Finding Faint Intermediate-mass Black Holes in the Radio Band

T. J. Maccarone (tjm@science.uva.nl)
University of Amsterdam

R. P. Fender
University of Southampton

A. K. Tzioumis
Australian National Telescope Facility

Abstract. We discuss the prospects for detecting faint intermediate-mass black holes, such as those predicted to exist in the cores of globular clusters and dwarf spheroidal galaxies. We briefly summarize the difficulties of stellar dynamical searches, then show that recently discovered relations between black hole mass, X-ray luminosity and radio luminosity imply that in most cases, these black holes should be more easily detected in the radio than in the X-rays. Finally, we show upper limits from some radio observations of globular clusters, and discuss the possibility that the radio source in the core of the Ursa Minor dwarf spheroidal galaxy might be a $\sim 10,000 - 100,000M_\odot$ black hole.

1. Introduction

Black holes are generally found to exist in two classes - the stellar mass (i.e. about $10M_\odot$) black holes which are usually found as a result of their being in X-ray binaries, and the galactic mass (i.e. $10^6 - 10^9M_\odot$) black holes found in the cores of massive galaxies. Some recent evidence has begun to develop for black holes with masses just below $10^6M_\odot$ (e.g. Fillipenko & Ho 2003; Greene & Ho 2004), and some of the ultraluminous X-ray sources show evidence for spectral (e.g. Jon Miller’s contribution in this volume) and variability (Strohmayer & Mushotzky 2003) characteristics that would indicate black holes of 100-1000 $M_\odot$.

Whether globular clusters and dwarf spheroidal galaxies have black holes in their centers is an especially controversial topic. Some authors have argued that globular clusters should build up black holes of roughly 0.1% of their total mass through mergers of stellar mass black holes (Miller & Hamilton 2002); this fraction of the total mass is roughly the same as the fraction of galactic bulges’ masses locked up in their central black holes (Magorrian et al. 1998), and there have been some claims of observational evidence for these intermediate-mass black holes (see e.g. Gebhardt, Rich & Ho 2002; Gerssen et al. 2002). On the other hand, it has been argued that the central increases in mass-to-light ratio

© 2002 Kluwer Academic Publishers. Printed in the Netherlands.
in globular clusters can be equally well explained by concentrations of white dwarfs (e.g. Baumgardt et al. 2003; Gerssen et al. 2003), and that black holes should be dynamically ejected from globular clusters (Portegies Zwart & McMillan 2000). It has been suggested (Drukier & Bailyn 2003) that searches for individual high velocity stars could be the most effective way to search for dynamical evidence of black holes in globular clusters, but that there might not be enough stars to sample the gravitational potentials of globular clusters well enough to make use of this method.

In dwarf spheroidal galaxies, the determination of whether there are intermediate-mass black holes is at least as wide open. As the escape velocities of dwarf spheroidal galaxies are typically smaller than those of globular clusters, it is more likely that the gravitational radiation recoil effect should work to eject black holes participating in unequal mass mergers from these systems (e.g. Favata et al. 2004). On the other hand, it has been suggested on theoretical grounds that because the dwarf galaxies are likely to be the first galaxies formed, they should have the densest peaks in their early-universe densities, and hence might have formed very high mass black holes during their Population III phases - black holes with 5-40\% of their stellar mass (Ricotti & Ostriker 2004). Observational constraints on the central mass concentrations of dwarf spheroidal galaxies are generally quite poor.

