A VARIABLE BLACK HOLE X-RAY SOURCE IN AN NGC 1399 GLOBULAR CLUSTER

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ABSTRACT

We have discovered an accreting black hole (BH) in a spectroscopically confirmed globular cluster (GC) in NGC 1399 through the monitoring of its X-ray activity. The source, with a peak luminosity of $L_X \simeq 2 \times 10^{39}$ erg s$^{-1}$, reveals an order of magnitude change in the count rate within $\pm 10$ ks in a Chandra observation. The BH resides in a metal-rich [Fe/H] $\simeq 0.2$ GC. After RZ 2109 in NGC 4472 this is only the second BH X-ray source in a GC confirmed via rapid X-ray variability. Unlike RZ 2109, the X-ray spectrum of this BH source did not change during the period of rapid variability. In addition to the short-term variability the source also exhibits long-term variability. After being bright for at least a decade since 1993, within a span of two years it became progressively fainter, and eventually undetectable, or marginally detectable, in deep Chandra and XMM-Newton observations. The source also became harder as it faded. The characteristics of the long-term variability in itself provide sufficient evidence to identify the source as a BH. The long-term decline in the luminosity of this object was likely not recognized in previous studies because the rapid variability within the bright epoch suppressed the average luminosity in that integration. The hardening of the spectrum accompanying the fading would also make this BH source indistinguishable from an accreting neutron star in some epochs. Therefore, some low-mass X-ray binaries identified as neutron-star accretors in snapshot studies of nearby galaxies may also be BHs. Thus, the discovery of the second confirmed BH in an extragalactic GC through rapid variability at the very least suggests that accreting BHs in GCs are not exceedingly rare occurrences.

Key words: galaxies: individual (NGC 1399) – galaxies: star clusters: general – X-rays: binaries

Online-only material: color figure

1. INTRODUCTION

The high spatial resolution of X-ray telescopes such as Chandra and XMM-Newton has led to the discovery of large populations of resolved X-ray sources around nearby galaxies. The vast majority of the point sources observed in elliptical galaxies are believed to be low-mass X-ray binaries (LMXBs). Recent studies have established that roughly 40% of these LMXBs are associated with globular clusters (GCs; e.g., Kundu et al. 2007; Sivakoff et al. 2007). This overabundance of LMXBs in GCs, that typically account for less than $\sim 0.1\%$ of the stellar mass of a galaxy, reflects the importance of stellar dynamical interactions in the dense inner regions of clusters that leads to the enhanced formation of close binaries.

This raises the interesting question of whether some of these LMXBs may be black hole (BH) accretors. There is much interest in BHs residing in GCs in part because it is often suggested that GCs are among the most likely hosts of intermediate-mass BHs. On the other hand, there have also been suggestions that most BHs are ejected from GCs due to dynamical processes (Sigurdsson & Hernquist 1993; Kulkarni et al. 1993).

One way to detect a BH in a GC is to search for a characteristic X-ray signature if the BH happens to be accreting from a nearby companion. So far no such accreting BHs have been observed in any of the GCs in the Milky Way. But Chandra and XMM-Newton observations have identified a number of GCs in nearby galaxies that host LMXBs that are brighter than the Eddington luminosity for an accreting neutron star (Angelini et al. 2001; Kundu et al. 2002; Kim et al. 2006). However, these bright sources may also represent the superposition of many neutron star LMXBs (e.g., Angelini et al. 2001; Kundu et al. 2007) in GCs. Detection of rapid X-ray variability in such sources may be the only definitive way to confirm a BH accretor with present instruments (e.g., Kalogera et al. 2004). We have previously discovered the first, and so far only, BH accretor in a GC through X-ray variability in RZ 2109, a GC in the bright Virgo cluster galaxy NGC 4472 (Maccarone et al. 2007; Shih et al. 2008; Zepf et al. 2008). Identification of a single such candidate leaves open many intriguing questions about the ubiquity of such systems. It is possible that the discovery of a BH in the GC RZ 2109 owes to an extraordinarily fortuitous set of circumstances. In this paper, we demonstrate the presence of a BH in a second extragalactic GC in NGC 1399 through variability in the X-ray flux of a luminous accretor in NGC 1399 is the giant elliptical galaxy at the center of the Fornax Cluster. It has a rich and well-studied GC system (e.g., Grillmair et al. 1999; Dirsch et al. 2003) with a bimodal GC metallicity distribution that is typical in such galaxies (e.g., Kundu & Whitmore 2001). Many joint optical and X-ray studies of NGC 1399 have showed that it has one of the highest fraction LMXBs associated with GCs of any galaxy studied to date. As in other galaxies metal-rich clusters are more likely to host LMXBs than metal-poor ones (Angelini et al. 2001; Kim et al.

