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THE CANDIDATE INTERMEDIATE-MASS BLACK HOLE IN THE GLOBULAR CLUSTER M54

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ABSTRACT

Ibata et al. reported evidence for density and kinematic cusps in the Galactic globular cluster M54, possibly due to the presence of a 9400 $M_\odot$ black hole. Radiative signatures of accretion onto M54's candidate intermediate-mass black hole (IMBH) could bolster the case for its existence. Analysis of new *Chandra* and recent *Hubble Space Telescope* astrometry rules out the X-ray counterpart to the candidate IMBH suggested by Ibata et al. If an IMBH exists in M54, then it has an Eddington ratio of $L(0.3\text{–}8\,\text{keV})/L(\text{Edd}) < 1.4 \times 10^{-10}$, more similar to that of the candidate IMBH in M15 than that in G1. From new imaging with the NRAO Very Large Array, the luminosity of the candidate IMBH is $L(8.5\,\text{GHz}) < 3.6 \times 10^{29}$ erg s^{-1} (3σ). Two background active galaxies discovered toward M54 could serve as probes of its intracluster medium.

Key words: black hole physics – globular clusters: individual (M54) – radio continuum: general – X-rays: general

1. MOTIVATION

Quantifying the space density of low-mass black holes (BHs) in the local universe has important implications for predicting gravity wave signals (Hughes 2009), for understanding formation channels for seed BHs (Volonteri et al. 2008), and for testing simulations of gravitational wave recoil (Holley-Bockelmann et al. 2008). Moreover, establishing the existence or breakdown of scaling relations between central BHs and galaxies at the low-mass end will help identify the physical processes driving the relation between BH mass M_{BH} and stellar velocity dispersion σ_* (e.g., Greene et al. 2010).

Planned NIR telescopes in the 30 m class will eventually offer access to BHs with $M_{\text{BH}} \gtrsim 10^5\,M_\odot$ in the local universe (Ferrarese 2003; Ferrarese & Ford 2005). But lower-mass BHs will remain difficult to find, as their observational signature on surrounding stars is limited to a prohibitively small spatial scale beyond the Local Group. We refer to these systems as intermediate-mass black holes (IMBHs), since they occupy the gap in mass between the well-studied stellar-mass BHs with $M_{\text{BH}} \sim 10\,M_\odot$ and the well-established BHs with $M_{\text{BH}} \gtrsim 10^5\,M_\odot$.

BH masses of order $10^4\,M_\odot$ have been estimated for two globular clusters, namely, G1 in M31 (Gebhardt et al. 2002) and ω Cen in the Galaxy (Noyola et al. 2010). Both estimates have been controversial. For G1 the objections of Baumgardt et al. (2003) were countered by Gebhardt et al. (2005). For ω Cen van der Marel & Anderson (2010) provide a contradicting mass upper limit.

Ibata et al. (2009) reported the detection of stellar density and kinematic cusps in M54 (NGC 6715), a globular cluster at a distance of 26.3 kpc in the center of the Sagittarius dwarf galaxy (Bellazzini et al. 2008).[4] Ibata et al. interpreted their findings as possible evidence for a central BH with $M_{\text{BH}} \sim 9400\,M_\odot$, similar to G1 and possibly similar to ω Cen. But Ibata et al. also noted that the orbits of the cusp stars in M54 could have moderate radial anisotropies. They demonstrated that the strong density gradient in a cusp could impede isotropic orbits from being established, contrary to the common view that isotropic orbits always arise when cluster relaxation times are relatively short. If such anisotropic orbits are present, they could mimic the signature of a central IMBH.

The interpretation of M54's cusp data is thus ambiguous, and other lines of evidence for, or against, an IMBH should be sought. Simulations suggest a globular cluster with primordial binary stars can achieve a ratio of core to half-mass radius of only 0.08 or less, whereas larger ratios can be realized by adding an IMBH (Trenti et al. 2007; Fregeau & Razio 2007). For M54 this ratio is about 0.2 (Harris 1996). Also, simulations of massive disk galaxies suggest that several tidally stripped cores of dwarf satellites could retain their IMBHs (Bellovary et al. 2010). This fits in with M54's location in the center of the disrupting Sagittarius dwarf galaxy (Bellazzini et al. 2008).

