Radio observations of NGC 2808 and other globular clusters: constraints on intermediate mass black holes

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ABSTRACT
We present the results of a deep radio observation of the globular cluster NGC 2808. We show that there are no sources detected within the core of the cluster, placing constraints on both the pulsar population of the cluster and the mass of a possible intermediate mass black hole in NGC 2808. We compare the results for this cluster with other constraints on intermediate mass black holes derived from accretion measures. With the exception of G1 in M 31 which has previously shown radio emission, even with considerably more conservative assumptions, only the clusters with the poorest of observational constraints are consistent with falling on the $M_{BH} - \sigma$ relation. This result is interpreted in terms of the fundamental differences between galaxies and globular clusters.

Key words: accretion, accretion disks – stellar dynamics – globular clusters: general – radio continuum: general – globular clusters, NGC 2808

1 INTRODUCTION

Starting with the discoveries of X-ray sources in globular clusters in the mid-1970’s (Clark 1975; Clark, Markert & Li 1975), considerable debate took place about whether globular clusters contain black holes of intermediate masses (i.e. greater than the $\sim 20 M_\odot$ maximum mass for black holes formed through normal single star evolution, but less than the $10^6 M_\odot$ masses seen in the smallest galactic nuclei). It was proposed that the X-ray emission seen from these clusters was due to accretion onto the central black holes of material released into the intracluster medium by stellar mass loss (Bahcall & Ostriker 1975; Silk & Arons 1975). Additionally, increases in the clusters’ central velocity dispersions were seen without corresponding increases in the central optical luminosity density (Newell, Dacosta & Norris 1976). Both arguments for intermediate mass black holes were refuted in relatively short order; Type I X-ray bursts were seen from the globular cluster X-ray sources (Grindlay et al. 1976), and explained to be due to thermonuclear burning on the surfaces of neutron stars (Woosley & Taam 1976). With regards to the second argument, it was shown that increases in central mass-to-light ratios of globular clusters were expected due to mass segregation in the clusters, which leaves the heavy, dark white dwarfs and neutron stars preferentially in the cluster cores (Illingworth & King 1977).

This controversy has been re-kindled recently based on the same lines of evidence. An intermediate mass black hole in M 15 has been claimed (Gerssen et al. 2002) and refuted (Baumgardt et al. 2003) on largely the same grounds as the debate over the same cluster in the late 1970’s. In fact, it has been argued that the finite number of stars within the sphere of influence of an intermediate mass black hole in a globular cluster will make it impossible to demonstrate conclusively through stellar dynamical measurements made in integrated light that a cluster contains an intermediate mass black hole (Drukier & Bailyn 2002). More indirect proofs may still be feasible, through, for example, measurements of high velocity stars (Drukier & Bailyn 2002; Baumgardt, Gualandris & Portegies Zwart 2006) or the presence of unusual binaries which can be best explained by recoil off a black hole-black hole binary (Colpi,Possenti & Gualandris 2002).

The inability of stellar dynamics to make clean measurements has led to the search for accretion constraints on the presence of intermediate mass black holes. The first attempts placed upper limits on the masses of black holes in M15 and 47 Tuc (Grindlay et al. 2001; Ho et al. 2003), based on particular accretion models. It was later pointed out that, following from the fundamental plane relation for black hole activity (Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2004), the radio emission expected from an intermediate mass black hole would be orders of magnitude higher than that expected from a stellar mass black hole or a neutron star at the same X-ray luminosity. This makes radio searches more sensitive, and also gives the possibility to place at least a crude constraint on black hole mass based on detection of radio emission (Maccarone 2004).

