Discovery of a 115 Day Orbital Period in the Ultraluminous X-ray Source NGC 5408 X-1

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ABSTRACT

We report the detection of a 115 day periodicity in *SWIFT*/XRT monitoring data from the ultraluminous X-ray source (ULX) NGC 5408 X-1. Our ongoing campaign samples its X-ray flux approximately twice weekly and has now achieved a temporal baseline of ≈ 485 days. Periodogram analysis reveals a significant periodicity with a period of 115.5 ± 4 days. The modulation is detected with a significance of 3.2×10^{-4}. The fractional modulation amplitude decreases with increasing energy, ranging from 0.13 ± 0.02 above 1 keV to 0.24 ± 0.02 below 1 keV. The shape of the profile evolves as well, becoming less sharply peaked at higher energies. The periodogram analysis is consistent with a periodic process, however, continued monitoring is required to confirm the coherent nature of the modulation. Spectral analysis indicates that NGC 5408 X-1 can reach 0.3 - 10 keV luminosities of $\approx 2 \times 10^{40}$ ergs s^{-1}. We suggest that, like the 62 day period of the ULX in M82 (X41.4+60), the periodicity detected in NGC 5408 X-1 represents the orbital period of the black hole binary containing the ULX. If this is true then the secondary can only be a giant or supergiant star.

Subject headings: black hole physics - galaxies: individual: NGC 5408 - stars: oscillations - X-rays: stars - X-rays: galaxies

1. Introduction

The existence of black holes in the mass range from $10^2 - 10^4$ $M_{\odot}$–intermediate mass black holes (IMBH)–is still not widely accepted. It has been argued based on their extreme luminosities that some of the bright X-ray sources found in nearby galaxies, the ultraluminous X-ray sources (ULXs), may be IMBHs (Colbert & Mushotzky 1999), but it has also been suggested that these objects may appear luminous due to beaming of their X-ray radiation (King et al. 2001). As yet there has been no direct measurement of the mass of a ULX.

At present the best IMBH candidates include X41.4+60, the brightest ULX in the starburst galaxy M82 (also referred to as M82 X-1, Kaaret, Feng & Gorski 2009; Strohmayer & Mushotzky 2003), and the ULX NGC 5408 X-1 (Strohmayer et al. 2007; Kaaret & Corbel 2009). Very recently, Farrell et al. (2009) have reported the identification of an X-ray source (2XMM J011028.1-460421) very near the absorption line galaxay ESO 243-49. They argue for a physical association with this galaxy which at a redshift of $z = 0.0224$ implies a luminosity in excess of 10^{42} erg s^{-1}, and suggest it is an IMBH in excess of 500 $M_\odot$. If the association with ESO 243-49 is correct then this object is the most luminous ULX currently known.

X41.4+60 is also amongst the most luminous ULXs, on occasion having a luminosity upwards of 10^{41} ergs s^{-1} (Kaaret et al. 2009). This object also shows a 62 day periodic modulation in its X-ray flux, which has been proposed to be the orbital period of the binary system containing the black hole (Kaaret, Simet & Lang 2006; Kaaret & Feng 2007). Both NGC 5408 X-1 and X41.4+60 show quasiperiodic oscillations (QPOs) in their X-ray fluxes, and these ULX QPOs appear at systematically lower frequencies than the analogous QPOs observed in Galactic black hole binary systems (Strohmayer & Mushotzky 2003; Strohmayer et al. 2007). Indeed, Strohmayer & Mushotzky (2009) have recently shown that the QPO properties in NGC 5408 X-1 correlate with the energy spectrum and X-ray flux in a manner fully consistent with the behavior observed for so-called Type C QPOs in Galactic systems. The Type C QPOs in stellar mass black holes are strong (fractional rms amplitude $\sim 15\%$), relatively coherent ($\nu_{qpo}/\Delta\nu > 10$) oscillations with characteristic frequencies of $\sim 1 - 10$ Hz that vary in frequency in correlation with source flux and spectral index (see Sobczak et al 2000; Vignarca et al. 2003; Casella, Belloni & Stella 2005). They are associated with an energy spectral state in which approximately half or more of the flux is carried by a power-law component with slope $\Gamma \sim 2 - 2.5$, commonly referred to as the Steep Power Law state (SPL, McClintock & Remillard 2006), or the Hard Intermediate State (HIMS, Belloni 2006). The precise origin of these QPOs is still uncertain, but their phenomenology has been used to estimate the masses of black holes (see Shaposhnikov & Titarchuk 2009).