Radiative signatures of accretion onto M54's candidate IMBH could bolster the case for its existence. Ramsay & Wu (2006a) detected several *Chandra* sources within M54's half-mass radius and suggested, based on the sources' X-ray luminosities and colors, that they were cataclysmic variables or low-mass X-ray binaries. However, they noted that one possibly blended source, X-ray Id 2, was located within 1″ (0.13 pc) of the center of the stellar density, taken a proxy for the center of mass. This led Ibata et al. (2009) to suggest that X-ray Id 2 could be the counterpart to the candidate IMBH in M54.

In this paper, we compare recent subarcsecond astrometry for the stellar density center (Goldsbury et al. 2010) to improved astrometry for X-ray Id 2 (Evans et al. 2010), ruling out an X-ray counterpart to the candidate IMBH. We also present new photometry of M54 with the NRAO Very Large Array (VLA;[5] Thompson et al. 1980), detecting neither the candidate IMBH nor any stellar emitters within the cluster's half-mass radius. Two X-ray sources with radio counterparts are detected within M54's limiting radius. The new X-ray and radio data are presented in Section 2 and their implications are explored in Section 3. A summary and conclusions appear in Section 4.

[4] 1″ = 0.13 pc. The core, half-mass, and limiting radii of M54 are 6.″6 = 0.86 pc, 29.″4 = 3.8 pc, and 6.′3 = 49 pc, respectively (Harris 1996; Ibata et al. 2009; Sollima et al. 2010).

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Table 1
Subarcsecond Astrometry of Cluster Components

R.A. (J2000) (1)	Decl. (J2000) (2)	Error (″) (3)	Component (4)	Ref. (5)
18 55 02.45	−30 28 57.6	0.56	X-ray Id 4	1
18 55 02.77	−30 28 53.1	0.59	X-ray Id 6	1
18 55 02.95	−30 28 45.1	0.43	X-ray Id 1	1
18 55 03.46	−30 28 47.6	0.46	X-ray Id 2	1
18 55 03.345	−30 28 47.1	0.72	Stellar density center	2
18 55 03.33	−30 28 47.5	0.2	Stellar density center	3
18 55 03.65	−30 28 41.0	0.62	X-ray Id 5	1
18 55 03.89	−30 28 38.1	0.53	X-ray Id 3	1

Notes. Columns 1 and 2: component position. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Column 3: radius of error circle at 95% confidence level. Column 4: component name. Column 5: reference.
References. (1) This work; (2) Ibata et al. 2009; and (3) Goldsbury et al. 2010.

2. DATA

2.1. Chandra Source Catalog

A cone search toward the stellar density center (Ibata et al. 2009) was made using version 1.1[6] of the *Chandra* Source Catalog (CSC; Evans et al. 2010). Table 1 gives the broadband (0.3–8 keV) ACIS positions returned for X-ray Ids 1–6 of Ramsay & Wu (2006a) along with the position error radii at the 95% confidence level that includes an absolute astrometric error. The faintest source reported by Ramsay & Wu (2006a), X-ray Id 7, was not recovered from the CSC. If the position error radius for the Ramsay & Wu (2006a) astrometry is dominated by the absolute accuracy of 0″.6 at the 90% confidence limit,[7] the Ramsay & Wu (2006a) positions for X-ray Ids 1–6 agree with those reported in Table 1. X-ray Id 2 was noted as a possibly blended source by Ramsay & Wu (2006a). This trait is confirmed from the broadband CSC data: X-ray Id 2 is spatially resolved, with a deconvolved 1σ radius of $0''.67 \pm 0''.18$, which is indicated in Figure 1.

2.2. VLA Imaging

The C configuration of the VLA was used, under proposal code AH1001, to observe M54 near transit on UT 2009 July 12, 16, 23 and 2009 August 13. The a priori pointing position for M54 was placed 10″ north of the stellar density center (Ibata et al. 2009) to avoid any phase-center artifacts. Observations were made assuming a coordinate equinox of 2000 and were phase referenced to the calibrator J1845-2852 at an assumed position of $\alpha(J2000) = 18^h45^m51^s.3683$ and $\delta(J2000) = -28^\circ52'40''.276$ with one-dimensional errors at 1σ better than 1 mas.[8] The switching time between M54 and J1845-2852 was 240 s, while the switching angle was 2°.6. A net exposure time of 11,500 s was achieved for M54. The center frequency was 8.4601 GHz, abbreviated as 8.5 GHz hereafter. Data were acquired with a bandwidth of 100 MHz for each circular polarization. Observations of 3C 48 were used to set the amplitude scale to an accuracy of about 3%. All but two or three of 27 antennas provided data of acceptable quality, with most data loss attributable to Expanded Very Large Array retrofitting activities.

