sobczak et al. 2000; Vignarca et al. 2003; Shaposhnikov & Titarchuk 2009). Assuming that the ULX mHz QPOs are analogous to the low-frequency QPOs of stellar-mass black holes (0.2-15 Hz: Casella et al. 2005), various authors have estimated some ULX black hole masses to be in the range of a few \times (100-1000) M_{\odot} (e.g., Dewangan et al. 2006; Strohmayer & Mushotzky 2009; Feng et al. 2010; Rao et al. 2010;

Dheeraj & Strohmayer 2012). However, this underlying assumption of mHz QPOs being the analogs of the low-frequency QPOs has been questioned by some authors (Middleton et al. 2011). In a few cases, in addition to the mHz QPOs, 3:2 frequency ratio high-frequency QPO analogs have also been discovered. Such twin pairs not only confirm that the mHz QPOs in these systems are indeed the analogs of the stellar-mass black hole low-frequency QPOs, but also enable independent, accurate black hole masses. Assuming the inverse mass-to-QPO frequency relation of stellar-mass high-frequency QPOs, the detected 3:2 pairs in M82 X-1 and NGC 1313 X-1 imply a black hole mass of $428 \pm 105 M_{\odot}$ (Pasham et al. 2014), and $5000 \pm 1300 M_{\odot}$ (Pasham et al. 2015), respectively.

Another direct method that can be employed to weigh black holes—but has not been hitherto exploited for ULXs—is the so-called reverberation mapping technique. It is now known that a significant fraction of the optical emission from accreting X-ray binaries is due to X-ray reprocessing in the surrounding accretion disk (van Paradijs & McClintock 1994; Reynolds & Miller 2013), and current evidence suggests that this may be the case in some ULXs (Tao et al. 2011; Gladstone et al. 2013). In simple models of this process the optical emission results from X-ray irradiation of the outer portions of the disk by the central continuum. The optical emission is thus correlated with the X-ray emission but delayed by the light travel time effects (Hynes et al. 1998; Gandhi et al. 2010). Measurement of the time delay, τ , will provide a direct estimate of the accretion disk’s (and hence the binary’s) size ($R \approx c\tau$, where c is the speed of light). A mass estimate can follow in a manner analogous to AGN reverberation mapping (Peterson & Wandel 2000). The difference is that in ULXs the optical flux is expected to reverberate in response to the variations in the central X-ray flux while in AGN the optical broad line flux responds to changes in the optical continuum. Nevertheless, a lag measurement gives a size scale of the accretion disk which can then be combined with measured line widths (Δv) due to the Keplerian motions in the disk. The mass of the ULX’s compact object (M) can then be estimated as,

$$M = \frac{f c \tau \Delta v^2}{G} \quad (1)$$

where G is the Gravitational constant and f is a geometric correction factor whose value is expected to be of order unity.

In practice, however, the reprocessed optical emission can originate from a wide range of accretion disk radii and from even further out from the face of the companion star illuminated by the X-rays (e.g., O’Brien et al. 2002). Therefore, in order to accurately measure the black hole’s mass one would need to particularly measure the lag between the X-rays and the reprocessed optical flux originating from the part of the accretion disk that is spatially coincident with the optical emission lines. This can, in principle, be achieved by simultaneous X-ray and narrow band optical photometry (e.g., see Muñoz-Darias et al. 2007 for the case of

Sco X-1). But even with simultaneous X-ray and broad band optical observations it should be possible to clearly distinguish a ULX IMBH from a ULX stellar-mass black hole. This is simply because for a fixed binary orbital period a system hosting an IMBH (say, $1000 M_{\odot}$) will be significantly larger than one with a stellar-mass black hole primary (say, $10M_{\odot}$). For example, the binary separation scales as $M_{tot}^{1/3}$, where M_{tot} is the total system mass and additionally, the radius of the Roche lobe of the accretor, which sets an upper limit on the size of the accretion disk, also grows significantly with M_{tot} (e.g., Eggleton 1983). On the other hand, the situation can be more complicated as the optical emission from X-ray binaries is not always from just X-ray reprocessing. Details of non-reprocessing optical emission and references thereof are discussed briefly in section 6. The proposed reverberation methodology will work when the reprocessed optical emission component can be confidently identified.

NGC 5408 X-1 (hereafter, X-1) is a ULX with an average X-ray (0.3-10 keV) luminosity of $\approx 10^{40}$ ergs s^{-1} (see, Table 4 of Dheeraj & Strohmayer 2012). Based on its high luminosity and the observed mHz QPO frequency range of 10-40 mHz (Dheeraj & Strohmayer 2012; Caballero-García et al. 2013), it has been suggested to host an IMBH with mass anywhere between a few $\times(100-1000) M_{\odot}$ (Dheeraj & Strohmayer 2012). Grisé et al. (2012) modeled the X-ray/UV/optical/NIR spectral energy distribution (SED) of the ULX and concluded that its optical emission is consistent with originating from an X-ray irradiated accretion disk. In addition, deep optical spectroscopy of this source has revealed the presence of a He II $\lambda 4686 \text{ \AA}$ emission line whose broad component has an average full width at half maximum (FWHM) of $\approx 780 \pm 64 \text{ km s}^{-1}$ (Cseh et al. 2011; 2013). Based on the observed $\approx 13\%$ variability of this broad emission component over a time span of roughly 4 years and its Gaussian profile, Cseh et al. (2011, 2013) argued that this broad line arises from Keplerian motion within an accretion disk rather than a donor star. Assuming that to be the case, if one can measure the distance of this optical broad line emitting site from the central black hole, it can be combined with the line width to directly measure the mass of the black hole using equation (1). It can be noted straightforwardly from this equation that for X-1’s black hole mass in the range of a few $\times(100-1000) M_{\odot}$ the expected time lags based on the line width are a few $\times(100-1000) \text{ s}$. The maximum of the optical and the X-ray time resolution sets a lower limit on the time lag, and hence the black hole mass that can be probed with this method. In this proof-of-concept study for X-ray – optical reverberation, we are sensitive to black hole masses greater than $600 M_{\odot}$ because of an optical time resolution of 440 s.

The article is arranged as follows. In section 2 we describe the optical data acquired by the Very Large Telescope (VLT) and the X-ray data taken with *XMM-Newton*. In section 3, we describe the procedure we used to extract the optical light curve while in section 4 we describe the X-ray data analysis. We present the cross-correlation analysis in section 5 and discuss the implications and future prospects in section 6.