The Type C QPOs in NGC 5408 X-1 identified by Strohmayer & Mushotzky (2009) have frequencies of a few tens of mHz, a factor of 100 lower than the Galactic black holes. Scaling the observed QPO frequencies in NGC 5408 X-1 to those observed in Galactic systems of known mass suggests that NGC 5408 X-1 is an IMBH with a mass greater than 1000 $M_\odot$ (Strohmayer & Mushotzky 2009). Moreover, recent optical spectroscopy reported by Kaaret & Corbel (2009) indicates that the optical counterpart to NGC 5408 X-1 is associated with reprocessed emission from an accretion disk as well as a strongly photoionized optical nebula. This, combined with the presence of a powerful radio nebula also appears consistent with the presence of an IMBH (Lang et al. 2007; Soria et al. 2006; Kaaret et al. 2003).

While it is likely that many of the ULXs are accreting black hole binary systems, very little is known about the nature of these putative binaries. If some of the brighter systems are indeed IMBHs accreting via Roche lobe overflow, then their orbital periods could be as long as a few hundred days (Portegies Zwart et al. 2004). With the exception of X41.4+60 noted above, very few objects have been monitored with a cadence and duration that would enable sensitive searches for X-ray periods in the range of 10s to 100s of days. The *Swift* observatory uniquely provides both the X-ray imaging sensitivity and scheduling flexibility to enable such searches. Starting with Observing Cycle 4 *Swift* has been monitoring NGC 5408 X-1 several times per week as part of an approved program. These observations have continued into Cycle 5 and are presently ongoing. Here we present results from this campaign which provide evidence for a 115 day periodicity in NGC 5408 X-1 which could very likely be the orbital period of a Roche lobe overflow binary containing an IMBH.

2. Data Extraction and Analysis

Monitoring of NGC 5408 X-1 with the *Swift* XRT began on 2008 April 9. Since then, the source has been observed 2 - 3 times per week with a typical exposure of 2 ksec. Aside from an $\approx$ 80 day gap beginning on 2008 September 26, the observing cadence has been unbroken. Results presented here include observations through 2009 August 5.

We began our analysis with the Level 2 cleaned XRT event files. The XRT was operated in photon counting mode. We extracted good events using an extraction radius of 25" around the position of NGC 5408 X-1. Most observation sequences were made up of one to two good time intervals (GTI). In general, we combined these to create a single count rate estimate for each observation sequence. An important issue is to account for bad pixels and columns present on the XRT CCD. The University of Leicester's XRT Digest webpage (see, http://www.swift.ac.uk/xrtdigest.shtml#analysis) provides a detailed discussion of the problem. In order to account for the potential loss of effective exposure due to bad pixels we constructed exposure maps for each observation using the tool *xrtexpomap*. We then integrated over the extraction region in the exposure map, weighted by the XRT point spread function (Moretti et al. 2006). This provides an effective exposure for each observation. We used the corrected exposures in order to estimate source counting rates for each observation. This procedure resulted in a total of 113 count rate estimates. The resulting light curve is shown in Figure 1. The mean rate is 0.061 s^{-1}, and excursions from 0.01 to 0.1 s^{-1} are evident.

We extracted spectra from each observation using the same extraction regions as for the count rate estimates. Background estimates were extracted from regions of the same

size nearby on the CCD. Previous observations of NGC 5408 X-1 suggest that the spectrum does not change dramatically (Kaaret et al. 2003; Strohmayer et al. 2007; Strohmayer & Mushotzky 2009), so we combined all observations into a single, average spectrum in order to obtain an average count rate to flux conversion. We fit the resulting spectrum with the sum of a power-law and disk blackbody (model *diskpn* in XSPEC), and fixed the absorbing column at the value measured previously (Strohmayer et al. 2007). We find a disk temperature $kT_{max} = 0.18 \pm 0.02$ keV and power-law index $\Gamma = 2.6 \pm 0.2$. These values are reasonably consistent with previous XMM-Newton measurements. We find that with this spectral form an XRT count rate of 0.06 s^{-1} corresponds to a 0.3 - 10 keV unabsorbed flux of 4.0×10^{-12} ergs cm^{-2} s^{-1}. At a distance of 4.8 Mpc this corresponds to a luminosity of 1.1×10^{40} ergs s^{-1}. The implied peak luminosity during these observations was $\approx 1.9 \times 10^{40}$ ergs s^{-1}. We quote fluxes and luminosities in the 0.3 - 10 keV range for comparison with previous measurements, however, we note that extending the band pass down to 0.1 keV increases these luminosity estimates by almost a factor of two.

