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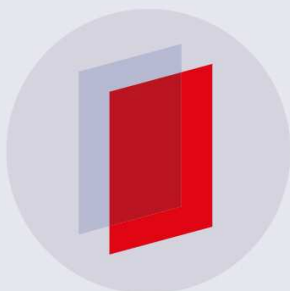
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Thai national telescope studies of ultraluminous X-ray sources

**K Thongpoyai¹, W Luangtip^{2,3*}, U Sawangwit³, T P Roberts⁴,
S Komonjinda⁵, V S Dhillon⁶ and T R Marsh⁷**

¹ Master of Science Program in Astronomy, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand

² Department of Physics, Faculty of Science, Srinakharinwirot University, Bangkok 10110, Thailand

³ National Astronomical Research Institute of Thailand, Chiang Mai 50180, Thailand

⁴ Centre for Extragalactic Astronomy, Department of Physics, University of Durham, Durham DH1 3LE, UK

⁵ Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand

⁶ Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

⁷ Department of Physics, University of Warwick, Coventry CV4 7AL, UK

*E-mail: wasutep@g.swu.ac.th

Abstract. Ultraluminous X-ray sources (ULXs) are extra-galactic, non-nuclear sources with X-ray luminosity in excess of 10^{39} erg s⁻¹. It has been thought that the majority of ULX populations are stellar-mass objects accreting matter at a super-Eddington rate. Although ULX studies are often focused in the X-ray regime, this work studied the ULXs in the optical regime, identified as the ULX counterparts (CTPs). The optical variability of nine CTPs were observed using the 2.4-m Thai National Telescope. Out of the nine ULXs, we detected three ULXs exhibiting strong variability up to ~ 1 magnitude, suggesting that the CTP light does not come from the donor star's emission. The paper discusses the physical origins of the variability which potentially explain the observed light curves.

1. Introduction

Ultraluminous X-ray source (ULXs) are extragalactic, non-nuclear point sources with X-ray luminosity (L_X) in excess of the Eddington limit for a 10 solar mass (M_\odot) black hole ($L_X \geq 10^{39}$ erg s⁻¹; see [1] for a recent review). It is thought that most ULXs are stellar-mass objects (i.e. black holes and neutron stars) accreting matter at a super-Eddington rate, although some ULXs could be candidates for intermediate mass black holes accreting material at a sub-Eddington rate (e.g. [2]). Generally, ULX studies focus on the X-ray waveband since the sources are extremely bright in this energy band. However, some ULXs are also seen to have discrete counterparts at optical wavelengths (CTPs; see e.g. [3–5]). In fact, the ULX CTPs are likely to be faint ($m_V \gtrsim 21$) and reside in crowded fields, meaning that powerful telescopes such as HST are often required to resolve and identify their CTPs. Given that the CTPs are associated with the ULXs, theoretically, the optical light could arise from the donor star emission, outer disc emission, or reprocessing emission of X-rays photons on the outer disc. In fact, the observed CTP light could be the combination of every emitting component. A previous CTP study [5] suggested that the



ULXs might have OB supergiant companions if the optical lights observed are dominated by the donor star emission. However, the study [4] indicated that CTP emission might be dominated by the X-ray heating of the outer disc, or even the X-ray heating of the donor star. Indeed, such an emission could lead to the orbital or superorbital modulations that were detected in the light curves. For example, in the ULX NGC 7793 P13, the orbital and super orbital periods detected have been reported to be ~ 65 days and 5-8.8 years, respectively [6].

As stated above, obtaining the ULX CTP data –in addition to the X-ray data– could provide more information about the ULXs, such as about the donor star properties, orbital modulations, and disc properties. Thanks to the great spatial resolution of HST and Chandra X-ray telescope, up to ~ 20 ULX CTPs have been resolved and identified in previous studies. Given that accurate positions of the ULX CTPs in the sky are well identified in the literature, there is an opportunity to study CTPs using a lower resolution telescope. This work studies the optical variability of nine ULX CTPs using the 2.4-m Thai National Telescope (TNT). The paper is laid out as follows. Section 2 describes the sample selection, data reduction and data analysis. Section 3 then presents and discusses the results. Finally, section 4 summarises the findings.