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Table 1

| Date       | Observatory | Obs. ID | Instrument | Effective Exposure Time | Detection |
|------------|-------------|---------|------------|-------------------------|-----------|
| 2000 Jan 18| Chandra     | 319     | ACIS-S3    | 5594 s (bright: 9873 s; faint: 46070 s) | Yes |
| 2001 Jan 7 | XMM-Newton  | 0055140101\(^a\) | EPIC-MOS2 | 47080 s | Yes |
| 2001 Jun 27| XMM-Newton  | 0012830101 | EPIC-MOS2, PN | 10085 s | Yes |
| 2003 Feb 13| Chandra     | 2942    | ACIS-S3    | 29420 s | Yes |
| 2003 May 26| Chandra     | 4172    | ACIS-13    | 44503 s | Yes |
| 2005 Jul 30| XMM-Newton  | 0304940101 | EPIC-MOS2, PN | 20007 s | No |
| 2006 Aug 23| XMM-Newton  | 0400620101 | EPIC all\(^b\) | 73040 s | No |
| 2007 Dec 24| Chandra     | 9798    | ACIS-S3    | 18302 s | No |
| 2007 Dec 27| Chandra     | 9799    | ACIS-S3    | 21288 s | No |
| 2008 Jun 8 | Chandra     | 9530    | ACIS-S3    | 59348 s | Yes\(^c\) |

Notes.

\(^a\) 2XMM catalog (Watson et al. 2009).

\(^b\) MOS1, MOS2, and PN cameras.

\(^c\) The luminosity of this marginal detection is lower than the upper limits implied in previous non-detections, and is in the range of typical neutron star accretors. See the text for details.

NGC 1399 has been observed multiple times by both the Chandra and XMM-Newton observatories in the past decade (Table 1). This provides a unique opportunity to trace X-ray activity in LMXBs, and in particular those associated with GCs for the purpose of this study.

2. OBSERVATIONS AND RESULTS

2.1. X-rays

NGC 1399 has been observed multiple times by both the Chandra and XMM-Newton observatories in the past decade (Table 1). This provides a unique opportunity to trace X-ray activity in LMXBs, and in particular those associated with GCs for the purpose of this study.

We downloaded the archival Chandra and XMM-Newton data of NGC 1399 listed in Table 1 and processed it following standard data reduction guidelines using CIAO v4.0 and SAS v8.0, respectively. Intervals of high background were filtered out from the data, and all images were corrected for exposure and vignetting. We adopted the wavelet method of source detection to identify point sources.

We discovered that one of the candidate LMXBs observed during the course of Chandra observation 319 displayed rapid X-ray variability on the timescale of ~10 ks (Figure 1). A literature search reveals that this source has been observed by ROSAT–HRI multiple times between 1993 and 1997 and is also listed in the 2XMM catalog as 2XMM J033831.7−353058:042943 (Paolillo et al. 2002; Liu & Bregman 2005; Watson et al. 2009). This object was also identified in Kundu et al. (2007) as X-ray source number 157, CXOKMZJ033831.7−353058 (hereafter, the source). The 5.4 × 10\(^{38}\) erg s\(^{-1}\) X-ray luminosity derived using the average count rate of the source through the entire Chandra observation is brighter than the Eddington luminosity of an accreting neutron star (also see Section 2.4.1), suggesting that this may be a BH candidate. However, the source lies outside the Hubble Space Telescope (HST) image of the inner region analyzed in Kundu et al. (2007). Thus, we turn to other data sets to check whether this object is associated with a GC.

