X-ray outbursts from a new transient in NGC 55

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ABSTRACT
We report the outbursts from a newly discovered X-ray transient in the Magellanic-type, SB(s)m galaxy NGC 55. The transient source, XMMU J001446.81-391123.48, was undetectable in the 2001 XMM-Newton and 2004 Chandra observations, but detected in a 2010 XMM-Newton observation at a significance level of 8σ in the 0.3–8 keV energy band. The XMM-Newton spectrum is consistent with a power law with photon index of Γ = 3.04±0.21 or a disk blackbody with kTin = 0.73 ± 0.06 keV. The luminosity was ∼ 10^{38} erg s^{-1}, and the source displayed strong short-term X-ray variability. These results, combined with the hardness ratios of its emission, strongly suggest an X-ray binary nature for the source. The follow-up studies with Swift XRT observations revealed that the source exhibited recurrent outbursts with period about a month. In the faint state, the XRT spectrum is described by a power law (Γ ∼ 2.5), and during the outburst, the source reached its peak luminosity ∼ 2 × 10^{39} erg s^{-1} without evidence for any changes of the photon index, which may be an indication of steep power law state outburst. Based on the X-ray spectral and temporal properties, we conclude that XMMU J001446.81-391123.48 is a new transient X-ray binary in NGC 55, which possibly contains a black hole primary.

Key words: X-rays: general – X-rays: binaries – X-rays: bursts – X-rays: galaxies – X-rays: individual(XMMU J001446.81-391123.48)

1 INTRODUCTION
Transient X-ray sources have been extensively studied from the beginning of X-ray astronomy. Most of them are binary systems with a black hole (BH) or a neutron star (NS) as the primary. These systems have been primarily discovered when they entered outbursts characterised by an episode of high accretion rates and abrupt increases of X-ray luminosity by several orders of magnitude. During an outburst, the source goes through different spectral states: low/hard state (LHS) and high/soft state (HSS) are the two principal states of black hole X-ray binaries (BHXBs). In the LHS, the spectrum is described by a hard power law with photon index in the range of 1.5 - 2.0, and in the latter, thermal emission (kT ∼ 1 keV) from an optically thick and geometrically thin accretion disc dominates. Transitions between the HSS and LHS frequently pass through intervals of steep power law state (SPL), described by a power law with photon index Γ > 2.4 and the quasi-periodic oscillations are common in SPL (see McClintock & Remillard 2006; Remillard & McClintock 2006, for extensive reviews on spectral states). These outbursts are few-month long with typical recurrence period of many years (∼ 2 – 57.8 yr;

Chen, Shrader & Livio 1997; Kuulkers et al. 1997). NS X-ray binaries also have such outbursts with much shorter recurrence period (∼ 100 – 200 d; Guerriero et al. 1994; Masetti 2002) compared to the BH systems. However, BH and NS systems both show many remarkable similarities in their spectral states (van der Klis 1994; Campana et al. 1998; McClintock & Remillard 2006).

NGC 55 is a Magellanic-type, SB(s)m galaxy and their X-ray properties has been well studied by two XMM-Newton observations (Stobbart, Roberts & Warwick 2000). They identified 137 X-ray sources in the field of view and classified 42 X-ray sources in the D25 region of the galaxy as X-ray binaries (XRBs), supernova remnants, and very soft sources. Moreover, this galaxy hosts a very bright BHXB candidate, which showed a marked upward drift, significant chaotic variability and pronounced dips in the XMM-Newton observations (Stobbart, Roberts & Warwick 2004). This particular source belongs to the ultraluminous X-ray source class with X-ray luminosity > 10^{39} erg s^{-1}.

In this paper, we report the outbursts from a new X-ray transient in NGC 55. The transient source was discovered serendipitously from the inspection of archival XMM-Newton observations, which were primarily selected for studying the variability of super soft X-ray sources. While a more detailed report on the variability of super soft X-ray sources will be presented later, in this paper, we concentrate
on this transient which exhibited recurrent outbursts in the Swift X-ray Telescope (XRT) observations. In the following, §2 describes the observations and data reduction techniques used. We explain the analysis and results in §3 and we discuss the possibilities for the nature of the transient in §4.