In both the dwarf spheroidal galaxy and globular cluster cases, it seems reasonable to search for new means of finding these black holes. Almost thirty years ago, it was suggested that the X-ray emission from globular clusters might be intermediate-mass black holes accreting from the interstellar medium (Bahcall & Ostriker 1975). The detection of Type I X-ray bursts from the bright globular cluster sources has since ruled out this possibility, but much deeper observations from the Chandra Observatory have placed tight constraints on the X-ray emission that could be coming from such sources (Grindlay et al. 2001; Ho, Terashima & Okajima 2003). In a few globular clusters (M 15 and 47 Tuc), variations in the pulsar dispersion measures provide measurements of the density of the interstellar medium (Freire et al. 2001), and combining these gas density measurements with the X-ray upper limits in these globular clusters still fails to prove that black holes of about 1/1000 of the total mass of the cluster are not present, if one makes reasonable assumptions about the fraction of the Bondi-Hoyle rate that is typically accreted in low luminosity systems (see e.g. Bower et al. 2003; Perna et al. 2003) and on the radiative efficiency of this accreted material (see e.g. Narayan & Yi 1994; Fender, Gallo & Jonker 2003). In light of the new fundamental plane relations for black hole activity (Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2004),
which show that the radio luminosity, $L_R$ and the X-ray luminosity $L_X$ of a black hole with mass $M_{BH}$ are related such that $L_X \propto L_R^{0.6} M_{BH}^{0.8}$, it has been shown that the most efficient way to search for evidence of accretion from low luminosity, high mass black holes such as those predicted to exist in globular clusters and dwarf spheroidal galaxies is by searching for radio emission (Maccarone 2004). For example, a single 12-hour observation of M 15 with the VLA would place a better constraint on the existence of a 1000 $M_\odot$ black hole than would the entire mission lifetime of the Chandra Observatory. The prospects for improving the sensitivity limits in the radio in the near future are excellent; the VLA expansion project will improve its sensitivity by a factor of about 10, making $\mu$Jy level observations possible in quite short exposure times; the High Sensitivity Array is already allowing $\mu$Jy level VLBI scale interferometry, and the Square Kilometer Array project provides some hope that these (and better) sensitivity levels will be reachable from the Southern Hemisphere within the next 20 years.

In this contribution, we will outline the basic method by which we attempt to predict the radio fluxes from intermediate-mass black holes in globular clusters, and then we will describe some progress that has been made towards this goal.

2. Methodology

In Maccarone (2004), a methodology for going from a globular cluster’s mass and distance to its expected radio flux was laid out. In this paper, we will briefly summarize the assumptions of that work, but we refer the reader to Maccarone (2004) and to the other cited references for a full justification of each assumption. Specifically, we assume:

- A black hole mass of 0.1% of the globular cluster’s stellar mass (Miller & Hamilton 2002)
- A gas density of 0.15 H cm$^{-3}$, approximately the value estimated from pulsar dispersion measures in M 15 and 47 Tuc, and expected from stellar mass loss (Freire et al. 2001).
- Accretion at 0.1-1% of the Bondi rate, with the sub-Bondi rate due to disk winds and/or convection as constrained by observations of low luminosity AGN in the Galactic Center and in elliptical galaxies and the lack of observations of isolated neutron stars accreting from the interstellar medium (e.g. Bower et al. 2003; Perna et al. 2003).
A radiative efficiency in the X-rays of:

\[ \eta = (0.1) \times \left( 1 + \frac{A^2}{2L_{\text{tot}}} - A \sqrt[4]{\frac{A^2}{4L_{\text{tot}}^2} + \frac{1}{L_{\text{tot}}}} \right), \]  

(1)

with \( A \) a constant to be fitted from observations (and being larger when the jet’s kinetic power is a larger fraction of the total accretion power), and \( L_{\text{tot}} \) the radiative plus kinetic luminosity of the system in Eddington units, as used by Fender, Gallo & Jonker (2003) to explain the \( L_X - L_R \) correlation observed by Gallo, Fender & Pooley (2003), with the idea being that enough kinetic power is pumped into a jet to make the accretion flow radiatively inefficient (see also, e.g. Malzac, Merloni & Fabian 2004). Whether the radiative inefficiency is due to mass and energy loss into a jet or also partially due to advection into the black hole (e.g. Ichimaru 1977; Narayan & Yi 1994) is not clearly established by these relations, and does not affect the results presented here. We have set \( A = 6 \times 10^{-3} \) for these calculations, which is based on a conservative estimate of the jet power. This relation is used to convert a calculated accretion rate (from the assumed fraction of the Bondi-Hoyle rate) into a calculated X-ray luminosity.

The fundamental plane relationship among X-ray luminosity, radio luminosity and black hole mass of Merloni et al. (2003), parameterized for convenient applications to Galactic globular clusters:

\[ F_{5 \text{GHz}} = 10 \left( \frac{L_X}{3 \times 10^{34} \text{ergs/sec}} \right)^{0.6} \left( \frac{M_{\text{BH}}}{100 M_\odot} \right)^{0.78} \left( \frac{d}{10 \text{kpc}} \right)^{-2} \mu\text{Jy}. \]  

(2)

