RADIO CONTINUUM OBSERVATIONS OF 47 TUCANAE AND ω CENTAURI: HINTS FOR INTERMEDIATE-MASS BLACK HOLES?

TING-NI LU AND ALBERT K. H. KONG
Institute of Astronomy & Department of Physics, National Tsing Hua University, Taiwan
Received 2010 December 16; accepted 2011 January 26; published 2011 February 16

ABSTRACT

We present results of deep radio continuum observations of two galactic globular clusters 47 Tucanae (47 Tuc) and ω Centauri (ω Cen) with the Australia Telescope Compact Array. No statistically significant evidence for radio emission was found from the central region for the two clusters. However, both clusters show a 2.5σ detection near the center that may be confirmed by future deeper radio observations. The 3σ upper limits of the radio observations are 20 and 40 μJy beam⁻¹ for ω Cen and 47 Tuc, respectively. By using the fundamental plane of accreting black holes, which describes the relationship between radio luminosity, X-ray luminosity, and black hole mass, we constrain the mass of a possible intermediate-mass black hole (IMBH) in the globular clusters. We also compare our results with other globular clusters and discuss the existence of IMBHs in globular clusters.

Key words: black hole physics – globular clusters: individual (47 Tucanae, Omega Centauri)

Online-only material: color figures

1. INTRODUCTION

Globular clusters are well-known exotic object factories because of their highly frequent dynamical interactions. It has been decades since the prediction was made that intermediate-mass black holes (IMBHs) might exist in globular clusters (e.g., Wyller 1970; Bahcall & Ostriker 1975; Frank & Rees 1976). IMBHs provide a possible connection between stellar-mass black holes and supermassive black holes, with their mass ranging from $10^2$ to $10^3 M_\odot$. There has been much conclusive evidence supporting the existence of stellar-mass black holes as in X-ray binaries and supermassive black holes as in active galactic nuclei (AGNs). However, the existence of IMBHs in globular clusters is still under debate. Although theoretical works provide possibilities of their existences, observational evidences are limited. There are many formation channels of IMBHs. One is that they may be the products of core collapses of population III stars (e.g., Fryer et al. 2001). IMBHs could also form through runaway merger processes in some young dense globular clusters (Portegies Zwart & McMillan 2002; Portegies Zwart et al. 2004). Moreover, it is possible that in globular clusters mergers of compact objects, such as stellar-mass black holes through interactions, would result in a central black hole with mass $\sim 0.001$ times the mass of its host cluster, which falls in the mass regime of IMBHs (Miller & Hamilton 2002). As a result, searching for IMBHs in globular clusters is crucial for understanding formation histories of dense stellar clusters, and it may further help us study the stellar dynamics and construct cluster evolution scenarios.

There is an established “M–σ” relation between the supermassive black hole mass and velocity dispersion in the host galaxies based on observations (Tremaine et al. 2002; Ferrarese & Ford 2005; Gültekin et al. 2009). The correlation implies that the formation of a supermassive black hole is possibly related to the formation of a galaxy. If the M–σ relation extends to the regime of dense stellar cluster systems, globular clusters may host central IMBHs with masses ranging from $10^2$ to $10^3 M_\odot$.

One of the formation scenarios of AGNs is that they may be grown from $10^2$ to $10^3 M_\odot$, formed from direct collapse of population III stars. If IMBHs do exist in globular clusters, the $M–\sigma$ relation may link the formation mechanisms of IMBHs and AGNs.

As far as observations are concerned, detecting IMBHs is achievable through many methods. Farrell et al. (2009) identified an IMBH in the galaxy ESO243-49 by its extremely high X-ray luminosity and variability in the X-ray luminosity and spectra. For IMBHs in globular clusters, the most common way is measuring velocity dispersion of cluster stars and then applying a dynamical modeling technique to constrain the mass-to-light ratio of globular clusters. Another method is detecting possible radio emissions from the center of globular clusters expected from the fundamental plane of black hole (Merloni et al. 2003). The dynamical modeling technique can constrain the central “dark” mass in globular cluster, while it fails to distinguish whether the “dark” mass is contributed from a single IMBH or a group of neutron stars, white dwarfs, or stellar-mass black holes. Moreover, during the past decade, because of the improvement of the instruments, the detection of possible radio/X-ray emissions predicted by the black hole fundamental plane becomes possible. As a result, several deep radio continuum observations of globular clusters have been carried out to search for IMBHs in globular clusters.

