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Millihertz quasi-periodic optical oscillations in 4U 0614+091

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ABSTRACT

We report the discovery of a 1-mHz optical quasi-periodic oscillation (QPO) in the candidate ultra-compact low-mass X-ray binary 4U 0614+091. The ultra-low-frequency QPO has no X-ray counterpart in contemporaneous *RXTE*/PCA data and is likely a signature of structure in the accretion disc. The QPO can be reasonably fitted with a single sine wave but with a phase jump part way through the observation, indicating that it is not coherent. We also identify a 48-min modulation, approximately consistent with the suggested orbital period of O'Brien and Shahbaz et al. If this is indeed orbital, it supports an identification of 4U 0614+091 as an ultra-compact source.

Key words: binaries: close – stars: individual: 4U 0614+091 – stars: individual: V1055 Ori – X-rays: binaries.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) can be divided into black hole candidates and neutron star systems. Those with orbital periods of hours to days are expected to have hydrogen-rich mass donors. A few ultra-compact X-ray binaries (UCXBs) containing hydrogen-deficient and possibly degenerate donors can evolve to extremely small binary separations, with orbital periods as short as a few minutes (Nelson, Rappaport & Joss 1986). Although these systems were initially assumed to be rare, many candidates have now been found (Nelemans & Jonker 2006; in't Zand, Jonker & Markwardt 2007).

The X-ray source 4U 0614+091 was first optically identified by Murdin et al. (1974) with a faint (∼18 mag), blue, variable star (V1055 Ori) located in the Galactic plane (van Paradijs & van der Klis 1994). Several arguments recently concluded that 4U 0614+091 is a UCXB hosting a neutron star. Juett, Psaltis & Chakrabarty (2001) found an enhanced neon to oxygen ratio in 4U 0614+091, similar to that seen in other UCXBs. Through sensitive optical spectroscopy, Nelemans et al. (2004) and Nelemans, Jonker & Steeghs (2006) found significant carbon and oxygen emission lines, but no hydrogen or helium. They argued that 4U 0614+091 contains a carbon–oxygen accretion disc. Recently, Madej et al. (2010) reported the discovery of a broad emission feature at ∼0.7 keV, which is attribute of O VIII Lyα emission, in the spectra of 4U 0614+09. This feature has so far been seen in two systems (Madej & Jonker 2011) that are receiving oxygen-rich material from the CO or ONe white dwarf. It is an endorsement of an oxygen-rich mass donor star. Thermonuclear type I X-ray bursts were observed by *OSO*-8 (Swank et al. 1978), and assuming that they were Eddington limited, Brandt et al. (1992) deduced a distance of probably <3 kpc to 4U 0614+091. More recently, Kuulkers et al. (2010) re-examined archival bursts from several satellites and derived a distance of 3.2 kpc. These authors argue that the bursts require more helium in the accreted matter than would be consistent with the optical spectra, leaving the nature of the mass donor still in question.

A straightforward resolution of this puzzle has been elusive due to the difficulty in identifying an orbital period. Machin et al. (1990) found a 10-d photometric modulation which might be caused by precession of an accretion disc. They then scaled the precession period of Her X-1 to 4U 0614+091 to infer the orbital period. If the ratio of the disc radius to the neutron star Roche lobe radius, ρ, is assumed to be ∼1, $P_{\rm orb} \approx 6.3$–9.4 h. If $\rho \sim 0.5$, then $P_{\rm orb} \approx 2.4$–3.3 h. Either way, this argument suggests a non-UCXB system with a hydrogen-rich donor. However, the faintness of its X-ray emission in spite of a nearby distance suggests that 4U 0614+091 has a very low accretion rate more consistent with an orbital period of <1 h (Deloye & Bildsten 2003). Recently, O'Brien (2005) reported a tentative 50-min optical period and Shahbaz et al. (2008) also claimed a strong modulation of 51.3 min. A spectroscopic modulation on a period close to this may also be present (Nelemans et al. 2006). These recent results support the case that 4U 0614+091 is a UCXB system.