This relation is used to convert the calculated X-ray luminosity from the previous step into a radio flux. We note that the relation found by Falcke et al. (2004), which considered only flat spectrum, low luminosity radio sources like those we expect to see in the centers of dwarf galaxies or globular clusters, is consistent with this relation within the uncertainties. Following these assumptions, several globular clusters should have central radio sources brighter than a few \( \mu\text{Jy} \), but only Omega Cen should have a radio source brighter than 40 \( \mu\text{Jy} \), and even Omega Cen should be that bright only if the accretion rate is closer to 1% of the Bondi-Hoyle rate than it is to 0.1% of the Bondi-Hoyle rate. Nonetheless, the predicted X-ray fluxes for the globular clusters are generally well below detectability levels, even with very long observations by the Chandra Observatory.
3. Applications to Globular Clusters

We have applied this method to two globular clusters so far, and in both cases have found no evidence for an accreting central black hole. Omega Cen was observed by us with the Australian Telescope Compact Array (ATCA) simultaneously at 4.8 and 8.6 GHz for 12 hours on 8 May 2004, with no detection made at either frequency. The non-detection yielded a $3\sigma$ upper limit on the flux of just under 100 $\mu$Jy, under the assumption that the radio spectrum of the source should be flat. Maccarone (2004) predicted that the flux level should be at least 150 $\mu$Jy under the most conservative set of parameter values used in that paper. This would seem to imply that there cannot be a black hole with 0.1% of the cluster’s mass in Omega Cen, but given the scatter in the fundamental plane relation, and the fact that the gas density in Omega Cen has been assumed to be similar to those in M 15 and 47 Tuc, rather than measured, this upper limit should not be interpreted as such strong evidence against an intermediate-mass black hole. The upper limit does, however, provide strong evidence against the combination of 0.1% of the cluster mass being in an intermediate black hole, with an accretion rate of $\sim$ 1% or more of the Bondi rate.

We have also considered previous radio observations of M 15 which were made with the Very Large Array (VLA) for the purposes of finding radio pulsars (Johnston, Kulkarni & Goss 1991). These data were taken at 1.4 GHz, and reached a noise level of 43 $\mu$Jy, with no unidentified sources found within the core of the globular cluster. The upper limits are thus rather similar to those found for Omega Cen, in terms of flux level. The constraints on whether there exists a black hole with 1/1000 of the cluster mass, though, are much weaker, because the cluster is smaller and further away than Omega Cen. A useful constraint can be made on whether there exists a black hole substantially more massive than this. In the context of the assumptions listed above, the $3\sigma$ upper limit for the radio flux corresponds to the flux level expected from a 700 $M_\odot$ black hole accreting 0.1% of its Bondi rate - therefore, the upper limit on the radio flux measured in this cluster’s core can be taken as evidence against the claimed 2500 $M_\odot$ black hole in M 15 (Gerssen et al. 2002), although it should be noted that the uncertainty on this mass measurement was rather large, and the measurement was not inconsistent with a black hole of 700 $M_\odot$. Proposed High Sensitivity Array observations could reduce the noise level in the radio data by a factor of about 10, which could, in turn allow for either a detection of the black hole or a truly constraining upper limit on its possible mass.
4. Applications to Dwarf Spheroidal Galaxies

We have also searched the NRAO VLA Sky Survey (NVSS) catalog around the centers of the Milky Way’s Northern Hemisphere dwarf spheroidal galaxies. This catalog has some sources as faint as 1 mJy, but is complete only at the level of about 3-4 mJy, and it covers the entire sky north of a declination of -40 degrees at a frequency of 1.4 GHz (Condon et al. 1998). One source was found within the 3σ error circle of the center of a dwarf spheroidal galaxy - a 7.1 mJy source about 20” from the reported center of the Ursa Minor dwarf spheroidal galaxy. The Ursa Minor galaxy is one of the nearest \((d=66 \text{ kpc})\), most diffuse (the 20” offset is roughly the 1σ error in the centroid position of the galaxy), and most massive \((M = 2.3 \times 10^7 M_\odot)\) of the Milky Way’s dwarf spheroidal satellites (see Mateo 1998 for a review of the properties of dwarf spheroidal galaxies including measurements of parameter values). The density of NVSS sources on the sky is such that there is about a 5% chance of finding a source within the 3σ error box of the center of the Ursa Minor dwarf spheroidal galaxy. The other dwarf galaxies are further away and more centrally concentrated, so their centroid positions are more well established and the chance of a spurious coincidence between a radio source and their core positions would be quite small. On the other hand, because they are further away and less massive, their expected radio fluxes would be smaller than that of the Ursa Minor’s core, if one assumes there should be a linear correlation between galaxy mass and black hole mass. The measurements of gas contents of dwarf spheroidal galaxies are mostly upper limits (although see Bouchard, Carignan & Mashchenko 2003 for one detection), so it is not as straightforward to convert a radio flux into a black hole mass as it would be in a globular cluster. If we assume that the gas density is 1/30 to 1/100 as high in dwarf spheroidal galaxies as in globular clusters (because the dwarf spheroidals are more diffuse), then we find a black hole mass of about \(1-2 \times 10^5 M_\odot\) would be required to produce the observed radio flux. The expected X-ray luminosity from such an object would be \(\sim \) a few \(\times 10^{34}\) ergs/sec, below the detection limits of past X-ray observations (e.g. Markert & Donahue 1985; Zang & Meurs 2001), but easily detectable by Chandra or XMM. Because the error circle of the NVSS source is about 4” in radius, it is not possible to identify a unique optical counterpart and determine whether this radio source is more likely to be in the Ursa Minor galaxy or a background AGN. Follow-ups in radio and X-ray have been proposed, both to obtain a better positional accuracy for the radio source, and to determine its X-ray to radio flux ratio.
5. Prospects for Future Improvements

