We present the spectral and temporal properties of 15 candidate transient X-ray sources detected in archival XMM-Newton and Chandra observations of the nearby Magellanic-type, SB(s)m galaxy NGC 55. Based on an X-ray color classification scheme, the majority of the sources may be identified as X-ray binaries (XRBs), and six sources are soft, including a likely supernova remnant. We perform a detailed spectral and variability analysis of the data for two bright candidate XRBs. Both sources displayed strong short-term X-ray variability, and their X-ray spectra and hardness ratios are consistent with those of XRBs. These results, combined with their high X-ray luminosities (\(\sim 10^{38} \text{erg s}^{-1}\)), strongly suggest that they are black hole (BH) binaries. Seven less luminous sources have spectral properties consistent with those of neutron star or BH XRBs in both normal and high-rate accretion modes, but one of them is the likely counterpart to a background galaxy (because of positional coincidence). From our spectral analysis, we find that the six soft sources are candidate super soft sources (SSSs) with dominant emission in the soft (0.3–2 keV) X-ray band. Archival Hubble Space Telescope optical images for seven sources are available, and the data suggest that most of them are likely to be high-mass XRBs. Our analysis has revealed the heterogeneous nature of the transient population in NGC 55 (six high-mass XRBs, one low-mass XRBs, six SSSs, one active galactic nucleus), helping establish the similarity of the X-ray properties of this galaxy to those of other Magellanic-type galaxies.

Key words: galaxies: individual (NGC 55) – Magellanic Clouds – X-rays: binaries – X-rays: galaxies – X-rays: general

1. INTRODUCTION

X-ray transients are an interesting class of sources, with quiescent luminosities below the detection limit, which are primarily discovered when they enter outbursts typically lasting from weeks to a few months. These bright outbursts are characterized by an episode of high accretion rates and abrupt increases of X-ray luminosity by several orders of magnitude. We now know that most of them are binary systems with a white dwarf (WD), a neutron star (NS), or a black hole (BH) as the accreting compact object. Monitoring observations at X-ray wavelengths have revealed a variety of spectral and temporal behavior in these sources, and have established distinct X-ray states for X-ray binaries (XRBs) in which the compact primary is either an NS or a BH (see McClintock & Remillard 2006; Remillard & McClintock 2006, for extensive reviews on spectral states).

X-ray transient events in nearby galaxies originate from different types of objects, which include ultraluminous X-ray sources (ULXs), super soft sources (SSSs), low-mass X-ray binaries (LMXBs), and high-mass X-ray binaries (HMXBs). Most of the ULXs identified in nearby galaxies are persistent sources with X-ray luminosities (\(\gtrsim 10^{36} \text{erg s}^{-1}\)) exceeding the Eddington limit for a 10-M$_\odot$ BH (see Feng & Soria 2011, for a review). Extensive monitoring observations with XMM-Newton, Chandra, and Swift identified two ULX transients in M31 (Kaur et al. 2012; Barnard et al. 2013). Multi-wavelength analysis suggests that the underlying sources are likely stellar-mass BHs with low-mass donors (Nooraei et al. 2012; Barnard et al. 2013). Another important class of X-ray sources in external galaxies is SSSs, usually characterized by values of $kT$ in the range of tens of eV, with X-ray luminosities between $10^{36}$ and $10^{38}$ erg s$^{-1}$ (Di Stefano & Kong 2003). They were first identified in the Large Magellanic Cloud (LMC; Long et al. 1981). A promising explanation for SSSs is quasi-steady nuclear burning on the surface of a WD, in which the compact object accretes at a high rate from a Roche lobe-filling companion (van den Heuvel et al. 1992). A sizable population of SSSs has been identified in external galaxies, for example, M31, M101, M83, M51, and NGC 4697 (Di Stefano & Kong 2004; Stiele et al. 2011), and some of these sources are subdivided into a new class called quasi-soft sources (QSSs; Di Stefano & Kong 2004). QSSs are sources with little or no emission above 2 keV with temperatures significantly higher than that of the typical SSSs, generally between 100 and 350 eV. Detailed studies of SSSs revealed that they are detected in both early- and late-type galaxies, identified in the field and globular clusters of a host galaxy, with a variety of temporal properties (Di Stefano & Kong 2003; Di Stefano et al. 2004; Jenkins et al. 2005; Brassington et al. 2012). Finally, there could be possible contamination from background active galactic nuclei (AGNs) in the X-ray source population of a galaxy, which are misidentified as sources in the host galaxy (Gutiérrez & López-Corredoira 2007; Gutiérrez 2013).

NGC 55 is a Magellanic-type, SB(s)m galaxy, a member of the nearby Sculptor group of galaxies. The first observation of NGC 55 at X-ray wavelengths by ROSAT (Read et al. 1997; Schlegel et al. 1997; Dahlem et al. 1998) identified 15 discrete X-ray sources in the D$_{25}$ ellipse of the galaxy. A detailed analysis of the X-ray properties of NGC 55 was presented by Stobbart et al. (2006, hereafter SRW06) using the XMM-Newton observations. They identified 42 X-ray sources within the optical confines of the galaxy and classified them as XRBs, supernova remnants (SNRs), and SSSs. A ULX, with X-ray luminosity $\gtrsim 10^{39}$ erg s$^{-1}$, is also present in this galaxy, which showed significant variability with pronounced dips and a flux increase in the light curves during the XMM-Newton observations (Stobbart et al. 2004). However, from the Swift monitoring campaign and Chandra observations, Pintore
et al. (2015) reported marginal evidence for limited dips in the light curves. Recently, Binder et al. (2015, hereafter BWF15) presented a comprehensive study of X-ray point sources in three galaxies, including NGC 55, as a part of the Chandra Local Volume Survey (CLVS). The purpose of the CLVS was to identify strong XRB candidates in nearby galaxies and compare the properties of the XRB population to the star formation histories of the host galaxies. They identified 154 X-ray sources in NGC 55 using multiple archival Chandra observations and studied the long-term variability using two XMM-Newton observations conducted in 2001. The X-ray hardness ratios, spectral properties, and temporal variability of the point sources were reported and tentative classification of these sources was provided as well.