We carried out a periodogram analysis using the methods of Scargle (1982) and Horne & Baliunas (1986). We calculated the periodogram at 140 frequency points, which is the number of independent frequencies estimated by the method of Horne & Baliunas (1986), and we normalized by the total variance in the data. The resulting power spectrum is shown in Figure 2. The highest peak in the spectrum appears at a frequency of 1.0018×10^{-7} Hz (corresponding to a period of 115.5 days), and has a value of 24.7. We estimate the significance of the peak by calculating the chance probability for obtaining this value from the χ^2 distribution with 2 degrees of freedom, and multiplying by the number of trials (140 frequency bins). This yields a significance of 6.1×10^{-4}, which is better than a 3σ detection. There is no evidence for significant power in any other frequency range. The coherence Q, defined as the center frequency divided by the width of the peak (measured as the FWHM), is 4.7 and is consistent with a periodic modulation. However, the present data cover only a bit more than 4 cycles, so further monitoring will be required to better assess the coherence of the modulation.

We note that Kaaret & Feng (2009) have recently submitted a paper to astro-ph (0907.5415) which reports results using some of the same data presented here. We became aware of this work after beginning work on this manuscript. Kaaret & Feng do not claim to detect a significant periodicity in the NGC 5408 X-1 light curve, but they do state that the highest peak they see is "near a period of 115 days." We believe the reason for this seeming discrepancy is two-fold. First, we have used more data in our analysis, that is, a longer temporal baseline, and secondly, we have included the exposure map corrections in our light curve. Indeed, when we restrict our analysis to the time range used by Kaaret & Feng, and ignore the exposure corrections, then we see a drop in the peak power at 115 days

to a level consistent with Kaaret & Feng. The fact that the exposure correction increases the Fourier power is further evidence that the 115 day modulation is a real signal.

To further explore the nature of the modulation we folded the data in several energy bands at the measured period of 115.5 days. To do this we placed each light curve measurement in its appropriate phase bin, and then we averaged all measurements in a given bin. Errors were determined by averaging the individual errors in quadrature. The resulting profiles in twelve phase bins are shown in Figure 3. We show profiles in the full band ($E > 0.2$ keV, upper left), two soft bands ($E < 1$ keV, upper right; $E < 0.7$ keV, lower left), and a hard band ($E > 1$ keV, lower right), and we plot two cycles for clarity. We fit a model to each profile that includes two Fourier components (the fundamental and first harmonic), $I = A + B \sin 2\pi(\phi - \phi_0) + C \sin 4\pi(\phi - \phi_1)$. Results of these fits are summarized in Table 1. For the hard band ($E > 1$ keV) profile the harmonic term is not statistically required. The folded profiles reveal interesting energy dependent behavior. For example, the modulation amplitude appears to clearly decrease with increasing energy. Defining the fractional amplitude $f_{amp} = (B^2 + C^2)^{1/2}/A$, we find a significant change from 0.133 ± 0.018 to 0.241 ± 0.017 in going from $E > 1$ to $E < 1$ keV. Indeed, recomputing the periodogram with only $E < 1$ keV photons results in an increase in the peak Fourier power to 27.33. The detection significance then improves to 3.2×10^{-4}, which includes an additional factor of 2 for the increased number of trials. In addition to the amplitude variations the profile appears smoother at higher energies, and the phase of the fundamental component is significantly different above 1 keV than below, in the sense that the harder photons appear to lag the soft photons with a relative phase difference of $0.11 \pm 0.025 = 12.6 \pm 2.9$ days. Finally, we computed the hardness ratio as a function of phase, where we define the hardness ratio as the count rate for $E > 1$ keV divided by the rate for $E < 1$ keV. Figure 4 shows the variation of the hardness with phase, and we have also plotted the full-band folded profile for comparison (dashed curve). The hardness ratio shows a sharp rise to a maximum near phase 0.45, followed by a more gradual decline. The peak of the modulation is clearly softer than the minimum.

3. Discussion and Implications

A number of accreting binaries show X-ray modulations at their orbital periods. Among black hole binaries Cyg X-1 and Cyg X-3 are well known examples (Wen et al. 1999; Elsner 1980), and more recent detections include LMC X-3 (Boyd et al. 2001), 1E 1740.7-2942 and GRS 1758-258 (Smith et al. 2002). Many neutron star binaries also show X-ray modulations at the binary orbital period. The orbital modulations in accreting binaries have typically

been attributed to periodic obscuration produced by a vertically and azimuthally structured accretion disk or scattering in an extending accretion disk corona or stellar wind from the donor (Parmar & White 1988; Wen et al. 1999). A recent example of an X-ray modulation at the putative orbital period in a neutron star system is that of GX 13+1 (Corbet 2003). Thus, if ULXs are indeed accreting black hole binaries, then it is not unexpected to detect X-ray modulations at their orbital periods.