One key area for future improvements of this work is to get deeper radio observations of the globular clusters and dwarf spheroidal galaxies most likely to show radio sources associated with intermediate-mass black holes. This work is already in progress, with an application in submission for High Sensitivity Array time to observe M 15. Unfortunately, most of the best globular cluster candidates are in the Southern Hemisphere, and with the ATCA data showing only upper limits for Omega Cen, the prospects of detecting a black hole in any other globular cluster by using ATCA seem remote.

The other key area that needs more work is in improving our measurements of the gas densities in these systems, especially in the dwarf spheroidal galaxies. The methodology for doing so is not as clear. Searches for absorption lines in the spectra of background AGN seem to be one of the most promising routes (Tinney, Da Costa & Zinnecker 1997), and such AGN should be detected as part of any program searching for X-ray emission from a central black hole as well.

Acknowledgements

It is a pleasure to thank the following for useful discussions which contributed to this work: Dave Meier, Heino Falcke, Eva Grebel, Russell Edwards, Andrea Merloni, Cole Miller, Simon Portegies Zwart, Fred Rasio, Ben Stappers and Kathy Vivas.

References

Bahcall, J.N. and J.P. Ostriker Massive black holes in globular clusters Nature 256:23–24, 1975.
Baumgardt, H., P. Hut, J. Makino, S. McMillan and S. Portegies Zwart On the Central Structure of M15. Astrophysical Journal Letters, 582:L21–L24, 2003.
Bouchard, A., C. Carignan and S. Mashchenko The HI Environment of the Sculptor Dwarf Spheroidal Galaxy. Astronomical Journal, 126:1295–1304, 2003.
Bower, G.C., M.C.H. Wright, H. Falcke and D.C. Backer Interferometric Detection of Linear Polarization from Sagittarius A* at 230 GHz Astrophysical Journal, 588:331–337, 2003.
Condon, J.J., W.D. Cotton, E.W. Greisen, Q.F. Yin, R.A. Perley, G.B. Taylor and J.J. Broderick The NRAO VLA Sky Survey. Astronomical Journal, 126:1295–1304, 2003.
Drukier, G.A. and C.D. Bailyn Can High-Velocity Stars Reveal Black Holes in Globular Clusters? Astrophysical Journal Letters, 597:L125–L128, 2003.
Falcke, H., E. Körding and S. Markoff A scheme to unify low-power accreting black holes. Jet-dominated accretion flows and the radio/X-ray correlation. *Astronomy and Astrophysics*, 414:895–903, 2004.

Fender, R.P., E. Gallo and P.G. Jonker Jet-dominated states: an alternative to advection across black hole event horizons in ‘quiescent’ X-ray binaries. *Monthly Notices of the Royal Astronomical Society*, 343:L99–L103, 2003.

Fillipenko, A.V. and L.C. Ho A Low-Mass Central Black Hole in the Bulgeless Seyfert 1 Galaxy NGC 4395. *Astrophysical Journal Letters*, 588:L13-L16, 2003.

Freire, P.C., M. Kramer, A.G. Lyne, F. Camilo, R.N. Manchester and N. D’Amico Detection of Ionized Gas in the Globular Cluster 47 Tucanae. *Astrophysical Journal Letters*, 557:L105–L108, 2001.

Gallo, E., R.P. Fender & G.G. Pooley A universal radio-X-ray correlation in low/hard state black hole binaries. *Monthly Notices of the Royal Astronomical Society*, 344:60–72, 2003.