Since approximately one-third of known Galactic XRBs show evidence of being X-ray transients (Tanaka & Shibazaki 1996) but the extragalactic X-ray transient population has been relatively little studied (except in M31), we have carried out studies of the transient X-ray source population in NGC 55. Such studies for external galaxies can provide us with a better understanding of the nature and evolution of these sources. In this work, we summarize our results.

2. OBSERVATIONS AND DATA REDUCTION

**XMM-Newton** observed NGC 55 three times; on 2001 November 14 and 15, and 2010 May 25 for exposure times of 33.6, 31.5, and 127.4 ks, respectively. The observations used in this work are summarized in Table 1. The European Photon Imaging Camera (EPIC) PN (Strüder et al. 2001) and metal oxide semiconductor (MOS; Turner et al. 2001) camera were operated in the full-frame mode using the thin optical blocking filter in the 2001 and 2010 observations. EPIC-PN and MOS data were reduced using standard tools (EPCHAIN and EMCHAIN, respectively) of XMM-Newton Science Analysis Software (SAS), version 14.0. The full-field background light curve was extracted to remove the particle flaring background. The good time intervals (GTI) were generated using periods with count rate $\leq 0.8$ and $\leq 0.3$ ct s$^{-1}$ in the 10–12 keV light curve for PN and MOS data, respectively. We selected the events corresponding to patterns 0–4 from the PN data and patterns 0–12 from the MOS data for the analysis with (FLAG == 0).

The source detection routine was carried out in the high-sensitivity EPIC-PN data over the entire energy band. The SAS task EBODetect was used to perform the initial source detection (with a detection threshold “likemin” = 8), employing a sliding box detection method. We provided the obtained source positions as input for the task ESPLINEMAP which constructs background maps using source-free regions of the image. The EBODetect task was performed again in “map” mode using the available background map, which improved detection sensitivity. We ran the EMLDetect task using these improved background maps with a minimum detection likelihood value of 10 (mlmin = 10). If this value is 10 or greater, then the sources were classified as significant detection and included in the final source list. Using the same criteria, we obtained the final source list from the 2001 and 2010 observations. The X-ray sources in the final list were then astrometrically corrected by correlating with the USNO A2.0 optical catalog (Monet 1998), in which the SAS task EPSCorr was used.

We also analyzed two archival Chandra observations of NGC 55, conducted in 2001 September 11 and 2004 June 29 with the Advanced CCD Imaging Spectrometer Imaging Array (ACIS-I). However, the second observation was too short and no transient sources were detected in it. Thus, we report no further analysis of this observation in the paper. The Chandra data were reduced and reprocessed using the science threads of Chandra Interactive Analysis of Observations software package (CIAO) version 4.6 and HEASOFT version 6.15.1.

In addition, we checked the archival Swift X-ray Telescope (XRT; Burrows et al. 2005) observations for possible detections of the sources reported in this paper. However, the sources, except for T1 (see Jithesh & Wang 2015, hereafter JW15), were too faint to be detected with the Swift XRT telescope.

The optical analysis was carried out using the six HST fields (see Table 1 for details). We searched the candidate optical counterparts of transient sources after performing an astrometric calibration of the X-ray and HST images using the bright point sources from the Two Micron All Sky Survey (2MASS) Source Catalog (Skrutskie et al. 2006). We computed the plate solution using the IRAF task ccmpap, and the root mean square (rms) residuals obtained from ccmpap are typically less than few hundredths of an arcsecond in both R.A and decl. Moreover, the total alignment error, computed by summing the X-ray and optical rms residuals in quadrature, are much smaller than the X-ray positional uncertainties. Thus, we continued the search for optical counterparts to the transient sources using the positional uncertainties quoted in Table 2.

| Data   | ObsID     | Date      | Exposure Time |
|--------|-----------|-----------|---------------|
| XMM1   | 0028740201| 2001 Nov 14| 33.6          |
| XMM2   | 0028740101| 2001 Nov 15| 31.5          |
| XMM3   | 0655050101| 2010 May 25| 127.4         |
| Chandra | 2255     | 2001 Sep 11| 60.1          |
| Chandra | 4744     | 2004 Jun 29| 9.7           |
| HST DISK | 9765   | 2003 Dec 16| 0.7 (F814W)   |
|        |          |           | 0.7 (F606W)   |
| HST FIELD | 9765   | 2003 Sep 23| 0.7 (F814W)   |
|        |          |           | 0.4 (F606W)   |
| HST WIDE-1 | 11307   | 2007 Jul 28| 2.6 (F814W)   |
|        |          |           | 0.9 (F606W)   |
| HST WIDE-3 | 11307   | 2007 Aug 07| 3.9 (F814W)   |
|        |          |           | 2.7 (F606W)   |
| HST WIDE-4 | 11307   | 2007 Aug 09| 3.9 (F814W)   |
|        |          |           | 2.7 (F606W)   |
| HST WIDE-5 | 11307   | 2007 Aug 06| 3.9 (F814W)   |
|        |          |           | 2.7 (F606W)   |

Note. Exposure time is in units of kiloseconds.
3. ANALYSIS AND RESULTS

3.1. Transient Source Selection

Transient X-ray sources were identified by visual inspection as well as by comparing the final source lists from the 2001 and 2010 XMM-Newton observations. We selected those sources which “disappeared” or “appeared” in the long, 127 ks XMM-Newton observation and classified them as transient candidates (TCs) or possible transient candidates (PTCs). These sources were detected in at least one observation with an unabsorbed 0.3–8 keV luminosity of >1 × 10^{36} erg s^{-1} at a >4σ confidence level and were not detected in another observation. In addition, we calculated the luminosity ratios between the “on-state” (the peak X-ray luminosities) and “off-state” (the non-detection upper limits) for these sources to confirm their transient nature. We classified the sources with ratios >5 as TCs and those with ratios between 1 and 5 as PTCs. The flux ratio used here is slightly different from the value used (high/low ratios ~8) in the Chandra studies of transient sources in M33 (Williams et al. 2008). The classification leads to the detection of 15 TCs and PTCs in NGC 55, listed in Table 2.

