VERY LARGE ARRAY LIMITS FOR INTERMEDIATE-MASS BLACK HOLES IN THREE GLOBULAR CLUSTERS

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ABSTRACT

The observational evidence for central black holes in globular clusters has been argued extensively, and their existence has important consequences for both the formation and evolution of the cluster. Most of the evidence comes from dynamical arguments, but the interpretation is difficult, given the short relaxation times and old ages of the clusters. One of the most robust signatures for the existence of a BH is radio and/or X-ray emission. We observed three globular clusters: NGC6093 (M80), NGC6266 (M62), and NGC7078 (M15), with the Very Large Array (VLA) in the A and C configuration with a $3\text{-}\sigma$ noise of 36, 36, and 25 μJy , respectively. We find no statistically significant evidence for radio emission from the central region for any of the three clusters. NGC6266 shows a $2\text{-}\sigma$ detection. It is difficult to infer a mass from these upper limits due to uncertainty about the central gas density, accretion rate, and accretion model.

Key words: accretion, accretion disks – black hole physics – globular clusters: general – radio continuum: general

Online-only material: color figures

1. INTRODUCTION

Although we do not understand how the nuclei of galaxies form or why they have black holes (BHs) at their centers, the correlation between the BH mass and bulge velocity dispersion does shed light on their formation and evolutionary histories (Gebhardt et al. 2000; Ferrarese and Merritt 2000). A number of different theories (e.g., Silk & Rees 1998; Haehnelt & Kauffmann 2000; Robertson et al. 2006) predict a BH mass–bulge-velocity-dispersion relation, although they predict different slopes and intercepts for this relation. Exploration of the extreme ends of this relationship will help illuminate the underlying physical model, and in this paper we focus on the low-mass end. BHs at the low end of the relations, with masses between 100 and $10^6 M_\odot$, are generally referred to as intermediate-mass black holes (IMBHs). There is a significant evidence that BH masses from 10^5 to $10^6 M_\odot$ exist from the work of Barth et al. (2005) and Greene & Ho (2006). To go to yet smaller BH masses, an extrapolation of the correlation between the BH mass and stellar velocity dispersion suggests studying stellar systems with velocity dispersions of $10\text{--}20 \text{ km s}^{-1}$. These dispersions are characteristic of globular clusters. Whether the existence of BHs in globular clusters could shed light on the formation and correlations of supermassive BHs is unknown, but clearly there is a possibility. Furthermore, the existence of massive BHs in clusters will have a significant effect on the cluster evolution. Thus, quantifying the demographics of BHs in clusters may be related to how the supermassive BHs grow, and will definitely yield useful information about the evolution of clusters.

Theoretical work suggests that we might expect IMBHs at the centers of stellar systems (Ebisuzaki et al. 2001; Portegies Zwart & McMillian 2002; Miller & Hamilton 2002), although it appears to be difficult to make BHs more massive than $100 M_\odot$. Gurkan et al. (2004) suggested that IMBHs may be easy to form through runaway collisions with massive stars.

Discoveries of BHs in globular clusters have been claimed – G1 in M31 (Gebhardt et al. 2002) and M15 (van der Marel et al. 2002). In fact, the M15 claim has been made for the past 30 years, starting with the result of Newell et al. (1976) and subsequently challenged by Illingworth & King (1977). The basic issue is being able to distinguish a rise in the central mass-to-light ratio being due to either a BH or the expected stellar remnants (neutron stars, massive white dwarfs and solar mass BHs). The most recent M15 result has been challenged by Baumgardt et al. (2003a). The result in G1 has also been challenged by Baumgardt et al. (2003b) but Gebhardt et al. (2005) included additional data and analysis that support the BH interpretation.