2 OBSERVATIONS AND DATA REDUCTION

We used archival XMM-Newton observations of NGC 55 performed in 2001 November and 2010 May. The data from the European Photon Imaging Camera (EPIC) PN detector were reduced and analysed using standard tools of the XMM-Newton Science Analysis Software (SAS) version 13.5.0. The full-field background light curve was extracted from the PN camera to remove the particle flaring background and create the good time intervals file. We used the PN events with the best quality data (FLAG = 0) and PAT-TERN ≤ 4, and removed the hot pixels in the data by using the flag expression #XMMEA_EP. The source detection routine (EDetect_Chain) was carried out using the standard parameters for EPIC-PN data over the entire energy bands and obtaining the final source list from 2001 and 2010 observations. We corrected the X-ray source positions by correlating the final source list with the USNO A2.0 optical catalogue (Monet & et al. 1998), using the SAS task EPOSCorr.

We also analysed two archival Chandra observations conducted in 2001 and 2004. The Chandra data were reduced and reprocessed using the science threads of Chandra Interactive Analysis of Observations (CIAO) version 4.6 and HEASOFT version 6.15.1. In addition, we used Swift XRT observations of the region carried out during 2013 April to 2014 October. We selected the observations with an exposure time of > 2 ks from the Swift program, which resulted in 24 observations (see Table 1). We reduced the Swift data using HEASOFT and the Calibration Database (CALDB) files as of 2014 June 10. We processed the photon counting mode of Swift observations using the Swift specific FTOOL XRTPipeLINE, by following the standard procedures.

The Optical analysis was carried out using the archival images taken by Hubble Space Telescope (HST) with Advanced Camera for Survey (ACS). Two sets of HST/ACS data at the F814W (I) and F606W (V) filters, taken in 2003 September, were analysed.

3 ANALYSIS AND RESULTS

The new transient was discovered by an inspection of the image from the 127 ks XMM-Newton observation conducted in 2010. To determine the source position, we compared the astrometrically corrected X-ray positions of the persistent sources in 2001 and 2010 observations. In Fig. 1, we show the field of three bright sources (S1, S2 and S3), which were identified in the catalogue of Stobbart, Roberts & Warwick (2004) as source #38 (XMMU J001444.62-391135.9), 43 (XMMU J001452.02-391045.2), and 47 (XMMU J001457.00-391139.2), respectively. We also detected a new source, XMMU J001446.81-391123.48, only in the 2010 observation with positional uncertainty of 0.71 arcsec. This source is located within the D25 ellipse of NGC 55.

We searched the on-line catalogues for X-ray sources consistent with the position of XMMU J001446.81-391123.48, but did not find any likely candidates. The analysis of Chandra observations conducted in 2001 and 2004 did not find any sources in the XMMU J001446.81-391123.48 positional error region. Also this particular source was not catalogued in the XMM-Newton observations (Stobbart, Roberts & Warwick 2004) and previous ROSAT observations (Read, Ponman & Strickland 1995, Schlegel, Barrett & Singel 1997), but only in the third generation XMM-Newton Serendipitous Source Catalogue (3XMM-DR4). Based on these, we concluded that XMMU J001446.81-391123.48 is a previously undetected source and it is a new transient in NGC 55.

To determine the significance of detection, we extracted the 0.3–8 keV counts from a 14 arcsec radius circle centred at position of the source (R.A.=0°14′46.81, DEC=−39°11′25″.48, equinox J2000.0). The background level was determined using a nearby source-free circular region with a radius the same as that for the source. After background subtraction, we obtained 1602 ± 45 and 713 ± 29 counts from EPIC-PN and MOS respectively; the combined detection significance is 8.4σ.

Note. — The prefix K, L and M on Swift denotes 000326190, 000821200 and 000334680 respectively.