To date, discoveries of IMBH candidates in some globular clusters have been claimed with different observational techniques (Table 1). The reported dynamical mass of a possible IMBH in G1 (in M31) is $M_{\text{BH}} = (1.8 \pm 0.5) \times 10^4 M_\odot$ (Gebhardt et al. 2002, 2005), while in M15 (in our Milky Way) $M_{\text{BH}} = 1.7_{-1.7}^{+2.7} \times 10^3 M_\odot$ (Gerssen et al. 2003). Nevertheless, the claims of G1 and M15 based on the dynamical method have suffered subsequent challenges. Theoretical models suggest that it is not necessary to invoke an IMBH to explain the data (Baumgardt et al. 2003a, 2003b). Furthermore, the latest radio continuum observations on several globular clusters could only set an upper limit on the possible central IMBHs (e.g., Mac Carrone et al. 2005; de Rijcke et al. 2006; Bash et al. 2008; Maccarone & Servillat 2008; Cseh et al. 2010). The only radio
Table 1
Recent Radio Continuum Observations on Globular Clusters

| Cluster Name | Distance (kpc) | \(n_H\) (H cm\(^{-3}\)) | \(T_{gas}\) (Kelvin) | \(F_{R,5GHz}\) (\(\mu\)Jy) | \(M_{BH,rad}\) (\(M_\odot\)) | \(M_{BH,dyn}\) (\(M_\odot\)) |
|-------------|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(\omega\) Cen | 5.3 | 0.044 | 10\(^4\) | 20 | 5200/1100 | 12000 |
| 47 Tuc | 4.5 | 0.28/0.07 | 10\(^4\) | 40 | 4900/520 | 1500 |
| NGC 6388 | 10.0 | 0.1 | 10\(^4\) | 81 | 1500/735 | 5700 |
| NGC 2808 | 9.5 | 0.26 | 10\(^4\) | 162 | 8500/1800 | 2700 |
| M15 | 10.3 | 0.42/0.2 | 10\(^4\) | 25 | 4900/700 | 1000 |
| M62 | 6.9 | 0.41 | 10\(^4\) | 36 | 2900/600 | 3000 |
| M80 | 10.0 | 0.21 | 10\(^4\) | 36 | 5300/1100 | 1600 |
| NGC 6397 | 2.7 | 0.16 | 10\(^4\) | 216 | 4300/900 | 50 |
| G1 | 780 | \(~ 1\) | 10\(^3\) | 28 | 4500 | 18000 |

Notes. The radio flux \(F_{R,5GHz}\) is the 3\(\sigma\) upper limit except for G1, which is a detection. The radio flux for NGC 6388 is taken from Cseh et al. (2010), for NGC 2808 from Maccarone & Servillat (2008); for M 15, M 60, and NGC 6266 from Bash et al. (2008); for NGC 6397 from de Rijcke et al. (2006); for G1 from Ulvestad et al. (2007). The dynamical black hole mass \(M_{BH,dyne}\) adopted for \(\omega\) Cen is from van der Marel & Anderson (2010); for 47 Tuc from McLaughlin et al. (2006); for NGC 6388 from Lanzoni et al. (2007); for M15, M62, and M80 come from Bash et al. (2008); for NGC 2808 and NGC 6397 from \(M_{\ast}\) relation of Tremaine et al. (2002); for G1 from Gebhardt et al. (2002). The radio black hole mass \(M_{BH,rad}\) for NGC 6388 is from Cseh et al. (2010).
and expressed with the black hole mass $M_{\text{BH}}$, the gas abundance $n$, and the gas temperature $T$ of the globular cluster, as shown in Equation (3). If we combine all the above information, the black hole mass can be constrained simply by radio flux and cluster properties:

$$L_X = \eta \epsilon M_{\text{BH}} \text{ erg s}^{-1}.$$  \hspace{1cm} (3)

