SUPERSOFT AND QUASISOFT X-RAY SOURCES IN THE GLOBULAR CLUSTERS OF NGC 4472: ARE THEY CANDIDATES FOR INTERMEDIATE-MASS BLACK HOLES?

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ABSTRACT

We report on possible associations between 6 globular clusters in the Virgo elliptical galaxy NGC 4472 (M49) and bright ($L_x > 10^{38}$ erg s$^{-1}$) very soft X-ray sources (VSSs). Two of the VSSs have broad-band spectral properties consistent with those of luminous supersoft X-ray sources (SSSs). The other VSSs are somewhat harder, possibly with values of $kT$ between roughly 150 eV and 250 eV. These sources may be too hot to be explained by the white dwarf models so promising for SSSs; they are members of the newly-established class of quasisoft sources (QSSs). We examine white dwarf, neutron star, and black hole models for the VSSs. One of the SSSs is hot and bright enough to be a possible progenitor of a Type Ia supernova, while the most natural model for the other VSSs is one in which the accretors are intermediate-mass black holes. Whatever their physical natures, these are unlike any X-ray sources in Galactic globular clusters. No Galactic globular cluster houses a quasisoft source and only one, M3, contains a dim ($L_x \sim 10^{36}$ erg s$^{-1}$) transient SSS.

Subject headings: black hole physics — galaxies: clusters — galaxies: individual (NGC4472) — globular clusters: general — X-rays: binaries — X-rays: galaxies

1. INTRODUCTION

1.1. Very Soft X-Ray Sources

Very soft X-ray sources (VSSs) were observed by the Einstein X-ray Observatory in the Magellanic Clouds (MCs; Long, Helfand, & Grabelsky 1981; Seward & Mitchell 1981). When ROSAT’s All Sky Survey discovered roughly 30 such soft X-ray, sources in the MCs, M31, and in the Galaxy, the class of luminous supersoft X-ray sources (SSSs) was established. (See Trümper et al. 1991, Supper et al 1997, and references in Greiner 2000.) The luminosities of the first SSSs to be discovered were in the range from $10^{37}$ ergs s$^{-1}$ to a few times $10^{38}$ ergs s$^{-1}$, with $kT$ in the range of tens of eV. With the advent of Chandra and XMM-Newton, the study of SSSs can be extended to more distant galaxies. We have therefore developed a systematic method to select soft sources from the pool of all X-ray sources detected by either Chandra or XMM-Newton in an external galaxy (Di Stefano & Kong 2003 a, b, c). We have applied this algorithm to M31 (Di Stefano et al. 2003 a); M104 (Di Stefano et al. 2003 b); NGC 300 (Kong & Di Stefano 2003); M101, M83, M51, NGC 4697 (Di Stefano & Kong 2003 c); and NGC 4472 (Friedman et al. 2002). We find that the algorithm selects not only SSSs, but also members of a new class of sources which have been dubbed quasisoft sources (QSSs). QSSs are luminous ($L_x$ typically $> 10^{36}$ erg s$^{-1}$) sources that appear to be slightly harder (150–250 eV) than SSSs, yet soft enough that their emission falls off at energies well below the energies characteristic of canonical X-ray binaries. We use the term VSS for any source that is either supersoft or quasisoft.

1.1.1. Models for Supersoft Sources

The measured values of $L$ and $T$ suggest white dwarf (WD) models. Indeed, almost half of the local SSSs with optical IDs are systems housing a hot WD or pre-WD (e.g., recent novae, symbiotics, planetary nebulae). (See Greiner’s [2000] SSS Catalogue.) Perhaps the most promising model for the remaining 9 SSSs with optical IDs is one in which a Roche-lobe-filling companion donates mass to a WD at rates high enough to allow quasi-steady nuclear burning (van den Heuvel et al. 1992; Rappaport Di Stefano & Smith 1994). Matter which is burned can increase the mass of the WD, potentially leading to a Type Ia supernova explosion. Nevertheless, neutron star (NS) models are not excluded (Kylafis & Xilouris 1993), and there have been suggestions that some of the local SSSs may be accreting stellar-mass black holes (BHs; Cowley, Schmidtke, Crampton, & Hutchings 1990, 1998; Hutchings, Crampton, Cowley, & Schmidtke 1998).

