Upper limits on the central black hole masses of 47Tuc and NGC6397 from radio continuum emission

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ABSTRACT
We present upper-limits on the masses of the putative central intermediate-mass black holes in two nearby Galactic globular clusters: 47Tuc (NGC104), the second brightest Galactic globular cluster, and NGC6397, a core-collapse globular cluster and, with a distance of 2.7 kpc, quite possibly the nearest globular cluster, using a technique suggested by T. Maccarone. These mass estimates have been derived from 3σ upper limits on the radio continuum flux at 1.4 GHz, assuming that the putative central black hole accretes the surrounding matter at a rate between 0.1 % and 1 % of the Bondi accretion rate. For 47Tuc, we find a 3σ upper limit of 2060 – 670$M_\odot$, depending on the actual accretion rate of the black hole and the distance to 47Tuc. For NGC6397, which is closer to us, we derive a 3σ upper limit of 1290 – 390$M_\odot$. While estimating mass upper-limits based on radio continuum observations requires making assumptions about the gas density and the accretion rate of the black hole, their derivation does not require complex and time consuming dynamical modeling. Thus, this method offers an independent way of estimating black hole masses in nearby globular clusters. If, generally, central black holes in stellar systems accrete matter faster than 0.1 % of the Bondi accretion rate, then these results indicate the absence of black holes in these globular clusters with masses as predicted by the extrapolated $M_\bullet – \sigma_*$ relation.

Key words: Galaxy: globular clusters: general – Galaxy: globular clusters: individual: 47Tuc, NGC6397 – black hole physics

1 INTRODUCTION
Theory provides us with different ways of producing intermediate-mass black holes (IMBHs) in dense stellar clusters, such as globular clusters. IMBHs are defined here as having a mass larger than that of stellar black holes but smaller than that of the super-massive black holes (SMBH) found in galaxies, so $10^2 M_\odot < M_\bullet < 10^6 M_\odot$. One scenario envisages an IMBH to grow from a stellar-mass seed black hole, the remnant of a massive star that exploded as a supernova (Miller & Hamilton 2002). This seed black hole rapidly sinks to the cluster center due to dynamical friction, or, in the case of a post-core-collapse cluster, was formed near the cluster center since that is where the most massive stars can be found, and grows by accreting stars, less massive stellar black holes or interstellar gas. In a core-collapse cluster, stars near the core are packed so densely that some may collide, causing a runaway growth of the remnant’s mass (Portegies Zwart & McMillan 2002). Both mechanisms seem to lead naturally to IMBHs with a mass that is about 0.1% of the cluster mass. The IMBH can be even more massive (up to $10^4 M_\odot$) if it originated from multiple seeds. Another suggested way of forming IMBHs considers the radiation drag that is exerted by stars on the interstellar medium (Kawakatu et al. 2003; Kawakatu & Umemura 2005). Radiation drag is expected to funnel gas, expelled by SNII and SNIa explosions, towards the cluster center where it is likely to form a massive central object surrounded by an accretion disk. It is expected that this central object will collapse into an IMBH if its mass exceeds a few 100 $M_\odot$. In massive galaxies, this process may lead to central black holes that have a mass of about 0.1% of the bulge mass (Kawakatu et al. 2003). However, in the case of globular clusters, IMBHs formed this way are expected to be much less massive than 0.1% of the cluster mass (the ratio of the IMBH mass to the cluster mass is rather of the order of $10^{-3}$). In fact, clusters less massive than $\sim 5 \times 10^5 M_\odot$ are not expected to contain a central black hole, although they can harbor a central object not massive enough to collapse into a black hole (Kawakatu & Umemura 2005). Yet another, somewhat more speculative, possibility is that Population iii stars, with masses of a few hundred solar masses, were the seeds of IMBHs (Madau

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& Rees 2001). Nuclear energy production in Population III stars more massive than $\sim 260 \, M_\odot$ cannot counteract gravity and such objects immediately collapse into black holes. Such very massive seed black holes, which could be called IMBHs in their own right, then grow further by accretion. This way of producing IMBHs, unlike the previous ones, does not require the host stellar system to be dense.

Therefore, even upper limits on the masses of central black holes in globular clusters are of great interest, since they constrain the possible formation scenarios for IMBHs and the nature of IMBH progenitors. In this paper, we present upper limits on the IMBH masses of 47Tuc and NGC6397, two of the nearest globular clusters, derived from 20 cm continuum observations, obtained with the Australia Telescope Compact Array (ATCA). In Section 2, we briefly discuss how IMBHs can be detected via their radio continuum emission. In Sect. 3, the observations and the data reduction procedures are presented, followed by a discussion of the results in Sect. 4. We summarize our conclusions in section 5.