6 http://cxc.harvard.edu/csc/
7 http://cxc.harvard.edu/cal/ASPECT/celmon
8 http://www.aoc.nrao.edu/software/sched/catalogs/sources.vlba

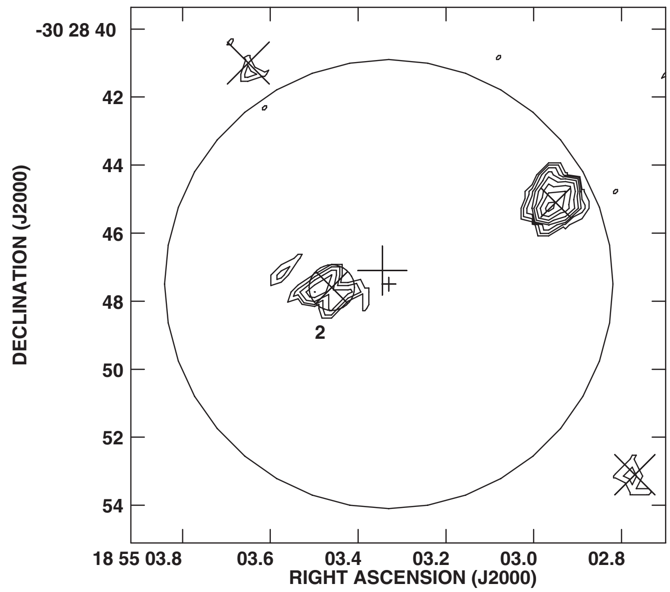

Figure 1. *Chandra* broadband (0.3–8 keV) ACIS image of the central 16″ (2.1 pc) of the globular cluster M54. Contours are separated by the square root of 2 and start at 2.0×10^{-6} photons cm^{-2} s^{-1}. The large circle shows M54's core radius ($6''.6 = 0.86$ pc) and its origin is at the stellar density center from Goldsbury et al. (2010) marked with a small plus sign. The stellar density center from Ibata et al. (2009) is marked with a large plus sign. The crosses mark the CSC version 1.1 locations of the innermost X-ray Ids given in Table 1. The sizes of the plus signs and the crosses convey position errors at the 95% confidence level. X-ray Id 2, labeled, is spatially resolved and its deconvolved 1σ radius of 0″.67 is indicated by the small circle.

The data were calibrated using the 2009 December 31 release of the NRAO AIPS software. No polarization calibration or self-calibrations were performed. After calibration, each day's visibility data for M54 were concatenated. The AIPS task `imagr` was applied to the concatenated data to form and deconvolve a naturally weighted image of the Stokes *I* emission. This image was corrected for primary-beam attenuation with the AIPS task `pbcor` and is shown in Figure 2. From Figure 2, a 3σ upper limit of 51 μJy beam^{-1} can be placed on any 8.5 GHz emitters within the cluster's half-mass radius.

2.3. Validating the Chandra Astrometry

Two *Chandra* sources (Ramsay & Wu 2006b) within M54's limiting radius have counterparts at 8.5 GHz. The VLA sources are J185500.12-303049.7 and J185510.68-302650.9, with integrated flux densities of 1.23 ± 0.07 mJy and 3.78 ± 0.13 mJy, respectively. Each has a diameter less than 3″ and a position error radius, dominated by the phase-referencing strategies, of 0″.2. Cone searches toward these two using CSC version 1.1 return broadband ACIS counterparts J185500.13-303049.4 with an error radius of 0″.53 and J185510.67-302651.1 with an error radius of 0″.48; each has a diameter less than 1″. The VLA and *Chandra* positions agree within their combined errors, offering an independent validation of the X-ray astrometry.

3. IMPLICATIONS

3.1. Candidate IMBH

The energy equipartition argument of Pooley & Rappaport (2006) implies that the candidate IMBH in M54, with mass $M_{BH} \sim 9400\, M_\odot$ (Ibata et al. 2009), should coincide with the cluster's center of mass to within 0″.18 (0.02 pc). Using the

