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# Time-Resolved Optical Photometry of the Ultracompact Binary 4U 0614+091

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**ABSTRACT.** We present a detailed optical study of the ultracompact X-ray binary 4U 0614+091. We have used 63 hr of time-resolved optical photometry taken with three different telescopes (IAC80, NOT, and SPM) to search for optical modulations. The power spectra of each data set reveals sinusoidal modulations with different periods, which are not always present. The strongest modulation has a period of 51.3 minutes, a semiamplitude of 4.6 mmag, and is present in the IAC80 data. The SPM and NOT data show periods of 42 minutes and 64 minutes, respectively, but with much weaker amplitudes, 2.6 mmag and 1.3 mmag, respectively. These modulations arise from either X-ray irradiation of the inner face of the secondary star and/or a superhump modulation from the accretion disk, or quasi-periodic modulations in the accretion disk. It is unclear whether these periods/quasi-periodic modulations are related to the orbital period; however, the strongest period of 51.3 minutes is close to earlier tentative orbital periods. Further observations taken over a long baseline are encouraged.

## 1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) are systems in which a low-mass companion star transfers material onto a neutron star or a black hole. Most of the systems have orbital periods of a few hours to days and contain ordinary hydrogen-rich donor stars. While these systems have minimum orbital periods around 80 minutes, systems with hydrogen-poor or degenerate donor stars can, however, evolve to extremely small binary separations with orbital periods as short as a few minutes (Nelson et al. 1986). Such systems are called ultracompact X-ray binaries (UCXBs) and have a range in orbital periods from 11 to 50 minutes (see Nelemans & Jonker 2006).

Finding UCXBs is difficult because measuring orbital periods ( $P_{\text{orb}}$ ) is generally difficult in LMXBs. The current known sample consists of 27 systems, 8 with known periods,

4 with tentative periods, and 15 candidate systems (in't Zand et al. 2007). The identification of UCXBs is mostly done through measuring  $P_{\text{orb}}$  via (1) timing of Doppler-delayed pulses if the accretor is a pulsar; (2) measuring periodic X-ray eclipses/dips if the binary inclination is high enough, and (3) through the measurement of periodic modulations resulting from X-ray heating of the inner side of the donor star or from the superhump phenomenon that is predicted for extreme mass ratio systems. There are also two indirect methods to identify UCXBs without measuring  $P_{\text{orb}}$ , which depend on the fact that in an UCXB the accretion disk is relatively small: (1) for the same X-ray flux,  $M_V$  is about 4 mags fainter for UCXBs than for normal LMXBs and (2) a method that depends on the critical accretion rate below which a system becomes transient, if the persistent accretion luminosity is 1% of Eddington (in't Zand et al. 2007).

4U 0614+091 is a low luminosity X-ray binary. Thermonuclear type I X-ray bursts were observed by *OSO-8* (Swank et al. 1978) and the compact object is a neutron star. Historically,

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TABLE 1  
LOG OF OBSERVATIONS

Date	Telescope	Exp. Time (s)	Duration (minutes)	Avg. Seeing ( $''$ )
2006 Nov 10 .....	IAC80	100	316	1.6
2006 Dec 13 .....	IAC80	200	410	1.9
2006 Dec 14 .....	IAC80	200	334	1.7
2006 Dec 14 .....	IAC80	200	354	1.5
2007 Jan 8 .....	SPM	100	205	4.1
2007 Jan 9 .....	SPM	100	411	4.1
2007 Jan 11 .....	SPM	100	391	5.4
2006 Feb 12 .....	NOT	40	296	1.7
2006 Feb 13 .....	NOT	40	238	1.5
2006 Feb 14 .....	NOT	40	271	1.4
2006 Feb 15 .....	NOT	40	271	2.4
2006 Feb 16 .....	NOT	40	258	1.7

