A new globular cluster black hole in NGC 4472

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ABSTRACT

We discuss CXOU 122941.0+075744, a new black hole candidate in a globular cluster in the elliptical galaxy NGC 4472. By comparing two Chandra observations of the galaxy, we find a source that varies by at least a factor of 4, and has a peak luminosity of at least $2 \times 10^{39}$ ergs/sec. As such, the source varies by significantly more than the Eddington luminosity for a single neutron star, and is a strong candidate for being a globular cluster black hole. The source’s X-ray spectrum also evolves in a manner consistent with what would be expected from a single accreting stellar mass black hole. We consider the properties of the host cluster of this source and the six other strong black hole X-ray binary candidates, and find that there is suggestive evidence that black hole X-ray binary formation is favored in bright and metal rich clusters, just as is the case for bright X-ray sources in general.

Key words: globular clusters: general – stellar dynamics – stars: binaries

1 INTRODUCTION

In recent years there has been a revolution in our understanding of black holes in globular clusters. Until the launches of Chandra and XMM-Newton, it had become widely, if not universally, accepted lore that stellar mass black holes could not exist in significant numbers in globular clusters. Spitzer (1969) considered a hypothetical star cluster whose stars had only two possible masses. He found that given a large mass ratio between the two components and a significant fraction of the stars in the more massive component, an instability would lead to severe mass segregation, such that the heavier stars would form a sub-cluster which would not be affected by the outer main cluster. This sub-cluster can then evaporate itself dynamically on a timescale much less than the Hubble time. The combination of theoretical work, plus the lack of observational evidence for stellar mass black holes in Milky Way globular clusters led to the suggestion that globular clusters should not, and did not, contain substantial populations of black holes. More recent theoretical work, however, has shown that substantial fractions of black holes can be retained in globular clusters (Mackey et al. 2007; Moody & Sigurdsson 2009). The finding that some black holes are retained should not be surprising given that the Spitzer instability requires that the ratio of the total mass in the heavy component to the total mass in the light component exceeds a critical value that is a function of the ratio of the masses; i.e. once a certain number of black holes are ejected, the Spitzer instability criterion is no longer satisfied.

In the early Chandra observations of elliptical galaxies, many sources were found with luminosities exceeding the Eddington luminosity of a single neutron star (e.g. Sarazin et al. 2000; Angelini et al. 2001). Nevertheless, there remained in those cases the possibility that the X-ray sources were not single black holes, but rather superpositions of several bright neutron stars; variability is needed to distinguish between the two possibilities (Kalogera et al. 2004). The discovery of strong variability from the $4.5 \times 10^{39}$ ergs/sec source, XMMU 122939.7+075333 in NGC 4472, by Maccarone et al. (2007) confirmed that, in at least one case, a source could not be explained as a superposition of Eddington-limited neutron stars, and thus had to be a black hole, or a highly beamed neutron star. The more recent discoveries of strong,
broad [O III] emission lines (Zepf et al. 2007; 2008) from this system ruled out the possibilities of substantial beaming (since the [O III] forbidden line emission, must come from an optically thin and hence isotropically emitting region – see e.g Gnedin et al. 2009). This result thus strongly supports a scenario with a $L_X > L_{\text{EDD}}$ system, in order to drive the strong outflows implied by the optical emission lines. The system is therefore likely to host a a stellar mass black hole accretor, rather than an intermediate mass black hole.

Recently, at least two other cases for black holes in globular clusters have been identified (Brassington et al. 2010; Shih et al., submitted to ApJ). Brassington et al. (2010) found evidence for a source in NGC 3379 near the Eddington luminosity for a stellar mass black hole, which varied by about 30% (with a $\Delta L$ larger than the Eddington luminosity for a neutron star), and with X-ray spectra consistent with the expectations for a stellar mass black hole in that luminosity range. Shih et al. (2010) report a more complicated pattern of source behavior – a source in NGC 1399 which has several epochs near or slightly above $L_X = 10^{39}$ ergs/sec, and variability of factors of several within an observation and a factor of $\sim 100$ on timescales of years. In neither case is there any evidence put forth to support the idea that these might be intermediate mass black holes. A different type of case has also been made for another black hole in a globular cluster in NGC 1399 on the basis of a high ($\sim 4 \times 10^{39}$ ergs/sec) X-ray luminosity and strong [O III] and [N II] emission lines (Irwin et al. 2010). While Irwin et al. (2010) argued for an interpretation favoring an intermediate mass black hole based on the soft X-ray spectrum and high luminosity, we note that there are alternative accretion disc models in which such a soft spectrum at a high luminosity can result from a mildly super-Eddington accretion flow (e.g. Soria et al. 2007; Gladstone et al. 2009).