2. Sample selection, data reduction and data analysis

The ULX sample studied in this work were selected from those that previous studies had detected possible optical counterparts [3–5]. From the catalogue, we only chose CTPs that were visible to TNT and had an observed V-band magnitude of $\lesssim 23$, so that they could be observed by TNT. Following these criteria, nine ULXs were selected (table 1). The TNT observations had began in 2017 and were performed using an ULTRASPEC camera [7] equipped with a SDSS g' filter. As all the ULX targets were quite faint and almost all reside in crowded fields, it was necessary for the observations to be done in dark time with minimal lunar light contamination. Thus the seven allocated nights were organised as follows: two nights in February; two nights in March; and three nights in April. The experiment was designed so that for each individual observation, the ULX data counts had to gain a minimum S/N of $\gtrsim 10$ (see column 5 of table 1), and most of the ULX targets were observed at least twice per night. Using this criteria, it was possible to track the ULX sample property changes on the time scales of hours, days, and months.

Table 1. ULX sample properties.

ULX Name	RA	Dec.	m_V^a	Exp. time (sec.) ^b	Δmag^c
Holmberg II X-1	08:19:29.00	+70:42:19.08	21.6	900	$\lesssim 0.3$
M81 ULS1	09:55:42.15	+69:03:36.2	21.8	180	$\lesssim 0.1-0.2$
NGC3034 ULX6	09:55:47.46	+69:40:36.28	18.46	90	~ 0.5
Holmberg IX X-1	09:57:53.28	+69:03:48.31	22.8	1200	~ 1.2
NGC4395 ULX1	12:26:01.44	+33:31:30.99	22.0	480	$\sim 0.3-0.6$
NGC4485 X-1	12:30:30.49	+41:41:42.24	22.2	300	~ 0.2
NGC4559 X-7	12:35:51.73	+27:56:04.41	23.14	1200	$\sim 0.3-0.4$
NGC5204 X-1	13:29:38.61	+58:25:05.55	22.4	360	$\lesssim 0.3$
M101 ULX-1	14:03:32.37	+54:21:02.75	23.3	900	$\gtrsim 0.4$

Notes. ^aThe observed magnitude in V band. ^bExposure time used for each single observation to obtain the S/N of $\gtrsim 10$. ^cMaximum magnitude change in SDSS g' filter during the observations in 2017. The data in columns 1-4 are obtained from the references [3–5, 8].

To obtain the scientific images, the standard data reduction method was performed using the IRAF package [9]. Astrometric corrections were completed using the SCAMP package [10], in

which accurate sky coordinates for each image were obtained from the reference star catalogue determined to best fit the image: GSC-2.3; SDSS-R7; USNO-B1; NOMAD-1; and 2MASS. We then studied the ULX property changes as a function of time by performing differential photometry for each ULX. The source counts were extracted from the circular region centred on the position of the ULX with a radius of $\sim 5''$ (or $< 5''$ in cases where the ULX resided in crowded fields), while the reference counts were extracted from isolated point sources which were outside the crowded fields from the same image. Here, up to five reference objects were selected for comparison to reduce the possibility of obtaining spurious results because the reference objects were variable. Moreover, to increase confidence, the selected references were crosschecked to ensure that they were not known variable sources which were already identified in the astronomical databases (i.e. NED and SIMBAD). The background counts were extracted from the source-free region in the field. Figure 1 illustrates the positions of the source and reference objects used to perform differential photometry on the ULX Holmberg IX X-1.