ω Cen was observed previously with ATCA simultaneously at 4.8 and 8.6 GHz over 12 hr, while 47 Tuc was observed briefly (3.5 hr) with ATCA at 1.4 GHz. Both observations failed to detect any central radio source and yielded 3σ rms noise levels of 96 $\mu$Jy and 225 $\mu$Jy for ω Cen and 47 Tuc, respectively (Maccarone et al. 2005; de Rijcke et al. 2006). With different combinations of BH accretion fraction and gas abundance in globular clusters, the radio upper limits corresponding to the most probable estimation for the upper limit of the IMBH mass in ω Cen and 47 Tuc are 2000 $M_\odot$ and 1000 $M_\odot$, respectively (see Maccarone & Servillat 2008, 2010, and references therein). The results could not exclude the possibility that there is no IMBH in ω Cen or 47 Tuc, which motivated us to propose deeper radio observations on both targets.

3. RADIO OBSERVATIONS

3.1. Data Analysis

47 Tuc and ω Cen were observed by ATCA during 2010 January 24 and 25. The observations were performed simultaneously at frequencies 5.5 GHz and 9 GHz with configuration 6A (with the baseline ranging from 337 m to 6 km) and the upgraded Compact Array Broadband Backend (CABB). The data were taken with the CFB 1M-0.5k correlator configuration with 2 GHz bandwidth and 2048 channels, each with 1 MHz resolution. The primary calibrator used was 1934-638 for both globular clusters, while the phase calibrators were 2353-686 and 1320-446 for 47 Tuc and ω Cen, respectively. At the start of each observation, we observed 1934-638 for 10 minutes. The phase calibrator was observed every 15 minutes. We use MIRIAD (Sault et al. 1995) to analyze the data with standard processes. When loading the ATCA data into MIRIAD, we use atcal with options birdie, xycorr, rfigflag, and noauto, which represents flagging out the channels affected by the ATCA self-interference, correcting the phase difference between the X and Y channels, discarding any autocorrelation data, and automatically flagging out frequency bands that are known to be heavily affected by radio frequency interference. We then perform the standard data reduction steps, including bandpass, phase, and amplitude calibrations. When producing the dirty maps, we use the multifrequency synthesis (MFS) method (Sault & Conway 1999) and natural weighting to suppress the noise. The effective on-source integration time of 47 Tuc is 11 and 9 hr, while the effective on-source integration time of ω Cen is 18 and 16 hr for frequencies 5.5 GHz and 9 GHz, respectively. The field of view of ATCA with configuration 6A is $\sim 10'\times 10'$ for 5.5 GHz and 9 GHz, respectively, in which both cover the entire area within the half-mass radius of 47 Tuc ($r_h = 3.17$) and ω Cen ($r_h = 5.90$). The spatial resolution of the radio observations can reach $\sim 1'\times 2'$.  

3.2. Results

Besides background quasars, we did not detect any radio sources at or near the central region of ω Cen and 47 Tuc with radio emissions higher than 3σ. In naturally weighted maps, the rms noise level for ω Cen is 7 (5.5 GHz) and 11 (9 GHz) $\mu$Jy beam$^{-1}$; while for 47 Tuc, it is 17 (5.5 GHz) and 20 (9 GHz) $\mu$Jy beam$^{-1}$. We combined the observations with different frequencies in order to obtain a lower rms noise level at frequency 6.8 GHz. As a result, the observations reached rms noise levels of 6.5 and 13.3 $\mu$Jy beam$^{-1}$, giving a 3σ upper limit of 20 and 40 $\mu$Jy beam$^{-1}$ for ω Cen and 47 Tuc, respectively. The brightest millisecond pulsar in 47 Tuc has a radio flux of $\sim 370 \mu$Jy at 1.4 GHz (McConnell et al. 2004). Assuming a spectral index $\alpha = -1.8$ for pulsar spectrum (Kramer et al. 1998), it would have a flux of $\sim 21 \mu$Jy at 6.8 GHz. Thus, the millisecond pulsars in 47 Tuc are all under the detection threshold of our observation. We overlapped the positions of the X-ray sources detected in ω Cen (Haggard et al. 2009), and there is no radio source with their signal-to-noise ratio higher than 3 matched to the 180 Chandra X-ray sources.