Recently, there has also been a discovery of a very strong intermediate mass black hole candidate in the galaxy ESO243-49, which has an extremely high luminosity, of about $10^{42}$ ergs/sec (Farrell et al. 2009). The source also shows spectral state transitions at about $3 \times 10^{42}$ ergs/sec (Godet et al. 2009), which imply a black hole mass of about $10^4 M_\odot$ if they occur at the typical 2% of the Eddington luminosity (Maccarone 2003). Recently, the source has been found to have an optical counterpart whose flux is consistent with expectations of a bright globular cluster in ESO 243-49 (Soria et al. 2010), but the identification of the optical counterpart as a globular cluster remains highly insecure for the time being. We thus mention this source for completeness, but do not include it in any of the analysis of the properties of globular clusters hosting black hole candidates. In this paper, we present evidence for a fourth variability-confirmed globular cluster black hole (and fifth strong candidate), and discuss the properties of the global sample of strong globular cluster black hole candidates found to date.

2 DATA ANALYSIS

Chandra has observed NGC 4472 three times, and there exists a fourth field not aimed at NGC 4472 itself, but which includes our source of interest. Two of the observations of NGC 4472 were taken in 2000, one with ACIS-I on 19 March 2000, and the other with ACIS-S on 12 June 2000. The most recent was taken on 27 February 2010. The observation in which our source appears, but which was not an observation of NGC 4472 was taken 23 February 2008 as part of the AMUSE-Virgo project (see e.g. Gallo et al. 2008). We produced a catalog of X-ray sources using WAVDETECT (Freeman et al. 2002) after processing the data to remove high background time intervals.

We then used TOPCAT to combine the catalog of X-ray sources produced from this observation with both the catalog from the previous Chandra observations of NGC 4472 discussed in Kundu et al. (2002) and published in Maccarone et al. (2003 – MKZ03) and the optical catalog of globular clusters published in MKZ03. We searched the list of sources that matched globular clusters in the optical catalog for sources with luminosities above $5 \times 10^{39}$ ergs/sec. We then checked these sources for variability between the two epochs of long Chandra integrations. We identified one new variable source associated with globular cluster 28 of the catalog of MKZ03. This source, located at 12h29m41.0s +7°57′44″, about 2.7′ from the center of NGC 4472, was detected in 2001 by Chandra, but we did not report on its in KMZ02 or MKZ03 because the source fell on the ACIS-S2 chip, and those papers reported only sources on ACIS-S3.

We find a separation of 0.5″ between the X-ray position from the 2010 observations and the optical position from MKZ03. We test the chance superposition probability by making shifts to the positions of the X-ray sources by small amounts, the determining the number of matches closer than 0.65″, the separation beyond which Kundu et al. (2002) found there were few additional matches, indicating that most of the additional matches were likely to be chance superpositions. We restrict our estimate of the number of false matches to the region between 2.2 and 3.2 arcminutes from the center of the galaxy in order to ensure that the space density of optical clusters in the region searched is similar to that around CXOU 122941+075744, which is located 2.7″ from the center of NGC 4472. Within this region, there are 23 X-ray sources, and 343 optical clusters. Formally, the region subtends a solid angle of about 61000 square arcseconds, but about 1/5 of the region was not covered with the HST observations used for the comparisons. Regions matching an optical cluster within 0.65″ thus subsest to about 1% of the region. We thus estimate a 1% chance superposition probability for a given X-ray source with an optical globular cluster (even considering a 1″ matching radius would give a less than 3% probability of a chance superposition). The particular cluster with which this X-ray source matches is among the brightest 10% of the clusters in NGC 4472, which can be taken as additional support of the idea that the match is genuine, albeit in an a posteriori manner that is difficult to quantify.

2.1 Deep Chandra observations

Having identified a strong black hole candidate, we then produced X-ray spectra of the source using the specextract tool and light curves of the source using the dmextract tool on the two deep ACIS-S observations. The spectra were extracted with an 8 pixel radius, and an offset background region of 20 pixel radius. The channels in the source spectrum were then binned in groups of 20 or more photons. Spectral fitting was done in XSPEC 12.5.1 (see Arnaud 1996 for
a description of an earlier version of XSPEC\footnote{For a more up-to-date description of XSPEC, see \url{http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/}}. Rebinned channels including photons below 0.5 keV and above 8 keV are ignored, because the response matrix for Chandra is better calibrated within this energy range than outside of it. We report the 1σ errors on source parameters.

