Hundred of stellar-mass black holes probably form in a typical globular star cluster, with all but one predicted to be ejected through dynamical interactions. Some observational support for this idea is provided by the lack of X-ray-emitting binary stars comprising one black hole and one other star ('black-hole/X-ray binaries') in Milky Way globular clusters, even though many neutron-star/X-ray binaries are known. Although a few black holes have been seen in globular clusters around other galaxies, the masses of these cannot be determined, and some may be intermediate-mass black holes that form through exotic mechanisms. Here we report the presence of two flat-spectrum radio sources in the Milky Way globular cluster M22, and we argue that these objects are black holes of stellar mass (each ≈10–20 times more massive than the Sun) that are accreting matter. We find a high ratio of radio-to-X-ray flux for these black holes, consistent with the larger predicted masses of black holes in globular clusters compared to those outside. The identification of two black holes in one cluster shows that ejection of black holes is not as efficient as predicted by most models, and we argue that M22 may contain a total population of ~5–100 black holes. The large core radius of M22 could arise from heating produced by the black holes.

We have obtained very deep radio continuum images of the Milky Way globular cluster M22 (NGC 6656) with the Karl G. Jansky Very Large Array (VLA). The principal goal of the observations was to search for a possible central intermediate-mass black hole via synchrotron emission from the accretion of intracluster gas; no central source was found. However, we serendipitously detected two previously unknown radio continuum sources in the core of the cluster (Fig. 1). We term the sources M22-VLA1 and M22-VLA2. Both sources have flat radio spectra and are unresolved at our ~1″ resolution.

The core radius of M22 is uncommonly large for a Milky Way globular cluster, namely, ~1.24 pc (ref. 11). These sources are well inside the cluster core, at projected radii of 0.4 pc and 0.25 pc for M22-VLA1 and M22-VLA2, respectively. The next source of comparable flux density is far outside the core, at a projected radius of 2.4 pc. These sources have no counterparts in shallow archival Chandra X-ray imaging. On the basis of these non-detections, the sources are constrained to have X-ray luminosities $L_X \lesssim 2.2 \times 10^{39}$ erg s$^{-1}$ over 3–9 keV at the distance of M22. The radio luminosities of the sources at 8.4 GHz are $L_R \approx 6 \times 10^{27}$ erg s$^{-1}$, assuming flat spectra. Therefore, if the sources are not variable, the limit of radio to X-ray luminosity is log ($L_R/L_X$) $\approx -2.6$.

The radio to X-ray, $L_R/L_X$ ratio and central location of the sources place significant constraints on their nature. The most likely explanation is that both sources are accreting stellar-mass black holes in M22. Other possibilities, all of which we consider unlikely, are discussed in Supplementary Information. These objects are the first strong candidates for stellar-mass black holes in any Milky Way globular cluster, and the first stellar-mass black holes to be discovered through radio emission rather than via X-rays.

The radio emission implies that the black holes are actively accreting, and the flat radio spectra are consistent with relatively low accretion rates ($\lesssim 2–3\%$ of the Eddington rate). Because globular clusters have modest amounts of interstellar gas, it is very unlikely that the radio luminosity can be explained by Bondi accretion. Thus the objects cannot be black-hole/black-hole binaries, and instead are probably in binary systems with Roche lobe-overflowing companions. Stellar-mass black holes, ~5–100 times the solar mass, $M_\odot$, offer the best explanation for the presence of multiple sources close to the cluster centre; objects more massive than the average cluster star will sink to the centre because of mass segregation.

To look for optical counterparts of the radio sources, we used archival Hubble Space Telescope (HST) imaging of M22, for which photometric catalogues are available. Figure 2 shows that M22-VLA1 is a close match (0.05″) to a moderately low-mass (~0.34 $M_\odot$) main sequence M dwarf in M22, as inferred from standard stellar isochrones (see Supplementary Information for more details). M22-VLA2 is 0.17″ from a known millisecond pulsar.
Eddington rate\(^{16}\) (in the so-called low/hard state) follow an empirical relation with the X-ray luminosity as faint as our sources\(^{18}\), and there is evidence for substantial (typically a factor of 2–10) variability in both radio and X-ray luminosity with a scatter of a factor of about two (ref. 17). Figure 3 shows this correlation with the radio–X-ray relation predicting an X-ray luminosity of \(10^{31}–10^{32}\) erg s\(^{-1}\) for black holes in the field. The radio–X-ray correlation for stellar-mass black holes has properties more consistent with black holes than with neutron stars or white dwarfs. Filled squares represent simultaneous radio and X-ray data; open squares are non-simultaneous measurements, the positions of which might have been affected by variability. Upper limits are also shown. Some objects have multiple measurements plotted that represent different phases of accretion. The open red circle represents both M22-VLA1 and M22-VLA2, which have very similar luminosities. The dotted black line represents the published correlation\(^{19}\) \(L_X \propto L_R^{0.35}\), normalized by a least-squares fit to the simultaneous detections with \(L_X < 2 \times 10^{34}\) erg s\(^{-1}\). The dashed and dotted blue lines show two possible radio–X-ray correlations for accreting neutron stars; this relation is poorly constrained by observations\(^{20}\). The solid green line shows the maximum radio continuum luminosity observed for accreting white dwarfs\(^{21}\). Neither neutron stars nor white dwarfs have properties consistent with the M22 radio sources. More information can be found in Supplementary Information.

from the nearest detected star, which is a \(\sim 0.62\,M_\odot\) main sequence star. Considering the distribution of stars in the inner 30° of the cluster, the probability of a chance coincidence as close as for M22-VLA1 is only 2%; for M22-VLA2 it is 26%. Thus we consider the optical association for source M22-VLA1 suggestive, but that for M22-VLA2 uncertain. However, for the case of M22-VLA1, there is an additional complication: because the average stellar mass in the core is greater than that of the putative companion, the low-mass main sequence star would probably be exchanged out of the binary in a three-body interaction with another star\(^4\). On the other hand, because of the low central density of M22\(^{21}\) (\(<10^4\,M_\odot\,\text{pc}^{-3}\)), a binary with a low-mass companion might survive longer than in a typical globular cluster. Nonetheless, it is possible that both radio sources are associated with low-luminosity objects below the detection limit of the HST data, such as white dwarfs.