One piece of strong evidence has emerged for an intermediate mass black hole in G1, an enigmatic star cluster in M 31 thought by some to be a globular cluster, but by others to be the core of a stripped dwarf galaxy, given that its mass is far above that of any globular cluster in the Milky Way, and that it contains multiple stel-
lar populations. Dynamical evidence in G1 suggested the presence of a 20,000 solar mass black hole (Gebhardt, Rich & Ho 2005), but was significant at less than the 3σ level and based on only a few pixels worth of HST data. X-ray measurements of this cluster revealed a source at $2 \times 10^{36}$ ergs sec$^{-1}$ (Trudolyubov & Priedhorsky 2004), and were suggested to be possible evidence of an intermediate mass black hole, but was certainly still consistent with emission from a single X-ray binary or a collection of X-ray binaries (Pooley & Rappaport 2005). The radio flux from G1 was then measured to be 28 $\mu$Jy (Ulvestad, Greene & Ho 2007), in good agreement with the prediction of Maccarone & Körding (2006) that the radio flux should be 30 $\mu$Jy for the suggested black hole mass and observed X-ray luminosity. We note that much of the information from this introduction is drawn from a recent review by Maccarone & Knigge (2007). For a more general and thorough, but somewhat dated review of binaries in globular clusters, see Hut et al. (1992). For a recent review on the topic of black holes and neutron stars in globular clusters, see Rasio et al. (2007).

On the other hand, searches for radio emission from globular clusters thought to be good candidates for hosting intermediate mass black holes have generally yielded only upper limits (Maccarone, Fender & Tzioumis 2005; De Rijcke et al. 2006; Bash et al. 2008). It is thus clear that more detailed searches for radio sources from Galactic globular clusters should be attempted. In this paper, we report an upper limit on the radio emission from the globular cluster NGC 2808. We discuss this result in the context of other radio upper limits from globular clusters, and show that there are already enough data to cast severe doubt on suggestions that globular clusters may follow the same $M_{\text{BH}} - \sigma$ relation as galaxies.

2 DATA USED

The Australia Telescope Compact array observed NGC 2808 for 12 hours in array configuration 6D, on 24 January 1992. The calibrators used are 0823-500 and 1934-638. The data were taken at 1.408 and 1.708 GHz, with 64 channels of 2 MHz each frequency range. The 1.708 GHz data were especially noisy and were not examined. We reduced the 1.408 GHz data with MIRIAD (Sault, Teuben & Wright 1995). We needed to excise the four lowest frequency channels, the four highest frequency channels, and the eight central channels in order to remove an artefact in the central pixel and considerable noise. A few other epochs of radio frequency interference activity were excised, as was the baseline between antennae 4 and 5 which showed strong noise throughout the observation. As a result, the rms obtained in these data is not as good as one might hope for, but after CLEANing, the data still produce a noise level of 54 $\mu$Jy, very similar to the theoretical noise level expected from the included baselines.

3 OTHER SOURCES

Several radio sources are detected in these data, within the tidal radius of the cluster but outside the half-light radius. Given that any radio source in a globular cluster is likely to be a source which is formed dynamically, which is far heavier than a typical star in the cluster, or both, any radio source associated with the cluster is likely to be near the centre of the cluster where dynamical interactions are most common and where mass segregation leaves the heaviest objects. These sources are therefore most likely to be background active galactic nuclei, although, owing to the relatively low Galactic latitude of this cluster ($b = -11.3$ degrees) some may be foreground object, such as HII regions. Correlations with X-ray detections from Servillat, Webb & Barret (2008) will be discussed in future work.