In observation 321, taken 12 June 2000, the cluster’s X-ray spectrum was well fitted ($\chi^2/\nu = 4.74/4$) with a disk blackbody model with foreground neutral hydrogen column density of $1.6 \times 10^{20} \text{cm}^{-2}$, $kT = 0.88_{-0.13}^{+0.16} \text{keV}$ and normalisation in XSPEC of $2.0_{-0.9}^{+1.6} \times 10^{-3}$, corresponding to a best-fitting inner disk radius of 72 km assuming a face-on disk and no spectral hardening correction (Mitsuda et al. 1984). The source flux from 0.5-8.0 keV is $2.2_{-0.9}^{+1.1} \times 10^{-14} \text{ergs/cm}^2/\text{sec}$. The best fitting value corresponds to a luminosity of $6.5 \times 10^{38} \text{ergs/sec}$ using a distance of 16 Mpc to NGC 4472, based on the distance to the Virgo Cluster in which it is contained (Macri et al. 1999).

In observation 11274, taken on 27 February 2010, the source spectrum was well fitted (i.e. $\chi^2/\nu=10.5/19$) with $kT = 1.52_{-0.13}^{+0.16} \text{keV}$ and normalization in XSPEC of $9.2_{-0.4}^{+3.0} \times 10^{-3}$, corresponding to a best-fitting inner disk radius of 34 km assuming a face-on disk and no spectral hardening correction. The source flux from 0.5-8.0 keV is $9.2_{-1.2}^{+0.8} \times 10^{-14} \text{ergs/cm}^2/\text{sec}$. The best fitting value corresponds to a luminosity of $2.7 \times 10^{39} \text{ergs/sec}$. The temperatures of the disk are thus different at nearly the 3σ level, and both spectra are consistent with standard phenomenology that the inner disk radius will vary little in high/soft states. The luminosity difference is significant at more than 4σ, and the 3σ lower limit to the luminosity difference is about $5 \times 10^{38} \text{ergs/sec}$, above the Eddington luminosity for a single neutron star. The Chandra spectra are shown in figure\footnote{http://ledas-www.star.le.ac.uk/flix/flix.html}.

We have also tried to fit power law models to the data. For observation 321, a power law model with the foreground $N_H$ gives an acceptable fit, with $\chi^2/\nu = 4.76/4$, with a power law index of $2.00_{-0.24}^{+0.24}$ and the 1σ confidence interval for the flux ranging from $2.3-3.4 \times 10^{-14} \text{ergs/sec/cm}^2$. The spectral shape is thus marginally consistent with expectations for a low/hard state, but the luminosity is well above the few percent of the Eddington luminosity in which hard states are typically found (Maccarone 2003). We thus favor the diskbb model fit as providing parameter values more likely to be indicative of the real physical state of the system, but we do note that the spectral fits do not distinguish between the two scenarios. For observation 11274, a power law model with the foreground $N_H$ is formally a good fit, with $\chi^2/\nu = 23/19$, but with a spectral index of $1.30 \pm 0.07$, considerably harder than is ever seen in a low hard state from a Galactic black hole X-ray binary. Since in the former case, the power law model provides a poor fit to the data, and in the latter case, the best fitting value of the power law index lies outside the range expected from phenomenology, there is a strong case to be made that the data are genuinely better explained with a strong thermal component than a pure power law spectrum.

2.2 Shallow Chandra observations

The two other Chandra observations of this field of view, observation 322 (made 19 March 2000), and observation 8095 (made 23 February 2008), have much shorter integration times. For CXOU 1229410+075744, observation 322 yields 40 counts in 10 kiloseconds with ACIS-I, and observation 8095 yields 24 counts in 5 kiloseconds with ACIS-S. Both observations yield flux levels of $\sim 5 \times 10^{38} \text{ergs/sec/cm}^2$. Because there are not enough counts for detailed spectral fitting, there is a considerable uncertainty on the counts-to-energy conversion. The Poisson errors are also substantial. As a result, it is difficult to determine whether the flux levels during the two short observations were higher or lower than those during the longer observations. The X-ray detections and upper limits are summarized in Table\footnote{http://xmm.esa.int/external/xmm_user_support/documentation/uhb/node17.htm}.