There have been two further observations which strongly support the existence of a BH in G1. Trudolyubov & Priedhorsky (2004) measured X-rays from G1 using the Chandra Observatory, centered at within $2''$ of the center of G1. Subsequently, Pooley & Rappaport (2006) suggested that the X-ray emission is from accretion onto a BH, and Maccarone & Koerding (2006) pointed out that if a BH is present then a 30 μJy radio source may be expected. The most significant observation comes from Ulvestad et al. (2007) who found a 28 μJy ($4.5\text{-}\sigma$) emission centered at G1. Other interpretations are a pulsar wind or a planetary nebula. The pulsar wind seems unlikely given the age of G1 and the point-like radio source (an old pulsar would have a large size). A planetary nebula would show optical emission lines which are not seen in the Hubble Space Telescope (HST) or Keck spectra of Gebhardt et al. (2005).

Other studies of the existence of BHs in globular clusters have been less compelling. Colpi et al. (2003) used indirect dynamical arguments to suggest a few hundred solar mass BHs in NGC 6752. McLaughlin et al. (2006) provided an estimate of BH in 47 Tuc of $900 \pm 900 M_\odot$. To date, there are no published upper limits of BH masses that are significantly below that expected from an extrapolation of the correlation between the BH mass and stellar velocity dispersion.

Table 1
8.6 GHz Flux Density Values

(1) Cluster	(2) M_{BH} Maccarone ($M_{\odot}$)	(3) M_{BH} This paper ($M_{\odot}$)	(4) Distance kpc	(5) Flux density μJy
NGC6093 (M80)	...	1600	8	$2 \times 10^3 - 10^5$
NGC6266 (M62)	450	3000	6	$3 \times 10^3 - 10^5$
NGC7078 (M15)	440	1000	10	$1 \times 10^3 - 10^5$

While the dynamical arguments strongly support the BH interpretation in at least G1, the radio emission provides a clear and obvious result. Unfortunately, it is difficult to predict the radio emission from a given BH mass. The next step is to explore other globular clusters with a similar setup and deep exposures.

2. TARGET SAMPLE AND RADIO FLUX DENSITY PREDICTIONS

We selected three globular clusters for observation. First, using the stellar velocity dispersion at the center of M15 (NGC7078) suggests a revision of the mass of the BH at the cluster's center to $1000 M_{\odot}$, higher than Maccarone's assumed value of $440 M_{\odot}$, making M15 a promising candidate. Second, noting that Baumgardt et al. (2005) argue that highly centrally condensed globular clusters, as seen from their luminosity profiles, are unlikely to harbor central IMBHs, we selected two globular clusters with large cores that are more likely to have central BHs. These clusters, NGC6093 and NGC6266, also have large central stellar velocity dispersions.

In order to predict the radio flux density, the first step is to use an expected BH mass. The BH masses can be estimated using an extrapolation of the correlations seen in galaxies, namely either the BH mass/velocity dispersion or the BH mass/galaxy bulge luminosity relations.

A precise prediction of the expected radio flux densities based on the BH mass is quite uncertain. Merloni et al. (2003) use radio flux densities, X-ray luminosities, and measured BH masses from both Galactic and extragalactic BHs to derive a fundamental plane for the three parameters. They argue that using any one parameter to predict another is quite uncertain. Unfortunately, X-ray luminosities do not exist for the three clusters studied here. Furthermore, the study of Merloni et al. does not include any BHs with masses from 10 to 10^6 , making any use of the fundamental plane suspect for the three globular clusters. Therefore, instead of directly using the expected BH mass and the measured X-ray luminosity to predict the radio flux density, we simply use the location between the $10^6 M_{\odot}$ BHs and the galactic BHs in the fundamental plane. In this region, the expected 5 GHz radio power ranges from 10^{30} to $10^{32} \text{ ergs s}^{-1}$. Indeed, for the G1 radio emission from Ulvestad et al. (2007) corresponds to $10^{32} \text{ ergs s}^{-1}$, which is consistent with the measured BH mass of 2×10^4 from Gebhardt et al. (2005). Thus, in order to predict the expected flux densities, we adopt this range in radio power and use the known distances of the globular clusters. A significant assumption in these estimates is that the physical conditions are similar; if, for example, the gas density were much lower in globular clusters, the predicted radio power would be much less.