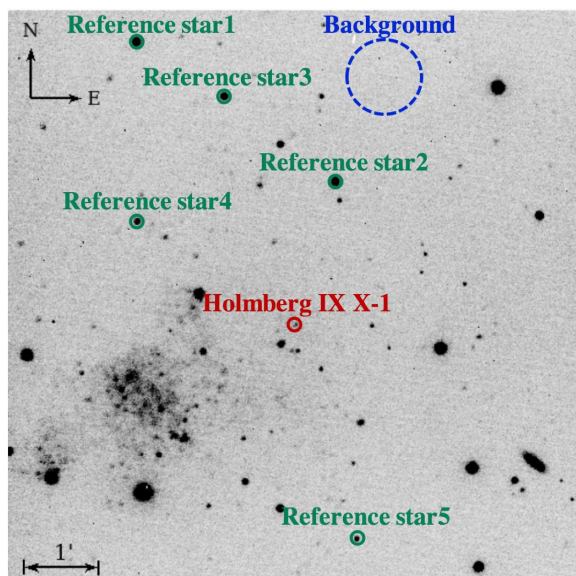


Figure 1. Position of the source and reference stars used to perform differential photometry on ULX Holmberg IX X-1.

Using the photometric results obtained, the maximum magnitude change for each ULX observed in 2017 was estimated, with the values reported in column 6 of table 1. Note that since five reference objects were selected for photometry measurement, there may be differences in the values of magnitude change obtained from each reference object. For example, the maximum magnitude change of the ULX NGC4395 ULX1 could range between $\sim 0.3 - 0.6$ magnitude. From the data, it was possible to roughly divide the ULXs into two sub-groups based on their level of variability: those which showed high levels of variability ($\Delta m \gtrsim 0.3$, i.e. NGC3034 ULX6, Holmberg IX X-1, NGC4395 ULX1, and M101 ULX-1); and those which had small or moderate levels of variability ($\Delta m \lesssim 0.3$, i.e. Holmberg II X-1, M81 ULS1, NGC4485 X-1, NGC 4559 X-7, and NGC5204 X-1). Due to the limited TNT time awarded, we decided to only conduct further study on sources that clearly showed significant variability. Note that although NGC3034 ULX6 exhibited a significant variability of ~ 0.5 magnitude, it was regarded that the source variability may be highly uncertain since bad fitting results were achieved from the astrometric correction of this source, so this was skipped for further study. Therefore, the TNT observations allocated during 2018 were focused on the variability of three ULXs: Holmberg IX X-1; NGC4395 ULX1; and M101 ULX-1. Three consecutive dark time nights in March 2018 and five consecutive dark time nights in April 2018 were dedicated to monitoring the variability of these ULXs. The 2018 season utilised the same observing instruments, data reduction, and analysis method that were

used during the 2017 season to attain photometric results for the observed ULXs.

3. Results and discussion

Light curves were constructed on the basis of all the photometric data obtained during the 2017 and 2018 seasons for Holmberg IX X-1, NGC4395 ULX1, and M101 ULX-1 (figure 2). However, before continuing to further interpret the data, a caveat in regards to the TNT resolution must be considered. Since ULXs are likely to reside in dense fields [5], a high spatial resolution telescope is required to resolve the ULX emission from that of any nearby objects. In fact, since the FWHM of the TNT ULTRASPEC observed under good weather conditions could be $\sim 1''$ [7], the ULX counts extracted from the defined region could be contaminated by nearby object emissions, thus distorting the ULX light curves. The following interpretation is discussed on the assumption that all the nearby object emissions were constant (at least on the timescales that the ULX CTPs were observed), so the observed variability properties are intrinsic to the ULXs.

As described in section 1, the optical light of the ULX CTPs could arise from the donor star or from the disc. However, it has been argued that the optical emissions of most ULXs are dominated by X-ray reprocessing on the disc [4]. Theoretically, if the ULX optical light is dominated by the donor star emission, it could be expected to see very low variability ($\lesssim 0.1$ mag) [4]. Of the nine ULX samples studied, the photometric results appear to support the reprocessed emission scenario, in which the ULX variabilities in this study are likely to be $\gtrsim 0.1$ magnitude. However, as the 2018 TNT season only focused on three ULXs, the variability will be discussed mainly based on the results from these three ULXs.