2 DETECTING IMBHs USING RADIO CONTINUUM EMISSION

While various approaches to the estimation of IMBH masses in globular clusters have been suggested and/or applied (such as dynamical modeling of stellar kinematics, see e.g. Gerssen et al. 2002), or the detection of high-proper-motion stars near the globular cluster center (Drukier & Bailyn 2003) one of the observationally least demanding methods is the possibility to detect black holes through the radio emission they produce. Gas that is accreted onto a black hole converts part of its rest mass into radiation which, in the mass regime of IMBHs, is most easily recovered at radio wavelengths. The equation that relates the mass of a black hole, $M_\bullet$, in a stellar system at a distance $d$ to its X-ray luminosity $L_X$ and radio continuum emission $F_{\text{cont}}$ reads as

$$F_{\text{cont}} = 10 \left( \frac{L_X}{3 \times 10^{31} \text{ergs}^{-1}} \right)^{0.6} \left( \frac{M_\bullet}{100 \, M_\odot} \right)^{0.78} \times \left( \frac{d}{10 \, \text{kpc}} \right)^{-2} \mu\text{Jy},$$

assuming a flat radio spectrum (Maccarone 2004) and the Fundamental-Plane relationship between radio luminosity, X-ray luminosity, and black hole mass (Merloni, Heinz, di Matteo 2003; Falcke, Körönd, Markoff 2004). For a given accretion rate, which is usually assumed to be a fraction of the Bondi accretion rate

$$M_{\bullet, \text{Bondi}} = 3.2 \times 10^{14} \left( \frac{M_\bullet}{200 \, M_\odot} \right)^2 \left( \frac{n}{0.2 \, \text{cm}^{-3}} \right) \times \left( \frac{T}{10^4 \, \text{K}} \right)^{-1.5} \text{kg s}^{-1},$$

(with $n$ and $T$ the gas density and temperature, respectively) the X-ray luminosity can be calculated, assuming that 10% of the rest mass energy of the infalling matter is converted into radiation, and that the total luminosity $L_{\text{tot}}$ is related to the X-ray luminosity as given by $L_{\text{tot}} = 6 \times 10^{-3} L_X^{0.5} + L_X$ (using the Eddington luminosity as unit). This relation takes into account the energy of a relativistic jet (Fender et al. 2003). This way, the radio continuum flux $F_{\text{cont}}$ can be expressed as a function of the black hole mass $M_\bullet$, the distance $d$, and the gas density $n$ and temperature $T$. In the following, we will assume $n = 0.067 \, \text{cm}^{-3}$ and $T = 10^4 \, \text{K}$ (see Freire et al. 2001) as typical values.

As shown by e.g. Di Matteo et al. (2001) and Quataert & Gruzinov (2000) for nearby early-type galaxies and for the Milky Way, respectively, massive central black holes seem to accrete much slower than predicted by the Bondi estimate (with $M_\bullet < 10^{-2} M_{\bullet, \text{Bondi}}$). The low number of Galactic neutron stars that were detected in the ROSAT All-Sky Survey can be explained if they are accreting at a rate of roughly 0.1% of the Bondi rate (Perna et al. 2003), although, of course, a neutron star accreting from the interstellar medium is a far cry from a central black hole. Theoretical models of the accretion of matter that has non-zero angular momentum onto a black hole (Krumholz, McKee, Klein 2005; Proga & Begelman 2003) show a reduction of the accretion rate down to the level of a few percent of the Bondi rate. In the following, we will assume an accretion rate in the range $10^{-3} M_{\bullet, \text{Bondi}} < M_\bullet < 10^{-2} M_{\bullet, \text{Bondi}}$, in agreement with Maccarone et al. (2004) and Maccarone et al. (2005). Thus, it is possible to estimate the masses (or place upper limits thereon) of central black holes in nearby globular clusters using straightforward and relatively short radio observations.