Table 1. Observation Log

| Mission | ObsID | Date       | Exposurea |
|---------|-------|------------|-----------|
| XMM-    | 0028740201, 0028740101 | 2001 Nov  | 33.6, 31.5 |
| Newton  | 0655050101    | 2010 May  | 127.4     |
| Chandra | 2255    | 2001 Sep   | 60.1      |
|         | 4744    | 2004 Jun   | 9.7       |
| Swift   | K01 - K07 | 2013 Apr - May | 4.9 - 5.6 |
|         | K09 - K20 | 2013 Jun - Aug | 4.5 - 4.7 |
|         | L01, L04 | 2013 Sep - Nov | 3.5, 2.7 |
|         | M01, M03, M05 | 2014 Oct | 2.9, 2.2, 3.7 |
| HST     | J8R302010, J8R302NVQ | 2003 Sep | 0.7, 0.4 |

Exposure time is in units of kilo-seconds.
The hardness ratios (HRs) were calculated from the count rates and defined as $HR_1=(M-S)/(M+S)$ and $HR_2=(H-M)/(H+M)$, where $S$, $M$ and $H$ are the count rates in soft (0.3–1 keV), medium (1–2 keV) and hard (2–6 keV) bands respectively. The ratios obtained for XMMU J001446.81-391123.48 are $HR_1=0.43 \pm 0.01$ and $HR_2=-0.36 \pm 0.01$. We used the X-ray colour classification scheme, tuned for XMM-Newton data (Jenkins et al. 2003), to classify the source. Using the same colour criteria as employed by Jenkins et al. (2003), we classified this source as an X-ray binary. Although we cannot definitely classify any sources by their X-ray colours alone, but this approach is a first step to identify the class for the source.

We extracted the background subtracted light curve for the transient source based on the combined EPIC-PN and MOS camera over 0.3–8 keV energy range. The short-term X-ray variability of the source was investigated by carrying out a Kolmogorov–Smirnov (K-S) test on an 800-s binned light curve and an additionally extracted 100-s binned light curve. From the K-S test, we found that the source showed a strong short-term X-ray variability at confidence level of $>99.99\%$ in both light curves.

The source and background spectra, together with response and ancillary response files, were obtained using the standard SAS tasks. The source spectrum grouped to a minimum of 20 counts per bin and the spectral analysis was performed with *XSPEC* version 12.8.1g. The X-ray luminosity was calculated by assuming the distance of 1.78 Mpc (Karachentsev et al. 2003). The source spectrum was fitted with single-component models, power law (PL), multi-colour disk blackbody (DISKBB), and blackbody (BBODY). An absorption component (TBABS) was also added to each model. The spectrum is best described by the power law model with a photon index, $\Gamma = 3.04^{+0.21}_{-0.19}$, $\chi^2/d.o.f = 87.1/80$, while the DISKBB model also provides a statistically acceptable fit, with $kT_{\text{in}} = 0.73 \pm 0.06$ keV, $\chi^2/d.o.f = 91.0/80$. In Fig. 2 the spectral fit with the DISKBB model is shown. However, spectral fit became worse (statistically) with BBODY model, $\chi^2/d.o.f = 104.7/80$, compared to the power law and disk blackbody models. The unabsorbed luminosity for the power law and disk blackbody spectral fits are, $2.09^{+0.60}_{-0.43} \times 10^{38}$ and $5.75^{+0.42}_{-0.38} \times 10^{37}$ erg s$^{-1}$ respectively. These results are summarized in Table 2. We note that the column densities obtained are higher than the Galactic foreground column towards NGC 55, $N_H = 1.72 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). We tested to fix the column density at the Galactic value in fitting, but the results were significantly worse for both models.

