An over-massive black hole in the compact lenticular galaxy NGC 1277

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Most massive galaxies have supermassive black holes at their centres, and the masses of the black holes are believed to correlate with properties of the host-galaxy bulge component. Several explanations have been proposed for the existence of these locally established empirical relationships, including the non-causal, statistical process of galaxy–galaxy merging, direct feedback between the black hole and its host galaxy, and galaxy–galaxy merging and the subsequent violent relaxation and dissipation. The empirical scaling relations are therefore important for distinguishing between various theoretical models of galaxy evolution, and they furthermore form the basis for all black-hole mass measurements at large distances. Observations have shown that the mass of the black hole is typically 0.1 per cent of the mass of the stellar bulge of the galaxy. Until now, the galaxy with the largest known fraction of its mass in its central black hole (11 per cent) was the small galaxy NGC 4486B. Here we report observations of the stellar kinematics of NGC 1277, which is a compact, lenticular galaxy with a mass of $1.2 \times 10^{11}$ solar masses. From the data, we determine that the mass of the central black hole is 1.7 per cent of its bulge mass, and 59 per cent of its total mass. We also show observations of five other compact galaxies that have properties similar to NGC 1277 and therefore may also contain over-massive black holes. It is not yet known if these galaxies represent a tail of a distribution, or if disk-dominated galaxies fail to follow the usual black-hole mass scaling relations.

Direct measurements of black-hole mass often rely on obtaining spatially resolved stellar or gas kinematics within the black hole’s sphere of influence, which is the region over which it dominates the gravitational potential. We have obtained long-slit spectroscopy of 700 nearby galaxies with the Marcario Low Resolution Spectrograph on the Hobby-Eberly Telescope, Texas, to find suitable targets for direct measurements of black-hole mass (Supplementary Information). As shown in Table 1, six of these galaxies have very peculiar properties; they have velocity dispersions of $\sigma > 350$ km s$^{-1}$ and half-light radii of $R_e < 3$ kpc. It is unusual for such small galaxies to have such large dispersions, which signify unusually high central mass concentrations: a simple virial mass estimate indicates that the central 200 pc of the galaxies listed in Table 1 contains more than 10 billion solar masses, which is 100 times more than typical galaxies of the same size.

Black-hole masses can be measured directly by fitting self-consistent Schwarzschild models to spatially resolved spectroscopy data and high-resolution imaging. Archival Hubble Space Telescope (HST) imaging is available for one of these six dense galaxies, NGC 1277. On the basis of the HST imaging (Fig. 1) and the stellar kinematics (Fig. 2), we constructed 600,000 orbit-based models using iterative refinement to search parameter space. The best-fit model is then found by marginalizing over all parameters: the stellar mass-to-light ratio, the black-hole mass and the mass and concentration of the Navarro–Frenk–White dark halo. The confidence intervals are determined with the goodness-of-fit statistic $\chi^2$. We measure a black-hole mass of $(17 \pm 3) \times 10^6$ solar masses ($M_\odot$) and a total stellar mass of $(1.2 \pm 0.4) \times 10^{11} M_\odot$, with 1-s.d. confidence intervals based on $\Delta \chi^2 = 1$ after marginalizing over the dark-halo parameters (Supplementary Information). The black hole in NGC 1277 is one of the most massive black holes to be dynamically confirmed, and moreover has a mass fraction of 14% of the total stellar mass in the galaxy.

No galaxy with such a large ratio of black-hole mass to stellar mass has previously been seen. Owing to the strong disk-like rotation (Fig. 2) and the lack of an unambiguous bulge in NGC 1277 (Fig. 1), it is unclear where to evaluate its black hole against the relation between black-hole mass and bulge luminosity. The central pseudo-bulge contains 24% of the light (Fig. 1) and the black-hole/bulge mass fraction is 59%. As shown in Fig. 3, NGC 1277 is a significant outlier from the mass–luminosity relation, by two orders of magnitude. At a fixed bulge luminosity of $3 \times 10^{10} L_\odot$ to $10^{11} L_\odot$, where $L_\odot$ is the K-band solar luminosity, dynamical measurements of black-hole mass now range over four orders of magnitude, from $10^6 M_\odot$ to $10^{10} M_\odot$, showing that bulge (or pseudo-bulge) luminosity is not a good predictor of black-hole mass.

We now place NGC 1277 on the relation between black-hole mass ($M_\bullet$) and velocity dispersion. The average velocity dispersion inside the half-light radius (2.8 $''$) and outside the sphere of influence (1.6 $''$) for NGC 1277 is $\sigma = 333$ km s$^{-1}$, according to a reconstruction of the best-fit orbit-based model. For this value of $\sigma$, the most recent inferred...
relation predicts a black-hole mass of $2.4 \times 10^9 M_\odot$, so the measured value is almost one order of magnitude higher, or a 2.1-s.d. outlier relative to the intrinsic scatter in the $M_\sigma$ relation.