4U 0614+091 has been associated with the brightest X-ray bursts. Based on the detection of a bright burst with *Watch*, and Eddington limit arguments, Brandt et al. (1992) argue that the distance to 4U 0614+091 is probably  $<3$  kpc. Several lines of evidence point to the conclusion that 4U 0614+091 is an UCXB. Based on the comparison of the enhanced neon to oxygen ratio to known UCXBs, Juett et al. (2001) argue that 4U 0614+091 is also an UCXB. Further support is provided by optical spectroscopy, which has revealed carbon and oxygen emission lines, but no evidence for hydrogen or helium (Nelemans et al. 2006). The optical counterpart to 4U 0614+091, V1055 Ori, is also intrinsically faint ( $V = 18.5$ ). The faintness of its persistent X-ray emission and nearby distance suggest a low accretion rate, which is consistent with an orbital period  $<1$  hr (Deloye & Bildsten 2003). In this article we present

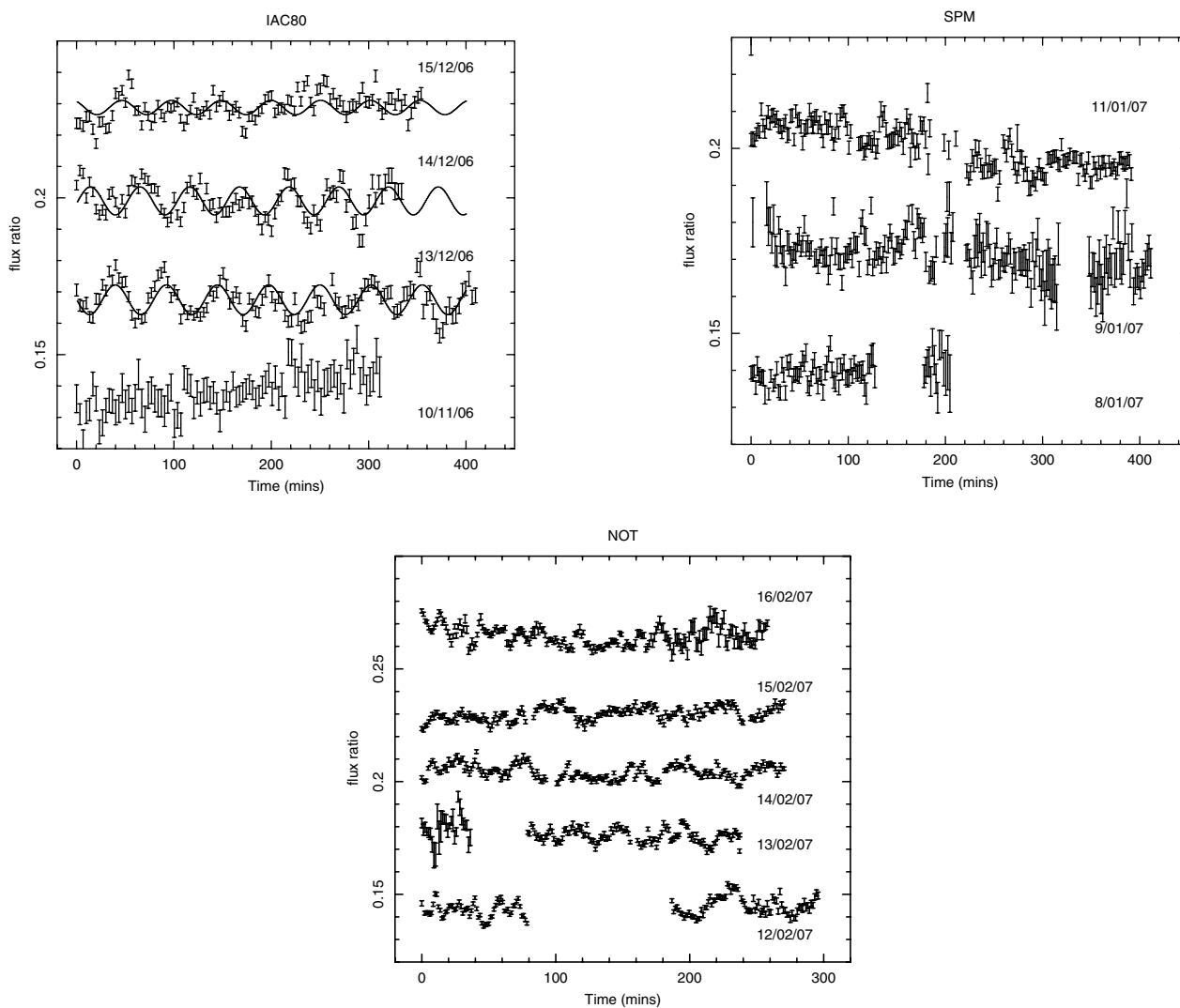


FIG. 1.—V-band light curves of 4U 0614+091 taken with the 80 cm IAC80 telescope (*left*), 1.5 m telescope at San Pedro Martin (*middle*), and the 2.5 m NOT (*right*). For the IAC80 data we also show a 51.3 minute sinusoidal modulation (*solid curve*).

the results of a long-term campaign to find a stable period in 4U 0614+091, which would most likely represent the orbital period.

## 2. OBSERVATIONS AND DATA REDUCTION

Our optical photometric observations were taken in 2006 and 2007 using the 80 cm IAC80 telescope (Izana, Spain), the 2.5 m Nordic Optical Telescope (NOT; La Palma, Spain), and the 1.5 m telescope at San Pedro Martin (SPM; Mexico). A log of the observations is given in Table 1. *V*-band images were taken using exposure times ranging from 40 to 200 s depending on the seeing, weather conditions, and the aperture of the telescope being used. Bias images and Dome flat fields were also taken for calibration purposes. Standard stars could not be taken due to nonphotometric weather conditions.