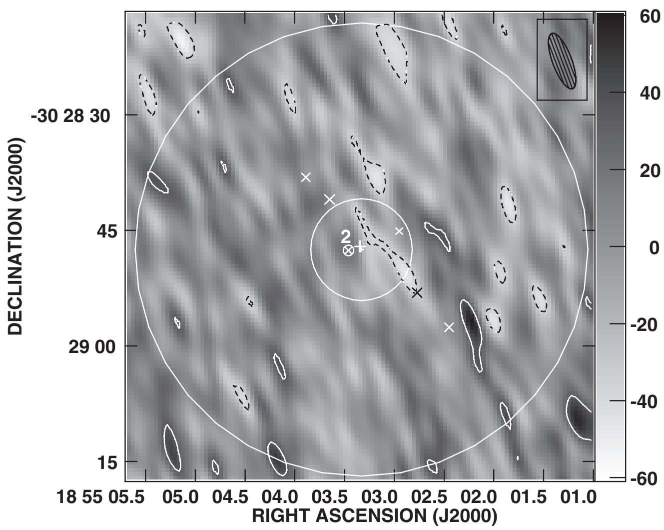

Figure 2. VLA image of Stokes I emission at 8.5 GHz of the central 1′ (7.8 pc) of the globular cluster M54. Natural weighting was used, giving an rms noise of 17 μJy beam^{-1} (1 σ) and beam dimensions at FWHM of 7.″64 × 2.″49 with elongation P.A. = 20.°6 (hatched ellipse). Contours are at −6, −4, −2, 2, 4, and 6 times 1σ. Negative contours are dashed and positive ones are solid. Linear gray-scale spans −60 μJy beam^{-1} to 60 μJy beam^{-1}. Concentric circles show M54's core radius (6.″6 = 0.86 pc) and half-mass radius (29.″4 = 3.8 pc), and their origins coincide with the stellar density center from Goldsbury et al. (2010). The symbol sizes and meanings are the same as for Figure 1.

center of the stellar density as a proxy for the center of mass, the position of the candidate IMBH will be indistinguishable from those for the stellar density center reported in Table 1. Under these assumptions, the best position for the candidate IMBH is that provided by Goldsbury et al. (2010).

Figure 1 shows the locations of the innermost cluster components in Table 1. The positions for the stellar density center (Goldsbury et al. 2010) and X-ray Id 2 are offset by 1.″7 (0.22 pc). The quadratic sum of the 1σ error in the stellar astrometry (0.″1) and the X-ray astrometry (0.″23) is about 0.″25. This leads to a normalized offset of 1.″7/0.″25 ∼ 6.8, larger than the upper limit of 3 signifying positional coincidence (Condon et al. 1995). Thus X-ray Id 2 coincides neither with the stellar density center nor, by the reasoning above, with the candidate IMBH. Although X-ray Id 2 is spatially resolved, its radial extent does not significantly alter this conclusion. This astrometric result for X-ray Id 2 is consistent with its luminosity and colors indicating a possible blend of cataclysmic variables or low-mass X-ray binaries (Ramsay & Wu 2006a).

Adopting the unabsorbed flux limit and power-law index quoted in Ramsay & Wu (2006a), the candidate IMBH in M54 has a luminosity of $L(0.3\text{–}8\,\text{keV}) < 1.7 \times 10^{32}$ erg s^{-1} and an Eddington ratio of $L(0.3\text{–}8\,\text{keV})/L(\text{Edd}) < 1.4 \times 10^{-10}$. This latter limit is similar to the limit of $L(0.2\text{–}10\,\text{keV})/L(\text{Edd}) < 2.2\times10^{-9}$ reported by Ho et al. (2003) for the candidate IMBH in M15. In contrast, the candidate IMBH in G1 has a considerably higher Eddington ratio of $L(0.3\text{–}7\,\text{keV})/L(\text{Edd}) \sim 10^{-6}$ (Kong et al. 2010). If an IMBH exists in M54, its accretion state resembles that of the candidate IMBH in M15 rather than that of G1. Interestingly, emerging evidence suggests that accreting BHs in active galactic nuclei might divide into "quiescent" and "low" states near an Eddington ratio of about 10^{-6} (e.g., Ho 2009; Yuan et al. 2009; and references therein).

For accreting BHs, the fraction of the accretion power that emerges in the radio is a strongly increasing function of BH mass (Merloni et al. 2003; Falcke et al. 2004). This empirical relation among X-ray and radio luminosity and BH mass was recast for the IMBH regime in Equation (1) of Maccarone (2004). From that relation, for the same X-ray luminosity, a $10^4\,M_\odot$ BH will have ∼200 times the radio flux density of a 10 $M_\odot$ BH. Such a difference is well beyond the factor-of-eight uncertainty in predicting the radio flux density from the empirical relation. In the case of G1, Ulvestad et al. (2007) successfully detected the flux density predicted from the dynamically measured BH mass and the X-ray luminosity. That finding effectively ruled out the possibility that the X-rays in G1 emanate from a stellar-mass BH. However, improvements in the radio versus X-ray localizations of G1 could invalidate this inference (Kong et al. 2010).