2. Data Description

The FOcal Reducer Spectrograph 2 (FORS2) on the VLT (UT1, “Antu”) observed the field of view containing X-1 ($\alpha = 14^{\text{h}}03^{\text{m}}19.62^{\text{s}}$ and $\delta = -41^{\circ}22'58''54$; Lang et al. 2007) in imaging mode on three consecutive nights—for approximately 16 ks each night—starting from 2014 February 12 until 2014 February 14¹. The typical exposure times were 165 s on the night of the 12th and 120 s on the nights of the 13th and the 14th. The source was also observed with *XMM-Newton* for approximately 2×36 ks on the nights of the 11th and the 13th providing roughly 16 ks of useful simultaneous X-ray and optical photometric data. As discussed earlier, the optical exposure time sets an absolute lower limit on the time lag, and hence the black hole mass that can be probed. As the time resolution of 120 s is much longer than the typical X-ray – optical lags of a few tens of seconds in stellar-mass X-ray binaries, these measurements are only sensitive to weigh IMBHs with masses greater than a few 100 M_{\odot} . A summary of the observational setup of the imaging mode is outlined in Table 1.

Since our main goal is to search for optical reverberation, we chose a standard FORS2 g_HIGH filter with an effective wavelength of 4700 Å and a FWHM of 1150 Å, which is the band that provided the most optical signal (see Figure 4 of Kaaret & Corbel 2009). Although the He II $\lambda 4686$ Å broad emission line falls in the same band it is expected to have negligible contribution to the overall optical variability. The He II $\lambda 4686$ Å flux is typically a factor of ≈ 80 lower than the optical continuum flux (see Table 3 of Kaaret & Corbel 2009). The same filter was used on all the nights.

3. Analysis: Optical Photometry

FORS2 is equipped with a mosaic of two $2\text{k} \times 4\text{k}$ MIT CCDs (CHIP1 & CHIP2) with a pixel size of $15 \times 15 \mu\text{m}$. Although the intrinsic pixel scale is $0.126''$ the standard data binning of 2×2 was used during all the observations providing a final pixel scale of $0.252''$. The observations were carried out such that the source was always on CHIP1. We used the Image Reduction and Analysis Facility (IRAF)² software for calibration and other image analysis.

¹Additional data was obtained on Feb 11th and the 12th in the so-called HIT–High Time Resolution–mode, which was not useful for this analysis due to lack of reference stars for calibration in the smaller field of view.

²IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3.1. Imaging Mode Data Analysis

We performed the following analysis to generate X-1’s optical light curves:

1) Basic data reduction: We first reduced the data through bias subtraction and flat fielding followed by the trimming of the vignetted regions of the images.

2) Data screening: X-1’s optical counterpart is faint with a V-band magnitude of 22.4– as measured in the F547M filter of HST (Grisé et al. 2012). We found that including images with seeing worse than 1” resulted in unusually large error bars on the light curve measurements compared with the expected error bars from Poisson statistics. We therefore removed images with seeing worse than this value from our analysis.

3) Image alignment: We aligned the images to a relative precision of $\lesssim 10\%$ of a pixel using the *Astromatic* software tools **SExtractor** (Bertin & Arnouts 1996), **SCAMP** (Bertin 2006), and **SWarp** (Bertin et al. 2002).

4) Image subtraction: We performed image subtraction using **HOTPANTS**³, which is a custom modification of the **ISIS** algorithm developed by Alard & Lupton (1998). We validated the subtracted images by randomly selecting 1000 locations around X-1 and ensuring their light curves were all consistent with being constant.

5) Extract X-1’s optical light curve: Finally, we extracted X-1’s light curve by performing aperture photometry on the subtracted images.

We now discuss in detail each of the above steps.

3.1.1. Image Reduction:

We first reduced all the images following the standard procedure of subtracting the bias followed by division by a bias subtracted, normalized flat field. We normalized the bias subtracted flat field by its mode value. We used the IRAF tasks **zerocombine** and **flatcombine** to construct the median bias and the flat field images, respectively. After the initial calibration, we trimmed the vignetted regions of the images.

³<http://www.astro.washington.edu/users/becker/v2.0/hotpants.html>

3.1.2. Data Screening:

On the night of the 13th the seeing (Point Spread Function’s (PSF’s) FWHM) varied between 0.5”-1.6” with the seeing degrading towards the end of the night. After the screening criterion of excluding images with seeing worse than 1”, we had 73 images of roughly 120 s exposure each. This gave us a total temporal baseline of $73 \times (120 + 27) \text{ s} \approx 10.7 \text{ ks}$ (here 27 s refers to the image readout time). The airmass was below 2 all throughout the night. A sample image with the entire field of view (CHIP 1) is shown in Figure 1.

3.1.3. Image Alignment:

We first obtained the plate solution—using the IRAF task `cmap`—of an image taken halfway through the night of the 13th. While the seeing worsened from the beginning to the end of the night, the airmass and the overall sky background (due to the moon) improved in a more or less monotonic fashion. Therefore, the optimum image for extracting the sources was the one at the middle of the image stack. Using 20 pointlike sources in the 2MASS catalog, we were able to achieve an absolute astrometric accuracy of $\approx 0.1''$ ($\approx 0.07''$ in both the RA and the declination coordinates).

We then noticed that even the images taken on the same night were slightly misaligned with respect to each other by a fraction of a pixel to a few pixels, despite the fact that the telescope was not dithered between successive exposures. We corrected this as follows:

(a) First, we extracted—using `SExtractor`—the locations of various point sources in the reference image above with absolute astrometry.

(b) We then used `SCAMP` to obtain an astrometric solution for each image to match with the positions of point sources derived from the reference image in the above step. We only allowed for linear distortions, i.e., the `SCAMP` parameter `DISTORT_DEGREES` was set to 1.

(c) Finally, we used `SWarp` to re-sample each image on a 1672×955 pixel grid as per the astrometric solution derived in the above step. In essence, we aligned every image with respect to the image in step (a).

The choice of the image in step (a) is not critical. We repeated the entire analysis with other images to find that the results are the same.

We tested the accuracy of the image alignment by tracking the centroid positions— (x,y) —of a sample of stars in the aligned images. We used `SExtractor` to estimate the centers of 20 point sources in all the 73 images after alignment. For the sake of convenience, we used the

same point sources used for plate solution above. These stars are indicated by blue colored circles and referenced as A followed by a number in Figure 1. Table 2 describes their WCS (J2000) coordinates and the RMS variation in units of fraction of a pixel after alignment. The observed RMS variation of 3-12% suggests that the images are aligned to less than one-eighth of a pixel with respect to each other.

3.1.4. Image Subtraction:

After aligning the images, we combined three consecutive images to improve the signal-to-noise. We then employed `HOTPANTS` to carry out image subtraction on these 24 (73 over 3) images. We only used a sub-region (350×350 pixels) of these images to perform subtraction (see Figure 1). To minimize PSF variation across the field, we varied the size of the sub-region using trial-and-error and found that a region of size 350×350 pixels (see Figure 2) gave the best image subtraction. While we set the background order to 2 (`-bg 2` in `HOTPANTS`) and the kernel order to 0 (`-ko 0` in `HOTPANTS`), the rest of the parameters were set to their default values. To be consistent, we always convolved with and normalized with respect to the template. The template—comprising of 31 images—was extracted by averaging all the aligned images with seeing less than $0.55''$. The night of the 13th had the best seeing conditions, hence the template image was constructed from images obtained on this night only. We also tested the image subtraction analysis with a template constructed from 35 images with seeing better than $0.65''$ from the night of the 12th (a template independent of Feb 13th data). The resulting ULX light curve was similar within the error bars. A sample image before and after subtraction is shown in the top left and the top right panels of Figure 2, respectively.