SRW06 identified 42 X-ray sources in the D25 region of NGC 55 using the XMM1 and XMM2 observations. We identified nine more sources in the XMM3 observation. Out of the nine sources, two (XMMU J001548.1-391612 and XMMU J001604.6-391538) of them were not cataloged in SRW06 but were detected in the XMM1 and XMM2 observations. Thus, these two sources do not satisfy our criteria and are not included in the analysis. The remaining seven sources in XMM3 were again verified by performing the source detection procedure in the 0.3–1 keV, 1–2 keV, and 2–6 keV images. These sources were detected with a 4σ threshold (mlim = 10) in at least one of the three energy bands. Moreover, they were cataloged in the third generation XMM-Newton Serendipitous Source Catalog (3XMM-DR4)1 and flagged as sources detected with high quality (summary flag ≤ 1, where a low summary flag value indicates a high quality for a detection2). In addition, there are eight sources identified in SRW06 but not detected in the XMM3 observation (see Table 2). In total, our classification identified six TCs and nine PTCs in NGC 55. Among them, T1, whose properties have been reported in JW15 in detail, is likely a transient black hole XRB in the star-forming region of NGC 55. For completeness, the source is also listed in this paper.

3.2. Hardness Ratio and Variability

Since transient sources have few net counts, hardness ratios (HRs) can be considered as a primary tool to investigate their spectral properties. Although we cannot conclusively classify an individual source based on its X-ray colors alone, it is possible to identify the trend in the source population. Therefore, the HRs of the transients were calculated from the count rates, which are defined as HR1 = (M – S)/(M + S) and HR2 = (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. For the sources detected with the EPIC-PN and MOS camera, we quote the weighted mean of the hardness ratios (weights were calculated using the count rates) and list them in Table 3. The X-ray color classification scheme of Jenkins et al. (2005), developed for XMM-Newton, was used to classify the transient sources. The scheme divides the X-ray sources into four broad categories: absorbed sources (ABSs; HR1 > 0.57), XRBs (−0.24 < HR1 < 0.57, −0.8 < HR2 < 0.8), SNRs (HR1 < −0.24, HR2 < −0.10), and background sources (HR1 < −0.24, HR2 > −0.10; see Table 3 of Jenkins et al. 2005 for more details). If we combine the “absorbed” and “XRB” categories into a single “XRB” category, as in SRW06, then 9 out of 15 sources fall in the XRB category. The remaining six sources are soft, and one of them, T10, falls under the SNR category.

Five transient sources were detected in the 2001 Chandra observation and we classified them using the color classification scheme of Kilgard et al. (2005), adjusted for Chandra data (see Table 2 of Kilgard et al. 2005 for more details). The

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1 http://xmmssc-www.star.le.ac.uk/Catalogue/3XMM-DR4/
2 http://xmmssc-www.star.le.ac.uk/Catalogue/2XMM/
UserGuide_xmmcat.html

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Table 2

| Src No. | Catalog No. | ObsID | R.A. (h:m:s) | decl. (°:′:″) | r_{ex} (arcsec) | Extr. Rad (arcsec) | Net Counts | Ratio | TC/PTC |
|---------|-------------|-------|-------------|--------------|----------------|-------------------|------------|-------|--------|
| T1  | T1(JW15) | XMM3 | 00:14:46.81 | −39:11:23.48 | 0.54 | 14 | 2134 | 10.7 | TC |
| T2  | 75(SRW06) | XMM1 | 00:15:34.27 | −39:14:24.80 | 0.52 | 15 | 3609 | 95.5 | TC |
| T3  | 27(SRW06) | XMM2 | 00:14:35.45 | −39:11:32.20 | 1.50 | 13 | 66 | 1.3 | PTC |
| T4  | 30(SRW06) | XMM2 | 00:14:37.18 | −39:11:22.00 | 2.26 | 14 | 69 | 1.1 | PTC |
| T5  | 37(SRW06) | XMM2 | 00:14:43.74 | −39:12:41.50 | 1.49 | 12 | 73 | 1.3 | PTC |
| T6  | 44(SRW06) | XMM1 | 00:14:52.68 | −39:12:23.90 | 1.26 | 20 | 103 | 4.1 | PTC |
| T7  | … | XMM3 | 00:14:54.86 | −39:14:16.97 | 1.79 | 20 | 87 | 1.0 | PTC |
| T8  | 51(SRW06) | XMM1 | 00:15:00.62 | −39:12:16.40 | 1.16 | 14 | 95 | 1.8 | PTC |
| T9  | 53(SRW06) | XMM2 | 00:15:03.79 | −39:14:59.80 | 1.52 | 15 | 45 | 6.5 | TC |
| T10 | … | XMM3 | 00:15:13.74 | −39:13:27.12 | 1.65 | 15 | 154 | 1.6 | PTC |
| T11 | … | XMM3 | 00:15:21.64 | −39:16:12.46 | 2.16 | 13 | 105 | 1.7 | PTC |
| T12 | … | XMM3 | 00:15:43.89 | −39:17:55.22 | 0.96 | 15 | 136 | 5.9 | TC |
| T13 | … | XMM3 | 00:15:52.85 | −39:16:34.39 | 1.81 | 20 | 94 | 5.0 | TC |
| T14 | … | XMM3 | 00:16:11.32 | −39:16:37.05 | 1.20 | 15 | 188 | 5.8 | TC |
| T15 | 122(SRW06) | XMM1 | 00:16:19.34 | −39:16:45.50 | 2.61 | 15 | 57 | 3.9 | PTC |

Note. (1) Source number used in this paper; (2) source identification number in JW15 and SRW06; (3) observation ID in which the source was detected; (4)–(5) right ascension (R.A.) and declination (decl.) of each source (J2000.0); (6) 1σ positional uncertainty of the source; (7) extraction radius; (8) net counts from the EPIC-PN and MOS in 0.3–8 keV; (9) luminosity ratio; (10) source classification as TC or PTC (see text for details).
obtained HRs for these sources are consistent with those from the XMM-Newton observations.