Using the upper limit to the X-ray luminosity at the stellar density center of M54 and applying Equation (1) of Maccarone (2004), the predicted flux density near 5 GHz is less than 20–1000 μJy beam^{-1} for a 9400 $M_\odot$ BH and 0.1–5 μJy beam^{-1} for a 10 $M_\odot$ BH. From Figure 2, the 8.5 GHz flux density is less than 51 μJy beam^{-1}, corresponding to a luminosity of $L(8.5\,\text{GHz}) < 3.6\times10^{29}$ erg s^{-1}. Detection of a 10 μJy source at the stellar density center of M54 could help distinguish between these two cases. Detecting such a faint source is now feasible (Perley et al. 2011) and would help validate the physically plausible radio predictions advocated by Maccarone & Servillat (2008) and Maccarone & Servillat (2010). Also, M54 is more distant than any other Galactic globular cluster surveyed deeply for radio emission (Johnston et al. 1991; De Rijcke et al. 2006; Bash et al. 2008; Cseh et al. 2010; Lu & Kong 2011; Miller-Jones et al. 2011), which serves to reduce contamination from low-luminosity stellar emitters.

3.2. *Stellar Populations*

The stellar population of M54 is old and metal poor (e.g., Siegel et al. 2007). The *Chandra* sources reported by Ramsay & Wu (2006a) and confirmed in Table 1 are typical for Galactic globular clusters (e.g., Heinke 2011). From Figure 2, any stellar emitters within the cluster's half-mass radius have a luminosity of $L(8.5\,\text{GHz}) < 3.6 \times 10^{29}$ erg s^{-1} (3σ). At this level, analogs of AC211 and M15 X-2 (Miller-Jones et al. 2011, and references therein) would escape detection. Planetary nebula are known to be associated with the Sagittarius dwarf (Zijlstra et al. 2006) but none have been reported for M54 itself. An analog of K648 in M15 (Johnston et al. 1991) would be a mJy-level source at M54. The mJy-level sources within M54's limiting radius have X-ray counterparts, inconsistent with being planetary nebulae.

3.3. *Intracluster Medium*

Because of M54's low Galactic latitude and distance (Harris 1996; Bellazzini et al. 2008), it is difficult to constrain its intracluster medium and thus the fuel available to the candidate IMBH. Burton & Lockman (1999) report an upper limit of 200 $M_\odot$ (3 σ) for the H I averaged over 20 km s^{-1} toward the inner 21′ = 160 pc of the Sagittarius dwarf. This H I mass limit encompasses M54 in space, velocity, and σ_*. Two X-ray sources (Ramsay & Wu 2006b) with 8.5 GHz counterparts each lie about 2′ = 16 pc from the cluster center and within M54's limiting radius. Their X-ray and radio properties strongly suggest that they are active galaxies beyond M54. As such, they could serve as probes of M54's intracluster medium through studies of their Faraday rotation measures.

4. SUMMARY AND CONCLUSIONS

Radiative signatures of accretion onto M54's candidate IMBH, with mass $\sim 9400\,M_\odot$ (Ibata et al. 2009), could strengthen the case for its existence. Comparison of new X-ray and recent optical astrometry does not support the suggestion by Ibata et al. (2009) that X-ray Id 2 is the counterpart to the candidate IMBH. Rather, the Eddington ratio of the candidate IMBH is constrained to be less than 1.4×10^{-10}, implying a very different accretion state than that of G1's candidate IMBH. The 8.5 GHz luminosity of M54's candidate IMBH is less than 3.6×10^{29} erg s^{-1}. Two background active galaxies behind M54 could serve as probes of the fuel available to the candidate IMBH.

This research has made use of data obtained from the Chandra Source Catalog, provided by the Chandra X-ray Center (CXC) as part of the Chandra Data Archive.