Alternatively, Maccarone (2004) estimated the expected radio emission based on the expected gas density and the correlation of Merloni et al. (2003). The gas density in the cluster come from the estimate of Freire et al. (2001) who used differences in column densities measured from pulsars in the front and back sides in the globular cluster 47 Tuc. While there is no reason

to expect similar gas densities from cluster to cluster, it is the best measure we have of gas density in a cluster and therefore we adopt that value. Maccarone (2004) further assumed that the BH is accreting the intra-cluster gas at 0.1 and 1% of the Bondi accretion rate. He assumes the BH mass to be 0.1% of the globular cluster mass, which he estimates from the cluster's total luminosity and an assumed mass-to-light ratio, and computes the expected 5 GHz flux density from the vicinity of the central BH for 15 globular clusters. Six of the globular clusters in Maccarone's list lie north of the southern declination limit of the Very Large Array⁴ (VLA) and have an estimated 5 GHz flux density of $40 \mu\text{Jy}$ or greater (at 1% of the Bondi rate). We searched the VLA archive for observations of the centers of these clusters with noise levels low enough to have allowed a detection at Maccarone's predicted levels. No VLA archive data were found which had the required sensitivity.

There have been two similar studies for the one presented here. Maccarone et al. (2005) provided upper limits for omega Cen using ATCA observations and for M15 from archival VLA observations. De Rijcke et al. (2006) provided upper limits for 47 Tuc and NGC 6397 based on ATCA observations.

Table 1 shows the computed flux densities for NGC6266, NGC7078, and NGC6093 at a frequency of 8.6 GHz. We assume a spectral index, $\alpha = -0.7$, to provide the predicted fluxes at 8.6 GHz, the frequency of our observations. Our BH masses come from the BH/sigma correlation (shown in the second column), and we also report those from Maccarone based on luminosity (the first column).

3. OBSERVATIONS

Source positions, integration times on source, beam dimensions and position angles, and our $3\text{-}\sigma$ limits are given in Table 2.

We used the position of the center of M15 determined by Noyola & Gebhardt (2006) using the optical surface brightness profile from the *Hubble Space Telescope* (HST), which are good to less than $1''$. We observed that position using the VLA for 7.5 hours on 2004 October 13 in the A configuration at 8.6 GHz (λ 3.5 cm), where the VLA has its maximum sensitivity. The resulting map has an rms noise level of $8.5 \mu\text{Jy/beam}$ and covers ≈ 1 arcmin positioned at the center of M15. We clearly see the source AC211 reported by Johnston et al. (1991) about 1.5 arcsec northwest of the cluster center at with a peak flux density on our map of $144 \mu\text{Jy}$. We do not detect the other known low mass X-ray binary, M15 X-2 (White & Angelini 2001), even at $1\text{-}\sigma$. The image also contains the planetary nebula K 648, for which we get R.A. $21^{\text{h}}29^{\text{m}}59^{\text{s}}.39$, decl. $12^{\circ}10'26''46$ (J2000). The measured flux density is $4.2 \pm 0.2 \text{ mJy}$ and the deconvolved size is 1.5×0.7 arcsec. We do not see the pulsar

⁴ The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

Figure 1. HST optical image of M15 overlaid with the VLA contours of the central $10''$. Positive $1\text{-}\sigma$, $2\text{-}\sigma$, and $3\text{-}\sigma$ noise contours (8.5 , 17 , and $25.5 \mu\text{Jy}$) are shown in green and negative contours are shown in red. The blue circle marks the center determined from Noyola & Gebhardt (2006), with a diameter of $0.5''$. North is up and east to the left. The radio source, AC211, is easily seen just north of the center. The other known X-ray source, M15 X-2, is not detected.

(A color version of this figure is available in the online journal)

Table 2
Observations

(1) Cluster	(2) RA J2000	(3) Decl. J2000	(4) Integration (hours)	(5) Beam; position angle (arcseconds; deg)	(6) $3\text{-}\sigma$ limit (μJy)
NGC6093	16:17:05.00	-22:59:47.3	7.0	3.9×2.3 ; -6	36
NGC6266	17:01:12.96	-30:06:46.2	7.0	4.7×2.2 ; -6	36
NGC7078	21:29:58.35	+12:10:01.5	6.5	0.2×0.2 ; -76	25

PSR 2127+12A or any other point source near the center of M15 at or above a level of $25 \mu\text{Jy/beam}$.