We used IRAF for our data reduction, which included bias subtraction using bias images or the overscan regions of the CCD, and flat-fielding using sky flat fields taken during twilight. The ULTRACAM reduction pipeline software (Dhillon & Marsh 2001) was then used to obtain light curves for 4U 0614+091 and several comparison stars by extracting the counts using aperture photometry. A variable aperture that scaled with the seeing was used. Differential light curves were then obtained by computing the count ratio of 4U 0614+091 with respect to a local standard (the same nonvariable star for each data set). As a check of the photometry and systematics in the reduction procedure, we also extracted light curves of a comparison star similar in brightness to the target. The

photometric accuracy of 4U 0614+091 for each exposure is about 2% and agrees with the scatter of the comparison star with similar brightness.

## 3. RESULTS

Figure 1 shows the light curve for 4U 0614+091 obtained from each observing site. The data clearly exhibits a periodic modulation, which changes strength with time. To search for periodic/quasi-periodic modulations, we use the method of Lomb–Scargle (Press et al. 1992) to compute the periodograms of all the data sets, using the constraints imposed by the Nyquist frequency and the typical duration of each observation. The results are shown in Figure 2. We also show the 99% confidence level, which allows us to demonstrate the significance of the peaks detected in the Lomb–Scargle periodogram. The level was calculated from a Monte Carlo simulation, using 10,000 sets of Gaussian noise with mean and variance taken from the data set. The periodogram for each data set shows many peaks significant at the 99% level. The strongest peak in the IAC80 data is at 51.3 minutes, whereas the NOT data shows a weaker peak at 64.1 minutes and the SPM data shows an even weaker modulation at 42 minutes. The semi-amplitudes of the modulations are 4.6 mmags, 2.6 mmags, and 1.3 mmags for the IAC80, the SPM, and the NOT data, respectively. We have looked at the *Rossi X-Ray Timing Explorer* All-Sky Monitor (*RXTE* ASM) light curves and the X-ray flux seems to be similar on the dates of our optical observations.