While their have been several claims of detection of orbital modulations in ULXs (see, Kaaret, Simet & Lang 2006 for a brief summary), the most compelling detection to date is that of the 62 day modulation from the M82 ULX X41.4+60 (Kaaret, Simet & Lang 2006; Kaaret & Feng 2007). The average modulation in X41.4+60 as observed with the RXTE/PCA is roughly sinusoidal with an amplitude of $\approx 20\%$ (Kaaret & Feng 2007). This is qualitatively consistent with the $0.2 < E < 8$ keV modulation amplitude and profile that we report here for NGC 5408 X-1, and suggests that similar physical processes may produce the observed modulation in both systems.

Superorbital periods are known in both neutron star and black hole binaries. Well known examples include the 35 day modulation in the neutron star system Her X-1, and the 164 day period in the putative black hole binary SS 433 (Wijers & Pringle 1999). These variations have generally been ascribed to accretion disk precession (Ogilvie & Dubus 2001). Kaaret & Feng (2007) argued that the 62 day period in X41.4+60 was unlikely to be a superorbital modulation because the observed period is only consistent with the observed superorbital periods of neutron star systems, but that the extreme luminosity of X41.4+60 comfortably rules out an accreting neutron star (see their Figure 4 for a distribution of observed superorbital periods). Similar arguments would appear valid for the 115 day modulation in NGC 5408 X-1. The 115 day period is shorter than all known superorbital periods for black hole candidate binaries, and its peak luminosity is well in excess of the Eddington limit for a neutron star ($\approx 10^{38}$ ergs s^{-1}).

Using X-ray timing measurements with *XMM-Newton*, Strohmayer et al. (2009) have recently shown that the strong QPO observed in NGC 5408 X-1 varies in frequency and amplitude with changes in the X-ray flux and energy spectrum in a manner that closely mimics the correlated temporal and spectral variations observed in stellar mass black holes in the so-called Intermediate State (also known as the Steep Power-law State). Moreover, recent optical spectroscopy reported by Kaaret & Corbel (2009) indicates that its optical counterpart has a significant contribution from reprocessing of the X-ray luminosity in the outer parts of the disk. The so-called "slim disks" that may exist at super-Eddington accretion rates preferentially radiate more flux out along the disk axis, and therefore have relatively less available for reprocessing (Abramowicz et al 1988). These models thus have

difficulty accounting for the observed optical to X-ray flux ratio in NGC 5408 X-1. Further, modeling of the observed nebular optical emission lines supports the conclusion that NGC 5408 X-1 radiates $\sim 10^{40}$ ergs s^{-1} in an approximately isotropic manner (Kaaret & Corbel 2009). These observations support the notion that NGC 5408 X-1 harbors a "standard" thin, optically thick accretion disk similar to those inferred to exist in Galactic black hole binaries.

The 115 day modulation we have found in NGC 5408 X-1 shows interesting energy dependent effects that would appear consistent with orbital modulation. A system which shows qualitatively similar effects to those seen in NGC 5408 X-1 is Cyg X-1. Specifically, the orbital modulation in Cyg X-1 has been modeled in the context of absorption and scattering of X-rays in the partially ionized wind from the companion star (Wen et al. 1999). This model predicts a decrease in modulation amplitude with increasing energy, and a minimum in the hardness ratio at the maximum of the modulation profile (see Wen et al. 1999, Figure 3), both of which are evident in the NGC 5408 X-1 data. While the shapes of the modulation profiles in Cyg X-1 do not exactly match the results we find for NGC 5408 X-1, the behavior of the $E > 1$ profile (see Figure 3) appears qualitatively similar. An important distinction would seem to be that in the case of NGC 5408 X-1 we can directly observe the thermal disk flux whereas the orbital modulation measurements for Cyg X-1 concern the low-hard state, when presumably its thermal flux is weak or absent. Moreover, any disk flux appears largely shortward of the RXTE/PCA energy band. Cyg X-1 is also a wind accreting system, whereas wind accretion would likely be unable to account for the high luminosity of NGC 5408 X-1.

If the 115 day period is indeed the orbital period of a Roche lobe filling binary, then the mean density of the secondary is constrained to be $\rho_{mean} \approx 0.2(P_{\text{days}})^{-2}$ g cm^{-3} (Frank et al. 2002). For a period of 115.5 days this gives $\rho_{mean} = 1.50 \times 10^{-5}$ g cm^{-3}, and the companion would have to be a giant or supergiant star. Recent observations suggest that a substantial fraction of the optical counterpart is due to reprocessing of the X-ray flux in an accretion disk, and while the companion star still has not been observed directly, the recent optical measurements suggest that it is probably a giant in the 3 - 5 $M_\odot$ range, and with a spectral type of B or later (Kaaret & Corbel 2009). Binary evolution calculations for IMBHs and massive companions appear consistent with the notion that NGC 5408 X-1 contains a $\sim 1000 M_\odot$ black hole with a 3 - 5 $M_\odot$ companion (Li 2004). Continued monitoring of NGC 5408 X-1 with *Swift* is important in order to confirm the orbital nature of the modulation.