The orbital period is not the only periodicity expected. Superhumps at close to the orbital period can occur in short period (and usually small mass ratio) LMXBs due to the beat between the orbital period and a slowly precessing accretion disc (Haswell et al. 2001). Millihertz quasi-periodic oscillations (QPOs) also occur, but are rarely observed at optical wavelengths. The exception is 4U 1626–67, which is an LMXB source containing a 7.66 s X-ray pulsar in an ultra-compact 42-min orbit. 130-mHz (∼7.7 s) X-ray pulsations

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Table 1. Optical observing log for 4U 0614+091.

Name	Observation date	Duration (s)	Exp. time (s)
Night 1	2007-12-8	27 330	10
Night 2	2007-12-9	27 450	10
Night 6	2007-12-13	26 540	10

are seen, a 48-mHz (∼20.8 s) QPO is produced by an interaction between the pulsar's magnetosphere and the accretion disc, and a 1-mHz (∼16.7 min) ultraviolet (UV) QPO was found (Chakrabarty et al. 2001). The 1-mHz QPO alone was not detected in simultaneous X-ray observations. Chakrabarty et al. (2001) suggested that the 1-mHz oscillations are due to warping of the inner accretion disc.

We present here new optical photometry of 4U 0614+091, revealing a new mHz QPO and further evidence for a ∼50 min period. In Section 2, we describe our data. The light curves are analysed in Section 3 and compared with contemporaneous X-ray observations in Section 4. Finally, in Section 5, we discuss the implications of a ∼50 min orbital period and the possible origin of the QPO.

2 OBSERVATIONS AND DATA REDUCTION

We performed fast optical photometry of 4U 0614+091 on three nights in 2007 December with the 2.1-m (82 inch) Otto Struve Telescope at McDonald Observatory, Texas (Table 1). Approximately 7 h of data were obtained on each night. For convenience, we will refer to the nights as night 1, night 2 or night 6 for the remainder of this work. We used the Argos CCD Photometer (Mukadam & Nather 2005). This is a CCD camera designed for fast photometry that was originally designed for pulsating white dwarfs, but has proved ideal for interacting binaries. It is possible to obtain exposures as short as 1 s with negligible dead-time between exposures. Hence, it is ideally suited to relatively short-period phenomena, such as UCXB orbital periods and mHz QPOs.

As listed in Table 1, a total of 8132 CCD image frames were taken with an exposure time of 10 s frame^{-1}. Timing was synced to GPS 1-s ticks and checked against multiple NTP servers. All images used a broad *BVR* filter to maximize the source count rate.

Custom IDL software written for Argos data was used to subtract dark current and bias, and apply flat-field corrections to the data before performing aperture photometry of 4U 0614+091 and a brighter comparison star. All results reported here are based on differential photometry relative to the comparison star, which showed no signs of variability.

3 OPTICAL ANALYSIS AND RESULTS

3.1 Light curves

Fig. 1 shows light curves of 4U 0614+091 for our three observations. While much of the variability appears to be aperiodic flickering, an oscillation with a ∼1000 s period is prominent throughout night 2 and possibly in shorter segments on the other two nights.

3.2 Periodicity analysis

To better quantify the periodicities present, fast Fourier transforms were computed to derive power spectra. These power spectra are shown in Fig. 2. Two major peaks are recurrent across multiple nights. A lower frequency at 0.34 mHz mainly appeared on nights 1 and 6, and is coincident with earlier claims of a tentative P_{orb} (O'Brien 2005; Shahbaz et al. 2008). The higher frequency signal at 1.03 mHz is strong only on night 2, but a weaker signal at a similar frequency is also detectable on the last night. The two peaks were fitted with Gaussians in order to measure characteristic frequencies. Fitting parameters are recorded in Table 2. The 1.03-mHz peak corresponds to a 16.2 ± 0.1 min period and the 0.34-mHz peak to a 49.0 ± 0.1 min period.