We performed aperture photometry at 1000 randomly sampled locations around the ULX (see Appendix A for aperture photometry methodology and error estimation). We avoided regions close to saturated stars. By choosing such a large number of points we ensured to sample the entire region within plus or minus 100 pixels around the ULX. We then modeled each of these relative background light curves with a constant model which yielded a reduced χ^2 between 0.5-1.5 providing confidence in the image subtraction procedure. Seven of the sample background light curves are shown in the bottom left panel of Figure 2.

Moreover, if the image subtraction was successful, the pixel values in the image should be distributed symmetrically around some mean value. Figure 3 shows histograms of pixel values around X-1 (excluding saturated stars) from three different subtracted images. The histograms were constructed from a square region of width 100 pixels centered on the ULX. We excluded the ULX aperture of 6×6 pixels centered on the ULX from these histogram

calculations. It is clear that these histograms are symmetric and again validate the image subtraction procedure.

3.1.5. NGC 5408 X-1's optical light curve:

We first performed aperture photometry at the ULX's location in all the subtracted images. This gave us X-1's count rates (e^-/s) relative to the template image ($c_i \pm \delta c_i$, $i=1\dots 23$). We then extracted X-1's count rate in the template used for image subtraction ($c_{template} \pm \delta c_{template}$). X-1's observed count rate was then estimated as the sum $c_i + c_{template}$. The uncertainties on these rates were calculated as the sum in quadrature of δc_i and $\delta c_{template}$. X-1's normalized optical light curve (fraction of its mean count rate) from the night of the 13th is shown in the bottom panel of Figure 4. Within the error bars, X-1's optical light curve is consistent with being constant giving a χ^2 of 20 for 23 dof, when modeled with a constant.

Following the same procedure as described above (section 3.1.1 – 3.1.5) we constructed X-1's normalized optical light curves from the nights of the 12th and the 14th. These are shown in Figure 5 and they are also consistent with being constant within the measured error bars. The best-fit constant model yielded χ^2/dof of 6/17 and 18/23 for the data on the 12th and 14th, respectively. Note the larger error bar on the 14th due to higher level of sky background.

On the night of the 12th we observed a standard star field (NGC 2268) for ≈ 3 s in the g_HIGH filter at an airmass of 1.02. Using a few bright, unsaturated stars in this image, we estimated based on the STETSON catalog⁴ the photometric zero-point count rate of the CCD to be $(8.68 \pm 0.36) \times 10^{10}$ e^-/s . The VLT/FORS2 g_HIGH filter is close to the SDSS g' band. Using the filter transformations of Lupton (2005)⁵ we estimated the mean V-band magnitude of NGC 5408 X-1's optical counterpart on the 12th, the 13th, and the 14th to be 22.523 ± 0.014 , 22.539 ± 0.015 , and 22.563 ± 0.016 , respectively. Since the quoted error bars only take into account the statistical uncertainty, the true uncertainty in the zero-point—including the systematic uncertainty—is likely larger than this. Nevertheless, these values are consistent with prior studies of this object (Kaaret & Corbel 2009; Grisé et al. 2012). X-1's template count rate was estimated to be 80.2 ± 1.3 e^-/s . As a sanity check, we compared this value to the expected count rate using the VLT/FORS2 online exposure time calculator

⁴<http://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/community/STETSON/standards/>

⁵<https://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php#Lupton2005>

(ETC)⁶. The observed values are consistent with the values estimated by the ETC.

In order to investigate if X-1’s optical counterpart varied on a timescale of ≈ 24 hours, we first estimated its mean count rate on each night. We then divided each of those by the mean over three nights to extract a normalized count rate for each night. Similarly, we estimated the normalized count rate of a sample of seven nearby point sources. The RMS scatter in the normalized count rates of the field stars—on each night—was added as an additional uncertainty to X-1’s normalized light curve measurement. The final long-term light curve of X-1 is shown in Figure 6. Since the evidence for variability on an \approx day timescale is only significant at the 3σ level, we consider it to be marginal.

3.1.6. Intra-Night RMS variability Upper limit

The amount of variability in a light curve can be quantified using the so-called normalized excess variance (σ_{NXS}^2 ; Edelson et al. 2002; Vaughan et al. 2003). The fractional root-mean-squared (RMS) amplitude is simply

$$F_{var} = \sqrt{\sigma_{NXS}^2}$$

At the n -sigma level, a source is considered to be variable only if $\sigma_{NXS}^2 > n \times \text{err}(\sigma_{NXS}^2)$, where $\text{err}(\sigma_{NXS}^2)$ is the error on the normalized excess variance. Using the analytical expression for $\text{err}(\sigma_{NXS}^2)$ derived by Vaughan et al. (2003), we estimate a 3- σ upper limit on X-1’s fractional RMS optical variability on the 12th, the 13th, and the 14th to be 3.3%, 4.8%, and 5.6%, respectively.

4. Analysis: X-ray Light Curve

For this study, we only used data acquired on 2014 February 13 by the European photon imaging camera (EPIC; both pn and MOS) on board *XMM-Newton*. We used the latest standard analysis system (XMMSAS) version 14.0.0 to reduce the images, and extract the filtered EPIC event lists. All the event lists were screened with a standard filter of (PATTERN

⁶<https://www.eso.org/observing/etc/bin/gen/form?INS.NAME=FORS+INS.MODE=imaging>. We used X-1’s V-band magnitude of 22.4 ± 0.6 as listed in Table 4 of Gladstone et al. (2013). Also for the ETC we assumed an airmass of 1.5 with a seeing of $0.6''$. The source spectrum was assumed to be a powerlaw with an index of -2 as derived by Kaaret & Corbel (2009). Note that by default the ETC assumes an aperture radius equal to the seeing. We, however, use $0.67 \times \text{seeing}$.

≤ 4), to include only the single and the double pixel events, and events in the complete band pass of 0.3-10.0 keV were considered for further analysis.

X-1’s mean X-ray count rate was 1.288 ± 0.006 counts s^{-1} . To be able to compare with the optical light curve we show the normalized X-ray light curve from 2014 February 13 (simultaneous with the optical observations) in the top panel of Figure 4. To test for variability we modeled the X-ray light curve with a constant. This yielded a χ^2 of 381 for 72 degrees of freedom (dof). This suggests that a constant model is strongly disfavored which is in agreement with earlier studies (e.g., Dheeraj & Strohmayer 2012; Caballero-García et al. 2013, etc). To quantify the variability, we calculated the normalized excess variance (σ_{NXS}^2) and the fractional root-mean-squared (RMS) amplitude following Vaughan et al. (2003). Using a light curve bin size of 440 s as in the optical light curve, we estimate the fractional RMS amplitude in X-rays to be $9.0 \pm 0.5\%$.