In external galaxies we can study the positions of SSSs relative to other galaxy inhabitants. In M101, M83, and M51, some SSSs are located in the spiral arms, some close to markers of young stellar populations. While some of these may be supernova remnants, the fact that many SSSs in external galaxies are variable suggests that are X-ray binaries. (Variability studies have been possible so far for SSSs in M31 and for the high-$L_x$ sources in a handful of nearby galaxies.) At least some accretors may therefore be NSs or BHs in young ($< 10^8$ yrs). In addition, some SSSs are ultraluminous, suggesting accretion onto an intermediate mass ($100$–$1000M_\odot$) BH. The ultraluminous SSSs represent an extension of the SSS class to luminosities so high that the accretors are almost certainly not WDs. In an analogous way, QSSs represent an extension to higher energy emission that also appears to be inconsistent with WD models. As discussed below (see Eq. 1), both the extension to higher luminosities and the extension to higher temperatures are consistent with models of accreting intermediate-mass BHs (IMBHs).

There are SSSs positioned within a few parsecs of the central black holes of some galaxies (e.g., M31 [Garcia et al. 2000; Kong et al. 2002]); these may be the stripped cores of tidally disrupted giants (Di Stefano et al. 2001).
1.1.2. Models for Quasisoft Sources

The luminosity and temperature of nuclear burning WDs both increase with the WD mass. Since the WD mass cannot be larger than $1.4 M_\odot$, the Eddington limit places an upper bound on the luminosity of $2 \times 10^{38}$ erg s$^{-1}$. Because the photospheric radius has a lower bound equal to the WD radius, this places an upper bound on the effective temperature of approximately 150 eV. In fact, this temperature is not likely to be achieved by a nuclear-burning WD, since the photosphere is generally above the WD's surface. Sources with higher $T$ and effective radii too small to be consistent with WDs, are likely to be accreting NSs or BHs. NS or stellar-mass BH accretors do not seem natural, because the photospheric radii would be 2–3 orders of magnitude larger than the NS or Schwarzschild radii. There is, however, one natural model: if the accretor is an IMBH, then the temperature and luminosities are expected to be in the range observed for both SSSs and QSSs. Let $M_{BH}$ be the mass of the accreting BH, and let $\alpha$ be the efficiency, with $L = \alpha M_{BH} c^2$. If we assume that the accretion is mediated by a thin disk, and that the disk is optically thick, with its inner edge coincident with the radius of the last stable orbit, then the temperature of the inner disk can be written as follows.

$$kT > \frac{158 eV \left(\frac{100 M_\odot}{M_{BH}}\right)^2 \left(\frac{L}{3.1 \times 10^{37} \text{ergs}^{-1}}\right)^{\frac{1}{2}}}{\left(\frac{0.1}{\alpha}\right)^{\frac{1}{2}}}$$

A better model is a multi-color disk, generally with a power law tail (Mitsuda et al. 1984). Using a more sophisticated model than the one that produced Eq. 1, by, e.g., taking effects such as spectral hardening or the possible BH spin into account, would tend to increase the estimated BH mass for any set of measured values of $kT$ or $L$; this is the reason for the inequality. The higher the mass of the BH, the lower the temperature.

1.2. SSSs in Galactic GCs

1.2.1. Observations

Only one SSS has been detected in a Galactic globular cluster (GC). 1E 1339.8+2837, located in M3 (NGC 5272), was observed both in the ROSAT all-sky survey (Verbunt et al. 1995), and in pointed observations using the HRI (Hertz, Grindlay & Bailyn 1993). Estimates of the temperature and bolometric luminosity based on the all-sky survey were $kT \sim 45$ eV, and $L \sim 10^{35}$ erg s$^{-1}$ (Verbunt et al. 1995); estimates based on the HRI observations were $kT \sim 20$ eV and $L \sim 1.6 \times 10^{36}$ erg s$^{-1}$ (Hertz et al. 1993). The source is a transient. Note that the inferred luminosity (though uncertain) is smaller than typical for SSSs found in the Galaxy, the M31, and M3. This source could be similar to V751 Cyg, a nova-like variable of the VO Scl class, which becomes a low-L SSS only during rare optical low states (Greiner et al. 1999, Greiner & Di Stefano 1999).