2.3 XMM-Newton observations

Two deep XMM-Newton observations of this source have been made as well. However, this source is close enough to the center of NGC 4472 that the diffuse gas emission significantly affects XMM’s sensitivity. The 2XMM catalog (Watson et al. 2009) reports a source 8” away from CXOU 1229410+075744, with a positional error of 4.47” at 12h29m40.49s, +7°57m47.1s on 5 June 2002. The source is given a quality flag (the SUM_FLAG parameter value) of 4, indicating that it is located within a region where spurious detections are likely, and that the source itself may be a spurious source. Formally, 4σ upper limits can be obtained from the FLIX tool\footnote{http://ledas-www.star.le.ac.uk/flix/flix.html} using data corresponding to the 2XMMi-DR3 data release. FLIX finds that the source was no brighter than about $7 \times 10^{38} \text{ergs/sec}$ on 5 June 2002, and $2 \times 10^{38} \text{ergs/sec}$ on 1 January 2004.

While the upper limits from FLIX appear to indicate that the source faded sometime after 2001, and re-brightened sometime between 2004 and 2008, we have also looked at the aperture photometry from the FLIX tool. We set the extraction region to 5”, in order to limit the effects of confusion from nearby gas emission and other point sources. We find that in the observations made on 1 January 2004, all three XMM instruments show a flux more than 3.8σ above background in the 0.2-12 keV band, with the most sensitive PN detection above 5σ. The flux within 5” is $1.9 \pm 0.3 \times 10^{-14} \text{ergs/sec in the EPIC-PN}, 2.1 \pm 0.6 \times 10^{-14} \text{ergs/sec in MOS1},$ and $3.0 \pm 0.6 \times 10^{-14} \text{ergs/sec in MOS2}$. The encircled energy fraction at 5” is about 40%\footnote{http://ledas-www.star.le.ac.uk/flix/flix.html}. Taking the aperture photometry at face value, we estimate that the source was at about $1 - 2 \times 10^{39} \text{ergs/sec}$. The aperture photometry from FLIX for the 5 June 2002 observation gives a flux level similar to that in the 1 January 2004 observation, but the source was only about 2σ above the background on 5 June 2002. We tentatively trust the aperture photometry results, in part because they indicate a more physically likely scenario - that the source did not change sharply in luminosity twice in less than a decade - but prefer a cautious approach regarding any conclusion sensitive to the results of the XMM analysis.
in both cases.

Figure 1. The spectra from the deep Chandra observations, showing that the strong variability is unambiguously detected, and that the ΔL is significantly larger than the Eddington luminosity of a single neutron star. The power law model plotted over the data in the figure on the left, and the disk blackbody model plotted over the data in the figure on the right. Observation 11274 is the upper curve.

2.4 Optical properties of the cluster

The cluster has V=21.77 and V−I = 1.34 (MKZ03). The object is spectroscopically confirmed to be a globular cluster (Zepf et al. 2000). Using the color-metallicity relation of Smits et al. (2006), the V-I color corresponds to a metallicity of [Fe/H]=+0.4. The cluster is thus at the metal rich end of the distribution of clusters, but is probably not quite as metal rich as suggested by the linear interpolation from Smits et al. (2006). We can also look at the ground-based optical photometry on this cluster. Imaging in BVR with the Mosaic camera on the NOAO-4m yielded V = 21.55, B−V = 0.85, V − R = 0.59 for the cluster (Rhode & Zepf 2001). found this cluster to have V = 21.55, B−V = 0.85, V − R = 0.59. The minor difference in V is likely mostly due to some combination of the slightly different bandpass for the HST V band filter than for ground-based Johnson filters and small differences in the aperture corrections needed for ground-based versus space-based photometry of mildly extended objects (e.g. Kundu 2008). The colors in both the HST data and ground-based data make this cluster among the 10% reddest clusters in NGC 4472. At the present time, there are not HST data deep enough to estimate either the core radius or the stellar interaction rate for this cluster.

| Date             | Observatory | Exposure | L_X (ergs/sec) |
|------------------|-------------|----------|---------------|
| 19 March 2000    | Chandra ACIS-I | 10 ksec | ∼ 5 × 10^{38} |
| 12 June 2000     | Chandra ACIS-S | 40 ksec | 6.5 × 10^{38} |
| 23 February 2008 | Chandra ACIS-S | 5 ksec  | ∼ 5 × 10^{38} |
| 27 February 2010 | Chandra ACIS-S | 40 ksec | 2.7 × 10^{39} |

Table 1. A summary of the Chandra observations of CXOU J1229410+075744. Because XMM’s angular resolution causes problems for sources this close to the center of the galaxy, and the results of the XMM analysis are ambiguous, we present the XMM results only in the text and not in the table. The two luminosities in the shorter Chandra observations are uncertain by a factor of ∼ 2 because the integrations were not long enough to allow for reliable spectral fitting, leaving the counts-to-energy conversion factor uncertain.