5. X-ray – Optical Cross-Correlation

To search for a reverberation signal we evaluated the discrete cross correlation function (DCF; Edelson et al. 1988) between the X-ray and the optical light curves taken on the 13th (see the left panel of Figure 7). There is no evidence for a statistically significant correlation between the X-ray and the optical variability.

We estimated the DCF’s error bars and the significance contours following these steps:

1) First, we constructed $N_{sample} = 10^6$ synthetic X-ray and optical light curves. These were drawn from the measured light curves—assuming for each time stamp in the measured light curve—the count rates are Gaussian distributed with a mean equal to the measured count rate and a standard deviation, σ , equal to the error bar.

2) We then extracted N_{sample} corresponding DCFs using the same input parameters as the observed DCF. The error bar at a given lag was then estimated to be twice the standard deviation in the DCF measurement within these N_{sample} values. In essence, an error bar at a given lag bin represents 4σ deviations.

3) Finally, we estimated the 3 and the 4σ confidence contours on the DCF using model-independent Monte Carlo simulations as follows:

- For each of the synthetic optical light curves derived in step 1, we randomized the count rate values but retained the time stamps.
- We then calculated the DCF between these randomized synthetic optical light curves

and a synthetic X-ray light curve. The time stamps of the synthetic X-ray light curve were kept the same (null hypothesis).

- After repeating the above two steps N_{sample} number of times we estimated—for each lag— 3σ and 4σ significance levels.

It can be seen from Figure 4 that both the X-ray and the optical light curves are regularly sampled for the most part. There are only a few segments of the light curves where data was unevenly sampled. After interpolating at these handful of data points, we constructed the regular cross correlation function (CCF) using the IDL function `C_CORRELATE`. The corresponding CCF is shown in the right panel of Figure 7. We set the lag limits to ensure that the entire optical light curve is within the bounds of the X-ray light curve. Thus, the maximum and the minimum lags were set to 15000 s and -7500 s, respectively. In this scheme, a positive lag would imply that the optical lags the X-ray and *vice versa for a negative lag*. As expected, the regular CCF (right panel of Figure 7) is very similar to the DCF (left panel of Figure 7). The error bars and the confidence contours were extracted using the same model-independent Monte Carlo methodology as described for the DCF. Again, the CCF indicates that there are no statistically significant features in the CCF.

6. Discussion

Timing studies of stellar-mass black hole binaries using simultaneous X-ray and optical/UV monitoring have found two main types of correlated behavior: (1) straightforward reprocessing lags where the optical emission is correlated with the X-ray but delayed by a time-scale consistent with the light travel time to reprocessing sites within the binary system, and (2) complex, non-reprocessing time lags where the optical emission can lead the X-rays (see, Gandhi et al. 2008; Durant et al. 2008; Motch et al. 1983, 1985 and references therein). Indeed, it appears that both processes can be present together with the non-reprocessing lags becoming dominant at time-scales much shorter than the expected light travel time delays (Gandhi et al. 2010). Further, evidence suggests that synchrotron emission from the jet may be responsible for this fastest, correlated variability seen to date in black hole systems (Hynes et al. 2003; Kanbach et al. 2001). For the purposes of mass estimates from reverberation mapping one strictly requires the first type of correlated variability.

The most clear-cut examples of such reprocessing are provided by simultaneous optical/X-ray observations of thermonuclear X-ray bursts from accreting neutron stars (see McClintock et al. 1979; Pedersen et al. 1982; Hynes et al. 2006). However, reprocessing time-scales (optical lagging the X-ray) have now also been measured from a handful of stellar-mass

black holes including GX 339-4 (Gandhi et al. 2010), GRO J1655-40 (Hynes et al. 1998; O’Brien et al. 2002), XTE J1118+480 (Hynes et al. 2003), and *Swift* J1753.5-0127 (Hynes et al. 2009). The time lags measured in these cases ($\approx 5 - 20$ s) are broadly consistent with their binary separations and expected accretion disk sizes. In the case of GRO J1655-40 the inferred lag of ≈ 20 s (O’Brien et al. 2002) can be combined with the measured widths of double-peaked HeII (4686 Å) lines arising in the accretion disk (Soria et al. 2000) to arrive at a mass estimate based on Equation (1). Taking half the peak separation of ≈ 550 km s⁻¹ for the HeII lines measured in 1996 June by Soria et al. (2000) as representative of velocities in the disk, one obtains a mass estimate of $M = 3.4M_{\odot}$ that is consistent with the mass measurements based on the radial velocity curve for GRO J1655-40 (Beer & Podsiadlowski 2002; Greene et al. 2001). This provides a basic consistency check that the method can provide reliable mass estimates.

On timescales relevant to reverberation, black hole binaries typically show optical fractional variability levels (RMS) in the range from $\approx 3 - 10\%$ (Hynes et al. 1998; Gandhi 2009). Assuming X-1 has a mass greater than $500M_{\odot}$ (Strohmayer & Mushotzky 2009; Cseh et al. 2013), the corresponding range of lag time-scales expected is of the order of 1000 s. We did not detect statistically significant variability from X-1 on such time-scales, and our 3σ upper limit of 3.3% is roughly consistent with the lower half of the optical RMS amplitude range quoted above. If X-1 were varying in the optical closer to the high end of this range then we would have likely detected such variability. Evidence of absorption-like dips in the X-ray flux from X-1 is suggestive of a high inclination (Pasham & Strohmayer 2013; Grisé et al. 2013), and it is conceivable that a high inclination could reduce the reprocessing response compared to a lower inclination system (see, for example, Figure 3 of O’Brien et al. 2002). Moreover, during reprocessing in X-ray binaries, the typical value of the ratio of the fractional RMS variability amplitude of the X-rays to the optical is roughly 5 (e.g., see Hynes et al. 1998; O’Brien et al. 2002). Assuming a similar ratio for X-1, the expected RMS optical variability is roughly 2% (9/5). This is still a factor of two lower than the fractional RMS upper limit we reached with the VLT data on the 13th (4.8%).

While this first attempt at measuring an optical/X-ray reverberation lag in X-1 was unsuccessful, it has “bounded” the problem and demonstrated what is required for success. Our best limits were achieved on the night of 12th February and corresponded to times of lowest sky background (largest moon angles). These observations are particularly challenging because of the need to simultaneously satisfy several observing constraints. First, the target must be visible from the optical telescope at low to modest airmass values, while also being simultaneously observable with *XMM-Newton*. Second, for optimum sensitivity the moon should also be below the horizon to limit the sky background. For these observations we achieved the first constraint, but not the latter. Moreover, assuming the lag time-scale is

~ 1000 s, then significantly more simultaneous X-ray/optical data is desirable than over a single night. It should be possible to achieve sensitivity to variability at the few percent level if all the above constraints can be satisfied. Nevertheless, even if the observing constraints are satisfied, ground-based optical observations remain at the mercy of weather and seeing conditions, and for this reason Hubble Space Telescope (HST) observations may provide a better solution.