The transient source was not detected in the 2001 XMM-Newton observation and we estimated the upper limit on the count rate using *ERGONANALYSE* task in SAS. After accounting for the background, we calculated a 90% confidence upper limit of $<1.5 \times 10^{-3}$ ct s$^{-1}$ on the count rate in 0.3–8 keV. We used the absorbed disk blackbody model to calculate the flux upper limit by assuming $kT_{\text{in}} = 0.7$ keV and $N_H = 0.3 \times 10^{22}$ cm$^{-2}$. The upper limit on the 0.3–8 keV flux is $<1.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ for this observation, which indicates that the flux from this source changed by a factor of $\sim 11$. For the Chandra observations, we analysed the ACIS data, and no sources were found at the position of XMMU J001446.81-391123.48 in the 0.3–8 keV or 3–8 keV images. Thus, we computed the 90% confidence upper limits on the count rates, using APRATES task in CIAO. The upper limits in the two epochs are $<3.2 \times 10^{-4}$ and $<1.1 \times 10^{-3}$ ct s$^{-1}$ respectively and the corresponding flux upper limits are $<2.7 \times 10^{-15}$ and $<8.2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. The former value constrains the source luminosity to be $<10^{36}$ erg s$^{-1}$.

In the Swift XRT observations, using the XRTCENTROID tool, we derived the position of XMMU J001446.81-391123.48 with a positional uncertainty of $\sim$ 5 arcsec, at 90% confidence level. For each observation, we extracted source and background spectra from a circular region of radius 20 arcsec centred on the source position determined with XRTCENTROID. The standard grade filtering of 0–12 was used. The ancillary response files were created using the tool XRTHAARF and appropriate response matrix files obtained from the HEASARC CALDB.

The upper panel of Fig. 3 shows the Swift XRT light curve in the 0.3–8 keV energy range. From the light curve, it is clear that the source exhibited substantial variability and showed distinct intensity states. During 2013 April observations, the source is in the “flaring state” and then becomes fainter on ~ day 20 in the light curve. The source remains in the “faint state” for about a month and then reaches the peak intensity ($\sim 0.03$ ct s$^{-1}$) on 2013 June 5. This intensity then decreases gradually and becomes fainter again after a month. The source reaches the peak intensity in $<2.5$ d and then declines by a factor of ~ 19 in ~ 28 d, to reach the fainter state. Thus, the source appears to have a Fast Rise Exponential Decay (FRED; Chen, Shrader & Livio 1997) kind of phenomenon in the light curve. During 2013 July – November observations, the source shows the same trend in the variations, but we could not follow up these variations because of the lack of monitoring. In addition, the source is in the rising stage during the latest Swift observations (2014 October).

In order to search for any modulation in the light curve, we used the Lomb-Scargle periodogram (LSP; Lomb 1976; Scargle 1982) and found a peak at ~ 7.8 d in the LSP. However, the peak is not statistically significant ($<99\%$ level) with a maximum power of 7.1.

In the lower panel of Fig. 3 we show the HR for these
data, defined using the Swift XRT hard and soft energy bands as the rate from 1.5–8 keV divided by the rate from 0.3–1.5 keV. Surprisingly, the variation pattern shown in the count rate does not reflect in the HR. The HR is almost constant during the entire Swift observations, although the uncertainties during the faint state are large.

Because of the low count rate, we co-added the Swift data to study the spectral behaviour of the source. We defined five count rate ranges as given in Table 2 by having roughly equal numbers of total counts (within a factor of 3). The spectrum of each count rate group was added by using the FTOOL ADDSPEC and the response files were weighted according to their counts. Since the statistical quality of the spectra are low, they can be well fit by an absorbed power law or absorbed disk blackbody model. The absorption column density was fixed during the fit to the best-fit values of XMM-Newton data. The co-added Swift spectra always favoured the power law over the disk blackbody model (spectral parameters are given in Table 2). We also fitted the spectra by minimizing the Cash (C) statistic (Cash 1979) for SWIFT1, SWIFT2, and SWIFT3. The C-stat values do not differ from the $\chi^2$ values, and the spectral parameters have negligible differences ($< 7\%$). It is also noted that the X-ray luminosity of the source is above $\sim 10^{38}$ erg s$^{-1}$ irrespective of the spectral models.