2.2. Optical Counterpart

We downloaded F606W band HST–ACS images of NGC 1399 from the archive (HST GO proposal 10129) and created an aligned mosaic of the nine independent pointings of the region around the galaxy. We used the Multidrizzle routine based on the drizzle code of Fruchter & Hook (2002) for this purpose, taking into account the small errors in the default header values. We aligned the HST mosaic to the USNO-A2.0 astrometric system (Monet et al. 1998). Next we identified the point sources corresponding to the spectroscopically confirmed GCs studied by Dirsch et al. (2004). The location of the GCs in the HST mosaic image was used to derive more secure positions for these objects. Finally, we spatially aligned the X-ray and optical images in the manner described in Maccarone et al. (2003). The rms of the optical and X-ray source matches was 0.′′2.

The variable X-ray source CXOKMZJ033831.7−353058 is coincident with the GC identified as 86:53.0 by Dirsch et al. (2004). The matching radius is only 0.′′3. It is located almost exactly 4.′′0 due south of NGC 1399 at R.A. = 03:38:31.7 and decl. = −35:30:59.21 (J2000). These coordinates are based on the location of the source in the HST image aligned to the USNO system. The host GC has a magnitude and color R = 22.02 ± 0.03 and C − R = 2.04 ± 0.09 (Dirsch et al. 2004). In the next few sections, we examine all the Chandra and XMM-Newton observations of NGC 1399 that covered the position of the source (Table 1).
2.3. Short-term Variability and Spectral Analysis

We created background-subtracted light curves from the observations in which the source can be detected. As the source is fairly isolated with no obvious X-ray emitters nearby we used an annular region surrounding the object with ∼1:1 area ratio to determine the background-subtracted count rate. Only the first data set, Chandra observation 319, revealed a rapid short-term variability (see Figure 1). The count rate declined by an order of magnitude during the first 10 ks. The source remained faint for the rest of the observation and showed no further evidence of measurable variability. To verify that the decline was not due to an instrumental effect we compared the light curves of other X-ray sources in the same CCD (ACIS-S3), and found no similar patterns. In the rest of this paper, we consider the first 9873 s of Chandra Obs. ID 319 in which the count rate of the is either high or declining the “bright” phase. The other 46,070 s during which the count rate is at a steady low level is referred to as the “faint” phase.

Spectroscopic analysis of the Chandra data was carried out using the Interactive Spectral Interpretation System (ISIS), version 1.4.9-55. Data were binned within ISIS into groups with signal to noise of at least 2.0, and all channels with at least this signal to noise within the range 0.3–8.0 keV were included in the fits. Due to the limited count rate we only attempted to fit two standard models which are commonly used to describe the continuum spectra of X-ray binaries, disk blackbody (DISKBB), and power-law (PO). The foreground absorption was fixed to the Galactic neutral hydrogen column density (nH) in the direction of NGC 1399, ∼1.31 × 10^20 cm^{-2} (Dickey & Lockman 1990).

The data were fit using the Gehrels statistic to define the errors (with the errors set to 1+√(N + 0.75), where N is the number of counts in the bin) on the individual bins, as this binning has been shown to provide more reliable fitting to bins with low count numbers. It was found that binning to the more standard signal to noise of 5.0 per bin led to too few channels for fitting and binned out real information in the data. The uncertainty estimates for all fits reflect 90% confidence limits.