Because GCs have been well-studied at X-ray wavelengths, we can determine whether systems like 1E 1339.8+2837 are common. By carrying out simulations in which GCs were “seeded” with SSSs (see Di Stefano & Rappaport 1994 for details), Di Stefano & Davies (1996) concluded that ROSAT observations of GCs should have produced an almost complete census of any active GC SSSs with characteristics similar to either 1E 1339.8+2837 or to the other known SSSs. Thus, SSSs in Galactic GCs are rare.

1.2.2. Theory

Globular clusters have per capita populations of low-mass X-ray binaries (LMXBs) roughly 100 times larger than in the Galactic disk. The enhancement is due to stellar interactions within or near the dense cluster cores. If the same ratio held for SSSs, then there would be $\sim 100$ SSSs in Galactic GCs. With just one observed, we can rule out the possibility that the stellar interactions are producing significant enhancements in the numbers of GC SSSs.

It is nevertheless worth noting that SSSs can be produced by 3 or 4 body interactions in GCs. The donor star would be a blue straggler, formed through the merging of two lower-mass stars. (In fact, M3 is rich in blue stragglers [Guhathakurta et al. 1994].) Di Stefano & Davies (1996) carried out simulations of the formation and binary evolution of GC systems that could become SSSs. They found that there should be $\sim 1$ SSS in Galactic GCs, comparable to predictions of the numbers of SSSs expected due to ordinary binary evolution, and consistent with the X-ray observations. In addition, GC SSSs were likely to have values of $m$ below the steady-burning region, and should therefore appear as SSS transients.

2. NGC 4472

2.1. NGC 4472 as a Testing Ground

NGC 4472 is a giant elliptical galaxy in the Virgo cluster. It houses about 6000 GCs (Rhode & Zepf 2001). Chandra discovered 144 X-ray sources in an $8' \times 8'$ region near the center of the galaxy (Kundu et al. 2002; Maccarone, Kundu, & Zepf 2003). There are more than 800 GCs in the region that Chandra observed (Kundu & Whitmore 2001). In the regions studied by both Chandra and HST, 40% of the bright ($>10^{37}$ erg s$^{-1}$) X-ray sources are associated with optically identified GCs (Kundu et al. 2002; Maccarone, Kundu, & Zepf 2003).

We conducted an independent analysis with two new elements. First, we considered data from all 6 CCDs. Second, we ran the detection algorithm (WAVDETECT) for energies in the range 0.1–7 keV, rather than 0.5–7 keV. Because emission from the softest sources begins to fall off by 0.5 keV, photons below 0.5 keV may combine with photons of higher energies, to make detections possible. To ensure that none of the sources are artifacts, we visually inspected the region containing each source, to verify that the spatial distribution of photons was consistent with the PSF at the source location.

We used lists of HST-identified GCs from Kundu et al. (2002), and of spectroscopically studied GCs from Sharples et al. (1998) and Zepf et al. (2000). To conduct a search for GCs in the vicinity of each X-ray source, we considered a sequence of search cones of radius $r$ ($0.5'' < r < 5''$). The optimal value of $r$ was 1.15''. Using this value we found 40 GCs near X-ray sources. An analysis using random shifts of the X-ray source positions, found that that $\sim 6$ identifications are likely to be due to chance superpositions.

2.2. VSSs in NGC 4472

We applied a uniform selection procedure (Di Stefano & Kong 2003a, b) to determine which X-ray sources are VSSs. Our selection algorithm identified 27 SSSs in NGC 4472. Six of these are associated with GCs. Some of the VSS-GC pairs may be artifacts. Since, however, we have estimated the number of spurious pairings to be 6, it is unlikely that all 6 false matches involve VSSs. We therefore conclude that at least several of the VSS-GC matches represent genuine physical correspondences. Table 1 lists the SSSs identified with NGC 4472’s
GCs. Sources 4 and 5 were identified as SSSs; the remaining sources were identified as QSSs.

Some of the VSSs may be background active galactic nuclei. We used results from the Chandra Deep Field Surveys (e.g., Brandt et al. 2001; Giacconi et al. 2001) to find that, at $4.5 \times 10^{37}$ erg s$^{-1}$ (the completeness limit), fewer than 10 sources are likely to be background objects. We expect that only a small fraction of these are soft enough to be identified as VSSs. To quantify this, we studied data from several fields observed by Chandra $^5$ and find that 1–3 VSSs unrelated to NGC 4472 are likely to be present in our data; these are most likely to be foreground stars (see e.g., Di Stefano et al. 2003a and Kong et al. 2003).