The HR–luminosity diagram (hardness–intensity proxy) of the TCS/PTCs detected in NGC 55 is given in Figure 1. From the figure, it is clear that the majority of the TCS/PTCs have color consistent with those of the persistent XRBs in the D_{25} region of the galaxy. For six source, their HR values are softer than the persistent XRB population, and their X-ray luminosities are lower compared to the other transient candidates, which suggest that they are the soft source population in this galaxy.

For the transient sources T1 and T2, we extracted the background-subtracted light curve based on the combined EPIC-PN and MOS camera over the 0.3–8 keV energy range. We investigated the short-term X-ray variability by performing a Kolmogorov–Smirnov (K–S) test on the light curves binned with 800, 300, and 100 s. From the K–S test, we found that these sources showed strong short-term X-ray variability at a confidence level of >99.99%.

### 3.3. Spectral Analysis

X-ray spectra of the transient sources within the D_{25} region of NGC 55 were extracted in the 0.3–8 keV band, using a circular extraction aperture with radius ranges from 12 to 20 arcsec. The different extraction radii were used to avoid contamination from nearby sources in the crowded region. Background spectra were extracted from nearby source-free regions, with the same aperture radius. We used the SAS task ESPECGET to obtain source and background spectra together with the ancillary response file (ARF) and redistribution matrix file (RMF) required in the spectral analysis. We binned the data to a minimum of 20 counts per bin and in many cases χ^2 minimization was used to fit the data. In other cases, where there were no sufficient spectral counts, the Cash Statistic (Cash 1979) was used for spectral fitting. Because the Cash Statistic does not provide a goodness-of-fit measure like χ^2, we additionally performed 5000 Monte Carlo simulations of each spectrum using the Goodness task (Arnaud 1996) to evaluate the quality of the fit for the Cash Statistic. The fit is considered to be acceptable, if the “goodness” is ≤50%. For χ^2 statistics, we used the null hypothesis probability to check the quality. The spectra were fitted in the xspec version 12.8.1 g (Arnaud 1996). The unabsorbed fluxes were derived using the convolution model CFLUX of xspec and the X-ray luminosities were estimated by assuming a distance of 1.78 Mpc (Karachentsev et al. 2003). All errors quoted were computed at a 90% confidence level.

We initially fitted both the EPIC-PN and MOS spectra simultaneously using single-component models such as power law (PL) and multicolor disk blackbody (DISKBB). In all cases, the preferred model is the model with the lowest χ^2 / dof. However, favoring the spectral models for the low counting statistics sources is difficult, and hence we report only the absorbed power-law model parameters for these sources. An intervening absorption column (TBABS) was also applied to each model, which includes the Galactic column density toward NGC 55. If the best-fit value of N_H was below the Galactic absorption, then we froze N_H to the Galactic value, 1.72 × 10^{20} cm^{-2} (Dickey & Lockman 1990). The spectral fitting results are summarized in Table 4. For the majority (13 out of 15 sources) of the sources, a power law provides a marginally or significantly better fit than a disk blackbody model.

### Table 3: Hardness Ratios and Luminosities of Transient Candidates

| Src No. | ObsID | HR1    | HR2    | Class | I_X |
|--------|-------|--------|--------|-------|-----|
| T1     | XMM3  | 0.55 ± 0.03 | −0.37 ± 0.02 | XRB   | 37.76±0.03|
| T2     | XMM1  | 0.31 ± 0.01 | −0.09 ± 0.01 | XRB   | 38.22±0.02|
| C-2255 | 0.54 ± 0.01 | −0.06 ± 0.01 | XRB   | 38.23±0.03|
| T3     | XMM2  | −0.78 ± 0.30 | 0.27 ± 0.93 | SOFT  | 36.42±0.30|
| T4     | XMM2  | −0.70 ± 0.26 | −0.17 ± 0.29 | SOFT  | 36.16±0.35|
| T5     | XMM2  | 0.66 ± 0.35 | −0.31 ± 0.09 | ABS   | 36.52±0.11|
| C-2255 | 0.55 ± 0.11 | −0.31 ± 0.07 | XRB   | 36.55±0.18|
| T6     | XMM1  | 0.76 ± 0.50 | −0.16 ± 0.05 | ABS   | 37.15±0.19|
|       |       | 0.91 ± 0.14 | −0.11 ± 0.02 | ABS   | 36.62±0.15|
| T7     | XMM3  | −0.68 ± 1.70 | 0.08 ± 1.59 | SOFT  | 36.10±0.14|
| T8     | XMM1  | 0.18 ± 0.07 | −0.13 ± 0.17 | XRB   | 36.94±0.20|
| C-2255 | 0.39 ± 0.09 | 0.30 ± 0.05 | XRB   | 36.79±0.13|
| T9     | XMM1  | −0.69 ± 0.30 | −0.33 ± 0.31 | SOFT  | 36.43±0.20|
| T10    | XMM3  | −0.51 ± 0.22 | −0.73 ± 1.26 | SNR   | 36.12±0.26|
| T11    | XMM3  | 0.61 ± 0.78 | 0.29 ± 0.12 | ABS   | 36.94±0.21|
| C-2255 | 0.64 ± 0.15 | 0.33 ± 0.07 | ABS   | 37.90±1.32|
| T12    | XMM3  | 0.14 ± 0.02 | −0.16 ± 0.03 | XRB   | 36.74±0.17|
| T13    | XMM3  | 0.56 ± 0.22 | 0.06 ± 0.01 | ABS   | 36.59±0.25|
| T14    | XMM3  | −0.74 ± 0.10 | −0.76 ± 0.43 | SOFT  | 36.42±0.12|
| T15    | XMM1  | 0.39 ± 0.25 | −0.30 ± 0.15 | XRB   | 36.70±0.20|

**Note.** (1) Source number; (2) observation ID, where C indicates the Chandra observation used in the analysis; (3)–(4) hardness ratios derived from the count rate (see Section 3.2); (5) nature of the source according to the classification scheme of Jenkins et al. (2005) and Kilgard et al. (2005); (6) unabsorbed 0.3–8 keV X-ray luminosity in units of erg s^{-1} derived from best-fit single-component model.
We estimated the upper limits on the count rates using the \textsc{eregsana} task in \textsc{sas} for the sources that were not detected in the \textit{XMM-Newton} observations. After accounting for the background, the 90% confidence upper limits in the 0.3–8 keV energy band were derived. Assuming for each source the best-fit spectral model derived from the observations with detection, the flux upper limits were also obtained.