3 DISCUSSION

There are now five strong candidate globular cluster black holes. For three of these sources, the black hole nature has been confirmed by a change in luminosity by an amount in excess of the Eddington limit for a neutron star (M07; Brassington et al. 2010; Shih et al. 2010), while for the fourth, the source luminosity is in excess of 10^{39} ergs/sec, and the source shows peculiar optical emission lines (Irwin et al. 2010). It is interesting to note that two of these sources showed strong variability within a Chandra observation (Maccarone et al. 2007; Shih et al. 2010), while this source does not show such variability. This source, and the black hole candidate in NGC 3379, show behavior typical of stellar mass black hole X-ray binaries in the Galaxy, with no strong variability on timescales of hours, and with spectral shapes consistent with hot (i.e. K_B T ∼ 1 keV) disk blackbodies. If CXOU 1229410+075744 continues to rise in luminosity, it may eventually make a transition to an “ultraluminous” state, with a softer spectrum, and it would then be interesting to search its host cluster for optical emission lines.

The properties of the host clusters are listed in Table 2. We have checked what fraction of clusters in each galaxy are redder than the clusters containing strong black hole candidates, using the catalog used to estimate the colours of the cluster in question. Two of the clusters, NGC 4472B and NGC 1399B, are in the reddest 10% of clusters in their host galaxies (these clusters are bluer than only 72/928 and 39/575 of the clusters in the catalogs of MKZ03 and Dirsch et al. 2004). The NGC 3379 cluster which contains a variability-confirmed black hole candidate is bluer than only 22/61 clusters, and the cluster hosting NGC 1399A is bluer than only 129/554 clusters in the catalog of KMZ07. Only NGC 4472A is in a cluster bluer than the mean value.
A Kolomogorov-Smirnov test can be performed to determine whether the suggestive evidence that the metal rich clusters are more likely to contain black holes than the metal poor clusters is statistically significant. We take the fraction of clusters bluer than the BH-hosting clusters for each galaxy, and make a cumulative distribution of them, then compare with a uniform distribution. The largest difference between the two distributions is 0.44, with 5 objects, giving a null hypothesis probability of about 11% – the evidence is thus merely suggestive for metal rich clusters being more likely to contain black holes than metal poor clusters.

Two additional candidate globular cluster black holes have been suggested which do not exceed (or which only marginally exceed) the Eddington luminosity for a neutron star (Barnard et al. 2008; Barnard & Kolb 2009) – Bo 45 and Bo 144. These sources have X-ray spectra dominated by hard power law components (reasonably well-fit with $\Gamma \approx 1.5$ power laws), and X-ray luminosities which exceed the few percent of $L_{Edd}$ at which such states are normally seen, if the sources are neutron star accretors. The case for these objects being accreting black holes, while suggestive, is less secure than for the brighter systems discussed above. Both are redder in $r - i$ than the median clusters in M 31 (using the confirmed old cluster sample and SDSS photometry from Peacock et al. 2010). Adding them into the sample and performing a KS test gives a null hypothesis probability of 5% that the clusters hosting black holes are more metal rich than the cluster sample as a whole.

We can also test whether the clusters containing black hole candidates are more luminous than the cluster population as a whole. A slightly more complicated procedure must be used here. For NGC 1399A, 25/554 clusters are brighter; for the NGC 3379 BH source, 15/61 are brighter; for NGC 4472B, 92/928 are brighter. The other two clusters, NGC 1399B and NGC 4472A, are not covered by the HST catalogs. For these two clusters, we determine where their magnitudes fall in the HST catalogs, rather than comparing with the ground-based catalog. The ground-based catalog of NGC 1399 from Dirsch et al. (2004) is especially biased in luminosity, since it represents a spectroscopically selected sample of clusters. This sample is in C and R, so we use the metallicity-color conversions from Smits et al. to convert from R to I, so that the magnitude can be compared with the HST catalog for NGC 1399. We thus obtain an estimate of $I = 21.3$ for NGC 1399B, brighter than all but 89/554 clusters in the HST catalog. The NGC 4472 brightness is directly comparable to the existing HST catalog, and, the cluster is brighter than all but 25/928 of the NGC 4472 clusters. Applying the same sort of KS test as was done for color, a 2.8% null hypothesis probability results that the clusters are more luminous than the cluster population as a whole. There may be a slight bias in favor of this hypothesis, given that spectroscopic confirmation was obtained for most of these clusters before papers were published, and that in several cases, the spectra were already existing in the archives. Both of the M 31 clusters suspected to contain black holes are also considerably more massive than the mean for M 31.