Finally, we reiterate that the time resolution and the overall temporal baseline of the optical and the X-ray light curves set the lower and the upper limits on the black hole masses that can be probed with the reverberation technique proposed here. With the current optical telescopes, ULX optical counterparts require exposures on the order of hundred seconds to reach the signal-to-noise to detect a reverberation signal. Thus with current technology, this method is more sensitive to IMBHs than stellar-mass black holes. However, the mass range can be extended to stellar-mass black holes with the next generation telescopes such as the James Webb Space Telescope (JWST) and the Thirty Meter Telescope (TMT).

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Table 1: Setup for VLT/FORS2 observations of NGC 5408 X-1

CCDs	MIT/LL Mosaic CCID20-14-5-3
Number of pixels	2 chips of 2048×1034 each ^{1,2}
Gain	0.8 e ⁻ ADU ⁻¹
Filter	g-HIGH
Pixel Size	0.252''×0.252'' ¹
Exposure³	≈ 120 s/165 s
Readout Noise	2.7 e ⁻ pixel ⁻¹

¹

After the standard 2×2 spatial binning.

² X-1 was always situated on Chip 1. Chip 2 data was not used in this work.

³ Mean exposure time per individual image. The exposures were each 120 s on the nights on the 13th and the 14th, while 165 s exposures were taken on the night of the 12th.

Table 2: Summary of Image Alignment for FORS2 data taken on 2014 February 13.

Source ID ¹	α (right ascension)	δ (Declination)	RMS ² (% of a pixel)
A1	14:03:33.16	-41:20:24.7	7.2
A2	14:03:28.15	-41:20:46.4	6.4
A3	14:03:27.14	-41:21:09.0	5.9
A4	14:03:24.29	-41:20:23.7	8.8
A5	14:03:18.69	-41:20:42.5	5.7
A6	14:03:21.36	-41:20:13.0	7.8
A7	14:03:16.49	-41:20:19.5	7.1
A8	14:03:09.58	-41:20:54.7	9.6
A9	14:03:11.52	-41:20:22.3	3.5
A10	14:03:14.44	-41:19:54.8	4.3
A11	14:03:02.30	-41:19:34.4	8.7
A12	14:03:05.65	-41:21:04.2	11.8
A13	14:03:04.68	-41:22:35.2	10.5
A14	14:03:03.83	-41:22:54.2	6.7
A15	14:03:10.98	-41:23:14.1	8.3
A16	14:03:12.77	-41:23:00.7	8.6
A17	14:03:18.00	-41:23:21.8	10.5
A18	14:03:15.01	-41:22:23.4	5.7
A19	14:03:27.56	-41:21:33.6	8.2
A20	14:03:23.75	-41:21:39.7	5.9

¹

See Figure 1 for the location of these sources.

²The root mean squared deviation of the centroid of the source as estimated over all the 73 images. It is expressed as percentage of a pixel.

Appendix

Methodology for Obtaining the Optical Count rate and their Error Bars

We performed aperture photometry at a given location on the subtracted images as follows.

(1) First, we estimated the total number of counts in a circular aperture of radius 3 pixels ($N_{src,uncorr}$). For a Gaussian point spread function (PSF), it can be shown straightforwardly that the signal-to-noise ratio is maximum when the aperture radius is $\approx 0.68 \times$ (Full-Width-Half-Maximum). In our case, the Full Width Half Maximum (FWHM) is equal to the seeing. Now, considering the worse seeing of our images of $1.0''$ or ≈ 4 pixels, this corresponds to $0.68 \times 4 \approx 3$ pixels.

(2) We then calculated the median background counts per pixel using a nearby region. This value was multiplied by the total number of background pixels, and then by the ratio of the source to the background aperture (η) to obtain the total background counts corrected for the difference between the source and the background area ratio. We call this quantity $N_{bkg,corr}$.

(3) The background-corrected source counts were then calculated as

$$N_{src,corr} = N_{src,uncorr} - N_{bkg,corr}$$

The error on $N_{src,corr}$ was estimated by a simple propagation of uncertainty in quadrature as,

$$\sigma_{N_{src,corr}} = \sqrt{\sigma_{N_{src,uncorr}}^2 + \sigma_{N_{bkg,corr}}^2}$$

where,

$$\sigma_{N_{src,uncorr}}^2 = |N_{src,uncorr}|$$

$$\sigma_{N_{bkg,corr}}^2 = \text{RMS}_{bkg} \times \sqrt{N_{bkg,pix}} \times \sqrt{\eta}$$

$N_{bkg,pix}$ is the total number of background pixels, and RMS_{bkg} is root-mean-squared variance in the background pixel values calculated as

$$\text{RMS}_{bkg} = \sqrt{\sum \frac{(z - z_{mean})^2}{N_{bkg,pix}}}$$

z are the pixel values and z_{mean} is the mean of those values.

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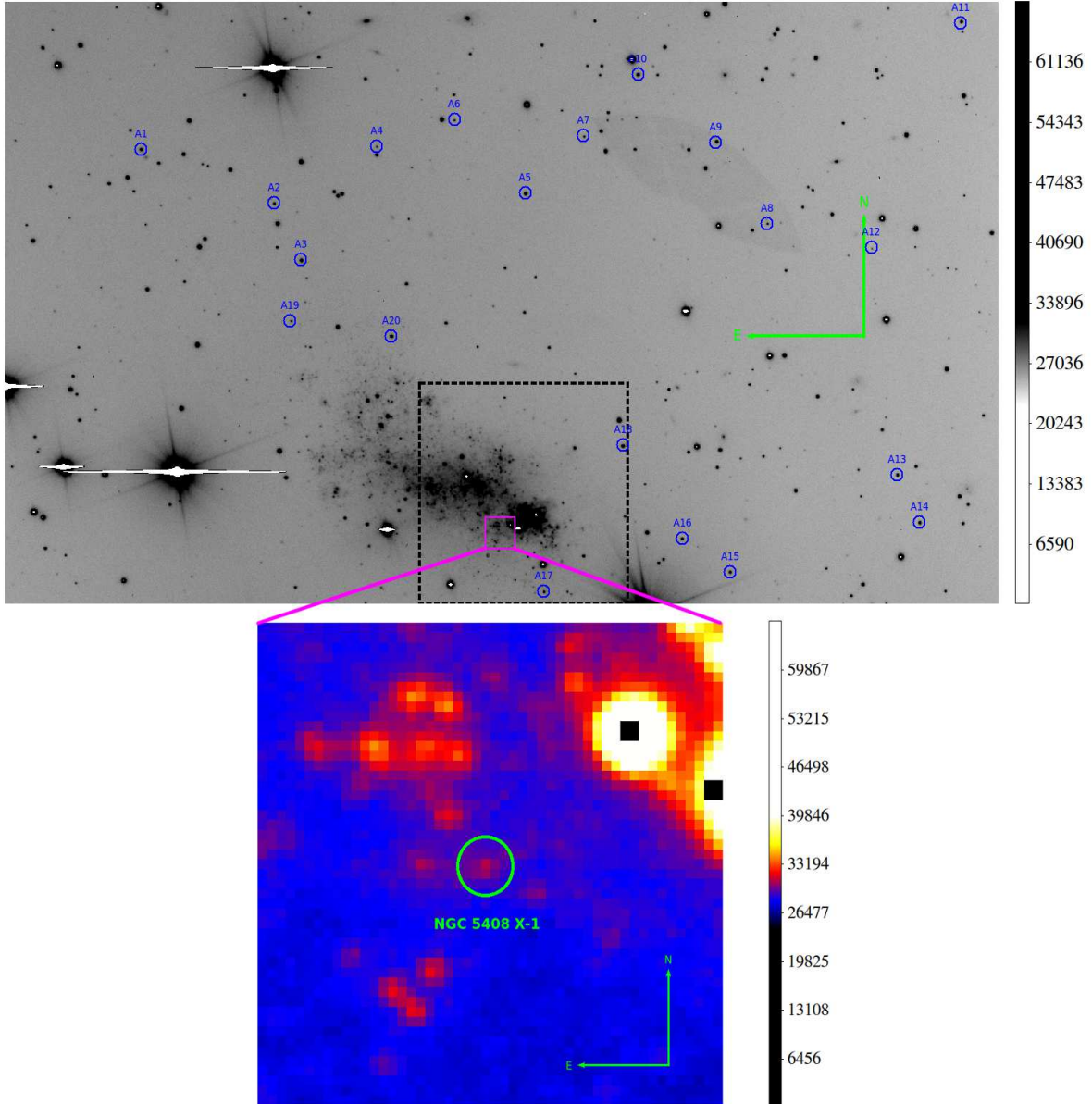