Apart from NGC 1277, NGC 4486B and Henize 2-1017 are known to lie significantly above the relations, and at least three galaxies are known to lie significantly below the relations. We do not yet know if these over-massive and under-massive black holes just lie in the tails of a relatively narrow distribution of joint black-hole/galaxy properties, or if they demonstrate non-universality. Only through more black-hole measurements, including those in the other five compact galaxies with high velocity dispersions, we will be able to establish the cause of the black-hole/galaxy connection.

![Figure 1](image1.jpg)

**Figure 1** Optical HST image of the compact lenticular galaxy NGC 1277. The image is scaled with the logarithm of the luminosity and is 19 kpc x 8 kpc, with north pointing up and east to the left. In this high-resolution optical image, the galaxy has a half-light radius of 1 kpc, is strongly flattened and is disky. It is clear that a superposition of multiple galaxies does not explain the high velocity dispersion. NGC 1277 has a small, regular, nuclear dust disk with an apparent axis ratio of only 0.3, which indicates that we see the galaxy close to edge-on. Through a multicomponent fit to the HST image, we identify the inner component, with a half-light radius of 0.3 kpc and a Sérsic index of $n = 1$, as a pseudobulge that contains 24% of the light. For the dynamical modelling, we construct a three-dimensional luminous-mass model of the stars by

de-projecting the two-dimensional light model from the HST image. Then the gravitational potential is inferred from the combined luminous, black-hole and dark-matter halo mass distribution. In this potential, representative orbits are integrated numerically, keeping track of the path and velocity along each orbit. We then create a reconstruction of the galaxy by assigning each orbit an amount of light, such that the model recreates the total light distribution, while simultaneously fitting the long-slit stellar kinematics observed with the Hobby-Eberly Telescope (Fig. 2). The models include the effect of the Earth’s atmosphere and the telescope optics without any a-priori assumption on the orbital configuration (Supplementary Information).

![Figure 2](image2.jpg)

**Figure 2** Line-of-sight stellar kinematics of NGC 1277. The stellar kinematics as observed with the Marcario Low Resolution Spectrograph, shown with 1-s.d. error bars, and measured at 31 locations along the major axis of NGC 1277 (Supplementary Information): mean velocity (a); velocity dispersion (b); and higher-order Gauss–Hermite velocity moments $h_3$ (c) and $h_4$ (d), respectively representing skewness and kurtosis. The kinematics show remarkably strong rotation and a dispersion profile that strongly peaks towards the centre. The best-fit Schwarzschild model (black line) corresponds to a $17 \times 10^9 M_\odot$ black hole. The relation between black-hole mass and host luminosity predicts a $10^8 M_\odot$ black hole, but the corresponding model (red dot–dash line) does not fit the data at all. The telescope resolution (seeing full-width at half-maximum, 1.6”) is indicated in b and is sufficient to resolve the sphere of influence of the black hole.

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![Figure 3](image3.jpg)

**Figure 3** The correlation between black-hole mass and near-infrared bulge luminosity, $L_{K_\odot}$. The black line shows the mass–luminosity relation for galaxies with a directly measured black-hole mass. NGC 1277 is a significant positive outlier. In addition to the galaxies (black dots) to which the relation has been fitted, eight black-hole masses (NGC 4486B, triangles, squares) have been added with 2MASS K-band bulge luminosities. The error bars denote 1-s.d. uncertainties, except for the NGC 1277 bulge luminosity, where we use its total luminosity as a conservative upper limit.
A stellar population analysis of NGC 1277 indicates that it contains only old (≥ 8 Gyr) stars and that there has not been any recent star formation. The black hole must thus have been in place for at least 8 Gyr, because black-hole accretion without much star formation or the formation of a (classical) bulge is highly unlikely. Furthermore, there is no strong evidence that NGC 1277 has been tidally stripped, because its isophotes are extremely regular and disky, it seems to have a normal dark-matter halo as inferred from the dynamical model, and at large radii the rotation curve is flat out to five times the half-light radius. Although the six compact galaxies presented in Table 1 are unusual in the present-day universe, they are quantitatively similar to the typical red, passive galaxies at much earlier times (at redshifts of z ≈ 2); those are also found, on average, to be smaller than similarly massive galaxies in the present-day universe, possibly possess high velocity dispersions and generally have a disk-like structure. Perhaps the compact systems we found are local analogues of these high-redshift galaxies.

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