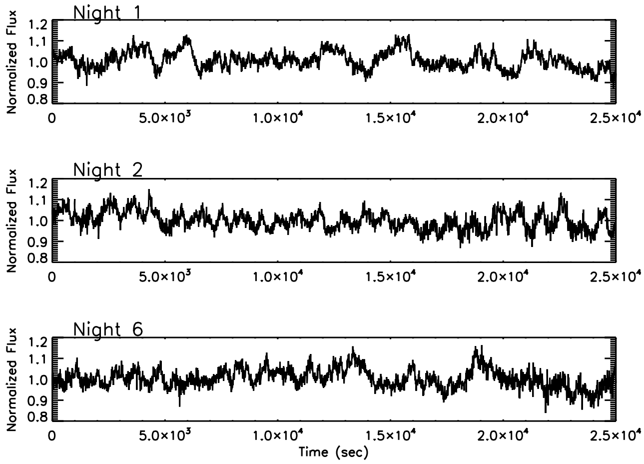

Figure 1. Light curves of 4U 0614+091 during the three nights (top panel: night 1; middle panel: night 2; bottom panel: night 6). All fluxes are measured relative to a comparison star and normalized to unit mean flux.

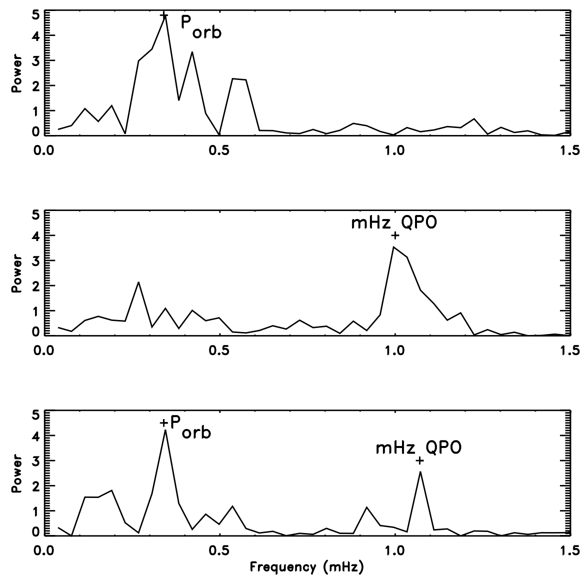

Figure 2. Linearly scaled power spectra of 4U 0614+091 for three observations (top panel: night 1; middle panel: night 2; bottom panel: night 6).

3.3 Multi-Lorentzian analysis

Where a mixture of periodic, quasi-periodic and aperiodic variability is present, as may be the case in these data, a superposition of multiple Lorentzians has become widely used for power spectral analysis in LMXBs (Nowak 2000; Belloni, Psaltis & van der Klis 2002; van Straaten et al. 2002). While these techniques were

Table 2. Results of fitting Gaussians to linearly scaled power spectra of 4U 0614+091.

Name		Peak freqency (mHz)	FHWM (mHz)	Period (min)
Night 1	Peak 1	0.34 ± 0.01	$0.09^{+0.01}_{-0.02}$	48 ± 2
Night 2	Peak 2	1.03 ± 0.01	0.10 ± 0.02	16.1 ± 0.2
Night 6	Peak 3	0.34 ± 0.12	0.09 ± 0.03	48 ± 3
	Peak 4	1.07 ± 0.12	0.19 ± 0.17	15 ± 2
Low-freq. avg.	Peaks 1 and 3	0.34 ± 0.01		49.0 ± 0.1
High-freq. avg.	Peaks 2 and 4	1.03 ± 0.01		16.2 ± 0.1

developed to describe X-ray data, there is no reason that they should not also be applicable to optical data. The primary advantage of a Lorentzian description of the variability components is that all QPOs and noise components can be fitted in the same way; it is not necessary to decide the nature of each component in advance. Following Nowak (2000), an individual Lorentzian component is given by

$$P(\nu) = \frac{r^2 \Delta}{\pi} \frac{1}{\Delta^2 + (\nu - \nu_0)^2}, \qquad (1)$$

where r is the integrated fractional rms of each Lorentzian, and Δ is its half-width at the half-maximum (HWHM).