Figure 1: *Top Panel:* Sample VLT/FORS2 image of NGC 5408 X-1 showing the full field of view. The sources used to check image alignment are indicated by blue circles (also see Table 2). The dashed black box is the sub-region used for image subtraction with **HOTPANTS** (see Figure 2). *Bottom Panel:* Zoomed-in view of the region around the ULX NGC 5408 X-1 (green circle). The north and the east arrows are each $50''$, and $2.5''$ in the top and the bottom panels, respectively.

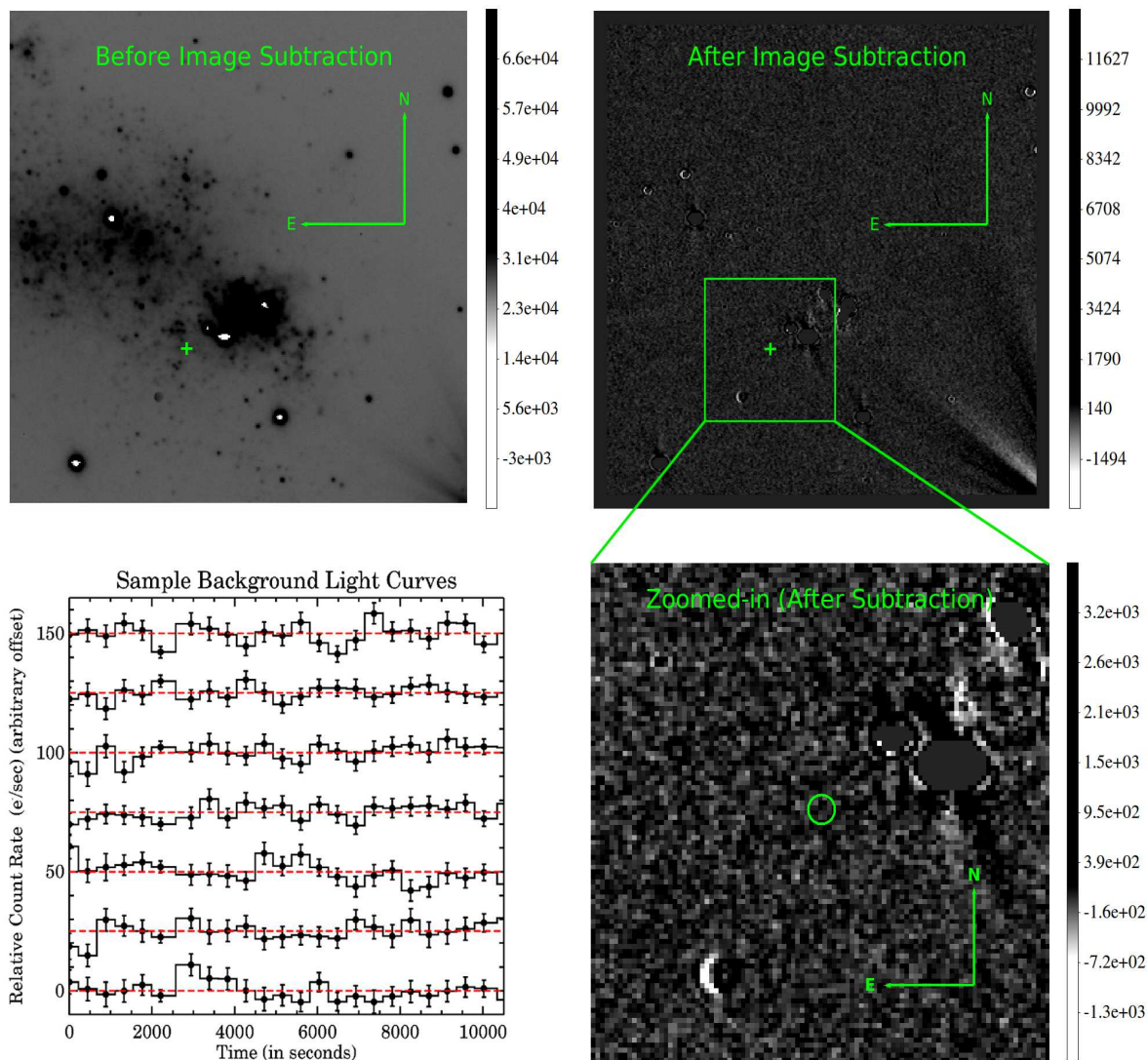


Figure 2: A sample FORS2 image before (top left panel) and after (top right panel) image subtraction. The arrows pointing north and east are each $20''$ long. In both the images the ULX’s location is marked with a green cross. *Bottom Right:* A zoomed-in image of 100×100 pixels wide centered on X-1. The north and the east arrows are each $5''$ long and the circle indicating the ULX’s position has a radius of 3 pixels (the aperture radius used for photometry). *Bottom Left:* Sample relative background light curves from the night of the 13th to validate image subtraction. They are all consistent with being constant.