3 OBSERVATIONS AND DATA REDUCTION

We observed both NGC6397 and 47Tuc with the ATCA on respectively 2004 December 23 and 26. We used the 1.5D configuration, with baselines ranging from 107 to 4439 m. The continuum observations were made at a central frequency of 1.384 GHz in the FULL128_1 correlator configuration with a bandwidth of 128 MHz divided over 32 channels into 4 products. At the start of each observation, we observed the standard ATCA primary calibrator 1934-638 for 10 min. A secondary calibrator was observed every 45 min. The total integration time (including the calibration) for each globular cluster was 3.5 h. The data reduction was performed with the MIRIAD package (Sault, Teuben, Wright 1995), the standard ATCA data analysis program. The observed data were loaded into MIRIAD with the birdie, xycorr, and reweight options, which respectively flags out the channels that are affected by the ATCA self-interference, corrects for the phase difference between the X and Y channels and re-weights the visibility spectrum in the lag domain to eliminate the effects of the Gibbs phenomena. This results in 13 channels, each 4 MHz wide. The usual data reduction steps, including phase, amplitude and bandpass calibration, were afterwards performed. Instead of applying the traditional CLEAN algorithm (Conway, Cornwell, Wilkinson 1990) we used the Multi-Frequency Synthesis (MFS) method (Sault & Conway 1999) with a natural weighting to suppress the noise. This improved drastically the $(u,v)$-coverage by eliminating spectral artifacts.

For NGC6397, after applying all above reduction steps, we constructed a radio continuum map with a beam size of $36.08'' \times 15.64''$ and a $1\sigma$ noise value of 72 $\mu$Jy. No radio continuum sources could be detected in this object at this resolution.
noise level. We therefore assume 216 μJy as the 3σ upper limit on the radio emission of the black hole.

Our 20 cm map of 47Tuc has a depth similar to that presented by McConnell et al. (2004) although it has higher spatial resolution: our final image has a beam size of 33.39″ × 12.55″ and a 1σ noise value of 75 μJy. None of the radio continuum sources is close enough to the cluster center to be associated with a putative black hole. We therefore assume 225 μJy as the 3σ upper limit on the radio emission of the black hole.

4 RESULTS

47Tuc is a massive globular cluster, with a total stellar mass $M \approx 1.5 \times 10^6 M_\odot$ (Gebhardt & Fischer 1995). Its large core radius suggests that it is a relaxed (and not a post-core-collapse) cluster (Howell, Guhathakurta, Gilliland 2000). We use the distance modulus $m - M = 13.50 \pm 0.08$ mag derived by Gratton et al. (2003). NGC6397 on the other hand is a much less massive cluster, with a total stellar mass $M \approx 1.0 \times 10^5 M_\odot$ (Meylan & Mayor 1991). It is a very centrally concentrated, collapsed cluster. Using accurate color-magnitude diagrams and luminosity functions of two fields inside NGC6397, Andreuzzi et al. (2004) found strong evidence for different mass distributions and hence for mass segregation to have occurred. We adopt a distance modulus $m - M = 12.13 \pm 0.15$ mag (Reid & Gizis 1998), determined by main-sequence fitting using lower main sequence stars and hipparcos parallaxes measured to a precision of better than 10%.

We estimate upper-limits on the masses of the putative central IMBHs in these globular clusters from 3σ upper limits on the radio continuum flux. We assume that the putative central black hole accretes the surrounding matter at a rate between 0.1 % and 1 % of the Bondi accretion rate and take into account the uncertainty on the distance modulus. For 47Tuc, we find a 3σ upper limit for the mass of the central black hole of 2060 – 670 $M_\odot$. For NGC6397, we derive a 3σ upper limit of 1290 – 390 $M_\odot$ for the black hole mass.

Massive elliptical and spiral galaxies seem to adhere closely to a relation between the mass of the central black hole, $M_\bullet$, and the central velocity dispersion, $\sigma_c$ (see Fig. 1). Depending on the sample selection and the way the linear regression is done, the slope and zero-point of this relation vary (Ferrarese & Ford 2005; Tremaine, Gebhardt, Bender 2002). The existence of this relation is however generally accepted. Although there is theoretically no obvious reason why this relation should hold with the same slope also in the mass regime of globular clusters, with the growth of SMBHs most likely being driven by the merger histories of their host galaxies, it is nevertheless tempting to do so. The central velocity dispersion of 47Tuc, $\sigma_0 \approx 12$ km/s (Gebhardt & Fischer 1995), corresponds to an IMBH mass $M_\bullet = 1600 M_\odot$. The central velocity dispersion of NGC6397 is very low, $\sigma_0 \approx 5.0$ km/s (Meylan & Mayor 1991), and corresponds to an IMBH mass $M_\bullet = 50 M_\odot$.