We have also investigated the optical properties of the GCs that house VSSs. We find that the VSSs are preferentially in luminous clusters. This parallels results for X-ray sources in general. (See e.g., Di Stefano et al. 2002.) The VSSs are found in both metal-poor and metal-rich GCs.

3. MODELS AND IMPLICATIONS

Because the portion of the galaxy for which we have GC positions is just a small portion of the region covered by the Chandra observations, any estimate of the fraction of X-ray sources residing in GCs is highly uncertain. Note however, that roughly 1/5 of the SSSs and 1/6 of all X-ray sources are associated with GCs. The fact that these 2 ratios are similar, and that, as in our Galaxy, the X-ray sources are over-represented in GCs of by a factor of $\sim 100$, suggests that X-ray sources in general, and SSSs in particular, are produced in the GCs of NGC 4472 through interactions. This is different from the situation in the Milky Way, where X-ray sources in general, but not SSSs, are overproduced in GCs.

3.1. Broad-Band Spectra

The number of counts from each GC SSS is too small to permit a spectral fit. We can, however, compare the distribution of counts from each source in the S (0.1-1.1 keV), M (1.1-2 keV), and H (2-7 keV) bands, with the distributions expected from known models. To this end, we used PIMMS (AO3 release) to compute the numbers of counts expected in S, M, and H from a blackbody source in NGC 4472, located behind a column with $N_{H}$ equal to each of 4 values: $(4 \times 10^{20}$ cm$^{-2}$, $1.6 \times 10^{21}$ cm$^{-2}$, $6.4 \times 10^{21}$ cm$^{-2}$ and $2.5 \times 10^{22}$ cm$^{-2}$). The values of $kT$ we considered ranged from 25 eV to 100 eV in 15 eV increments, then to 250 eV in 25 eV increments, and then to 500 eV and beyond by increments of 250eV. For each VSS, we scaled the luminosity of the model source so that it produced the same total number of counts. If the computed counts in each band were within 1–$\sigma$ of the observed counts, we counted the model as a possible match. The results are shown in Figure 1.

3.2. Physical Models

3.2.1. Supersoft Sources

The softest source is source 5, with the associated models shown as magenta pentagons. The fits are highly degenerate. Source 5 could be either an ultraluminous source with a very low value of $kT$, or a source with the characteristics of a classical SSS. In the latter case, it is likely to have $kT$ near or just under 100 eV, and to have $L$ close to the Eddington limit for a 1.4$M_{\odot}$ object. Thus, this particular SSS could be an accreting high-mass WD, perhaps a good candidate for the progenitor of a Type Ia supernova explosion. It has not been anticipated that GCs serve as sites of Type Ia SNe. Nevertheless, we can construct scenarios in which progenitors can be formed in GCs. If the SSS is WD binary with orbital period less than a few days, it is likely that the donor is a 1–2$M_{\odot}$ star that may be slightly evolved. This is possible if the cluster is young, or if the donor is a blue straggler (see §1.2.2). If, instead, source 5 is very soft (with $kT$ possibly as low as 10 eV), and very luminous, then the most likely interpretation is that it is an IMBH, with mass that could be as high as $10^{3} - 10^{4} M_{\odot}$. Although the presence of IMBHs in GCs has been suggested, the more conservative model for this source is likely to be the WD model.

Source 4 (cyan boxes) is also chosen as an SSS. It appears to be not as soft as source 5; values of $kT < 100$ eV are ruled out. This means that the range of possible luminosities is also more restricted. If source 4 is a nuclear-burning WD it is marginally hotter, while at the same time being somewhat less luminous, than expected for a high-mass WD. In fact, source 4 is consistent with models very similar to those that apply to the QSSs, discussed below.

3.2.2. Quasisoft Sources

The QSSs appear to be too hot to be compatible with WD models. The associated values of $kT$ appear to be clustered between roughly 150 eV and 250 eV, while the luminosities all lie near $10^{38}$ erg s$^{-1}$. Although the nature of these sources is not determined, IMBH models are well suited to them. The minimum computed values of the BH masses range from approximately $50 M_{\odot}$ to $150 M_{\odot}$. The mass accretion rates would

$^5$ http://hea-www.cfa.harvard.edu/CHAMP
be similar among the systems, around $10^{-8} M_\odot$ yr$^{-1}$.