We also searched the possible counterpart for the transient source in the HST observations. The region of the source position is crowded and the XMM-Newton error circle itself contains multiple optical objects. Thus, we could not find a unique counterpart for the transient. We computed the absolute magnitudes of all sources in the error circle using DAOPHOT (Stetson 1987) package in IRAF. The absolute magnitudes ($M_V$) of all sources range from $-2.5$ to $-3.4$ and their $V - I$ colours are blue ($V - I \sim 0.18 - 0.81$).

### 4 Discussion and Conclusion

We serendipitously discovered a new transient source in NGC 55 using the archival XMM-Newton data obtained in 2010. The source was undetected in the XMM-Newton 2001 observation, and 2001 and 2004 Chandra observations, whose deep sensitivities indicate a flux change of at least one order of magnitude from $< 10^{36}$ to $\sim 10^{38}$ erg s$^{-1}$. Thus, these observations establish that XMMU J001446.81-391123.48 is a new X-ray transient source in NGC 55.

In considering the nature of XMMU J001446.81-391123.48, the X-ray colour classification scheme of Jenkins et al. (2005) identifies this source as an X-ray binary system. The high luminosities ($\sim 10^{38}$ erg s$^{-1}$) during the outbursts are consistent with the luminosity range of bright X-ray binaries, and also help to rule out the low-luminosity source classes, such as magnetic and non-magnetic Cataclysmic Variables (Kuulkers et al. 2006) and Magnetars (Mereghetti 2013), as a possible candidate for this transient. Apart from the high luminosity, the source displayed a strong short-term X-ray variability in the 2010 observation, further supporting the X-ray binary nature. The source spectrum is well described by both power law and disk blackbody model. However, the steeply falling power law index ($\Gamma \simeq 3$) may suggest that the emission probably has thermal origin.

The follow-up studies with Swift XRT revealed the source’s outburst activity and it is possibly a FRED phenomenon. During the 2013 May Swift observations, the source had an outburst and reached the peak intensity, by having a factor $\sim 13$ flux increase, within $< 2.5$ d. After the outburst, the flux decayed exponentially with an e-folding time of $> 22.8$ d. This time scale is consistent with the e-folding time of black hole candidates in outburst (Tanaka & Shibazaki 1996; Chen, Shrader & Livio 1997; Yan & Yu 2014). There are secondary peaks occurred prior (2013 April observations) and after the outburst (2013 August observations), but the peaks only reached a level of $\sim 78\%$ of the main outburst peak. In addition, the peak prior to the outburst decayed very rapidly compared to the main outburst decay. Thus, the source possibly showed a repeated outburst. The outburst recurrence period would be about a month, which is much smaller than the reported recurrence periods for the NS and BH systems (Kuulkers et al. 1997; Masetti 2002).

In terms of $\chi^2$ from our fitting, the co-added Swift spectra of this source always favour the power law over the disk blackbody model (see Table 2). In the fainter state (Swift 1), the spectrum is described by power law with index $\sim 2.5$, which is similar to SPL state seen in BHXBs (McClintock & Remillard 2006; Remillard & McClintock 2006). The source changed its luminosity by an order of magnitude and reached $\sim 2 \times 10^{39}$ erg s$^{-1}$ in the Swift 5 compared to Swift 1, but probably remained in the SPL ($\Gamma \sim 2.6$). Although the large uncertainties on the photon index measurements do not allow us to draw a clear conclusion, the results may be an indication of SPL outburst. Moreover, the X-ray luminosity of XMMU J001446.81-391123.48 is $\sim 110 - 1200\%$ of the Eddington limit for a canonical 1.4 M$_\odot$ NS, suggesting that the primary is more likely a BH. Also, if we see power law emission without any significant thermal emission at luminosities higher than $3 \times 10^{37}$ erg s$^{-1}$.
Table 2. Spectral Fitting Parameters of XMMU J001446.81-391123.48.