It is clear that *these three ULXs show a variability of $\sim 0.4 - 0.5$ magnitude on the timescales of hours, and up to the level of ~ 1 magnitude on the timescales of \sim a day.* Given the strong variability of the ULXs, it is suggested that optical emission does not arise from the direct emission of the donor star. In fact, the absolute level of the observed variability detected in this study is consistent with the optical variability reported in previous studies [4, 5, 11]. For further interpretation, periodic modulation is one data element that could be studied from the light curves. In fact, constraining the orbital period from the light curves could be used as a technique to measure ULX mass. For example, the detection of ~ 6 days modulation in the optical study of NGC1313 X-2 yields an estimation of 50-100 M_{\odot} black hole mass powering the ULX [12]. According to the variability in figure 2, although the data does not allow us to accurately constrain the modulation timescale, it can be roughly estimated that the magnitude changes of the ULXs are on the timescales of hours to days. The black hole binary evolutionary model [13] theoretically predicts an orbital period of $\sim 1-6$ days for stellar mass black hole ULXs ($20 M_{\odot}$). Moreover, recent studies have reported the detection of X-ray eclipses of ULXs in M51, with a binary period of either ~ 6 or ~ 13 days. So if it is assumed that the ULX variability is due to orbital modulation, the variability on the timescale of days appears to broadly support that the ULXs Holmberg IX X-1, NGC4395 ULX1, and M101 ULX-1 are powered by stellar mass black holes. However, other X-ray studies have also suggested a longer ULX modulation period: 62 days for M82 X-1; 115 days for NGC5408 X-1; and 78 days for NGC 5907 ULX-1. This could also be interpreted as an orbital period or superorbital origin (see [1] and the references therein). In fact, since this study found no strong evidence for a sustained sinusoidal pattern in the light curves, this is regarded as a potential explanation for the variability, although clearly additional data is required to clarify this.

Another possible cause for the optical variability could be intrinsic to the accretion disc. This could be the variation of the outer disc itself, or due to the inner disc photons irradiating and reprocessing on the outer disc. The former scenario is unlikely since the viscous timescales of the outer disc should be longer than a few days (e.g. equation (1) of [14]). In the latter case, one might expect to see a correlation between the X-ray and optical variability [15]. The