Source T2 has 3009 and 1781 net counts detected in the \textit{XMM-Newton} and \textit{Chandra} observations, respectively. A single-component model, absorbed power law, provided an acceptable fit (see Figure 2) with $\Gamma = 1.71 \pm 0.09$, $\chi^2$/dof = 183.5/150 for the \textit{XMM-Newton} and $\Gamma = 1.56 \pm 0.13$, $\chi^2$/dof = 77.1/70 for the \textit{Chandra} observations. The implied 0.3–8 keV luminosity from our best-fit model is $1.70^{+0.11}_{-0.10} \times 10^{38}$ erg s$^{-1}$. We also attempted a two-component model fitting, power law plus disk blackbody, for T2. The two-component model provided a marginal improvement to the spectral fit, with $\Delta \chi^2 \sim 4$ for two extra dof over the single-component fit. The best fit yielded a power-law index of $\Gamma = 1.79 \pm 0.15$ plus $0.14^{+0.09}_{-0.03}$ keV disk blackbody, absorbed by (0.36 $\pm$ 0.16) $\times 10^{22}$ cm$^{-2}$, with $\chi^2$/dof = 179.8/148 and the unabsorbed luminosity is $L_X = 2.74^{+3.15}_{-0.77} \times 10^{38}$ erg s$^{-1}$. The marginal improvement over the single-component fit indicates that the presence of the second component is tentative, and we do not have a good constraint on the flux contribution from the disk. The estimated disk blackbody

![Figure 2. \textit{XMM-Newton} EPIC-PN 0.3–8 keV spectrum of T2, fitted with an absorbed power-law model.](image)
component contribution to the total 0.3–8 keV source flux is <35%.

Barnard et al. (2014) successfully classified the X-ray transient sources in the galaxy M31 using the double thermal model (disk blackbody and blackbody), which was proposed by Lin et al. (2007) to examine the spectral evolution of transient LMXBs. Barnard et al. (2014) identified 36 BH candidates that exhibit apparent hard-state spectra with luminosities much higher than those for NS LMXBs. Using the double thermal model parameters, they found that none of the BH candidates occupied the NS LMXB region. We also tested the double thermal model for T2 and the spectral fit is not significantly improved ($\chi^2$/dof = 182.9/149, $\Delta\chi^2 \sim 1$ for one extra dof) over the absorbed power-law model, but the spectral parameters, $kT_{in} = 0.54 \pm 0.12$ keV, $kT_{BB} = 1.30^{+0.15}_{-0.13}$ keV, and $L_X(2–10$ keV$) = 1.2\times10^{37}$ erg s$^{-1}$, are consistent with the case of the BH candidates.

Seven sources (T5, T6, T8, T11, T12, T13, and T15) have spectra marginally well fit or well fit to the absorbed power law with $\Gamma \sim 1.6–2.4$ and the model luminosities are in the range of $\sim 3.3\times10^{36}$ erg s$^{-1}$. For the disk blackbody model, the inner disk temperature obtained ranges of $1.2–2.9$ keV for the sources T11, T12, and T13. In most cases, the values of $N_H$ obtained were higher than the Galactic foreground column density toward NGC 55. These spectral analyses suggest that these sources are consistent with being NS and BH binaries in either a hard state or a thermally dominated state (Remillard & McClintock 2006).

In Section 3.2, we found that the source T10 had HRs consistent with those of SNRs. We fit its spectrum with a thermal plasma model, APEC in XSPEC. The spectrum is best-fit by a thermal plasma temperature of $0.17^{+0.24}_{-0.21}$ keV, a solar metal abundance, and an absorption of $0.77^{+1.15}_{-0.51} \times 10^{22}$ cm$^{-2}$ ($\chi^2$/dof = 18.5/20). The estimated unabsorbed 0.5–2 keV X-ray luminosity is $3.3\times10^{37}$ erg s$^{-1}$. We also tried the blackbody (Bbody) model for this source and the obtained parameters are given in Table 5.

The sources that are classified as soft sources by the HRs (T3, T4, T7, T9, and T14) have spectra favored by the power-law model as well as the disk blackbody model. In all cases, the power-law model fits yielded steep power-law indices ($\Gamma \sim 3.4–5.6$), reflecting the soft nature of the emission. Moreover, the inner disk temperature of these sources obtained from the disk blackbody model fits are much softer ($kT_{in} \sim 0.1–0.12$ keV) than those of typically observed Galactic XRBs ($kT_{in} \sim 0.7–2$ keV). For these sources, we tested the Bbody model, and the spectral parameters are given in Table 5. The spectral fits obtained from the Bbody model are very similar to the power law or disk blackbody, except for T14. For T14, the Bbody fit is worse compared to the power law (see Figure 3). The temperatures yielded from the Bbody model for these sources are in the range of $\sim 50–180$ eV, consistent with that of SSSs, and the X-ray luminosities are $\sim 10^{36}$ erg s$^{-1}$.

We note that among the 154 X-ray sources in NGC 55 identified by BWF15, five sources (T2, T5, T6, T8 and T11) of ours were also listed. The rest of the transient sources were not included in BWF15 and half of them were detected in the 2010 XMM-Newton observation. We compared the results of these five sources with BWF15 and their hardness ratio classification are consistent with our results. They have studied the spectral properties of X-ray sources with $>50$ net counts from Chandra data and only one source (T2) is listed in our transient catalog. Their best-fit model for this source is an absorbed power law and the best-fit parameters are $N_H = 0.15 \pm 0.06 \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.5 \pm 0.1$ (the unabsorbed $L_X$ in 0.3–8 keV band is $\sim 2 \times 10^{38}$ erg s$^{-1}$), consistent with that of ours. They have identified long-term variations for four sources listed in this work (T2, T5, T6 and T11) from Chandra and XMM-Newton observations, which are confirmed by our analysis presented here.