| Data   | Count Rate | $n_p$ | PL$^a$ | $L_X^c$ | $\chi^2$/d.o.f | $n_H^c$ | DISKBB$^a$ | $L_X^c$ | $\chi^2$/d.o.f |
|--------|------------|-------|--------|--------|----------------|--------|------------|--------|----------------|
| XMM1   | –          | 0.63$^{+0.07}_{-0.07}$ | 3.04$^{+0.21}_{-0.10}$ | 38.32$^{+0.11}_{-0.10}$ | 87.1/80 | 0.30$^{+0.04}_{-0.04}$ | 0.73$^{+0.06}_{-0.06}$ | 37.76$^{+0.03}_{-0.03}$ | 91.0/80 |
| SWIFT1 | 0.00 – 0.01(10) | 0.63(f) | 2.48$^{+0.36}_{-0.36}$ | 38.16$^{+0.11}_{-0.11}$ | 8.9/11 | 0.30(f) | 1.01$^{+0.04}_{-0.04}$ | 37.76$^{+0.07}_{-0.07}$ | 11.3/11 |
| SWIFT2 | 0.01 – 0.015(4) | 0.63(f) | 2.68$^{+0.36}_{-0.36}$ | 38.81$^{+0.11}_{-0.11}$ | 9.5/14 | 0.30(f) | 0.90$^{+0.24}_{-0.24}$ | 38.37$^{+0.06}_{-0.06}$ | 12.1/14 |
| SWIFT3 | 0.015 – 0.02(4) | 0.63(f) | 2.70$^{+0.28}_{-0.28}$ | 39.00$^{+0.12}_{-0.10}$ | 27.5/23 | 0.30(f) | 0.95$^{+0.19}_{-0.19}$ | 38.57$^{+0.05}_{-0.05}$ | 33.1/23 |
| SWIFT4 | 0.02 – 0.025(5) | 0.63(f) | 2.74$^{+0.20}_{-0.19}$ | 39.11$^{+0.07}_{-0.07}$ | 48.5/43 | 0.30(f) | 0.86$^{+0.11}_{-0.10}$ | 38.60$^{+0.03}_{-0.04}$ | 63.9/43 |
| SWIFT5 | 0.03 – 0.035(1) | 0.63(f) | 2.61$^{+0.39}_{-0.40}$ | 39.19$^{+0.17}_{-0.13}$ | 14.9/11 | 0.30(f) | 1.01$^{+0.30}_{-0.23}$ | 38.89$^{+0.07}_{-0.08}$ | 16.3/11 |

Note. — $^a$Spectral models used for fitting: PL - power law continuum; DISKBB - multi-colour disk blackbody. $^b$Count rate range used for the co-adding the Swift data and the no. of observations co-added are given in bracket. $^c$Absorption column density; including Galactic absorption, in 10$^{22}$ cm$^{-2}$. $^d$Power law index. $^e$Unabsorbed 0.3–8 keV X-ray luminosity in erg s$^{-1}$, calculated by assuming the distance of 1.78 Mpc [Kara\textsc{h}tsev et al. 2003]. $^f$The $\chi^2$/d.o.f values for the model. $^g$Inner disk temperature in keV.

Finally, the transient source is located in the bar region which is displaced $\sim 3$ arcmin from the geometrical centre of NGC 55 [Robinson & van Damme 1966]. The Very Large Array observations at 6 cm and 21 cm revealed that the radio continuum emission is concentrated on the bar region [Hummel, Dettmar & Wielebinski 1986]. Moreover, the 6 cm radio emission is dominated by a triple source and this triple coincides with discrete H$_2$ and H$_\alpha$ emission. Also, the on-going star formation rate (SFR) in the bar region is consistent with the global SFR of NGC 55 ($\sim 0.22$ M$_{\odot}$yr$^{-1}$; Engelbracht et al. 2004) and suggests that the bar region is a young star formation complex with an age of $< 2$ Myr. Thus, the transient source could be a young stellar system in the bar region of NGC 55.

In summary, XMMU J001446.81-391123.48 is a new X-ray transient in the young stellar region of NGC 55, possibly being a black hole X-ray binary. The repeated outbursts and prominent radio emission from the young stellar region made this source as a good candidate for the further follow-up studies at X-ray and radio wavelengths. Such multi-wavelength studies can shed further light on the nature of XMMU J001446.81-391123.48.

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