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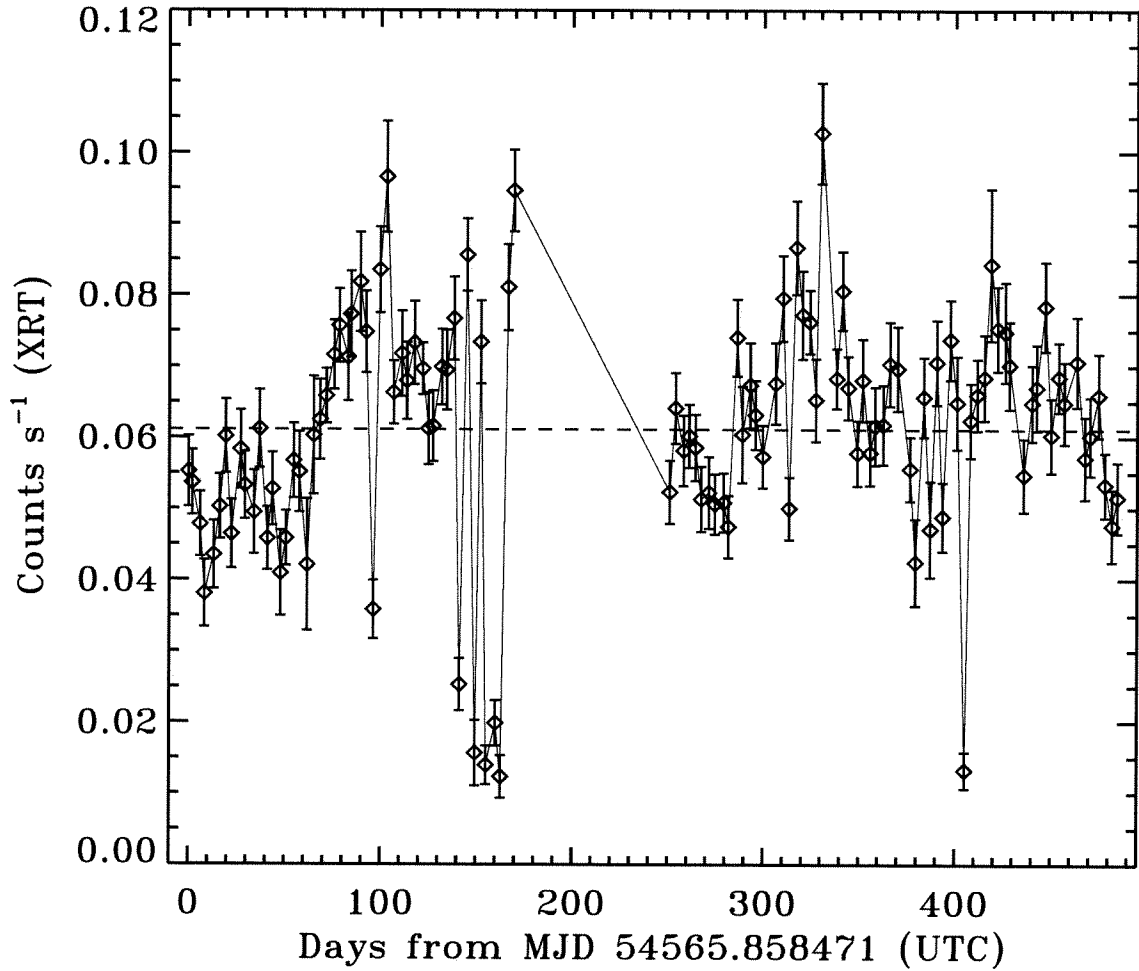Wijers, R. A. M. J., & Pringle, J. E. 1999, MNRAS, 308, 207.