The results of the spectral fitting of the bright and faint epochs of the Chandra 319 observations are summarized in Table 2 and plotted in Figure 2. Both the DISKBB and PO fits reveal a soft spectrum for both time periods, with the PO model providing a marginally better fit. This is consistent with a luminous X-ray binary in a very high state, where the PO component dominates the luminosity (Nowak 1995; McClintock & Remillard 2006). We note here that some of the inordinately large uncertainty estimates in the normalization of the DISKBB models, for these and other fits listed in Table 2, are correlated to the large errors in the temperature, but lead to consistent total luminosity.

There is no statistically significant difference between the spectral properties of the source in the two epochs. Using the PO model the X-ray flux of the source in the energy range of 0.3–8.0 keV is estimated to be 2.8 × 10^{-14} erg cm^{-2} s^{-1} in the bright phase and 2.8 × 10^{-15} in the faint phase. Adopting a distance of 20 Mpc (Tonry et al. 2001) this implies an isotropic luminosity of 1.3 × 10^{39} erg s^{-1} during the bright epoch and 1.3 × 10^{38} erg s^{-1} during the faint one. We note here that the average luminosity quoted in Kundu et al. (2007), and mentioned in Section 2.1 was calculated using fixed a spectral index Γ = 1.7 for all sources in NGC 1399 due to the difficulty of reliably measuring this parameter for many of the sources superimposed on the bright hot gas in the inner regions.

2.4. Long-term Variability

We searched for the source in all of the Chandra and XMM-Newton data sets listed in Table 1. The source was
detected in all observations through the middle of 2003 but appears to have subsequently turned off indicating long-term variability. The individual observations are briefly discussed below.

### 2.4.1. XMM-Newton Observation 0055140101

These XMM-Newton observations were taken one year after the Chandra 319 observations discussed above. The source is located on the edge of the XMM-Newton EPIC MOS2 image and is the basis for its detection and listing as 2XMM J033831.7−353058:042943 in the second XMM-Newton Serendipitous Source Catalogue (2XMM; Watson et al. 2009). The XMM-Newton observations were analyzed using standard data reduction guidelines using SAS v8.0. As in the Chandra analysis we used an annular region surrounding the object with ∼1:1 area ratio to account for the background.

We fit the XMM-Newton data of the source in XSPEC 11.0 using the Gehrels statistic, without binning channels. Within the uncertainties the spectral properties of the source are indistinguishable from the Chandra 319 observations (Table 2). The flux, \( F_X \approx 4.2 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) for the PO fit, is similar to the level of the bright phase of the Chandra 319 observations. Thus, the source regained its luminosity within a year of the short-term variability observed in the earlier Chandra data. This translates to an isotropic luminosity of \( L_X \simeq 2 \times 10^{39} \) erg s\(^{-1}\), which is slightly brighter than the estimate from the bright phase of Chandra Obs. ID 319, but consistent with previous ROSAT estimates (Liu & Bregman 2005). However, we note that the short timescale variation in Chandra Obs. ID 319 occurred at the very beginning of the observation leaving open the possibility that the source was in fact brighter immediately prior to this observation. Thus, we consider the \( L_X \simeq 2 \times 10^{39} \) erg s\(^{-1}\) luminosity from this XMM-Newton observation to be a fairer estimate of the peak brightness of this source.

### 2.4.2. XMM-Newton Observation 0012830101

The source was detected in the 10 ks XMM-Newton observations of NGC 1399 on 2001 June 27 (Obs. ID 0012830101). Given the short exposure and consequently low counts we do not attempt to fit the spectrum. The 2XMM flux of this source is estimated to be \( 4.1 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), which implies an isotropic luminosity of \( L_X \simeq 1.9 \times 10^{39} \) erg s\(^{-1}\). Thus, the source appears to have remained as bright as observed in the previous XMM-Newton observation obtained 6 months before.