### 3.4. Optical Analysis and Comparison with Multi-wavelength Catalogs

The transient sources were cross-correlated with the multi-wavelength catalogs available in the NED$^3$, VizieR$^4$, and SIMBAD$^5$ data bases. We searched these catalogs for matches within the 3$\sigma$ error radius of each XMM-Newton position. Of the 15 transient sources, source T15 positionally coincides with a galaxy, LCRS B001349.4-393325 (Shectman et al. 1996), and is likely a background AGN (SRW06). BWF15 reported the counterpart for T2 and T11 from the GALEX GR6 data release. However, these GALEX sources are not in the 3$\sigma$ error circles of the XMM-Newton positions we have derived, and hence we do not consider them to be associated with any of the X-ray sources.

We searched possible counterparts for the transient sources in the HST observations. Out of the 15 TCS/PTCs sources, 7 are covered in the fields of view of HST. For all of these sources, the source region is crowded and the XMM-Newton error circle itself contains multiple optical sources. The HST fields are shown in Figure 4. We computed the magnitudes of sufficiently bright sources in each error circle using the DAOPHOT (Stetson 1987) package in IRAF in F814W ($I$) and F606W ($V$) bands. The magnitudes and colors, not corrected for reddening, of the brightest objects are given in Table 6. The absolute $V$ magnitudes and $V – I$ colors of the optical sources have values of $\sim [–0.2, –0.5]$ and $\sim [–0.8, 1.5]$, respectively, which are broadly consistent with blue/red bright giants or supergiants, or with background AGNs. We also estimated the logarithmic X-ray-to-optical flux ratio log($f_x/f_o$), where $f_x$ is the 0.3–8 keV flux and $f_o$ is the F606W flux.

In addition to the HRs and X-ray spectral fitting, we added the X-ray-to-optical flux ratios and multi-wavelength information to characterize the possible nature of the transient sources. Table 6 summarizes the X-ray, optical, and multi-wavelength

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**Table 5**

| Src No. | $N_H$ | $kT$ | $\log L_X$ | $\chi^2$/dof | $G$ |
|---------|-------|------|------------|-------------|-----|
| T3      | 1.72(f) | 120±34 | 36.17±0.22 | 4.9/6 | 13% |
| T4      | 1.72(f) | 170±45  | 36.08±0.17 | 4.4/7 | 6%  |
| T7      | 1.72(f) | 78±24   | 36.08±0.13 | 31.4/25 | 0.18 |
| T9      | 1.72(f) | 50±26   | 36.41±0.24 | 6.2/11 | 2%  |
| T14     | 1.72(f) | 90±27   | 36.31±0.14 | 17.5/10 | 0.06 |
| T10     | 1.72(f) | 229±40  | 35.83±0.27 | 18.0/21 | 0.65 |

Note: (1) Source number; (2) absorption column density in $10^{20}$ cm$^{-2}$; (3) black body temperature in eV; (4) logarithmic unabsorbed 0.3–8 keV X-ray luminosity in erg s$^{-1}$; (5) the $\chi^2$/dof values for the model; (6) goodness of fit.

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3 http://ned.ipac.caltech.edu/
4 http://vizier.u-strasbg.fr/viz-bin/VizieR/
5 http://simbad.u-strasbg.fr/simbad/
observations available for each of the transient sources. Stars exhibit a wide range of flux ratio values, but typically $\log(f_{\text{opt}}/f_{\text{X}}) < 0$. For AGNs and BL Lac objects, their flux ratios are $>1$ (Maccacaro et al. 1982; Stocke et al. 1991). Moreover, the known accreting X-ray pulsars and HMXBs in the Small Magellanic Cloud (SMC) have a flux ratio of $\lesssim 1$ with $B - V \lesssim 0$ (McGowan et al. 2008). If one of the optical sources in an error circle is the counterpart, then the flux ratios would suggest that T1 and T2 are an AGN, and the rest of them are possible HMXBs. However, T1 exhibited outburst activity where accretion might occur only during certain parts of an orbit, which could fit with a high-mass donor star. Moreover, the colors of the optical sources in its error circle are not very blue in nature. If one of them is the counterpart of T1, then it is more consistent with those of types A or F bright giant stars. Source T2 also has a possible blue optical counterpart. BWF15 classified this source as an LMXB from their analysis using color–magnitude diagrams, X-ray color–magnitude diagrams, and the X-ray-to-optical flux ratio. Therefore, the optical data suggest that most of them are HMXBs, and for T1 and T2 their overall properties favor XRB nature.

4. DISCUSSION

4.1. BH and NS Candidates

In addition to T1, which has been identified as a candidate BH XRB (JW15), T2 is another bright source and was detected in the XMM1, XMM2, and 2001 Chandra observations. However, it completely disappeared in the long 127 ks XMM-Newton observation. The analysis showed that T2 changed its luminosity by at least two orders of magnitude from $\sim 10^{38}$ to $< 10^{36}$ erg s$^{-1}$. The HRs derived from the XMM-Newton and Chandra observations classified this source as an XRB system and it exhibited strong short-term variability in these observations. The spectrum of T2 is better described by an absorbed power law with $\Gamma \sim 1.7$, indicating that the source was likely in the hard state (Remillard & McClintock 2006). The hard state is observed in BH and NS LMXBs (van der Klis 1994) only at luminosities $\lesssim 10$% Eddington luminosity $L_{\text{Edd}}$ (Gladstone et al. 2007). Given its X-ray luminosity of $\sim 1.7 \times 10^{38}$ erg s$^{-1}$ in the 0.3–8 keV band, which is 90% $L_{\text{Edd}}$ for a 1.4 $M_e$ NS, we suggest that T2 is likely a BH XRB exhibiting hard-state behavior during an outburst in 2001.