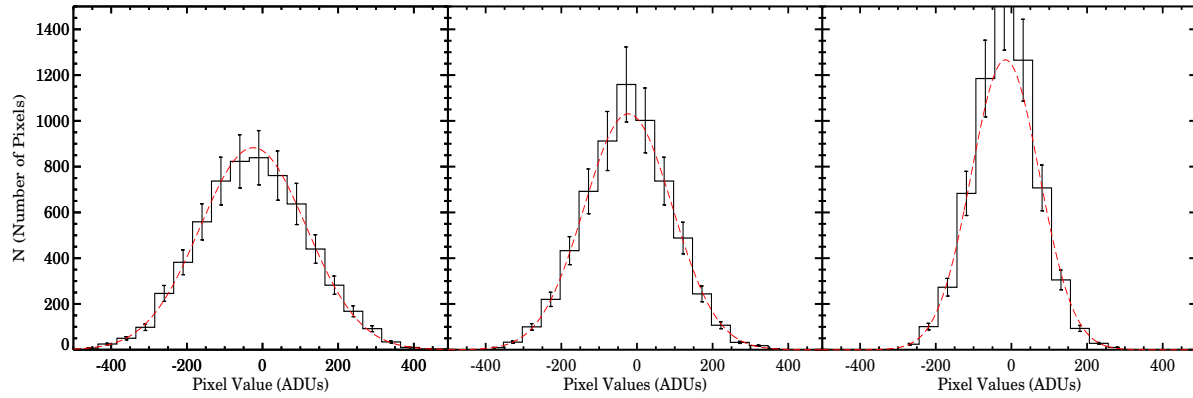


Figure 3: Histograms of pixel values around X-1 (± 50 pixels centered on X-1) in three subtracted images. Clearly, they are all symmetrically distributed. These are reasonably represented by a Gaussian model (red curves). Deviations are likely due to systematic uncertainties introduced by the image subtraction process (mis-alignment, PSF mismatch, etc).

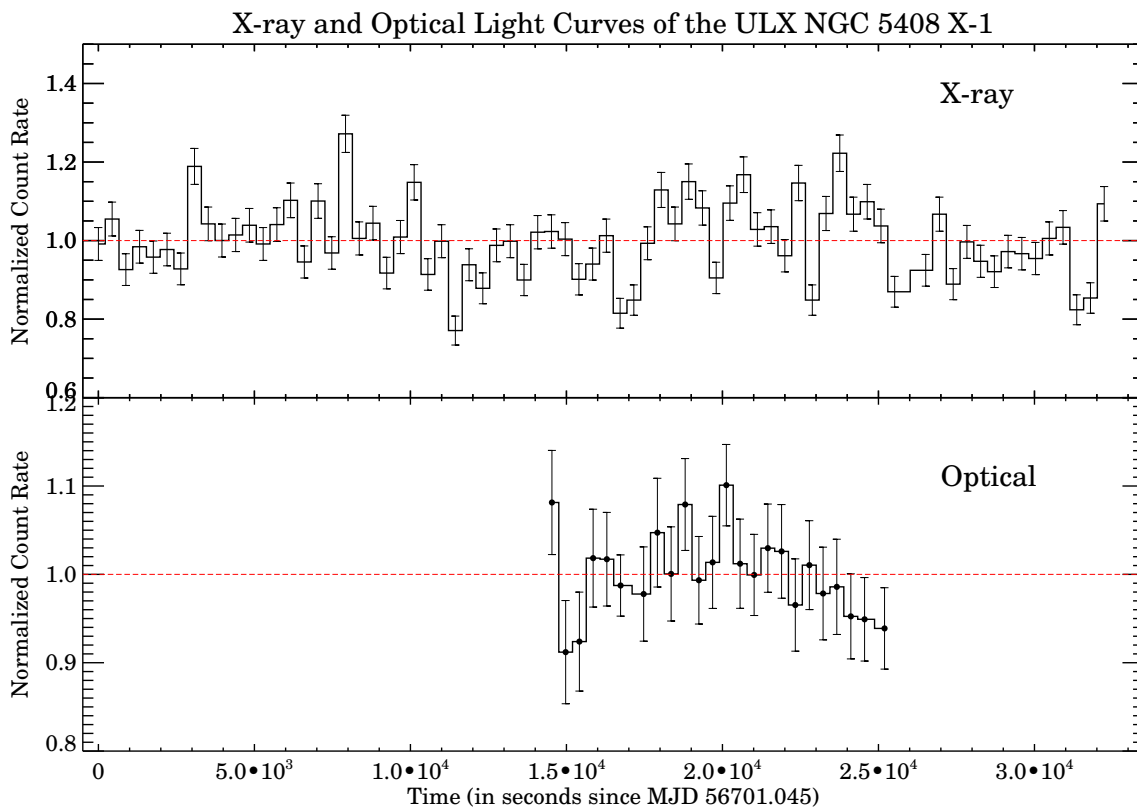


Figure 4: Normalized X-ray (top) and optical (bottom) light curves of NGC 5408 X-1 taken on 2014 February 13. While the X-rays are variable (fractional RMS variability of $9 \pm 0.5\%$), the optical light curve—within the error bars—is consistent with being constant. An upper limit on the fractional RMS amplitude in order to be considered variable at the 3σ level is 4.8%. For consistency, both the X-ray and the optical light curves have the same time bin size of 440 s.