The positions of the centers of NGC6093 and NGC6266 also come from Noyola & Gebhardt (2006) (with a similar accuracy of around $1''$). These clusters were observed on 2005 August 11, 20, and 26 using the VLA in the C configuration at 8.6 GHz . Each map has an rms noise of $12 \mu\text{Jy/beam}$. These maps cover an area of 5.4 arcmin centered at each cluster's center. No radio source is seen at or above a level of $36 \mu\text{Jy/beam}$ near either cluster's center. In the case of NGC6093 a source is detected 82 arcsec to the SE of the cluster center at R.A. $16^{\text{h}}17^{\text{m}}05^{\text{s}}.00$, decl. $-22^{\circ}59'47''.3$ (J2000) with a flux density of $0.32 \pm 0.05 \text{ mJy}$. The distance from the cluster center makes it unlikely that this source is related to NGC6266. No source is seen convincingly in the image of NGC6266.

Figures 1–3 plot the HST optical images (as used in Noyola & Gebhardt) with the VLA radio contours. None of the three clusters shows a significant detection at 8 GHz at the cluster center. However, NGC 6266 (M62) shows about a $2\text{-}\sigma$ peak at the center.

4. DISCUSSION

Failure to detect radio radiation at 8.6 GHz from the centers of the three globular clusters does not prove that no globular clusters have IMBHs at their centers. Besides not having a BH, other interpretations include (1) accretion by the BH could be episodic and we happened to observe the BHs in an “off-state,” (2) the gas density could be much lower compared to galaxies, (3) the radiative efficiency may be lower than assumed (although the assumed efficiencies are already quite low), (4) or the accretion model may not be adequate in general. We would predict, using the relation of Merloni et al. (2003) or using standard accretion models and gas density estimates (as done in Maccarone 2004), that we should have detected radio radiation at 8.6 GHz if the accretion is steady and the accretion rate times the Bondi rate is 10^{-4} or higher. We would not have been able to detect the flux density predicted by a rate of 10^{-5} or less. Ulvestad et al. (2007) estimated the fraction of the Bondi rate of just below 1% for G1, but it is difficult to interpret due to the unknown radiative efficiency. For

Figure 2. HST optical image of NGC 6093 (M80) overlaid with the VLA contours of the central $10''$. Positive $1\text{-}\sigma$, $2\text{-}\sigma$, and $3\text{-}\sigma$ noise contours (12, 24, and 36 μ Jy) are shown in green and negative contours are shown in red. The blue circle marks the center determined from Noyola & Gebhardt (2006), with a diameter of $1''$. North is up and east to the left.

(A color version of this figure is available in the online journal)

Figure 3. HST optical image of NGC 6266 (M62) overlaid with the VLA contours of the central $10''$. Positive $1\text{-}\sigma$, $2\text{-}\sigma$, and $3\text{-}\sigma$ noise contours (12, 24, and 36 μ Jy) are shown in green and negative contours are shown in red. The blue circle marks the center determined from Noyola & Gebhardt (2006), with a diameter of $1''$. North is up and east to the left. There is about a $2\text{-}\sigma$ positive 8 GHz signal at the center.

(A color version of this figure is available in the online journal)

galactic BHs, the radiative efficiencies appear to vary greatly with some lower than 10^{-5} (Lowenstein et al. 2001), although they are consistent with rates of around 10% of the Bondi rate.

Models which predict 8.6 GHz flux densities from the central BHs in globular clusters above about $25 \mu\text{Jy}/\text{beam}$ can be tested with the VLA currently. The EVLA should produce, for continuum observations, a sensitivity improvement of about a factor of 15, making 8.6 GHz flux densities above about $2 \mu\text{Jy}/\text{beam}$ detectable.

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