Figure 1 shows the HST optical images overlaid with ATCA radio map contours of 47 Tuc and ω Cen. The radio position of 47 Tuc and ω Cen has an estimated error of $\sim 1.4''$ by 0.6 and 1.1'' by 0.7, respectively, derived by dividing the beam size by the signal-to-noise ratio. Although we did not find any statistically significant radio emission, there is a 2.5σ detection near the center of both globular clusters ($\sim 0.4''$ from 47 Tuc center and $\sim 0.7''$ from ω Cen center). We calculated the average source number within the error ellipse of the globular cluster center by computing the area ratios of the error ellipse to the field of the $10''\times 10''$ region and also the total number of the sources (with their signal-to-noise ratio larger than 2.5) inside the field of view of the $10''\times 10''$ region. With the assumption of the Poisson distribution, we obtained the probabilities of finding one or more radio sources inside the error circle, which is $\sim 2\%$ for both 47 Tuc and ω Cen. That is to say, the probability of chance coincidence is quite low and the nearby source could really be the central radio source.

3.3. Constraints on IMBH Masses

The 3σ upper limits of radio emissions could be applied to the mass constraints on IMBHs in globular clusters, using the fundamental plane of black hole activity described in Section 2. We estimate the most probable mass and conservative mass of the IMBHs in ω Cen and 47 Tuc as described in Maccarone & Servillat (2008), with the accretion efficiency $\epsilon = 0.1\%$–3% and the radiative efficiency described in Maccarone & Servillat (2008). The gas abundance in globular clusters could be estimated either based on dispersion measurements of pulsars, such as M15 and 47 Tuc (Freire et al. 2001), or based on the stellar mass loss rate (Pfahl & Rappaport 2001). We adopt the gas abundance calculated from Pfahl & Rappaport (2001) in our calculation for ω Cen, while for 47 Tuc we use the gas abundance from pulsar measurements as their conservative estimation. The resulting mass of IMBH is 1100–5200 $M_\odot$ for ω Cen and 47 Tuc, respectively. We list the summary of recently observed globular clusters and our observation results in Table 1.

4. DISCUSSION

To date, several radio continuum observations have been performed on a few globular clusters in order to detect possible IMBHs in the cluster center. There is a radio source detected in G1. However, whether the radio source in G1 is related to an IMBH or an LMXB is still under debate (Kong et al. 2010). Except for G1, no central radio source has been detected in the other globular clusters. Nevertheless, the non-detections did
Figure 1. HST R-band image overlaid with ATCA contours at frequency 6.8 GHz within the central 10′′ × 10′′ region of the clusters. The red contours are 1σ, 2σ, and 3σ noise levels, while the green contours are −1σ and −2σ noise levels. The center of the cluster is denoted by the blue cross. The blue ellipse represents the 95% positional error ellipse of the globular cluster center. Left: 47 Tuc. Right: ω Cen.

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

not rule out the existence of IMBHs in globular clusters. The radio flux upper limits are used to constrain the IMBH masses, regarding certain assumptions of gas properties in globular clusters and accretion model. Based on Pfahl & Rappaport (2001), the gas abundance in globular clusters could vary from 0.1 to 1 H cm$^{-3}$. The accretion efficiency of the putative IMBH in G1 is just below 1% (Ulvestad et al. 2007). Moreover, according to the standard accretion disk theory, the IMBH in globular clusters would be in an extremely low state, while as suggested in Cseh et al. (2010) both the accretion efficiency and radiative efficiency could vary in a wide range. The scatter in the black hole fundamental plane correlation would also contribute errors in IMBH mass estimates. Combined with all of these uncertainties, the estimation of IMBH masses is actually model dependent and under strong model assumptions.