### 2.4.3. Chandra Observation 2942

The source was in the field of view (FOV) of the Chandra ACIS observation of NGC 1404, taken roughly three years after the Chandra 319 observation. At this time, the spectrum was harder than at earlier epochs (Table 2). The X-ray flux in the 0.3–8.0 keV band from the PO fit is \( 1.9 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), a factor of ∼2 lower than the previous epoch. However, the harder spectrum and the \( kT \approx 0.9 \) keV estimate suggests that the source may have undergone a state transition to a high/soft state as observed in stellar mass BHs (Nowak 1995; McClintock & Remillard 2006) and may be better described by a DISKBB model. The flux estimate of \( F_X \simeq 1 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) from a DISKBB fit implies a luminosity of \( 4.8 \times 10^{38} \) erg s\(^{-1}\), and a factor of four decline in the brightness from the previous XMM-Newton epoch.

### 2.4.4. Chandra Observations 4172 and 4174

Both of these observations were part of the Fornax Cluster survey. The source was in the FOV of the Chandra ACIS I3 (4172) or I0 (4174) chips. Although it was detected at or near the location of the source, the measured count rate \( 0.3–8.0 \) keV estimate suggests that the source was fainter than \( 1.9 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) at this time. Thus, the luminosity of the source has dropped by another factor of two to \( 1.8 \times 10^{38} \) erg s\(^{-1}\) luminosity since the Chandra 2942 observation.

### 2.4.5. XMM-Newton Observations 0304940101 and 0400620101

The source is not detected in the XMM-Newton observations 0304940101 and 0400620101. Neither automated routines nor a careful visual inspection revealed any evidence of an object at or near the location of the source. The measured count rate at the position of the source is indistinguishable from that of the nearby background. Using the XMM-Newton FLIX tool we estimate an upper limit of \( 2.7 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) on 2005 July 30 and \( 1 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) on 2006 August 23. Thus, the source was fainter than \( L_X \lesssim 4.8 \times 10^{38} \) erg s\(^{-1}\) at this time.

### Table 2: Spectral Fitting Results and Flux Estimates

| Date       | Obs. ID/Epoch | \( kT_{\text{in}} \) (keV) | Norm. | \( \chi^2 \) | Unabsorbed Flux (erg cm\(^{-2}\) s\(^{-1}\)) |
|------------|---------------|-----------------------------|------|-------------|---------------------------------|
| 2000 Jan 18| Chandra 319 (bright) | 0.29±0.09 | 0.17±0.2 | 0.44 | 1.9 \times 10^{-14} |
| 2000 Jan 18| Chandra 319 (faint)  | 0.21±0.01 | 0.077±0.08 | 0.62 | 2.1 \times 10^{-15} |
| 2001 Jan 7 | XMM-Newton 0055140101 | 0.42±0.3 | 0.061±0.06 | 0.26 | 3.3 \times 10^{-14} |
| 2003 Feb 13| Chandra 2942     | 0.90±0.3 | 7.74±10\(^{19000} \times 10^{-4} \) | 0.66 | 1.0 \times 10^{-14} |

| Date       | Obs. ID/Epoch | \( \Gamma \)  | Norm. | \( \chi^2 \) | Unabsorbed Flux (erg cm\(^{-2}\) s\(^{-1}\)) |
|------------|---------------|-------------|------|-------------|---------------------------------|
| 2000 Jan 18| Chandra 319 (bright) | 2.42±0.07 | 5.81±2 \times 10^{-6} | 0.43 | 2.8 \times 10^{-14} |
| 2000 Jan 18| Chandra 319 (faint)  | 2.93±0.1  | 5.53±4 \times 10^{-7} | 0.31 | 2.8 \times 10^{-15} |
| 2001 Jan 7 | XMM-Newton 0055140101 | 2.47±0.9 | 8.91±4 \times 10^{-6} | 0.29 | 4.2 \times 10^{-14} |
| 2003 Feb 13| Chandra 2942     | 1.33±0.1  | 2.21±0 \times 10^{-6} | 0.60 | 1.9 \times 10^{-14} |
2.4.6. Chandra Observations 9798 and 9799