We show in Fig. 3 the power spectra and the fitting functions in the (νP_ν) representation (Nowak 2000), where the power spectral density is multiplied by its Fourier frequency. It is helpful to associate a characteristic frequency with each Lorentzian component. We follow X-ray convention and use $\nu_{\rm max}$ as the characteristic frequency for broad features. This is the maximum in the νP_ν representation and defined by

$$\nu_{\rm max} = \sqrt{\nu_0^2 + \Delta^2} = \nu_0 \sqrt{1 + \frac{1}{4Q^2}} \qquad (2)$$

(see Belloni et al. 2002), where Q is the quality factor defined as $Q \equiv \nu_0/2\Delta$. For narrow features, $\nu_{\rm max} \approx \nu_0$.

Previous research using this technique on different sources was done in a higher frequency range, 0.01–100 Hz, typical of frequencies seen in X-ray data, e.g. van Straaten et al. (2002) and Belloni et al. (2002). These authors have found correlations between characteristic frequencies and break frequencies of low- and high-frequency noise. Our optical results show similar complexity, with multiple components required, but in a lower frequency range than typically studied in X-ray observations, exploiting the longer uninterrupted time series obtainable from the ground.

We found that to obtain a satisfactory fit, four Lorentzian components plus statistical white noise were needed. We began with the two frequencies already isolated, but found that we could not obtain a fit without excess power remaining at both higher and lower frequencies. One zero-centred Lorentzian component was added for very low frequency (VLF) noise; this is a band-limited noise component. The last Lorentzian component is fitting the higher frequency peak revealed only in the νP_ν representation as residual power around 3 mHz. The characteristic frequencies and integrated noise are listed in Table 3. The errors quoted in ν_0, $\nu_{\rm max}$ and r are 1σ confidence limits.

As clearly seen in Fig. 3, the three peak features can all be identified on each night in this representation. The first two of them are relatively narrow features. Because no significant differences are present between ν_0 and $\nu_{\rm max}$, we take $\nu_{\rm max}$ as the frequency of the feature. Feature 1 with an average of 0.35 mHz is most significant on