Stellar-mass black holes with accretion rates below \(\sim 2\%\) of the Eddington rate\(^{16}\) (in the so-called low/hard state) follow an empirical correlation between radio and X-ray luminosity with a scatter of a factor of about two (ref. 17). Figure 3 shows this correlation with the M22 data overplotted. The radio–X-ray relation predicts an X-ray luminosity of \(10^{31}–10^{32}\) erg s\(^{-1}\) for this radio luminosity\(^{19,21}\), above the completeness limit of the archival Chandra data. There are several plausible explanations for this discrepancy. First, there is the possibility of variability. The X-ray data were taken in 2005, six years earlier than the radio data. Field stellar-mass black holes in the low/hard state show substantial (typically a factor of 2–10) variability in both radio and X-rays\(^{20,21}\). Therefore, concurrent radio and X-ray data are necessary for precise constraints on \(L_R/L_X\). We found marginal evidence for radio variability in M22-VLA2 on the timescale of a week; more details can be found in Supplementary Information. Another plausible explanation is that there is larger scatter in the radio–X-ray correlation at very low accretion rates. Only a single known black-hole binary has a measured radio luminosity as faint as our sources\(^{19}\), and there is evidence that some stellar-mass black holes with low X-ray luminosities may not fall on the correlation\(^{19}\).

An intriguing possibility is that these sources have high values of \(L_R/L_X\) because they are more massive than typical stellar-mass black holes in the field. The radio–X-ray correlation for stellar-mass black holes is a special case of a ‘fundamental plane’ for black-hole accretion in the low/hard state that includes the black-hole mass as a third parameter\(^{22}\). In this relation, more massive black holes have larger values of \(L_R/L_X\). If our sources have masses of \(15–20\,M_\odot\) rather than the \(5–10\,M_\odot\) typical of field stellar-mass black holes\(^{23}\), then their X-ray luminosities should be lower than predicted by the correlation in Fig. 3 by a factor of \(\sim 2–3\). It is reasonable to expect that black holes in globular clusters will be more massive than those in the field. Field black holes with measured dynamical masses are all in binary systems, and were probably affected by mass transfer during a common envelope stage that reduced the mass of the resulting black holes\(^{24}\). This need not be the case in globular clusters, because black holes can form as single objects or in wide binaries, and then be exchanged into pre-existing binaries or tidally capture companions owing to the high stellar densities\(^{25}\). Globular cluster black holes also form at lower metallicity than in the field, leading to less mass loss from the progenitor and thus more massive remnants\(^8\).

As mentioned above, the location of stars in a cluster also gives information about their masses. Stellar-mass black holes will mass-segregate to the core of the cluster. This process can be used to roughly estimate their masses by assuming thermalization, for which this relation holds\(^1\): \(m_{\text{BH}}/m_* = (r_*/r_{\text{BH}})^{1.5}\), where \(m_{\text{BH}}\) and \(r_{\text{BH}}\) are the characteristic black-hole mass and radius, \(m_*\) is the typical stellar mass, and \(r_*\) is the core radius. Assuming \(m_* = 1M_\odot\) in the segregated cluster core and taking the observed values of \(r_* = 1.24\,\text{pc}\) and \(r_{\text{BH}} = 0.33\,\text{pc}\), we estimate \(m_{\text{BH}} \approx 15M_\odot\).

The existence of black holes in a low-density globular cluster such as M22 constrains the magnitude of the initial velocity kicks received by the black holes at birth. The current central escape velocity of M22\(^{11}\) is \(\sim 34\,\text{km s}^{-1}\). This value may have been higher in the past, owing to a larger cluster mass and a more compact structure. Nonetheless, the retention of two black holes in a globular cluster with a modest escape velocity implies that the black holes could not have received large natal kicks. Large kicks are inferred for some stellar-mass black holes in the field\(^{26}\). Low kick velocities can originate from supernovae if the
black-hole mass is large, or if the black holes form from direct collapse with no supernovae. In either case, higher black-hole masses are favoured.

The presence of black holes in a globular cluster can lead to an expansion of the core radius through interactions between black holes and stars. This could explain why M22 has the fifth-largest core radius among luminous (\( \gtrsim 2 \times 10^5 L_\odot \)) Milky Way globular clusters. Additional discussion can be found in Supplementary Information. Most theoretical models in the literature predict that only a single black hole (or black-hole/black-hole binary) will survive the dynamical processes by which black holes mass-segregate to the cluster centre, form an unstable subcluster, and evaporate. In some cases, more than one black hole may temporarily survive for an additional black-hole relaxation time (\(< 1 \) Gyr), if the extra black holes are kicked into orbits outside the core. Additional discussion can be found in Supplementary Information.

In contrast to these theoretical predictions, M22 contains more than one black hole. In fact, it is possible that more than two black holes are present in M22, either as single black holes or in binary systems that are not undergoing observable mass transfer. Under the uncertain assumption that both of the M22 sources are black-hole/white-dwarf binaries, published calculations can be used to estimate the fraction of surviving black holes that are actively accreting in present-day globular clusters. Over 10 Gyr, 2–40% of black holes are expected to become members of binary systems with observable accretion. Our two observed sources thus suggest a total population of \(~5–100\) black holes in M22.

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