We also investigate the two Chandra observations 9798 and 9799 aimed at SN2007on. Since they were taken only three days apart, it makes sense to combine the results from the analyses of the two data sets to get one flux value/upper limit. The BH candidate is 4.9 off axis in these observations, but is undetected in both. We attempt to estimate an upper limit on the flux by determining how many photons are within 2" of its location. In observation 9798, we find four photons from 0.5 to 8.0 keV within that radius, with an expectation value of 0.96 ± 0.03 photons estimated by looking at an off-axis background region. In observation 9799, we find seven photons with an expectation value of 1.24 ± 0.03. The source is thus marginally detected when the two observations together are considered—there is only a 2 × 10^{-5} probability that 11 photons will be detected, given a background expectation value of 2.2 photons. However, if one considers the trials incurred by checking all positions on the ACIS-S3 chip the detection is not statistically significant.

One can also make an estimate of the upper limit to the luminosity of the source during these two observations, given that the source is marginally detected, with 11 photons seen in 40 ks. The 99% confidence level upper limit on the underlying count rate is then 20.5 photons, of which 18.3 would be expected to be source photons. This translates to a count rate of 4.6 × 10^{-4} photons s^{-1}. Assuming the spectrum was unchanged since the Chandra 2942 observations, this corresponds to a flux limit of 4.6 × 10^{-15} erg cm^{-2} s^{-1} and a luminosity upper limit L_X ≲ 2.2 × 10^{38} erg s^{-1}.

2.4.7. Chandra Observation 9530

The source was in the FOV of the Chandra 9530 observation of NGC 1399 obtained on 2008 June 8. No object is detected at the location of the source with the probability of false detection set to 10^{-16}. However, there is a marginal detection when the false source probability is relaxed to 10^{-4}. This yields 13 background-subtracted counts during the course of the 60 ks observation. Although it is insufficient to fit a spectrum, we can estimate the luminosity by comparing the count rate to previous Chandra observations. If the source had a soft spectrum similar to that observed on 2001 January 18 then scaling the count rate to the Chandra 319 observations yields a luminosity of L_X ≲ 4.1 × 10^{37} erg s^{-1}. If on the other hand it retained the harder spectral shape of the 2003 February 13 Chandra 2942 detection, scaling the count rate to that observation estimates a luminosity of L_X ≲ 4.8 × 10^{37} erg s^{-1}. Thus, irrespective of the details of the spectrum the source was L_X ≲ 4.8 × 10^{37} erg s^{-1} or fainter at this epoch. This is fainter than the upper limit of the luminosities derived from the previous observations in which the source was not detected, and confirms that it faded since the 2003 Chandra detection. We also note that a luminosity of L_X ≲ 4.8 × 10^{37} erg s^{-1} is typical of bright neutron star accretors. There is a high probability of such an object being associated with a high-mass, metal-rich GC such as the one being studied here (Kundu et al. 2007). Thus, the BH accretor itself may in fact be fainter than the luminosity estimated from the Chandra 9530 observation.

2.5. Discussion and Analysis

We have confirmed that the X-ray source previously identified as CXOMKZJ033831.7–353058 (Kundu et al. 2007) and 2XMM J033831.7–353058:042943 (Watson et al. 2009) is associated with the spectroscopically confirmed GC 86:53.0 (Dirsch et al. 2004) in NGC 1399. We have examined the X-ray activity of the source over a period of eight years using archival Chandra and XMM-Newton data.

Between 2000 January and 2003 February the X-ray luminosity of the source was above 10^{39} erg s^{-1}, based on an estimated distance of 20 Mpc to NGC 1399 (Tonry et al. 2001). Earlier ROSAT observations sampling various epochs between 1993 and 1997 estimated a similar luminosity of 2 × 10^{39} erg s^{-1} (Liu & Bregman 2005). This is well beyond the Eddington luminosity of spherical accretion onto a neutron star and places the source into the category of an ultra luminous X-ray source.