4 DISCUSSION

A few key points result from the non-detection of radio sources associated with NGC 2808. First, the non-detection of any sources in the core implies that there are no bright radio pulsars here. The collision rate, $\Gamma$ in NGC 2808, approximated as $\Gamma = \rho r_c^2$ (Verbunt & Hut 1987), where $\rho_c$ is the stellar density in the core, is slightly higher than that in 47 Tuc, which has more than 20 known pulsars (Camilo et al. 2000); pulsar production is expected to be well-correlated with the collision rate, in the same way that X-ray source production is enhanced (Gendre et al. 2003; Pooley et al. 2003, 2006). While none of the pulsars in 47 Tuc is bright enough to be seen in this exposure at the distance of NGC 2808, the integrated emission from pulsars in 47 Tuc would be detectable at this distance. Given that the core of NGC 2808 is only about 4 x 4 angular resolution elements for the ATCA’s angular resolution at 1.4 GHz, and that most of the ATCA baselines are sufficiently short that the full cluster core is well-probed by the baselines, it seems unlikely that the pulsars are over-resolved by the array. The level of emission really is likely to be lower than in 47 Tuc. Part of the reason for this may be the lower metallicity of NGC 2808 relative to 47 Tuc – it has recently become well established that the metallicity of a globular cluster affects its probability of hosting an X-ray source (see Silk & Arons 1975 for the first suggestion of this effect; Kundu, Maccarone & Zepf 2002 for the first definitive evidence; Kim et al. 2006; Kundu et al. 2007; Sivakoff et al. 2007 for demonstrations from large samples of elliptical galaxies). Deeper observations in radio continuum would be useful for constraining whether these are real differences in the pulsar properties of these two clusters, or if the issue is just the combination of deeper data on 47 Tuc so far, combined with its smaller dispersion measure which makes pulsar timing detections at low frequencies easier to make.

Second, we consider the case of a possible intermediate mass black hole in NGC 2808. The interpretation of the non-detection depends strongly on the assumptions made about the efficiency of Bondi-Hoyle accretion (i.e. what fraction of the classical Bondi rate is actually accreted), the gas density in the cluster, the radiative efficiency of accretion, and the correlation between X-ray and radio power. We will present here both the most likely parameter values and a more conservative estimate which consists of considering values for each parameter near the lower end of the plausible range.

A variety of approaches can be used to estimate the fraction of the Bondi rate at which spherical accretion takes place in Nature. Pellegrini (2005) examines a sample of active galactic nuclei in elliptical galaxies, where the gas density can be estimated from X-ray imaging. Nearly all these galaxies are underluminous compared to what would be expected for radiatively efficient accretion at the Bondi rate. When radiatively inefficient accretion, with $L_X \propto m^2$ is implemented (as we do here – see below), the accretion rates predicted from the Bondi relation are still too low to match the observed data, but typically by a factor of only about 10-30 – see Figure 3 of Pellegrini (2005), with the most underluminous AGN only a factor of about 1000 below its Bondi rate for radiatively inefficient accretion. Various authors have also considered the kinetic power of jets from AGN in clusters of galaxies based on the bubbles they inflate in the intracluster medium (see e.g. Dunn, Fabian...
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& Celotti 2005). They typically find that at least 10% of the power which would be generated by efficient accretion at the Bondi rate is required (RJ Dunn, private communication). Finally, Perna et al. (2003) have estimated that the lack of detection of isolated neutron stars accreting from the interstellar medium implies a fraction of Bondi accretion of $10^{-2} - 10^{-3}$. We thus take $3 \times 10^{-3}$ times the Bondi rate as the most likely value and $10^{-3}$ as our more conservative reasonable value.

The gas content of globular clusters is also an issue of debate. Four globular clusters clearly show evidence for an intracluster medium, with the rest generally showing upper limits consistent with being well above the measured values in the clusters with good measurements (e.g. Bowyer et al. 2007; Knapp et al. 1996). The two Galactic globular clusters with evidence for gas, 47 Tuc and M 15 show systematic correlations between the dispersion measures of their pulsars and the accelerations of their pulsars, indicating that the pulses from the pulsars in the back of the cluster are moving through larger column densities of material (Freire et al. 2001; 2003). The cluster G1 in M31 shows evidence for gas in it that verifies the picture we are presenting here. Finally, the cluster RZ2109 shows a strong, broad [O III] emission line, powered by the accreting, likely stellar mass, black hole within it (Maccarone et al. 2007; Zepf et al. 2007).