Figure 1: X-ray lightcurve of NGC 5408 X-1 in the 0.2 - 8 keV band derived from *Swift*/XRT measurements. A count rate of 0.06 s^{-1} corresponds to a 0.3 - 10 keV unabsorbed flux of 4×10^{-12} ergs cm^{-2} s^{-1}. The mean count rate of 0.061 s^{-1} is marked by the dashed horizontal line. Time zero corresponds to MJD 54565.85847 (UTC).
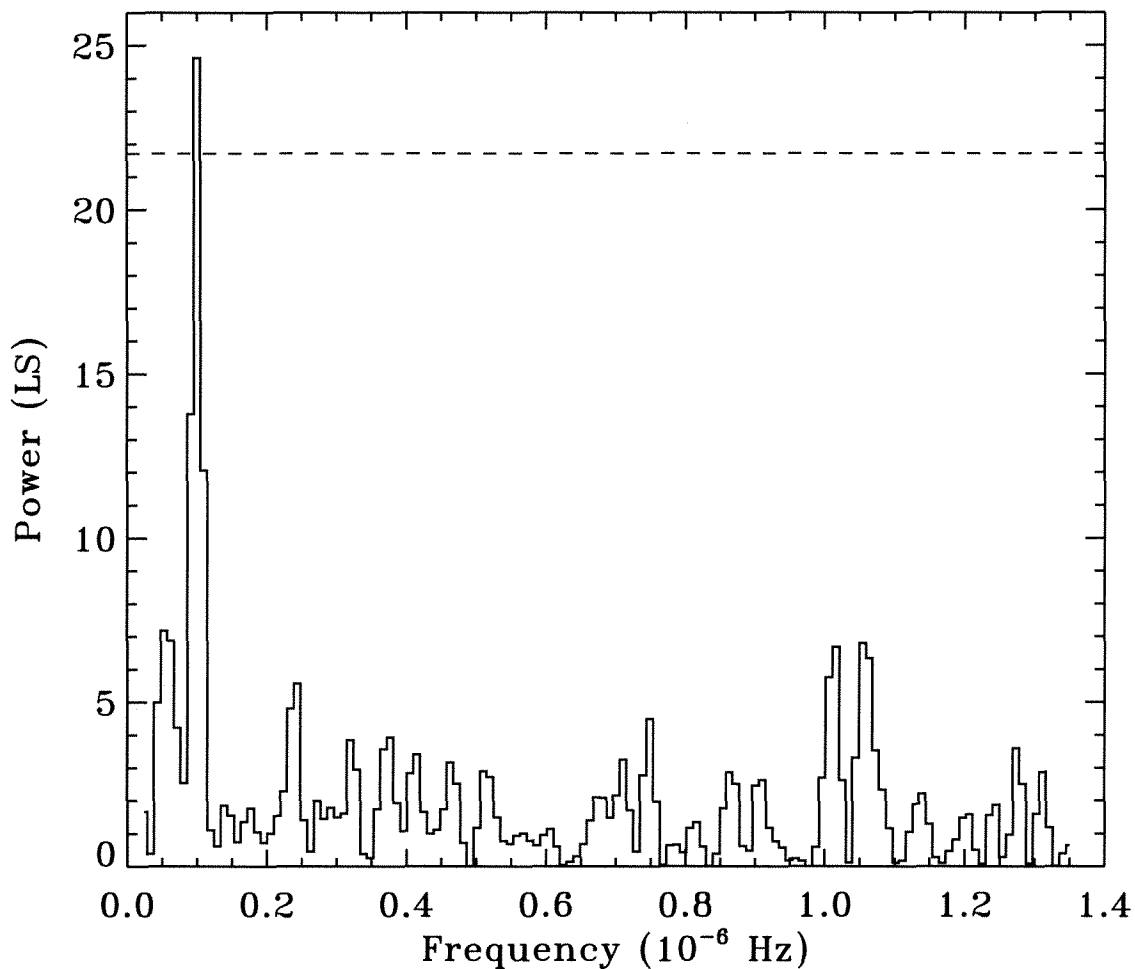
Figure 2: Lomb-Scargle periodogram computed from the *Swfit*/XRT light curve of NGC 5408 X-1. There are 140 independent frequency bins plotted with a resolution of 9.54 *nano*Hz. The Nyquist frequency is 1.35 μHz (corresponding to a period of 8.6 days). The horizontal dashed line denotes the 3σ detection level. The peak value of 24.7 occurs at a frequency of 1.0018×10^{-7} Hz (a period of 115.5 days).
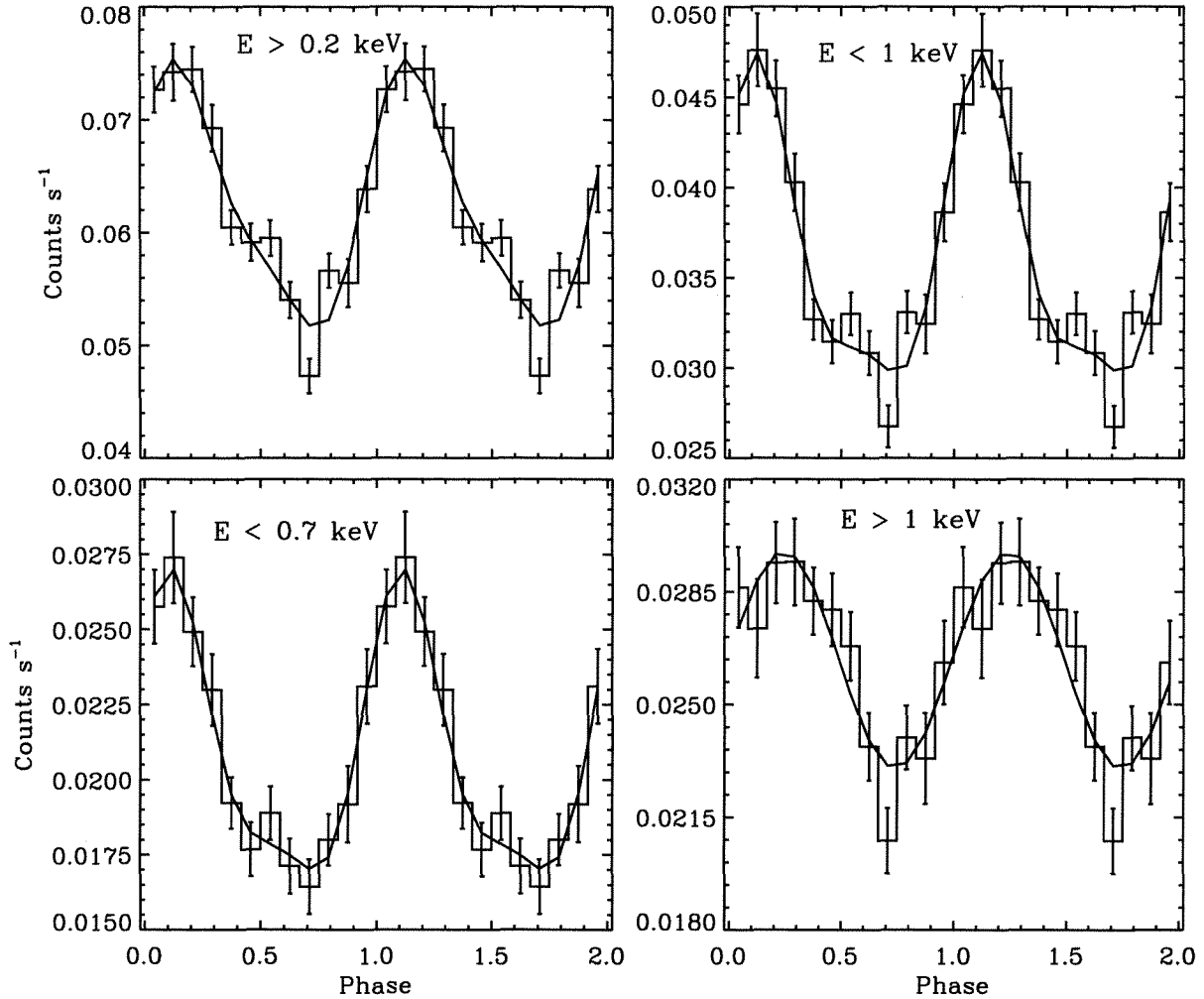