The canonical model for BH XRB sources, namely, a combination of power-law and disk blackbody components, marginally improved the spectral fit for T2. The resulting inner disk temperature is unusually low ($\sim 0.14$ keV) indicating the presence of a cooler disk, which accounts for $< 35$% of the total observed X-ray flux. However, the $\Delta \chi^2 \sim 4$ improvement for T2, for two extra dofs was not significant. Hence, the presence of the soft component is tentative. Spectral modeling with double thermal components also marginally improves the fit compared to the single-component model. For such a case, the analysis still suggests a BH system, since the disk blackbody temperature and 2–10 keV disk blackbody luminosity of T2 do not fall in the NS LMXB parameter space.

Six sources (T5, T6, T8, T11, T12, and T13) are likely to be in either a hard state or a thermally dominated state. The X-ray luminosities of all these sources are $\lesssim 10$% Eddington luminosity for either NS or BH primaries. This low accretion is observed in NS and BH XRBs in the hard state and suggests that the accretors of these binaries may be NSs or BHs. However, there is no significant difference in the spectral fits, and hence we cannot rule out a thermally dominated state from...
these low-quality data. These sources could be NSs or BH XRBs, and deeper observations are required for further classification.

4.2. Super Soft Sources

SSSs are classically defined as X-ray sources with temperatures \( \sim 100 \text{ eV} \) (Di Stefano & Kong 2003) and typical X-ray luminosities between \( \sim 10^{36} \) and \( 10^{38} \text{ erg s}^{-1} \). The steady nuclear burning of matter accreted onto the surface of a white dwarf (van den Heuvel et al. 1992) seems to be the most promising explanation for the majority of these sources. SRW06 identified seven SSSs, which is one-sixth of the total X-ray population in NGC 55. We identified five transient sources, which are soft sources based on their HRs. Their soft emission is modeled by a simple absorbed blackbody with temperatures of \( \sim 50-180 \text{ eV} \). The cool emission indicates that these sources are most likely WD systems. The HRs of three sources are consistent with those of “typical” SSSs. Due to the given transient nature of these sources, they are likely to be classical novae which are identified as the major class of SSSs in the galaxies M31 and M33 (Pietsch et al. 2005). The X-ray emission from these systems arises due to the episodic thermonuclear burning of matter on the surface of the WDs, which leads to the transient nature (Pietsch et al. 2007).

We found that only one source (T10) had HRs consistent with those of SNRs, although the uncertainties on the HRs, particularly on HR2, are quite large. If we consider the thermal plasma model as a “standard SNR” model, then the best-fit plasma temperature of \( \sim 0.2 \text{ keV} \) is lower than that of the SNR candidates in M33 and the unabsorbed 0.5–2 keV luminosity is higher than the luminosities observed for the SNRs in M33 (Long et al. 2010). The blackbody fit instead provided a meaningful result, with temperatures \( kT \sim 230 \text{ eV} \) consistent with QSSs. The emission from QSSs is too hot to be from WDs and the alternative physical systems include NS or BH binaries (Di Stefano et al. 2010) and SNRs (Orio 2006).

4.3. Possible Optical Counterparts

We searched the optical fields of seven transient sources that are available from HST observations, which provide constraints on their source types. Although each XMM-Newton source position contains multiple optical sources, if one of the sources is the counterpart, then the X-ray-to-optical flux ratios suggest most of the transients to be HMXBs, which is supported by the classification based on all of the available data. Further HST
observations of the fields can identify the true counterparts by detecting variables among the optical sources.

We also cross-correlated the sources with publicly available multi-wavelength catalogs. Three of them, T2, T11, and T15, have a counterpart identified in the multi-wavelength data, but the positions for the first two are not consistent with that from our XMM-Newton analysis. T15 could be either an NS or a BH XRB based on the spectral properties, but it is optically identified as a background AGN from multi-wavelength catalogs. SRW06 estimated 10–15 background objects in the D25 region of the galaxy. We note that some of the new sources identified in the long 127 ks observation have a color consistent with the absorbed color and they may be background objects. We estimated the number of background AGNs in the D25 region of NGC 55 using the log N−log S relation reported in Campana et al. (2001), and the chance probability for detecting a background AGN inside the D25 region is ∼26%.

4.4. Comparison to Other Galaxies

From the X-ray perspective, NGC 55 is a typical Magellanic-type dwarf galaxy with a structure similar to that of the LMC (de Vaucouleurs 1961). The X-ray properties of NGC 55 (SRW06), such as the total mass, neutral hydrogen mass, star formation rate (SFR), diffuse emission component, and discrete point-source luminosities, illustrate the striking similarity with other nearby Magellanic systems, NGC 4449 and LMC (Wang et al. 1991; Vogler & Pietsch 1997; Summers et al. 2003). The bright X-ray sources in these galaxies are spatially associated with star-forming regions and broadly follow the correlation between X-ray luminosity and SFR established for active systems (Ranalli et al. 2003).

The transient source population has been extensively studied in the Milky Way (Jain et al. 2001; Tombsick et al. 2005; McClintock & Remillard 2006, and many others), but relatively little work has been conducted on the extragalactic siblings. Due to their proximity, most extragalactic studies of transient sources concentrated on the Magellanic Clouds (MCs; Kahabka & Pietsch 1996; Cooke et al. 2001) and M31 (Williams et al. 2006 and references therein). A known population of transient sources in the MCs includes XRBs and SSSs (Kahabka et al. 2008; Haberl et al. 2012; Sturm et al. 2013). The sources identified as LMXB transients are rare in the Magellanic Clouds, but the SMC hosts a large number of high-mass X-ray binaries with possible B/Be-type companions (Kahabka & Pietsch 1996; Haberl & Pietsch 2004). Approximately 25–35 SSSs (including candidates) are observed in MCs, which are associated with magnetic cataclysmic variables, close binary SSSs (likely white dwarf and Be XRBs), and classical post-nova (Kahabka & Haberl 2006; Kahabka et al. 2006, 2008; Sturm et al. 2013), implying that the SSS population is an essential component in the Magellanic systems. Such an effort