Gas densities can also be estimated based on empirical knowledge about stellar mass loss. Pfahl & Rappaport (2001) showed that if the gravitational potentials of globular clusters are ignored, so that the mass loss from stars is treated as free expansion, that core densities of gas of $n_H \approx 1 \left( \frac{M_c}{10^5 M_{\odot}} \right) \left( \frac{r_c}{200 \text{ pc}} \right)^{-1} \left( \frac{\sigma_v}{5 \text{ km s}^{-1}} \right)^{-2}$ cm$^{-3}$, would result, where $M_c$ is the cluster core mass, $r_c$ is the cluster core radius, and $\sigma_v$ is the characteristic wind velocity for the outflows. When we apply this result within this paper, we will assume a characteristic wind speed of 50 km sec$^{-1}$ (allowing for a rather conservative limit), a cluster mass-to-light ratio of 2 (e.g. Piatek et al. 1994), and will take the central luminosity densities and core radii from the Harris (1996) catalog. We note that the values inferred from this equation are a factor of about 2 higher than the values derived from pulsar measurements, but that the pulsar measurements are sensitive only to ionized gas.

A conservative estimate of the gas content in NGC 2808 would be that it is similar to the gas content in 47 Tuc (i.e. $n_H=0.07$ H cm$^{-3}$). In fact, it is unlikely that the gas content in NGC 2808 will be as low as in 47 Tuc. Pure stellar wind mass loss should yield a gas density of $0.5$ H cm$^{-3}$, without any retention of the gas in both these clusters – it is likely that millisecond pulsar winds are responsible for removing some of the gas in 47 Tuc. Faulkner et al. (1991) found tentative evidence for $200$ $M_{\odot}$ of neutral hydrogen in NGC 2808, presuming the gas is located predominantly in the cluster core. If this were confirmed, it would represent a gas density about 4 orders of magnitude higher than the values used in this paper. However, this gas density is highly unlikely - an unusually low dust-to-gas ratio would be required in order not to see reddening within the cluster, since $n_H=500$ H cm$^{-3}$ with a cluster core radius of 0.7 pc gives a column density $N_H$ of more than $10^{23}$ H cm$^{-2}$. Furthermore, if there really were this a gas density in the core of NGC 2808 of $5000$ H cm$^{-3}$, not only an intermediate mass black hole, but also the isolated neutron stars in the cluster would be easily detectable as X-ray sources (see e.g. Pfahl & Rappaport 2001).

The radiative efficiency of accretion and the relation between radio and X-ray powers have, in fact, become well established in recent years. The fundamental plane relation for black hole activity, $L_R \propto L_X^{0.6} M_{BH}^{0.8}$ (Merloni et al. 2003) requires radiatively inefficient accretion (e.g. from an advection dominated accretion flow – see Narayan & Yi 1995) in the low/hard state (i.e. below about 2% of the Eddington limit – Maccarone 2003; Maccarone, Gallo & Fender 2003). We thus assume that the radiative efficiency of accretion is $0.1 \, e^2$ for $L > 0.02 \, L_{EDD}$ and $0.5 \, \dot{m} c^2 \, L_{EDD}$ for lower luminosities, so that the function is continuous at $L = 0.02 \, L_{EDD}$.

The different radio/X-ray relations for black holes and neutron stars (Migliari & Fender 2006) argue strongly for a radiative efficiency law where $L_X \propto \dot{m}^{2}$ in the low hard state of black holes, and the lack of abrupt changes in luminosity at the state transitions to and from the high soft state, which is widely believed to be a radiatively efficient standard optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973) argue for a smooth transition in radiative efficiency (Maccarone 2005; Russell et al. 2007). The mass term in the fundamental plane relation follows in a straightforward manner from standard synchrotron theory for compact conical jets (Blandford & Königl 1979; Falcke & Biermann 1995; Heinz & Sunayev 2002). Confidence in this relation is also bolstered by the fact that the scatter in the correlations reduces to being consistent with measurement errors when AGN samples are chosen carefully, so as to include only AGN in the low/hard state and without significant relativistic beaming (Kording, Falcke & Corbel 2006). Scatter nonetheless, may exist – the most likely reasons being due to variations in black hole spins, and Doppler boosting (although there are several lines of indirect evidence that the jets from low luminosity systems are only mildly relativistic – see e.g. Gallo, Fender & Pooley 2003). Below we describe how its effects may be parameterized.