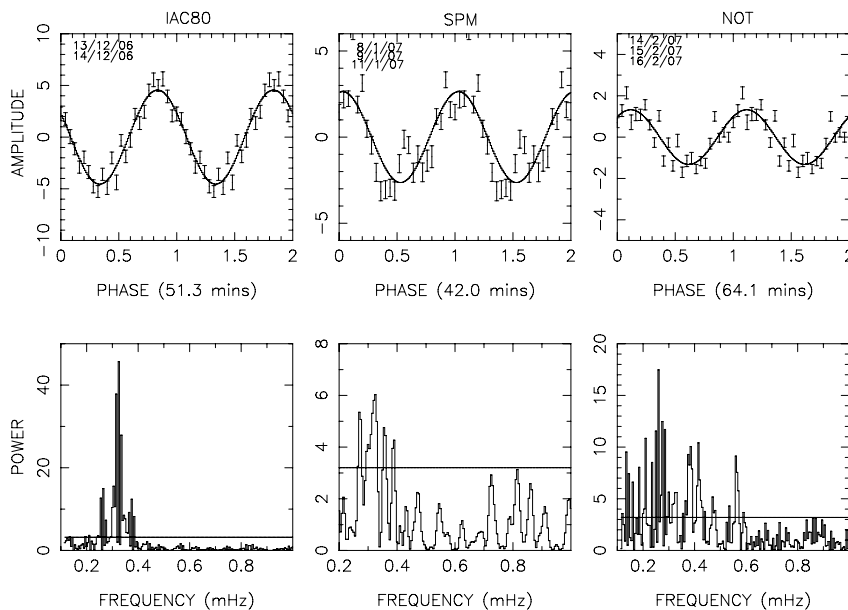


FIG. 2.—Power spectra (*bottom panels*) of the light curves taken with the IAC80, NOT, and SPM telescopes. The dates in each panel show the data that were used to compute the power spectrum. Monte Carlo simulations provide the 99% confidence levels indicated by the solid horizontal lines. The top panels show the light curves folded and binned on the significant period found for the data from each telescope.

#### 4. DISCUSSION

Nelemans et al. (2004) obtained VLT optical spectra of 4U 0614+091 and identified features of relatively low ionization states of carbon and oxygen. This clearly identifies 4U 0614+091 as an UCXB and suggests that the donor in the system is a carbon-oxygen white dwarf. For 4U 0614+091 and 4U 1626–67 there are clear indications that the disks are dominated by carbon and oxygen. Werner et al. (2006) have also obtained VLT spectra and compared them with detailed non-LTE (NLTE) models for spectra of UCXBs. Unfortunately, the NLTE models do not sufficiently agree with the observed spectra for quantitative abundance analysis. Although simple LTE models seem to fit the data better, they also cannot be used for quantitative measurements because NLTE effects mainly due to X-ray irradiation need to be taken into account.

We have found several sinusoidal modulations in the optical light curve of 4U 0614+091. These modulations most likely arise from either X-ray irradiation of the inner face of the secondary star and/or a superhump modulation from the accretion disk, or quasi-periodic oscillations in the accretion disk. This is not surprising as UCXBs are known to show orbital modulations as well as quasi-periodic oscillations (QPOs).

For example, strong 15 minute optical/UV quasi-periodic oscillations were previously detected in the 42 minute UCXB 4U 1626–67 (Chakrabarty et al. 2001), showing that photometric variability in an UCXB need not only occur near the orbital period.

O’Brien (2005) has reported a 50 minute periodicity in high-speed optical data taken with ULTRACAM. Time-resolved VLT spectroscopy also shows some evidence, although marginal, for a 49 minute periodicity in the weak absorption line near 4960 Å (Nelemans et al. 2006). The strongest period we detect is at 51.3 minutes and is present in the IAC80 data. This may reflect the superhump period, slightly longer than the orbital period. However, only observations long enough to contain many modulation cycles can distinguish between a periodic and a quasi-periodic modulation and allow a secure measurement of the orbital period.

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