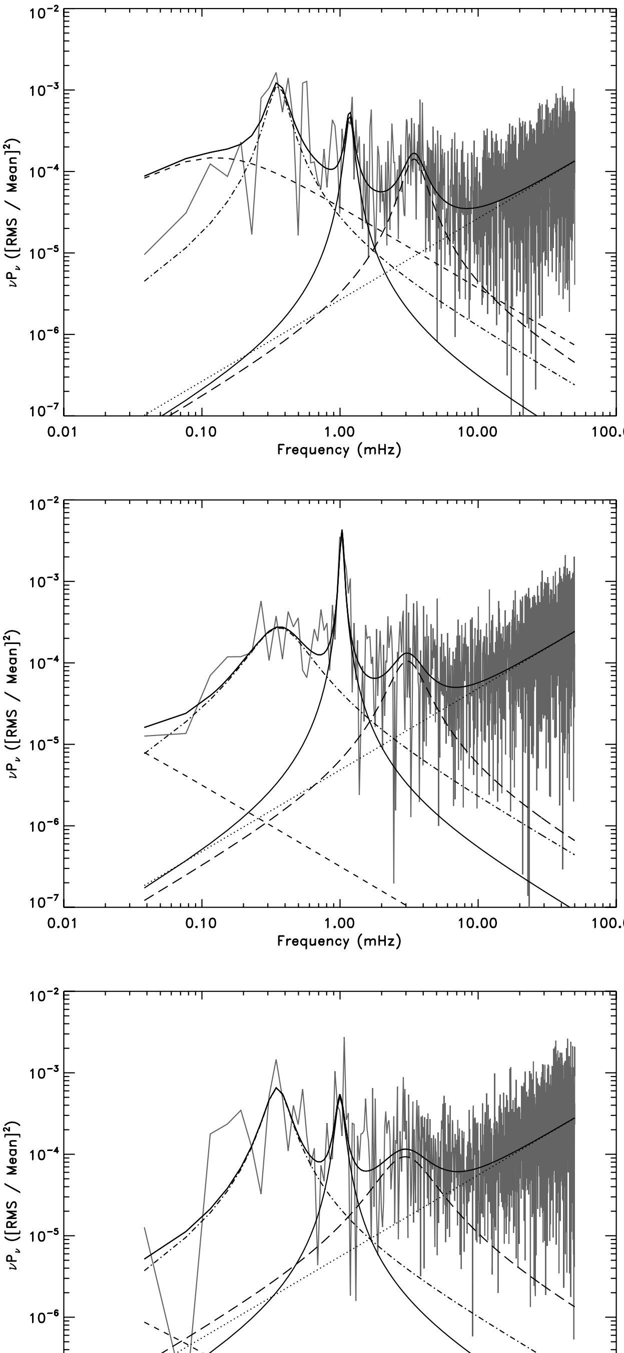

Figure 3. Power spectra and fit functions in the power spectral density times frequency representation for three observations (top panel: night 1; middle panel: night 2; bottom panel: night 6). The different dotted lines mark the individual Lorentzian components of the fit. The dark line displays the final model.

nights 1 and 6. Hence, we ignore results from night 2 for this period. The second sharp feature with average of 1.03 mHz is especially strong on night 2 but is also present on night 6. Results from night 1 are ignored for feature 2. Generally, the average results for these features are very consistent with results from Gaussian fitting of the linearly scaled power spectra. Feature 3 is quite broad. The average

Table 3. Best-fitting parameters for multiple Lorentzian model. Average of feature 1 considers nights 1 and 6. Average of feature 2 includes night 2 and 6.

Number	White noise	VLF noise		Feature 1		
	Γ (10^{-3})	ν_{max} (mHz)	r (10^{-3})	ν_0 (mHz)	ν_{max} (mHz)	r (10^{-3})
Night 1	2.66 ± 0.06	0.25 ± 0.13	0.93 ± 0.02	0.35 ± 0.01	0.37 ± 0.01	0.62 ± 0.03
Night 2	4.84 ± 0.08	0.02 ± 0.04	0.12 ± 0.23	0.32 ± 0.08	0.46 ± 0.03	0.41 ± 0.03
Night 6	5.56 ± 0.13	0.03 ± 0.02	0.01 ± 0.01	0.34 ± 0.02	0.37 ± 0.01	0.42 ± 0.02
Average frequency				0.35 ± 0.01[a]		
Average period				48 ±2 min		
Number		Feature 2			Feature 3	
	ν_0 (mHz)	ν_{max} (mHz)	r (10^{-3})	ν_0 (mHz)	ν_{max} (mHz)	r (10^{-3})
Night 1	1.17 ± 0.01	1.18 ± 0.01	0.10 ± 0.03	3.37 ± 0.15	3.64 ± 0.15	0.09 ± 0.02
Night 2	1.03 ± 0.01	1.03 ± 0.01	0.43 ± 0.06	2.94 ± 0.10	3.46 ± 0.04	0.10 ±0.01
Night 6	0.99 ± 0.03	1.01 ± 0.01	0.11 ± 0.01	2.64 ± 0.50	3.76 ± 0.20	0.14 ± 0.01
Average frequency	1.03 ± 0.01[b]			3.46 ± 0.04[c]		
Average period	16.2 ±0.2 min			4.8 ±0.1 min		

[a]Average of nights 1 and 6 only.
[b]Average of nights 2 and 6 only.
[c]For broad features, ν_{max} is considered.