Figure 3: X-ray flux from NGC 5408 X-1 in different energy bands folded at a period of 115.5 days. Profiles were computed with 12 phase bins, and two cycles are shown for clarity. Proceeding clock-wise from the upper left panel the energy bands are, $0.2 < E < 8$ keV; $0.2 < E < 1$ keV; $1 < E < 8$ keV; and $0.2 < E < 0.7$ keV. The best fitting model with two Fourier components is also plotted in each panel. Note the change in profile amplitude and shape with energy. See Table 1 for a summary of the model fits, and the text for additional discussion.
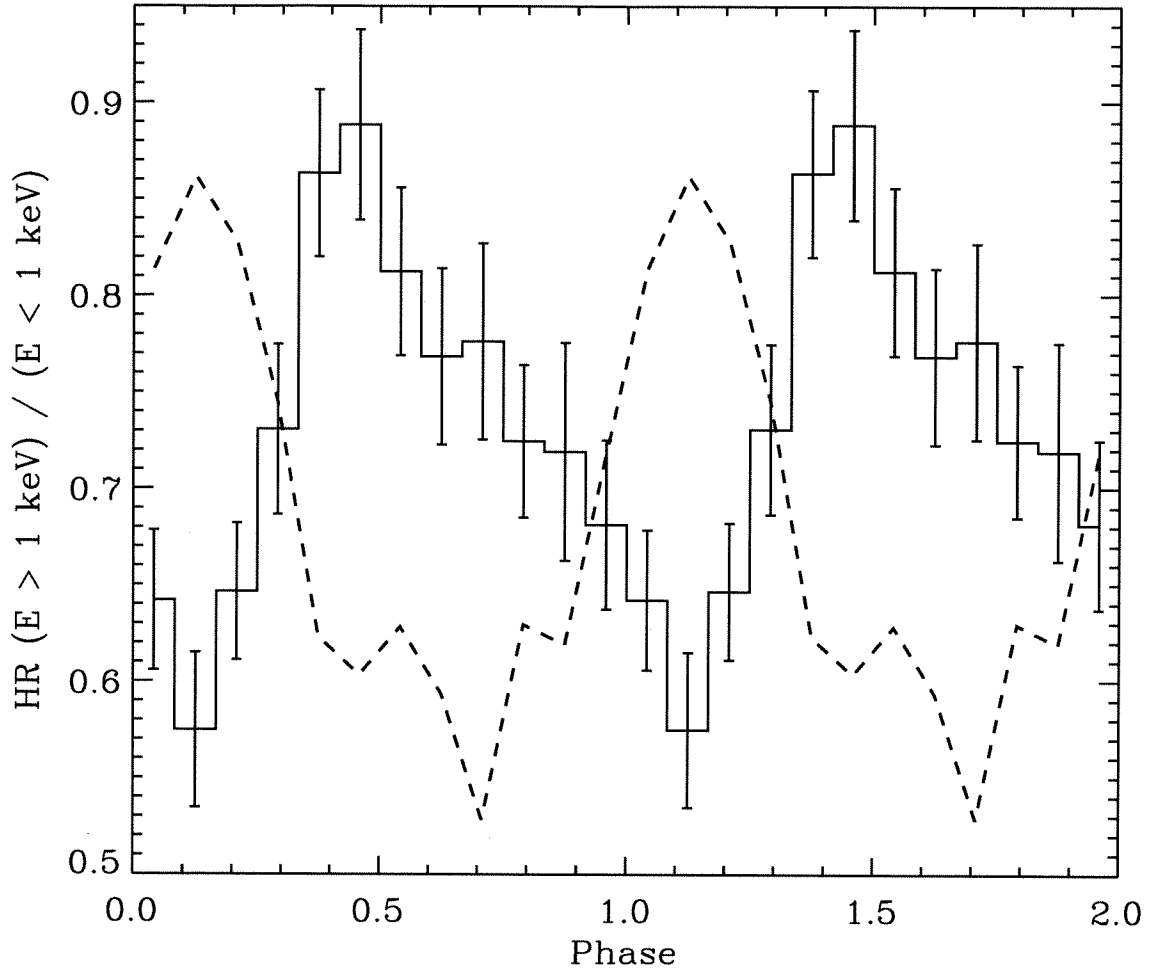
Figure 4: Hardness ratio as a function of phase of the 115.5 day modulation in NGC 5408 X-1. The hardness ratio is defined as the ratio of count rates for photons with energy > 1 keV to that for photons with energy < 1 keV. We also plot the full-band (0.2 - 8 keV) folded profile for comparison (dashed curve).