We then can obtain two limits on the mass of the black hole based on the radio data. In all cases, we use the radiative efficiency prescription described above, and the value for the gas density given by Pfahl & Rappaport (2001). The conservative limit on black hole mass will come from taking the accretion rate to be $10^{-3}$ of the Bondi rate, and using the $5 \sigma$ upper limit for the radio flux. Furthermore, in the two clusters where there are estimates of the ionized gas mass from pulsar velocity dispersions, this gas density, rather than the density estimated from Pfahl & Rappaport (2001) is used for the conservative limit. This can be regarded as a clear upper limit on the mass of a black hole. The second limit can be obtained by using the $3 \sigma$ upper limit on the radio flux and using $3\%$ of the Bondi rate as the most likely accretion rate. For NGC 2808, the conservative upper limit on the radio flux density will then be $270$ $\mu$Jy, while the more realistic upper limit is $162$ $\mu$Jy. These yield limits on the black hole mass from the data of $2100$ $M_{\odot}$ and $370$ $M_{\odot}$, respectively.

For the reader who wishes to consider cases which span an even larger range of parameter space than that covered by our best guess and our more conservative estimate, we derive the scaling relations for mass versus other parameter values. Let us define $b$ to be the fraction of the Bondi rate one assumes, and $p$ to be the fraction of the fundamental plane radio luminosity used and $g$ to be the fraction of the Pfahl & Rappaport gas density used. Then, since $\dot{m} \propto b \dot{M}^2$, $L_X \propto \dot{m}^2$, and $L_R \propto b L_X M_{BH}^{0.8}$, then one can see $L_R \propto p(bg)^{3/2} M_{BH}^{3/2}$. Solving for $M$, instead, one finds that $M \propto p^{0.31}(bg)^{0.38}$, the errors in the mass inferred are a factor of roughly 2 even if there exists an order of magnitude error in the gas density, the fraction of the Bondi rate used, or the scaling from X-rays to radio provided by the fundamental plane relation. Since we have taken our more conservative case to be the multiplications of a conservative estimate of each parameter value, it is very unlikely
that our conservative upper limits on black hole masses will be too low by even an order of magnitude.

We can contrast these results with previous discussion of a possible intermediate mass black hole in NGC 2808. NGC 2808 is considered a good candidate to host an intermediate mass black hole on the basis of its morphological properties. It has a large ratio of core radius to half-light radius – expected since an intermediate mass black hole will heat its host cluster dynamically (Trenti 2006). It also shows a density cusp (Noyola & Gebhardt 2006) argued to form a piece of the evidence for a black hole between 110 and 3100 solar masses (Miocchi 2007), assuming that the cusp is Bahcall-Wolf (1975) cusp, which arises from the deeper gravitational potential well near an IMBH than would otherwise be expected in a Wolf (1975) cusp, which arises from the deeper gravitational potential well near an IMBH than would otherwise be expected in a globular cluster. On the basis of a lack of X-ray sources down to 10^{32} ergs/sec at the position of the cluster’s centre, Servillat et al. (2008) suggested an upper limit of about 290 M_{\odot} on the mass of an intermediate mass black hole in the cluster. The assumptions used by Servillat et al. (2008) are similar to our most reasonable case. In this case, the radio and X-ray provide rather similar limits on the black hole mass – in cases where the gas density is relatively high, as is the most reasonable assumption for NGC 2808, X-ray measurements and radio measurements are about equally sensitive. Only when either the gas density, or the fraction of the Bondi rate at which accretion actually takes place are low, does the advantage of using radio data really manifest itself.

5 COMPARISON WITH OTHER CLUSTERS

Numerous groups have now made observations of globular clusters in the radio with the aims of testing whether they contain intermediate mass black holes. There have been many different sets of parameters used for converting the observations into constraints on the masses of the black holes in the cluster. We collect observed constraints on radio flux densities, along with the conservative and most likely constraints in Table 1.