Facilities: CXO, VLA

REFERENCES

Bash, F. N., Gebhardt, K., Goss, W. M., & Vanden Bout, P. A. 2008, AJ, 135, 182
Baumgardt, H., Hut, P., Makino, J., McMilan, S., & Portegies Zwart, S. 2003, ApJ, 583, L21
Bellazzini, R. A., Ibata, R. A., Chapman, S. C., et al. 2008, AJ, 136, 1147
Bellovary, J. M., Governato, F., Quinn, T. R., et al. 2010, ApJ, 721, L148
Burton, W. B., & Lockman, F. J. 1999, A&A, 349, 7
Condon, J. J., Anderson, E., & Broderick, J. J. 1995, AJ, 109, 2318
Cseh, D., Kaaret, P., Corbel, S., et al. 2010, MNRAS, 406, 1049
De Rijcke, S., Buyle, P., & Dejonghe, H. 2006, MNRAS, 368, L43
Evans, I. N., Primini, F. A., Glotfelty, K. J., et al. 2010, ApJS, 189, 37
Falcke, H., Koerding, E., & Markoff, S. 2004, A&A, 414, 895
Ferrarese, L. 2003, in ASP Conf. Ser. 291, Hubble Science Legacy: Future Optical/Ultraviolet Astronomy from Space, ed. K. R. Sembach et al. (San Francisco, CA: ASP), 196
Ferrarese, L., & Ford, H. 2005, Space Sci. Rev., 116, 523
Fregeau, J. M., & Rasio, F. A. 2007, ApJ, 658, 1047
Gebhardt, K., Rich, R. M., & Ho, L. C. 2002, ApJ, 578, L41
Gebhardt, K., Rich, R. M., & Ho, L. C. 2005, ApJ, 634, 1093
Goldsbury, R., Richer, H. B., Anderson, J., et al. 2010, AJ, 140, 1830
Greene, J. E., Peng, C. Y., Kim, M., et al. 2010, ApJ, 721, 26
Harris, W. E. 1996, AJ, 112, 1487
Heinke, C. O. 2011, arXiv:1101.5356v1
Ho, L. C. 2009, ApJ, 699, 626
Ho, L. C., Terashima, Y., & Ulvestad, J. S. 2003, ApJ, 589, 783
Holley-Bockelmann, K., Gultekin, K., Shoemaker, D., & Yunes, N. 2008, ApJ, 686, 829
Hughes, S. A. 2009, ARA&A, 47, 107
Ibata, R., Bellazzini, M., Chapman, S. C., et al. 2009, ApJ, 699, L169
Johnston, H. M., Kulkarni, S. R., & Goss, W. M. 1991, ApJ, 382, L89
Kong, A. K. H., Heinke, C. O., Di Stefano, R., et al. 2010, MNRAS, 407, L84
Lu, T.-N., & Kong, A. K. H. 2011, ApJ, 729, L25
Maccarone, T. J. 2004, MNRAS, 351, 1049
Maccarone, T. J., & Servillat, M. 2008, MNRAS, 389, 379
Maccarone, T. J., & Servillat, M. 2010, MNRAS, 408, 2511
Merloni, A., Heinz, S., & DiMatteo, T. 2003, MNRAS, 345, 1057
Miller-Jones, J. C. A., Sivakoff, G. R., Heinke, C. O., et al. 2011, ATel, 3378
Noyola, E., Gebhardt, K., Kissler-Patig, M., et al. 2010, ApJ, 719, 60
Perley, R. A., Chandler, C. C., Butler, B. J., & Wrobel, J. M. 2011, arXiv:1106.0532v1
Pooley, D., & Rappaport, S. 2006, ApJ, 644, L45
Ramsay, G., & Wu, K. 2006a, A&A, 447, 199
Ramsay, G., & Wu, K. 2006b, A&A, 459, 777
Siegel, M. H., Dotter, A., Majewski, S. R., et al. 2007, ApJ, 667, L57
Sollima, A., Cacciari, C., Bellazzini, M., & Colucci, S. 2010, MNRAS, 406, 329
Thompson, A. R., Clark, B. G., Wade, C. M., & Napier, P. J. 1980, ApJS, 44, 151
Trenti, M., Ardi, E., Mineshige, S., & Hut, P. 2007, MNRAS, 374, 857
Ulvestad, J. S., Greene, J. E., & Ho, L. C. 2007, ApJ, 661, L151
van der Marel, R. P., & Anderson, J. 2010, ApJ, 710, 1063
Volonteri, M., Lodato, G., & Natarajan, P. 2008, MNRAS, 383, 1079
Yuan, F., Yu, Z., & Ho, L. C. 2009, ApJ, 703, 1034
Zijlstra, A. A., Gesicki, K., Walsh, J. R., et al. 2006, MNRAS, 369, 875