| Src No. | HR Class | Variability | X-ray Spectrum | $M_V$ | $V - I$ | Range of $V - I$ | log($f_{X}/f_{V}$) | Multi-wavelength |
|--------|----------|-------------|----------------|-------|--------|-----------------|----------------|----------------|
| T1     | XRB      | LONG        | DISKBB         | −2.64 | 0.72(a)| [0.18, 0.72]    | [1.77, 2.06] (AGN) | ...            |
|        |          |             |                | −2.33 | 0.18(b)|                 |                 |                |
|        |          |             |                | −1.93 | 0.62(c)|                 |                 |                |
| T2     | XRB      | LONG        | PL             | −1.22 | 0.55(a)| [−0.82, 1.05]   | [2.79, 3.20] (AGN) | FUV? (BWF15) |
|        |          |             |                | −1.01 | −0.45(b)|                 |                 |                |
|        |          |             |                | −0.92 | 0.46(c)|                 |                 |                |
| T3     | SOFT     |             | ...            | −3.22 | −0.23(a)| [−0.23, 1.08]   | [0.18, 0.71] (HMXB) | ...            |
|        |          |             |                | −2.35 | 1.08(b)|                 |                 |                |
|        |          |             |                | −2.12 | 0.55(c)|                 |                 |                |
| T4     | SOFT     |             | ...            | −5.10 | 0.99(a)| [−0.40, 1.46]   | [−0.83, 0.55] (HMXB) | ...            |
|        |          |             |                | −3.86 | 0.48(b)|                 |                 |                |
|        |          |             |                | −3.68 | −0.38(c)|                 |                 |                |
| T5     | ABS      | LONG        | ...            | −3.45 | −0.15(a)| [−0.15, 1.04]   | [0.83, 1.49] (HMXB?) | ...            |
|        |          |             |                | −2.93 | 0.79(b)|                 |                 |                |
|        |          |             |                | −2.25 | 0.27(c)|                 |                 |                |
| T7     | SOFT     |             | BBODY          | −2.84 | 0.79(a)| [−0.10, 0.79]   | [0.86, 1.36] (HMXB?) | ...            |
|        |          |             |                | −2.40 | 0.09(b)|                 |                 |                |
|        |          |             |                | −2.37 | −0.10(c)|                 |                 |                |
| T8     | XRB      |             | ...            | −3.61 | 0.77(a)| [−0.19, 1.41]   | [−0.27, 0.58] (HMXB) | ...            |
|        |          |             |                | −3.36 | 0.79(b)|                 |                 |                |
|        |          |             |                | −3.30 | 1.16(c)|                 |                 |                |
| T11    | ABS      | LONG        | PL             | ...   | ...    | ...             | ...            | FUV? (BWF15) |
| T12    | XRB      |             | PL             | ...   | ...    | ...             | ...            | ...            |
| T13    | ABS      |             | PL             | ...   | ...    | ...             | ...            | ...            |
| T14    | SOFT     |             | PL             | ...   | ...    | ...             | ...            | ...            |
| T15    | XRB      |             | ...            | ...   | ...    | ...             | ...            | Optical (SRW06) |

Note. (1) Source number; (2) source classification based on the HRs; (3) observed X-ray variability; (4) best-fit X-ray spectral model when $\chi^2$ statistics are used; (5)–(6) the absolute $V$ magnitudes and $V − I$ colors of the brightest objects inside the XMM-Newton error circle and their labels are given in brackets; (7) range of $V − I$ color of the optical sources in the error circle; (8) range of logarithmic X-ray-to-optical flux ratio of the optical sources and the likely class given in bracket; (9) multi-wavelength information available from the literature (see the text for more details).
has not been undertaken for NGC 4449. In Table 7, we summarize the comparison of the transient properties of NGC 55 with MCs. Since MCs are frequent targets of many different X-ray observatories, a large number of transient sources were identified with luminosity ranges of \(10^{34} - 10^{35}\) erg s\(^{-1}\) compared to NGC 55. However, the fractions of transient types in NGC 55 differ by no more than a factor of three with MCs. The marginal difference in the fractions of transient types may be due to observational effects such as effective extinction and the luminosity threshold of the available observations. This difference could be better investigated through continuous monitoring observations of NGC 55, as is done for the MCs. The similarity in the transient and SSS populations, along with the X-ray properties of NGC 55 with other nearby Magellanic systems mentioned above, supports NGC 55 as a typical Magellanic system.

### 5. SUMMARY

We have presented a study of the transient X-ray source population in the Magellanic-type galaxy NGC 55. We analyzed the archival XMM-Newton and Chandra observations of NGC 55 and identified 15 candidate transient sources in the D\(_{25}\) region of the galaxy. Their X-ray luminosities are in the range \(10^{36}\) to \(10^{38}\) erg s\(^{-1}\). The high sensitivities of the archival observations indicate a flux change of 1–2 orders of magnitude for some of these sources. The X-ray colors of these sources suggest that the transient population is dominated by XRBs. We performed detailed spectral and timing analysis of the data for two bright transient X-ray sources in the D\(_{25}\) region of the galaxy. The strong short-term variability seen in the sources and their X-ray colors support speculation that their high X-ray luminosity arises from an XRB system with a BH as the primary accretor. Six sources have spectral properties consistent with NS and BH XRBs accreting at both normal and high accretion rate. The transient population also seems to contain a sizable SSS component, perhaps one-third of the detected transient sources. Their soft emission indicates that they are likely white dwarf binaries. Optical analysis of archival HST data provides constraints on the likely nature for the sources and most of them are possible HMXBs. The cross-correlation with multi-wavelength catalogs identified one source as a possible background object, which is classified optically as a galaxy. From the spectral analysis, a variety of properties have been determined revealing the heterogeneous nature of transient sources in NGC 55. Our study suggests that the Magellanic-type galaxies could be a potential factory of transients, and comparative studies with other Magellanic-type galaxies and continuous monitoring at X-ray (multi-wavebands will help us understand the physical nature of various types of high-energy objects that comprise the transient population.

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