Despite the large uncertainties in the estimation of IMBH masses based on radio observations, there are discrepancies between the IMBH masses estimated from accretion model constraints and dynamically inferred IMBH masses, especially for the case of ω Cen (see Table 1). The measurement of IMBH masses based on stellar dynamics is limited to the instrument ability, which could not achieve high enough spatial resolution, although it provides a more accurate estimation on the IMBH masses. We further compare the upper limits of IMBH masses of some globular clusters to the $M$−$σ$ relation of galaxies (Figure 2). The upper limit for the mass of the IMBH in 47 Tuc is consistent with the $M$−$σ$ relation of Gültekin et al. (2009), while for ω Cen the upper limit of the IMBH mass is within the region of the $M$−$σ$ relation of Ferrarese & Ford (2005). As the true masses of IMBHs must be lower than the upper limits, ω Cen, 47 Tuc, and M15 do not show inconsistency of the $M$−$σ$ relation. There is no reason that globular clusters should obey the same relation that is confirmed to exist in massive galaxies. However, the consistency may suggest similar formation mechanisms or similar content between globular clusters and galaxies. If we could lower the upper limits of the IMBH masses in globular clusters, it may provide evidences of different formation mechanisms between globular clusters and galaxies.

Figure 2. $M$−$σ$ relation of galaxies derived by Ferrarese & Ford (2005, black dashed line) and Gültekin et al. (2009, blue dotted line). The red data points represent the 3σ upper limits on the masses of IMBHs in globular clusters, with accretion efficiency $ε = 3%$. The velocity dispersion for ω Cen comes from van der Marel & Anderson (2010), for 47 Tuc comes from Gebhardt & Fischer (1995), for M15 comes from (Gerssen et al. 2002), for NGC 6397 comes from Meylan & Mayor (1991), for G1 comes from Meylan et al. (2001), for M33 comes from Merritt et al. (2001), and for M110 comes from Valluri et al. (2005).

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

In summary, we estimate the 3σ upper limit for the mass of the central IMBH in ω Cen of 1100−5200 $M⊙$, and for 47 Tuc we estimate the 3σ upper limit of 520−4900 $M⊙$. The estimations strongly depend on the accretion model and the gas properties of globular clusters. We detect a 2.5σ radio emission near the center of both globular clusters. Future radio observations with
a sensitivity improvement to $\sim 5 \mu$Jy may be able to confirm whether the sources are real or further constrain the parameters of the accretion model.

This project is supported by the National Science Council of Republic of China (Taiwan) through grants NSC 96-2112-M-007-037-MY3 and NSC 99-2112-M-007-004-MY3. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