4. CONCLUSIONS

One VSS has already been associated with a GC in the Sombrero galaxy, M104 (Di Stefano et al. 2003). Nevertheless, the discovery of a set of VSSs in the GCs of NGC 4472 is remarkable. First, the discovery of 6 VSS-GC matches rules out the possibility that all of them are spurious. In combination with the M104 results, we can now more firmly establish that GCs do house luminous ($\sim 10^{48}$ erg s$^{-1}$) VSSs. There is no precedent for this in the Galaxy or in M31. Second, our NGC 4472 results provide examples of VSS-GC matches in an elliptical galaxy. Third, the set of GC-VSSs allows us to begin studying the statistics of this connection. Much more data, from a larger number of galaxies is needed. But, e.g., if it remains the case that there is no obvious connection between GC metallicity and the likelihood of hosting an SSS, this would be a significant contrast with other X-ray binaries, suggesting that different processes create the VSSs than those that create other X-ray binaries.

If some of the VSSs in GCs are WDs accreting matter at high enough rates to allow nuclear burning, then Type Ia SNe may occur in GCs. Young GCs, or extremely massive centrally dense GCs would be favored. If Type Ia supernovae can occur in GCs, it is possible that surveys designed to study Type Ia supernovae will discover an example.

Most sources in the range $150-250$ eV sources are likely not hot WDs. The most natural alternatives are accreting IMBHs. It is interesting that the properties of the QSSs in GCs seem roughly similar across clusters, and that the minimum values of the BH masses are also similar ($50-150 M_\odot$).

The presence of IMBHs in GCs has been predicted by a number of authors. Dynamical evidence for such BHs in M15 and G1 has been offered (Gerssen et al. 2002; Gebhardt, Rich, & Ho 2002), although these results have generated some controversy (McNamara, Harrison, & Anderson 2003; Baumgardt et al. 2003). The discovery of SSSs, and especially of QSSs, in GCs may provide independent observational evidence that BHs with masses larger than standard stellar remnants do inhabit GCs. If so, studies like the one described here will provide an avenue to establish the statistics and general properties of the connection between globular clusters and intermediate-mass black holes.

It is a pleasure to acknowledge conversations with P. Barmby, which helped us to select NGC 4472 as a target of study. This work was supported by NASA under an LTSA grant, NAG5-10705 and by NSF grant AST-9731923 to the SAO Summer Intern program. A.K. acknowledges NASA for support via LTSA grant NAG5-12795. A.K.H.K. acknowledges support from the Croucher Foundation.

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Table 1
VSSs in NGC 4472’s GCs

| Source | R.A. (h:m:s) | Dec. (°:′:″) | Net Counts | Hardness Ratios |
|--------|--------------|--------------|------------|-----------------|
|        |              |              | Soft       | Medium          | Hard            | HR1  | HR2  |
| 1      | 12:29:47.8  | +07:59:19    | 9.26 ± 2.43 | 5.84 ± 1.91    | 1.00 ± 0.40     | -0.23 | -0.81|
| 2      | 12:29:47.8  | +07:59:44    | 9.27 ± 2.62 | 5.55 ± 1.87    | 0.78 ± 0.31     | -0.25 | -0.84|
| 3      | 12:29:40.1  | +07:58:29    | 12.91 ± 2.97| 5.46 ± 1.82    | 0.00 ± 0.00     | -0.41 | -1.00|
| 4      | 12:29:48.6  | +07:59:13    | 15.52 ± 3.36| 2.62 ± 1.10    | 1.28 ± 0.53     | -0.71 | -0.85|
| 5      | 12:29:45.0  | +08:01:06    | 15.26 ± 3.25| 1.09 ± 0.44    | 0.00 ± 0.00     | -0.87 | -1.00|
| 6      | 12:29:55.8  | +07:57:23    | 6.46 ± 1.89 | 3.28 ± 1.24    | 0.00 ± 0.00     | -0.33 | -1.00|

Note. — The columns give the source number, the position (J2000.0), the net counts in the three energy bands (soft: 0.1–1.1 keV; medium: 1.1–2 keV; hard: 2–7 keV), and the hardness ratios (HR1: (medium-soft)/(medium+soft); HR2: (hard-soft)/(hard+soft). Note that the selection procedure does not rely solely on hardness ratios (see Di Stefano & Kong 2003a,b).