During the course of the first Chandra observation in this analysis (Obs. ID 319 in 2000 January) the source revealed a rapid short-term decline in the count rate within 10 ks, demonstrating that the source is not a superposition of multiple neutron star binaries and confirming that it is a BH. After RZ 2109 in NGC 4472 (Maccarone et al. 2007) this is only the second BH X-ray accretor positively identified through short-term variations in the count rate. Curiously both sources revealed a roughly fourfold decline in magnitude over similar time periods of ≲10 ks.

But the parallels appear to end there. The decline in the count rate in RZ 2109 was primarily in the soft X-ray band, indicating a change in the X-ray spectrum consistent with foreground absorption and not a variation in the inherent X-ray luminosity of the source (Shih et al. 2008). On the other hand, there is no statistical difference in the spectrum of CXOMKZJ033831.7–353058 between the bright and faint phases in the Chandra 319 observations (Table 2 and Figure 2). This suggests that either the luminosity of the source changed during the course of the Chandra 319 observation or that a portion of the X-ray emitting region was obscured by an eclipsing event.

The NGC 1399 BH also reveals long-term variability. Other than a portion of the Chandra Obs. ID 319 integration the sources remained brighter than 10^{39} erg s^{-1} from the 1993 ROSAT observations through the 2001 XMM-Newton observations. Thereafter it became progressively fainter. It was not detected in XMM-Newton and Chandra observations between 2005 and 2007. An L_X ≲ 4.8 × 10^{37} erg s^{-1} source was marginally detected in a deeper 2008 June 8 Chandra observation. However, such a luminosity is typical of bright neutron star accretors and there is a high probability of such an object being associated with the host GC of this source. The BH accretor itself may in fact be even fainter than L_X = 4.8 × 10^{37} erg s^{-1} at this point.

The Chandra 2942 observation from 2003 which showed the first clear evidence of a long-term decline in the luminosity has a spectral index of Γ = 1.3, considerably harder than the Γ = 2.4–2.9 spectrum at earlier epochs. This suggests that the source underwent a state transition from a very high state where the PO component dominates to a high/soft state where the emission is primarily thermal (Nowak 1995; McClintock & Remillard 2006). Such state changes accompanying luminosity variations in a GC BH points to some interesting issues about identifying and quantifying BHs in GCs.

BH candidates in nearby galaxies (and their GC systems) are identified on the basis of their higher luminosities and softer spectra as compared to NS accretors. However, the hardening of the spectrum of CXOMKZJ033831.7–353058 as it faded places both its luminosity and its spectrum in the range of typical neutron star LMXBs (L_X ≲ 10^{38} erg s^{-1}, Γ ≳ 1.7) in the latter epochs of our survey. Thus, an unrecognized fraction of the
LMXBs in GCs tagged as neutron star systems in snapshot observations of extragalactic systems are likely BH accretors. The long-term variability of CXOKMZJ033831.7−353058 itself provides strong evidence that the source is a BH. The source was consistent in the ultraluminous regime for at least a decade prior to 2003, before fading relatively rapidly within a span of less than two years. If this object were a superposition of multiple close to Eddington limited neutron star LMXBs it is highly unlikely that they would all conspire to change luminosity within such a short time period. Moreover, given the fact that this is similar to the light travel time across the core of a typical cluster (where neutron star LMXBs are expected to reside) the degree of coincidence required is even more unlikely. The fact that a confirmed X-ray bright BH system in a GC undergoes physical changes similar to those seen in stellar mass BHs in the Milky Way on the timescales of years is encouraging in terms of identifying and studying the demographics BHs in GCs. It indicates that BHs can be securely identified by monitoring on month-to-year scales without requiring fortuitous occurrences of short-term variations within a single observation.