REFERENCES

Bahcall, J. N., & Ostriker, J. P. 1975, Nature, 256, 23
Bash, F. N., Gebhardt, K., Goss, W. M., & Vanden Bout, P. A. 2008, AJ, 135, 182
Baumgardt, H., Hut, P., Makino, J., McMillan, S., & Portegies Zwart, S. 2003a, ApJ, 582, L21
Baumgardt, H., Makino, J., Hut, P., McMillan, S., & Portegies Zwart, S. 2003b, ApJ, 589, L25
Bondi, H. 1952, MNRAS, 112, 195
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Cseh, D., Kaaret, P., Corbel, S., Kording, E., Coriat, M., Tzioumis, A., & Lanzoni, B. 2010, MNRAS, 406, 1049
de Rijcke, S., Buyle, P., & Dejonghe, H. 2006, MNRAS, 368, L43
Falcke, H., Kording, E., & Markoff, S. 2004, A&A, 414, 895
Farrell, S. A., Webb, N. A., Barret, D., Godet, O., & Rodrigues, J. M. 2009, Nature, 460, 73
Fender, R. P., Falcke, H., & Jonker, P. G. 2003, MNRAS, 343, L99
Ferrarese, L., & Ford, H. 2005, Space Sci. Rev., 116, 523
Frank, J., & Rees, M. J. 1976, MNRAS, 176, 633
Freire, P. C., Kramer, M., Lyne, A. G., Camilo, F., Manchester, R. N., & D’Amico, N. 2001, ApJ, 557, L105
Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372
Gallop, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60
Gebhardt, K., & Fischer, P. 1995, AJ, 109, 209
Gebhardt, K., Rich, R. M., & Ho, L. C. 2002, ApJ, 578, L41
Gebhardt, K., Rich, R. M., & Ho, L. C. 2005, ApJ, 634, 1093
Gerssen, J., van der Marel, R. P., Gebhardt, K., Guhathakurta, P., Peterson, R. C., & Pyor, C. 2002, AJ, 124, 3270
Gerssen, J., van der Marel, R. P., Gebhardt, K., Guhathakurta, P., Peterson, R. C., & Pyor, C. 2003, AJ, 125, 376
Güttler, E., et al. 2009, ApJ, 698, 198
Haggard, D., Cool, A. M., & Davies, M. B. 2009, ApJ, 697, 224
Ho, L. C., Terashima, Y., & Okajima, T. 2003, ApJ, 587, L35
Hoyle, F., & Lyttleton, R. A. 1941, MNRAS, 101, 227
Kong, A. K. H., Heinke, C. O., di Stefano, R., Cohn, H. N., Luger, P. M., Barmbay, P., Lewin, W. H. G., & Primini, F. A. 2010, MNRAS, 407, L84
Kramer, M., Xilouris, K. M., Lorimer, D. R., Doroshenko, O., Jessner, A., Wielebinski, R., Wolszczan, A., & Camilo, F. 1998, ApJ, 501, 270
Lanzoni, B., Dalessandro, E., Ferraro, F. R., Micocchi, P., Valenti, E., & Rood, R. T. 2007, ApJ, 668, L139
Maccarone, T. J. 2004, MNRAS, 351, 1049
Maccarone, T. J., Fender, R. P., & Tzioumis, A. K. 2005, MNRAS, 356, L17
Maccarone, T. J., Gallo, E., & Fender, R. 2003, MNRAS, 345, L19
Maccarone, T. J., & Servillat, M. 2008, MNRAS, 389, 379
Maccarone, T. J., & Servillat, M. 2010, MNRAS, 408, 2511
McConnell, D., Deshpande, A. A., Connors, T., & Ables, J. G. 2004, MNRAS, 348, 1409
McLaughlin, D. E., Anderson, J., Meylan, G., Gebhardt, K., Pyor, C., Minniti, D., & Phinney, S. 2006, ApJS, 166, 249
Merloni, A., Heinz, S., & di Matteo, T. 2003, MNRAS, 345, 1057
Merritt, D., Ferrarese, L., & Joseph, C. L. 2001, Science, 293, 1116
Meylan, G., & Mayor, M. 1991, A&A, 250, 113
Meylan, G., Sarajedini, A., Jablonka, P., Djorgovski, S. G., Bridges, T., & Rich, R. M. 2001, AJ, 122, 830
Miller, M. C., & Hamilton, D. P. 2002, MNRAS, 330, 232
Pfahl, E., & Rappaport, S. 2001, ApJ, 550, 172
Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J., & McMillan, S. L. W. 2004, Nature, 428, 724
Portegies Zwart, S. F., & McMillan, S. L. W. 2002, ApJ, 576, 899
Sault, R. J., & Conroy, J. E. 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San Francisco, CA: ASP), 419
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 433
Tremaine, S., et al. 2002, ApJ, 574, 740
Ulvestad, J. S., Greene, J. E., & Ho, L. C. 2007, ApJ, 661, L151
Valluri, M., Ferrarese, L., Merritt, D., & Joseph, C. L. 2005, ApJ, 628, 137
van der Marel, R. P., & Anderson, J. 2010, ApJ, 710, 1063
Wyller, A. A. 1970, ApJ, 160, 443