Table 1.   Results of Pulse Profile Modeling for NGC 5408 X-1[1]

Profile	A (10^{-2})	B (10^{-2})	ϕ_0	C (10^{-2})	ϕ_1	f_{amp}[a]
$E > 0.2$ keV	6.23 ± 0.05	1.10 ± 0.08	0.915 ± 0.011	0.27 ± 0.07	0.46 ± 0.02	0.182 ± 0.013
$E < 0.7$ keV	2.09 ± 0.03	0.48 ± 0.05	0.874 ± 0.014	0.14 ± 0.04	0.473 ± 0.024	0.238 ± 0.022
$E < 1$ keV	3.64 ± 0.04	0.83 ± 0.06	0.882 ± 0.011	0.27 ± 0.06	0.485 ± 0.016	0.241 ± 0.017
$E > 1$ keV	2.64 ± 0.03	0.34 ± 0.05	0.992 ± 0.023	0.096 ± 0.05	0.853 ± 0.040	0.133 ± 0.018

[1]Summary of fits to energy dependent pulse profiles for NGC 5408 X-1. The fitted model is $I = A + B \sin[2\pi(\phi - \phi_0)] + C \sin[4\pi(\phi - \phi_1)]$.

[a]Fractional modulation amplitude defined as $(B^2 + C^2)^{1/2}/A$.