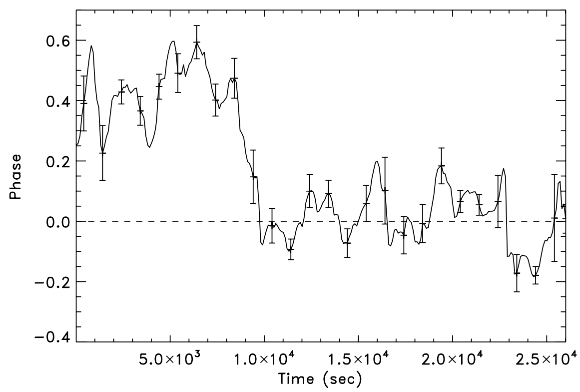

Figure 4. Phase plot of night 2 at 1.03 mHz using 1000 s as window size and step is 100 s. The error bars are measured for each 1000-s window.

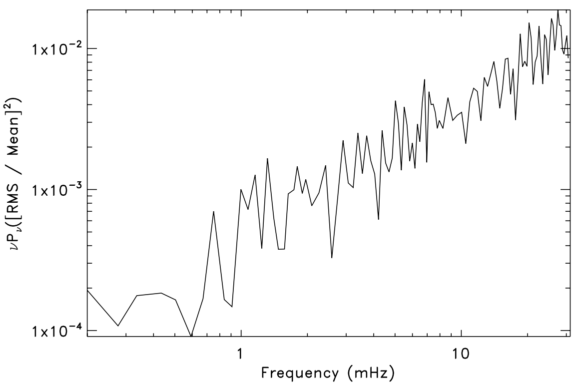

Figure 5. Power spectrum of *RXTE* PCA *B*-band data from 2007 December 13–15.

of ν_{max} from all three nights is calculated. It is centred at 3.46 mHz with about a 4 per cent uncertainty.

3.4 Phase stability of the 1-mHz QPO

Unlike the other features, the 1-mHz QPO can be clearly seen in the light curves, allowing direct study in the temporal domain. In order to better understand the 1-mHz QPO, we examined the stability of its phase. To do this, we performed a sliding sine wave fit to the night 2 data. We used a 1000-s window shifting with small step sizes of 100 s and fitted a sine wave fixed at the 16.2-min period, but with its phase and amplitude as a free parameter. The change in phase with time is shown in Fig. 4. An unexpected phase change occurs around 9500 s. The phase is basically separated into two segments, differing by 0.34 in phase. As a check, we also examined individual segments of the light curve by eye and confirmed that the phase change can be seen at this time. This confirms that the signal is quasi-periodic in nature and not a true period.

4 COMPARISON WITH X-RAY DATA

Our observations lie outside of the frequency range commonly studied in X-rays. For example, van Straaten et al. (2002) terminate the power spectra densities (PSDs) of 4U 0614+091 around 10 mHz. Some of their PSDs do reveal a very low frequency noise component overlapping with our frequency range.

We have searched for an X-ray mHz QPO with contemporaneous X-ray observations from the *Rossi X-Ray Timing Explorer* (*RXTE*). We chose the Proportional Counter Array (PCA) *B*-band data, which is concentrated in a low-energy band, 2–5 KeV, and examined data from dates nearest to our observation, from 2007 December 13–15. Light curves were produced in the usual way using HEASOFT version 6.8. Light curves were extracted in 16-s bins, with a maximum duration of 51.2 min.