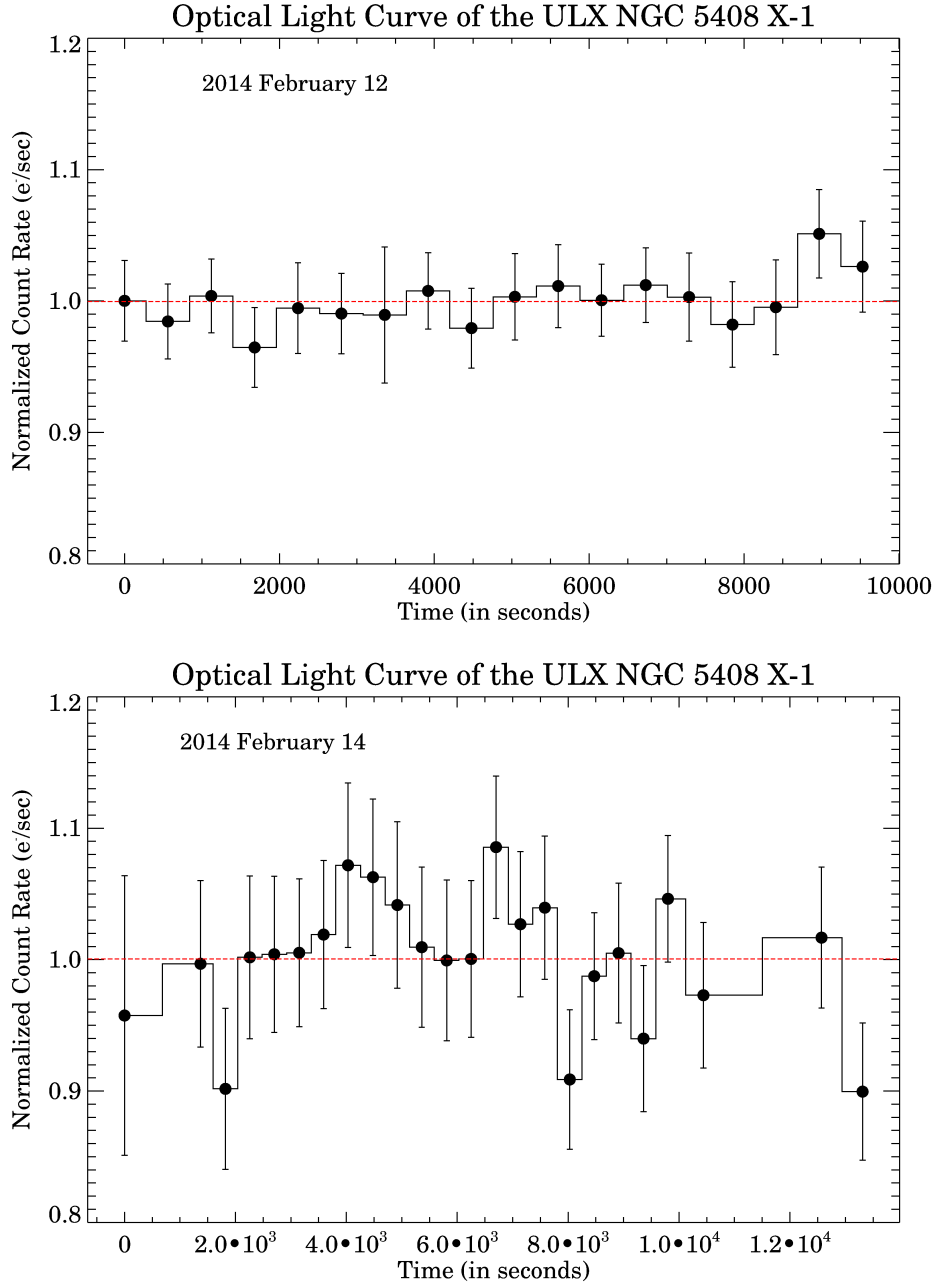


Figure 5: X-1’s normalized optical light curve from 2014 February 12 (top) and 2014 February 14 (bottom). Similar to the optical light curve from 2014 February 13, these are also consistent with being constant. The 3σ upper limits on the optical variability are 3.3% and 5.6% for the 12th and the 14th, respectively.

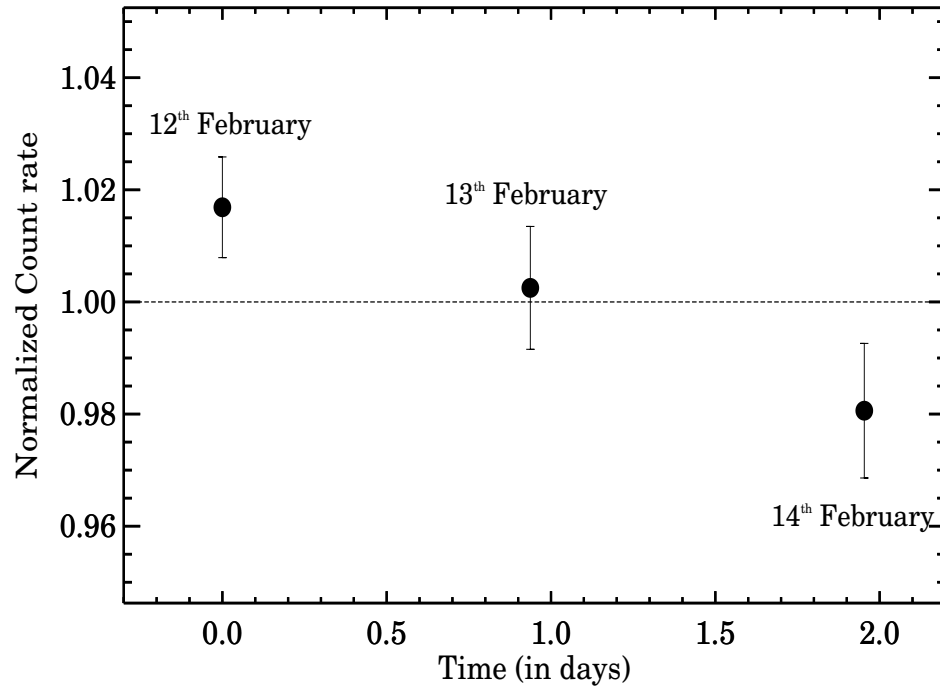


Figure 6: NGC 5408 X-1’s normalized optical light curve over the three nights in 2014. The evidence for variability on a day timescale is only marginal ($\approx 3\sigma$).

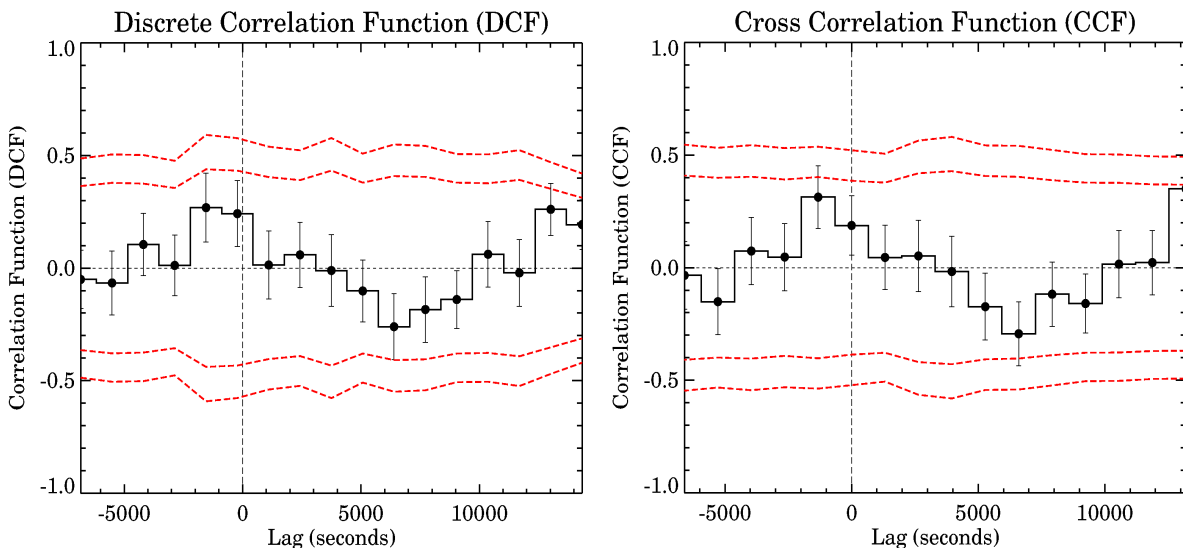


Figure 7: Discrete Cross Correlation Function (DCF) (left panel) and a regular cross correlation function (CCF) (right panel) between the X-ray and the optical light curves of NGC 5408 X-1. Clearly, they both are consistent with each other. The 3 and the 4 σ significance contours (dashed red curves) were calculated using model-independent Monte Carlo simulations (see section 5). There are no statistically significant features. A positive lag in these plots would imply that the optical lags the X-ray emission.