It has already been well established that the clusters containing X-ray sources in general are more massive (Verbunt 1987) and redder than a randomly selected sample of clusters would be (see e.g. Silk & Arons 1975 for the first suggestion of this effect; Bellazzini et al. 1995 and Kundu et al. 2002 for the first strong observational evidence for it). In recent years, it has become clear that clusters with higher collision rates are more likely to have bright X-ray sources, even after accounting for the fact that such clusters are also more massive (e.g. Jordán et al. 2007; Peacock et al. 2009, 2010b). At the present time, there are not yet high enough quality data from HST to estimate King model parameters for these clusters, but obtaining such data would be of great interest. The same recent theoretical work that demonstrates that many globular clusters will retain substantial fractions of their stellar mass black holes also shows that the core radii of clusters with black holes can be enlarged (Mackey et al. 2007).

4 SUMMARY

We have reported the detection of a new globular cluster black hole candidate, confirmed to be a black hole rather than a collection of neutron stars by its strong variability. The source is the fifth object with this type of convincing evidence of its black hole nature. Even with this small population of objects, it now seems likely, but not conclusively demonstrable, that the formation of X-ray sources with black hole accretors is favored in red clusters, and it is clear that luminous globular clusters are more likely to host black hole accretors. Given the suggestions that black holes should have strong effects on the dynamical evolution of globular clusters, estimation of the King model parameters of these clusters would be especially valuable.

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REFERENCES

Angelini L., Loewenstein M., Mushotzky R., 2001, ApJ, 557L, 35
Arnaud, K.A., 1996, Astronomical Data Analysis Software and Systems V, eds. Jacoby G. and Barnes J., p17, ASP Conf. Series volume 101
Barnard R., Kolb U., 2009, MNRAS, 397L, 92
Barnard R., et al., 2008, ApJ, 689, 1215
Brassington N., et al., 2010, ApJ, in press,astro-ph/1003.3236
Brassington N., et al., 2008, ApJS, 179, 142
Dirsch B., Richtler T., Geisler D., Forte J.C., Bassino L.P., Gieren W.P., 2003, AJ, 125, 1908
Farrell S.A., Webb N.A., Barret D., Godet O., Rodrigues J.M., 2009, Nature, 460, 73
Freeman P.E., Kashyap V., Rosner R., Lamb D.W., 2002, ApJS, 138, 185
Gallo E., Treu T., Jacob J., Woo J.-H., Marshall P.J., Antonucci R., 2008, ApJ, 680, 154
Gladstone J.C., Roberts T.P., Done C., 2009, MNRAS, 397, 1836
| Source  | RA     | Dec    | $M_V$        | Color   | Metallicity | References                        |
|---------|--------|--------|--------------|---------|-------------|-----------------------------------|
| NGC 4472A | 12 29 39.7 | +7 53 33 | V=20.99      | $B-R = 1.06$ | -1.7        | Maccarone et al. 2007; RZ01      |
| NGC 4472B | 12 29 40.5 | +7 57 47 | V=21.77      | $V-I = 1.34$ | +0.5        | this paper; MKZ03                 |
| NGC 1399A | 3 38 31.8 | -35 26 04 | I=21.0       | B-I=2.25  | +0.5        | Irwin et al. 2010; Kundu et al. 2007 |
| NGC 1399B | 3 38 31.7 | -35 30 59.2 | R=22.02     | C-R=2.04  | +0.2        | Shih et al. 2010, in submission; Dirsch et al. 2004 |
| NGC 3379  | 10 47 52.7 | +12 33 38.0 | V=21.88      | V-I=1.13  | -0.5        | Brassington et al. 2008, 2010; Kundu et al. 2007 |

Table 2. The strong candidates for being globular cluster black holes. The metallicities in the table are the color-metallicity relation of Lee et al. for the NGC 1399 source, and the relations of Smits et al. (2006) for the other sources. The extreme red colors of NGC 4472B and the NGC 1399 source may take them outside the range where the linear metallicity-color correlations are most reliable, but it is clear that these are among the reddest and hence most metal rich clusters in their respective systems.