We used the light curves to generate low-frequency power spectra, and show these in Fig. 5. There is no evidence for an X-ray oscillation coincident with our 1-mHz optical feature, although this may be a consequence of the non-simultaneity of the data. This is similar to the situation in 4U 1626–67 (Chakrabarty et al. 2001). This is a 42-min orbital period system showing a strong 15-min UV and optical QPO without an X-ray counterpart.

5 DISCUSSION

Including the new results here, there are now four independent observations supporting an optical periodicity of approximately

50 min (O'Brien 2005; Nelemans et al. 2006; Shahbaz et al. 2008 and our results). Besides confirming the nature of 4U 0614+091 as an ultra-compact source, identification of the 50-min period as orbital would have important implications for the nature of the companion star. We should keep in mind, however, that a periodicity that is detected repeatedly is not necessarily an orbital period. The possible presence of it in spectroscopic data would suggest an orbital origin, but this detection was very marginal (Nelemans et al. 2006).

Nelemans et al. (2004) suggested that the companion was a CO white dwarf based on optical detections of carbon and oxygen lines, but an absence of hydrogen and helium. Nelemans et al. (2010) reconsidered this argument based on chemical abundance predictions from new models and favour either a hybrid white dwarf or a very evolved helium star donor. For a 50-min orbital period, these two possibilities become observationally similar.

An additional consideration is that the presence of type I X-ray bursts suggests the presence of helium in the accreted material (Kuulkers et al. 2010). Both helium star and hybrid white dwarf models could include mass-transfer phases where CO-enriched material with a non-negligible helium fraction is transferred, although the upper limits on the helium fraction implied by the non-detection of helium lines seem in contradiction to the helium fraction required for X-ray bursts (Kuulkers et al. 2010). The presence of apparent helium bursts in helium-deficient UCXBs appears to be a recurrent problem (Juett & Chakrabarty 2003). These authors proposed a generic solution to this problem in which CO-rich material is accreted but then spallation reactions near the surface of the neutron star break these elements up into hydrogen and helium which can then be burnt back to heavier elements during bursts (Bildsten, Salpeter & Wasserman 1992). We note that this mechanism will not work in pure CO material as spallation requires elements of quite different atomic number to be present. If some helium is present in the accreted material, however, then this mechanism could potentially work to increase the helium fraction above that seen in the disc spectra.

A third possibility for a 50-min binary would be that the donor star is an evolved main-sequence star that has lost most of its hydrogen envelope. In this case, however, we would expect CNO-processed abundances with nitrogen more abundant than carbon and oxygen, in contradiction to optical spectroscopy (Nelemans et al. 2004), so this possibility can probably be discounted.

A major difficulty with identifying the donor as a white dwarf or evolved helium star comes in the expected X-ray luminosity of the system. X-ray observations indicate an average luminosity of 3.6×10^{36} erg s^{-1}. In a neutron star system with no event horizon, the X-ray luminosity should be a reasonable indicator of mass transfer rate, and in any case a lower limit on it. One uncertainty remaining is that 4U 0614+091 does eject jets (Migliari et al. 2006). A more comprehensive study, however, suggests that only 10 per cent of the accretion luminosity is being carried by the jets (Migliari et al. 2010). This constraint, together with the observed X-ray luminosity, implies a mass transfer rate of $3 \times 10^{-10}\,M_{\odot}\,yr^{-1}$. This is much larger (by an order of magnitude) than expected for the hybrid white dwarf or evolved helium star models at 50 min and evolving to longer periods (Nelemans et al. 2010). The inferred mass transfer rate would be about right for an evolved main-sequence star, but as discussed above this appears inconsistent with the chemical abundances.

It is certainly possible that the 50-min periodicity is not the orbital period, as none of the measurements demonstrates that the deduced modulations have to be orbital in origin. A white dwarf or helium star scenario would give the right mass transfer rate for a shorter period below ∼30 min (as earlier suggested by Nelemans et al. 2004). In this case, our mHz QPO would be a candidate for the orbital period, and might then be attributed a superhump (Haswell et al. 2001). It is probably not the orbital period which should be strictly coherent, as we have seen phase shifts. Even in the case of a superhump, however, it is hard to see how a phase shift such as this could arise since it would involve a readjustment of the accretion disc on close to its dynamical time-scale. If the orbital period is indeed below 30 min, we then also have to explain the origin of the recurrent 50-min time-scale.