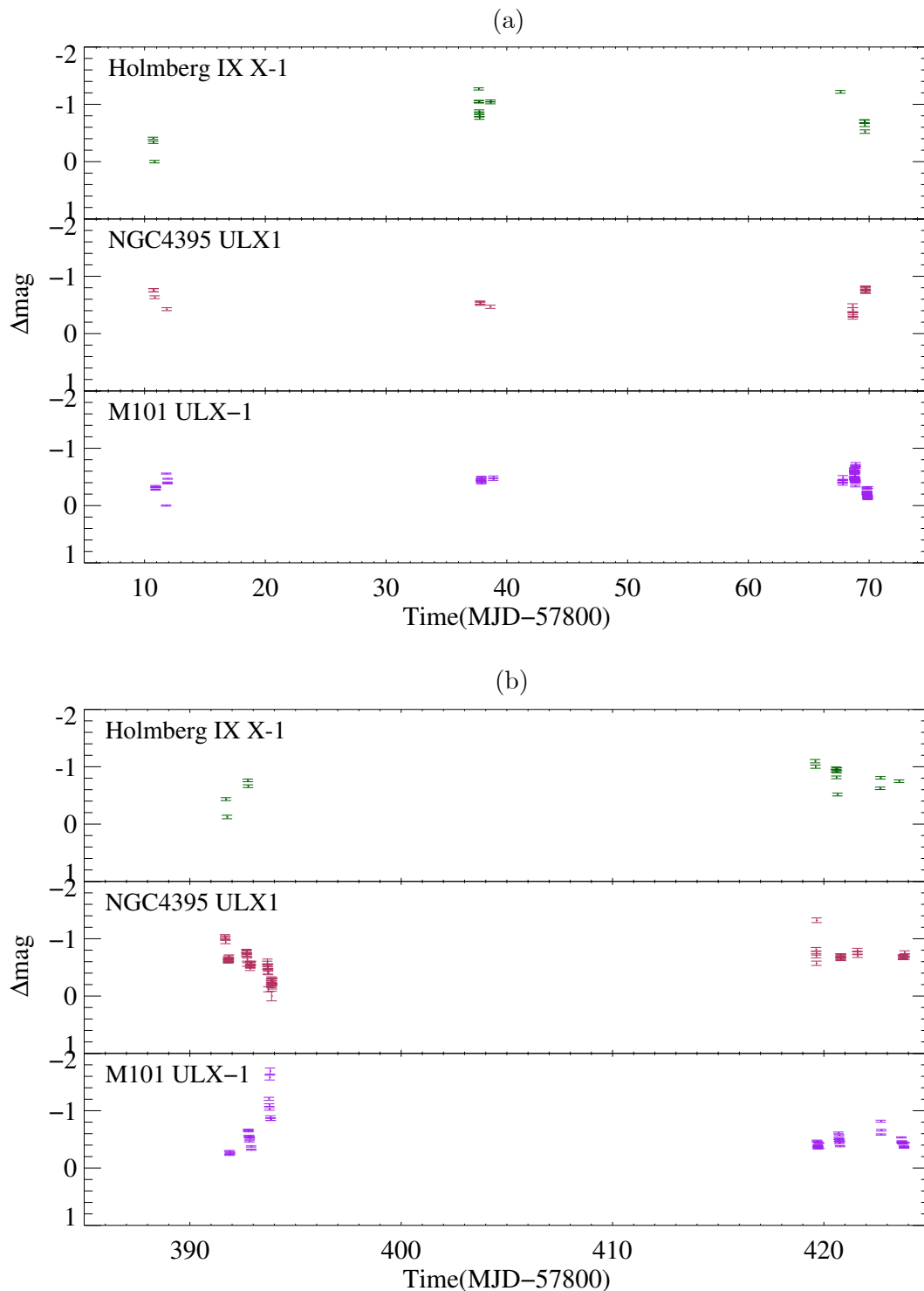


Figure 2. Light curves of the three ULXs focused in this study, observed during the 2017 (a) and 2018 (b) seasons.

X-ray flux monitoring of the ULX Holmberg IX X-1, NGC4395 ULX1, and M101 ULX-1 show X-ray variability on different timescales, varying from years to days [16–18], and even at the timescales of \sim a minute [19]. Although we found an optical variability on the timescale of days in this sample, more data is required to clarify the correlation between X-ray and optical

variability. Finally, since some ULXs have been confirmed to be powered by super-Eddington neutron stars (see [20]), they could at some point enter a propeller phase, in which the X-ray flux may decrease by a 1-2 order of magnitude, since the magnetic pressure becomes dominant and then suppresses the accretion. This mechanism would result in a bimodal flux distribution which would be visible in the light curve (see [21]). Therefore, if this effect is directly seen in optical light curves, it is possible to expect a variability of ~ 3 -5 magnitude. Yet since ~ 1 magnitude of change is found, this might suggest a few percent of X-ray flux reprocessing on the outer disc. Yet since no strong evidence of a bimodal flux is seen in the light curves, more data is required to support this scenario. In fact, simultaneous X-ray/optical observations would be very helpful in further clarifying this issue.

4. Conclusion

In this work, we analysed the optical variability of nine ULXs using TNT. All the ULX samples showed a significant variability of $\gtrsim 0.1$ magnitude, suggesting that the variation is unlikely to arise from the donor stars. We proceeded to focus on the three ULXs which exhibited strong variability: Holmberg IX X-1; NGC4395 ULX1; and M101 ULX-1. The photometric results of these three ULXs observed during the 2017 and 2018 seasons suggest that the maximum variability of the ULXs could be ~ 1 magnitude. The paper then discussed the physical processes which could potentially cause the ULX flux changes: orbital motion; variation of X-ray flux reprocessing on the outer accretion disc; and the magnetic field suppressing the accretion. However, no scenarios could be ruled out due to the lack of data points. Further TNT observations are therefore required to clarify the physical origin of the variability.

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