The upper limit for the mass of the black hole in 47Tuc lies just below the extrapolated $M_\bullet - \sigma_c$ relation of massive elliptical and spiral galaxies as derived by Tremaine et al. (2002). As this concerns a 3σ upper limit, this means that the mass of the central black hole in 47Tuc must be much lower than predicted by this relation, on the condition, of course, that the black hole accretes at a rate higher than 0.1 % of the Bondi rate. It also excluded the presence of a IMBH with a mass of about 0.1 % of the cluster mass. The extrapolated $M_\bullet - \sigma_c$ relation as derived by Ferrarese & Ford (2005) predicts lower $M_\bullet$-values in the globular-cluster regime than the Tremaine et al. (2002) version and is potentially consistent with our results. The upper limit for the mass of the black hole in NGC6397 lies above both renditions of the $M_\bullet - \sigma_c$ relation and thus puts no extra constraints on this relation in the globular-cluster regime. Given the uncertainty concerning the detection of a black hole in M15 (Gerssen et al. 2002; McNamara, Harrison, Anderson 2003; Maccarone, Fender, Tzioumis 2005), this means that no secure detection of an IMBH exists in the low-mass regime ($\sigma_c < 15$ km/s) of the $M_\bullet - \sigma_c$ relation. Radio-continuum observations of ωCen yielded a 3σ upper limit of $M_\bullet = 1470 - 460$, depending on the accretion rate (Maccarone, Fender, Tzioumis 2005). We adopt a distance of 4.8±0.3 kpc and a central velocity dispersion 18±2 km/s (van de Ven et al. 2006). Dynamical modeling of the central regions of the Local Group galaxies NGC205 (Valluri et al. 2005) and M33 (Merritt, Ferrarese, Joseph 2001; Gebhardt et al. 2001) has yielded no conclusive evidence for IMBHs in the $\sigma_c \sim 30$ km/s regime (with M33, in fact, well below the 1σ uncertainties of the extrapolated $M_\bullet - \sigma_c$ relations). This leaves G1 as the only object with a relatively secure detection of a sub-10$^6 M_\odot$ IMBH (Gebhardt, Rich, Ho. 2002; Baumgardt et al 2003; Gebhardt, Rich, Ho 2005) and that agrees with the extrapolated $M_\bullet - \sigma_c$ relation.
5 CONCLUSIONS

Using radio-continuum observations with the ATCA radio telescope array, we estimate the $3\sigma$ upper-limits on the masses of the putative central IMBHs in two nearby Galactic globular clusters, 47Tuc and NGC6397, at respectively $2060 - 670M_\odot$ and $1290 - 390M_\odot$. These mass estimates have been derived from $3\sigma$ upper limits on the radio continuum flux. We assume that the putative central black hole accretes the surrounding matter at a rate between 0.1 % and 1 % of the Bondi accretion rate and take into account the uncertainty on the distance modulus.

Black hole masses estimated using radio-continuum observations by necessity depend on assumptions regarding the density and temperature of the interstellar medium, and on the accretion rate. Observations of a few globular clusters provide “typical” values for the characteristics of the interstellar medium. The black hole accretion rate can be constrained by observations of the central black hole of the Milky Way and by theoretical models of accretion disks. Still, radio-continuum estimates of black hole masses probably cannot boast the same degree of accuracy as mass estimates from e.g. dynamical models. However, while dynamical models fitted to radial velocities and proper motions of stars near the center of a globular cluster yield the most accurate mass estimates, their spatial resolution is not high enough to identify the central dark mass as a black hole. If, on the other hand, one detects radio emission coming from accreted matter falling into a steep gravitational well then one can be sure that the central object must be very compact, i.e. a black hole. A cluster of white dwarfs or neutron stars would not be able to generate such a feature. In a way, both methods are complementary. Still, it seems telling that we obtain a $3\sigma$ upper-limit for the mass of the putative central black hole in 47Tuc, a nearby massive globular cluster, that places this object marginally below the extrapolation of the $M_\bullet - \sigma_c$ relation of the bright ellipticals and spirals.

The data for NGC6397 unfortunately do not constrain the low-mass end of the $M_\bullet - \sigma_c$ relation. Our results hopefully form the basis for further attempts to detect IMBHs in these global clusters, which, in the case of a detection, would lead to a better understanding of the low-mass tail of the black-hole population and of the accretion rates of central IMBHs in globular clusters.

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