A more natural explanation for a large-amplitude mHz oscillation seen in the optical but not X-rays, and that is able to undergo large phase shifts in a single cycle, is that it originates further into the accretion disc but in regions too cool to produce X-rays. Optical light in 4U 0614+091 appears to be dominated by the accretion disc (Migliari et al. 2006, 2010) so participation by the disc is probably necessary to obtain a 10 per cent amplitude. The frequency and strong amplitude of our mHz oscillation strikingly resembles that seen in 4U 1626–67 (Chakrabarty et al. 2001). That system too shows a CO spectrum and is identified as likely containing a hybrid white dwarf or helium star donor (Nelemans et al. 2010). The orbital period of 42 min is a close match to that proposed for 4U 0614+091, but much more secure since it is seen in pulse-timing residuals. For this orbital period the mass transfer rate inferred for a white dwarf donor is also about an order of magnitude greater than that expected from gravitational radiation (Chakrabarty 1998), a problem similar to that encountered if we attribute a 50-min orbital period to 4U 0614+091.

Chakrabarty et al. (2001) suggested that the oscillation in 4U 1626–67 arises from a purely geometric effect, the tilt angle of the normal to the local disc surface varies with azimuth. The reprocessed emission would be expected to be sensitive to warping material along the line of sight. Shirakawa & Lai (2002) suggested the magnetic torque from the pulsar interacting with the accretion disc may produce the warping effect. The similarity of behaviour in 4U 0614+091, however, appears at odds with this as there is no evidence that this system also harbours a neutron star with a significant magnetic field. A possible solution is proposed by Lai (2003). In the absence of a magnetized compact object, it is suggested that magnetic fields threading the disc itself could cause magnetically driven warping. This idea was proposed in the context of systems with a magnetically driven outflow. Multiwavelength observations suggest the presence of a jet-like outflow in 4U 0614+091 (Migliari et al. 2006, 2010) and so this may be a natural system in which to invoke this effect.

As a final remark, we note that the mHz oscillation is not seen alone, but as one of three frequencies that are recurring from night to night. While one of these may be orbital, it is possible that none is. We are thus not looking for a mechanism that can give rise to a single oscillation, but to a more complex multiperiodic behaviour, rather reminiscent of that see at much higher frequencies in X-rays (van Straaten et al. 2002). This would suggest a more complex multimodal warping of the accretion disc as a possible mechanism. We have focused on the 1-mHz QPO here because it can be seen clearly in the light curves, and so studied in the time domain. The 3.5-mHz QPO is certainly also of interest but with less information, and no obvious time-scale to associate it with, it is harder to say anything about it. More observations will be needed to properly disentangle the behaviour seen, for example by looking for correlations between changes in the oscillation frequencies to test if they are linked or independent.

6 CONCLUSIONS

We have identified three persistent, distinct, periodic or quasi-periodic oscillations in the optical flux from 4U 0614+091. The 0.35-mHz (48 min) period was suggested to be an orbital period by O'Brien (2005) and Shahbaz et al. (2008), and supported by Nelemans et al. (2006). If it is indeed orbital, it would confirm 4U 0614+091 as an ultra-compact binary (Juett et al. 2001; Nelemans et al. 2004).

The origin of the 1-mHz QPOs now seen in both 4U 0614+091 and 4U 1626–67 remains unknown, if they are even related to each other. It likely originates in the accretion disc and could arise as the precession period of inner disc regions that are not hot enough to produce X-ray emission. The less prominent 3-mHz QPO may be related to this, or may be distinct.

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