Gebhardt, K., Rich, R.M. & Ho, L.C. A 20,000 $M_{\odot}$ Black Hole in the Stellar Cluster G1. *Astrophysical Journal Letters*, 578:L41-L45, 2002.

Gerssen, J., R.P. van der Marel, K. Gebhardt, P. Guhathakurta, R.C. Peterson and C. Pryor Hubble Space Telescope Evidence for an Intermediate-Mass Black Hole in the Globular Cluster M15. II. Kinematic Analysis and Dynamical Modeling. *Astronomical Journal*, 124:3270–3288, 2002.

Gerssen, J., R.P. van der Marel, K. Gebhardt, P. Guhathakurta, R.C. Peterson and C. Pryor Addendum: Hubble Space Telescope Evidence for an Intermediate-Mass Black Hole in the Globular Cluster M15. II. Kinematic Analysis and Dynamical Modeling. *Astronomical Journal*, 125:376–377, 2003.

Greene, J.E. and L.C. Ho Active Galactic Nuclei with Candidate Intermediate-Mass Black Holes. *Astrophysical Journal*, 610:722–736, 2004.

Grindlay, J.E., C. Heinke, P.D. Edmonds and S.S. Murray High-Resolution X-ray Imaging of a Globular Cluster Core: Compact Binaries in 47Tuc. *Science* 2525:2290–2295, 2001.

Ho, L.C., Y. Terashima and T. Okajima A Stringent Limit on the Accretion Luminosity of the Possible Central Black Hole in the Globular Cluster M15. *Astrophysical Journal Letters*, 587, L35–L38, 2003.

Ichimaru, S. Bimodal behavior of accretion disks - Theory and application to Cygnus X-1 transitions. *Astrophysical Journal*, 214:840–855, 1977.

Johnston, H.M., S.R. Kulkarni and M.W. Goss Deep VLA images of globular clusters. *Astrophysical Journal Letters*, 382:L89–L92, 1991.

Maccarone, T.J. Radio emission as a test of the existence of intermediate-mass black holes in globular clusters and dwarf spheroidal galaxies. *Monthly Notices of the Royal Astronomical Society*, 351:1049–1053, 2004.

Magorrian, J., et al. The Demography of Massive Dark Objects in Galaxy Centers. *Astronomical Journal*, 115:2285–2305, 1998.

Malzac, J., A. Merloni, and A.C. Fabian Jet-disc coupling through a common energy reservoir in the black hole XTE J1118+480. *Monthly Notices of the Royal Astronomical Society*, 351:253–264, 2004.

Markert, T.H. and M.E. Donahue Observations of four nearby galaxies with the Einstein Observatory. *Astrophysical Journal*, 297:564–571, 1985.

Mateo, M. Dwarf Galaxies of the Local Group. *Annual Review of Astronomy and Astrophysics*, 36:435–506, 1998.

Miller, M.C. and D.P. Hamilton Production of intermediate-mass black holes in globular clusters. *Monthly Notices of the Royal Astronomical Society*, 330:232–240, 2002.
Narayan, R. and I. Yi  Advection-dominated accretion: A self-similar solution  *Astrophysical Journal Letters*, 428:L13–L16, 1994.

Perna, R., R. Narayan, G. Rybicki, L. Stella and A. Treves Bondi Accretion and the Problem of the Missing Isolated Neutron Stars  *Astrophysical Journal*, 594:936–942, 2003.

Portegies Zwart, S.F. and S.L.W. McMillan  Black Hole Mergers in the Universe  *Astrophysical Journal Letters*, 528:L17-L20, 2000.

Ricotti, M. and J.P. Ostriker  X-ray pre-ionization powered by accretion on the first black holes - I. A model for the WMAP polarization measurement  *Monthly Notices of the Royal Astronomical Society*, 352:547–562, 2004.

Strohmayer, T.E. and R.F. Mushotzky  Discovery of X-Ray Quasi-periodic Oscillations from an Ultraluminous X-Ray Source in M82: Evidence against Beaming  *Astrophysical Journal Letters*, 586:L61–L64, 2003.

Tinney, C.G., G.S. Da Costa and H. Zinnecker  QSOs behind the nearest Milky Way satellite galaxies.  *Monthly Notices of the Royal Astronomical Society*, 285:111–124, 1997.

Zang, Z. and E.J.A. Meurs  The Cores of Local Group Galaxies at X-Rays  *Astrophysical Journal*, 556:24–34, 2001.

*Address for Offprints:*  tjm@science.uva.nl