Only G1 is detected in the radio. Many of the existing upper limits, even with the conservative parameter values taken, are well below the predictions made from assuming that the clusters fit on the M – σ relation. This should not be surprising. There is no physical reason why the M – σ relation should apply to globular clusters. Globular clusters fit to King models, while other classes of objects fit to De Vaucouleurs or Sersic models. While both classes of objects do show some mild deviations from these simple parameterisations of surface brightness, it has been shown clearly that the homology of these different classes of objects is quite different. Again, this is not surprising – globular clusters are dynamically relaxed and show little or no evidence of containing dark matter, while the galaxies which have similar values of σ, the dwarf spheroidal galaxies, are among the most dark matter dominated structures in the universe. While it is true that the locus of globular clusters is in a region of parameter space that intersects the fundamental plane relation for bulges (Dressler et al. 1987; Djorgovski & Davis 1987) and the fundamental manifold relation which is extended also to include clusters of galaxies (Zaritsky, Gonzalez & Zabludoff 2006), the slope for the globular clusters in nearly any two dimensional projection is quite different from the slope for the dark matter dominated systems (e.g. Burstein et al. 1997).

Some special attention should be devoted to the case of ω Cen, since it presents the strongest differences between claims from stellar dynamics measurements and accretion constraints. On its face, it appears to present a clear discrepancy between the predictions of an accretion based model, and the results from a stellar dynamical estimate which is far more sophisticated than a mere application of the M – σ relation – in this cluster. Noyola et al. (2008) have presented a rotation curve for the cluster indicating that the best fitting mass of a central dark object is 4 × 10^4 M_{\odot}. Even using our more conservative formulation, a black hole of 4 × 10^4 M_{\odot} in ω Cen would yield an X-ray luminosity of 3 × 10^{34} ergs s^{-1} – two orders of magnitude higher than the observational upper limit from Gendre, Barret & Webb (2003) – and a radio flux of about 250 mJy – more than enough to have called attention to itself long before the M – σ relation had even first been presented. One would need to scale the accretion rate downwards by another factor of 1000 from these more conservative parameter values in order for the accretion from the black hole not to be detectable. The cause of the discrepancy is thus almost certainly with the dynamical mass estimate. However, since an axisymmetric orbit-based model indicates that a black hole is significant at slightly less than the 2σ level (Noyola et al. 2008), the issue may simply be random measurement errors, with no methodological problems in either the accretion-based or dynamics-based measurements. Additionally, single-epoch spectroscopy of integrated light leaves in additional radial velocity components associated with binary motions, which can be a significant source of excess radial velocity for clusters of relatively low central density such as ω Cen (see e.g. Kouwenhoven & De Grijs 2008). Therefore, we find the radio and X-ray constraints on the black hole mass in ω Cen to be indicative of genuine upper limits on the black hole mass which argue strongly against a black hole of ~ 10^4 M_{\odot}, but which are not necessarily inconsistent with the results from dynamical studies.