There have been previous attempts to detect BHs in elliptical galaxies by such monitoring (e.g., Irwin 2006; Brassington et al. 2008). However, the only likely BHs identified using this technique (Fabbiano et al. 2006; Sivakoff et al. 2008) have been field sources that are not associated with GCs. It is particularly interesting that Irwin (2006) which studied NGC 1399 using a subset of this data set did not recognize the transient nature of CXOKMZJ033831.7−353058. The luminosity of the source varied by about an order of magnitude between the (bright phase of the) Chandra 319 observations and Chandra 4172 observations that bookend the Irwin (2006) analysis. This can likely be attributed1162465402855246724859263335552122201711102844365592276403660677485202342524212414350533357803202222170132497429273282736610532322536672475426902158343254499103253058. The luminosity of the source varied by about an order of magnitude between the (bright phase of the) Chandra 319 observations and Chandra 4172 observations that bookend the Irwin (2006) analysis. This can likely be attributed across the short-term variation in the first epoch which leads to an underestimate of the consistently higher luminosities observed over a decade. We note that the luminosity quoted in our own Kundu et al. (2007) study similarly underestimated the brightness of CXOKMZJ033831.7−353058 in the Chandra 319 integration for the same reason. Given that at least four accreting BH systems in elliptical galaxies (Fabbiano et al. 2006; Maccarone et al. 2007; Brassington et al. 2010; and this source) are known to show short-term X-ray flux variability (accompanied by spectral changes in some cases) this strongly argues that careful analysis of both short and long-term variations of potential BH candidates must be carried out in concert if more BHs are to be identified by this method.

Another feature of accreting BHs in GCs may be the presence of optical emission lines. The optical spectrum of RX 2109 reveals broad, ≈2000 km s−1 wide, bright [O III] emission associated with the BH (Zepf et al. 2008). Irwin et al. (2010) argue that another ultraluminous X-ray source in a GC in the inner region of NGC 1399 is a BH on the basis of a 75 km s−1 [O III] and [N II] lines. An optical spectrum of the host GC of our source taken with the SOAR optical telescope in 2009 shows no evidence of emission lines. A previous 2 hr Magellan/IMACS optical spectrum of this GC taken in 2006 November (J. Irwin 2010, private communication) also reveals no emission lines. However, we note, on the basis of our X-ray monitoring, that the X-ray source had faded considerably before either set of optical spectra were obtained.

The host GC of CXOKMZJ033831.7−353058 also differs from RX 2109 in NGC 4472 in important ways. While RX 2109 is a metal-poor cluster, 86:53.0 in NGC 1399 (Dirsch et al. 2004) has a color of C − R = 2.04 ± 0.09. This places it at the reddest, and hence the most metal-rich end of the metal-rich subpopulation of GCs (Dirsch et al. 2004). Based on the calibration of Lee et al. (2008) this translates to a supersolar metallicity of [Fe/H] ≃ 0.2 dex. RX 2109 is also one of the most luminous, and hence most massive GCs in NGC 4472. While 86:53.0 is also among the largest GCs in NGC 1399, unlike RX 2109 it is not at the tail end of the luminosity function. In quantitative terms RX 2109 is about 2.6 mag brighter than the peak of the GC luminosity function while 86:53.0 in NGC 1399 is only 1.3 mag brighter than the peak. In other words, 86:53.0 is about one-third the 2 × 106 M⊙ mass of RX 2109 (Zepf et al. 2008).

Our discovery of the second confirmed BH accretor in a GC on the basis of X-ray variability indicates that the discovery of RX 2109 in NGC 4472 was not due to a particularly fortuitous configuration in that system and provides encouraging evidence that more such BHs can be identified by monitoring the X-ray activity. Further studies of temporal variability of luminous X-ray sources in nearby galaxies are needed to establish reliable statistics on the ubiquity of BHs in GCs.

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