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REFERENCES

Bahcall J.N., Ostriker J.P., 1975, Nature, 256, 23
Bahcall J.N., Wolf R.A., 1976, ApJ, 209, 214
Bash F.N., Gebhardt K., Goss W.M., Vanden Bout P.A., 2008, AJ, 135, 182
Blandford R.D., Königl A., 1979, ApJ, 232, 34
Baumgardt H., Hut P., Makino J., McMillan S., Portegies Zwart S., 2003, ApJ, 582, L21
Baumgardt H., Gualandris A., Portegies Zwart S., 2006, MNRAS, 372, 174
Bayer M., McDonald I., van Loon J.T., Woodward C.E., Gehrz R.D., Evans A., Dupree A.K., 2008, arXiv:0801.2172
Burstein D., Bender R., Faber S., Nolthenius R., 1997, AJ, 114, 1365
Camilo F., Lorimer D.R., Freire P., Lyne A.G., Manchester, R.N., 2000, ApJ, 535, 975
Colpi M., Possenti A., Gualandris A., 2002, ApJ, 570, L85
Clark G.W., 1975, ApJ, 199, 143L
Clark G.W., Markert T.H., Li F.K., 1975, ApJ, 199, 99L
De Rijcke S., Buyle P., Dejonghe H., 2006, MNRAS, 368, 43L
Djorgovski S., Davis M., 1987, ApJ, 313, 59
Dressler A., Lynden-Bell D., Burstein D., Davies R., Terlevich R., Wegner G., 1987, ApJ, 313, 42
Drukier G.A., Bailyn C.D., 2003, ApJ, 597, 125L
Dunn R.I.H., Fabian A.C., Celotti A., 2006, MNRAS, 372, 1741
Falcke H., Biermann P., 1995, A&A, 293, 665
Faulkner D.J., Scott T.R., Wood P.R., Wright A.E., 1999, ApJ, 374, L45
Freire P.C., Kramer M., Lyne A.G., Camilo F., Manchester R.N., D’Amico N., 2001, ApJ, 557, L105
Freire P.C., Camilo F., Kramer M., Lorimer D.R., Lyne A.G., Manchester R.N., D’Amico N., 2003, MNRAS, 340, 1359
Gallo E., Fender R.P., Perna R., 2002, ApJ, 578, L41
Gendre B., Barret D., Webb N., 2003, A&A, 400, 521
Gerssen J., van der Marel R.P., Gebhardt K., Guhathakurta P., Peterson R.C., Pryor C., 2002, AJ, 124, 3270
Gnedin O.Y., Zhao H.S., Pringle J.E., Fall S.M., Livio M., Meylan G., 2002, MNRAS, 360, L60
Maccarone T.J., 2005, MNRAS, 360, L60
Maccarone T.J., 2003, A&A, 409, 697
Maccarone T.J., 2005, MNRAS, 360, L60
Maccarone T.J., Gallo E., Fender R.P., 2003, MNRAS, 345, L19
Maccarone T.J., Kundu A., Zepf S.E., Rhode K.L., 2007, Nature, 445, 183
Maccarone T.J., Knigge C., 2007, A&G, 48e, 12
Maccarone T.J., Fender R.P., Tzioumis A.K., 2005, MNRAS, 356, L17
Maccarone T.J., Koerding E., 2006, A&G, 47f, 29
Maccarone T.J., Kundu A., Zepf S.E., Rhode K.L., 2007, Nature, 445, 183
McLaughlin D.E., Anderson J., Meylan G., Gebhardt K., Pryor C., Minniti D., Phinney S., 2006, ApJS, 166, 249
Merloni A., Heinz S., DiMatteo T., 2003, MNRAS, 345, 1057
Migliari S., Fender R.P., 2006, MNRAS, 366, 79
Miocchi P., 2007, ApJ, 660, 1246
Narayan R., Yi I., 1995, ApJ, 452, 710
Newell B., Dacosta G.S., Norris J., 1976, ApJ, 208, L55
Noyola E., Gebhardt K., 2006, AJ, 132, 447
Noyola E., Gebhardt K., Bergmann M., 2008, arXiv:0801.2782
Perna R., Narayan R., Rybicky G., Stella L., Treves A., 2003, ApJ, 594, 936
Pellegrini S., 2005, ApJ, 624, 155
Phinney S., 2006, ApJ, 644, 1
Pooley D., Rappaport S., 2001, ApJ, 550, 172
Pooley D., Rappaport S., 2001, ApJ, 550, 172
Piatek S., Pryor C., McClure R.D., Fletcher I.J.M., Hesser J.E., 1994, AJ, 107, 1397
Rasio F.A., 2007, HiA, 14, 215
Russell D.M., Maccarone T.J., Kording E., Homan J., 2007, MNRAS, 379, 1401
Sault R.J., Teuben P.J., Wright M.C.H., 1995, ASPC, 77, 433
Serrillat M., Webb N., Barret D., 2008, A&A, 480, 397
Shakura N.I., Sunayev R.A., 1973, A&A, 24, 337
Silk J., Arons J., 1975, ApJ, 200, L131
Sivakoff G.R., 2007, ApJ, 660, 1246
Tremaine S., et al., 2002, ApJ, 574, 740
Tremi N., 2006, astro-ph/0612040
Trudolyubov S., Priedhorsky W., 2004, ApJ, 616, 821
Ulvestad J.S., Greene J.E., Ho L.C., 2007, ApJ, 661, L151
Verbunt F., Hut P., 1987, IAU, 125, 187
Woosley S.E., Taam R.E., 1976, Nature, 263, 101
Zaritsky D., Gonzalez A.H., Zabludoff A.I., 2006, ApJ, 638, 725

Table 1. Summary of radio continuum observations of globular clusters. Where upper limits are given, they are at the 3σ level. It should be noted that there does exist a 2σ detection of a radio source in NGC 6266 (Bash et al. 2008). All distances come from Harris (1996), except the distance to G1 which comes from Holland (1998). Mass constraints from radio emission are given using the preferred and conservative set of parameters from above. The values of n_H listed in the table are those expected using the relation of Pfahl & Rappaport (2001) for the cluster parameter values in the Harris catalog. These are used generically, unless another value is quoted in the literature; if the literature value is larger, it is used in both cases. If the literature value is smaller, it is used as the conservative value, while the PR value is used as the most likely one, since the literature values probe only one phase of the ISM. The dynamical mass estimate for G1 comes from Gebhardt, Rich & Ho (2005); for ω Cen comes from Noyola et al. (2008); for 47 Tuc comes from McLaughlin et al. (2006). The others come from the M – σ relation – with the values for M 15, M 30 and M 62 taken from Bash et al., and the remainder computed using the relation of Tremaine et al. (2002). Values of σ are taken from Pyor & Meylan (1993), with the exceptions of Pal 2 and NGC 6440 which are taken from photometric modeling of Gnedin et al. (2002) – which yields velocity dispersions of 7 km/sec and 20 km/sec, respectively. The radio data are taken from: Ulvestad et al. (2007) for G1; Maccarone, Fender & Tzioumis (2005) for ω Cen, Bash et al. (2007) for M 15, M 60 and NGC 6266; De Rijcke et al. (2006) for NGC 6397 and 47 Tuc; Knapp et al. (1996) for Pal 2, NGC 1851, NGC 6440 and NGC 7099; and are new to this paper for NGC 2808. Knapp et al. (1996) also presented observations of NGC 6624, but the presence of a bright X-ray binary, 4U 1820-30 within 1” of the core of this cluster makes it difficult to estimate the radio flux from any possible IMBH in this cluster. The first listed radio mass limit is the more conservative one, while the second is the more likely one.

| Cluster | Distance (kpc) | L_R (μJy kpc^-2) | M_{BH, dyn} | M_{BH, rad} | n_H (cm^-2) |
|---------|----------------|------------------|------------|------------|------------|
| G1      | 780            | 1.7×10^7         | 18000      | 4500       | ~ 1        |
| ω Cen   | 5.3            | < 2700           | 4×10^4     | 2340/390   | 0.044      |
| M 15    | 10.3           | < 2700           | 1000       | 1150/140   | 0.42/0.2   |
| NGC 6397| 2.7            | < 1600           | 50         | 1000/170   | 0.16       |
| 47 Tuc  | 4.5            | < 4600           | 900±900    | 2300/200   | 0.28/0.07  |
| M 80    | 10.0           | < 3600           | 1600       | 1250/210   | 0.21       |
| NGC 6266| 6.9            | < 1700           | 3000       | 900/160    | 0.41       |
| NGC 2808| 9.5            | < 14600          | 2700       | 2100/370   | 0.24       |
| Pal 2   | 27.6           | < 34300          | 202         | 4400/750   | 0.08       |
| NGC 1851| 12.1           | < 11900          | 1000       | 1500/270   | 0.37       |
| NGC 6440| 8.4            | < 4900           | 13000      | 925/192    | 0.51       |
| NGC 7099| 8.0            | < 5200           | 70         | 1800/300   | 0.13       |
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2007, ApJ, 669, L69