THE BINARY NUCLEUS IN VCC 128: A CANDIDATE SUPERMASSIVE BLACK HOLE IN A DWARF ELLIPSEAL GALAXY

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Abstract

Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) images of the Virgo Cluster dwarf elliptical galaxy VCC 128 reveal an apparently double nucleus. The two components, which are separated by $\sim 32$ pc in projection, have the same magnitude and color. We present a spectrum of this double nucleus and show that it is inconsistent with one or both components being emission-line background objects or foreground stars. The most likely interpretation is that, as suggested by Lauer et al. (1996) for the double nucleus in NGC 4486B, we are seeing a nuclear disk surrounding a supermassive black hole. This is only the second time an early-type dwarf (dE/dSph) galaxy has been suggested to host a SMBH.

Subject headings: galaxies: dwarf — galaxies: individual (VCC 128) — galaxies: nuclei — galaxies: photometry — galaxies: stellar content

1. INTRODUCTION

The centers of galaxies often host supermassive black holes (SMBHs) with masses $M_\bullet$ ranging from $\sim 10^6$ to $\sim 10^9$ M$_\odot$ (Kormendy & Richstone 1995). SMBH masses exhibit a variety of scaling relations including the $M_\bullet - \sigma$ relation (Gebhardt et al. 2000) and an $M_\bullet - M_{DM}$ relation, where $M_{DM}$ is the mass of the host dark halo (Ferrarese 2002) and Baes et al. (2003). These correlations are evidence for a coupling between the formation of SMBHs and galaxies. One key to unraveling this coupling is to identify the seeds of SMBHs in dwarf galaxies. Ground-based stellar kinematic data of dwarf elliptical galaxies (dEs) (Geha et al. 2002) rule out $M_\bullet > 10^7$ M$_\odot$. In the M31 globular cluster G1, thought to be the stripped nucleus of an accreted dE, Gebhardt et al. (2002) report finding an intermediate mass black hole (IMBH) with $M_\bullet > 10^4$ M$_\odot$, consistent with the extrapolation of the $M_\bullet - \sigma$ relation. Nuclear activity in low-luminosity dwarf galaxies has turned up a number of IMBHs with estimated masses from $10^4$ to $10^6$ M$_\odot$ (Filippenko & Ho 2004). There is instead no evidence of a SMBH in either M33 (Merritt et al. 2001; Gebhardt et al. 2001) or NGC 205 (Valteri et al. 2005). The paucity of SMBHs in dwarf galaxies led Ferrarese (2002) to suggest that low mass galaxies are inefficient at forming SMBHs. Côté et al. (2006), Ferrarese et al. (2006), and Wehner (2006) find instead a continuity in scaling relations, with $M_\bullet$ replaced by $M_{CMO}$, the mass of a central massive object, which is either a SMBH or a compact nucleus.

HST does not permit many dynamical $M_\bullet$ measurements below $\sim 10^6$ M$_\odot$. An alternative approach to finding SMBHs in low surface brightness dwarf galaxies is a morphological one. In a few galaxies, HST has found double nuclei; the clearest examples are in M31 and in NGC 4486B (Lauer et al. 1993, 1996, 2005). The two nuclei in M31, dubbed P1 and P2, are separated by 0′′ 49 or 3.6 pc and have unequal surface brightness, with P2 having the lower surface brightness but sitting very close to the global photocenter. In contrast, in NGC 4486B the two nuclei are equal in magnitude, color and displacement from the photocenter, with a total separation of 12 pc. The generally accepted model of the nucleus in M31 identifies P2 as the center of the galaxy surrounding its SMBH and P1 as the bright off-center apoposis of an eccentric Keplerian disk (Tremaine 1995). Self-consistent models and simulations of such nuclei can be constructed (Salas & Statler 2001; Jacobs & Sellwood 2001; Sambhus & Sridhar 2002). Lauer et al. (1996) proposed a similar model for the double nucleus in NGC 4486B with the difference that the SMBH is located on the global photocenter between the two peaks. They suggested that binary nuclei are morphological indicators of SMBHs.

Here we present another example of a galaxy with a double nucleus, the Virgo Cluster dE VCC 128. Its nucleus is very similar to that of NGC 4486B. Section 2 presents the archival HST data, Section 3 presents new spectra and their modeling and in Section 4 we propose that the double nucleus is best explained by a disk surrounding a SMBH at the center of VCC 128 and explore its likely position in the $M_\bullet - \sigma$ plane.

2. ANALYSIS OF HST ARCHIVAL IMAGES

Using the HST archive, we explored the nuclear morphologies of the sample of dEs imaged in the WFPC2 snapshot surveys Prop-ID GO-8600 and GO-6352 (PI Ferguson). These surveys imaged 50 galaxies, which were analysed by Lotz et al. (2004) to show that typical dE
stellar envelopes are 0.1-0.2 mag. redder in V − I than their nuclei. In most of the galaxies we either found no nucleus or a single nucleus. VCC 1107, FCC 208 and VCC 128 contained what appeared to be double nuclei; of these the two nuclei in VCC 128 are the closest, and are most similar in magnitudes making this galaxy a prime candidate for spectroscopic follow-up.

VCC 128 (UGCA 275) is a dE galaxy of $M_B = 15.6$ ($M_V = -15.5$) in the outskirts of the Virgo Cluster. VCC 128 was imaged for 460 seconds in the F555W (V-band) and 300 seconds in the F814W (I-band) filter. Its two nuclei are separated by 4 pixels of WF3 (see Figure 1), i.e. ~ 0.4' or 32 pc (assuming a Virgo Cluster distance of 16.5 Mpc). Tonyv et al. [2001] Jerjen et al. [2004]. We label the component to the south-west as P1 and the one to the north-east as P2. These are equally bright, with apparent magnitudes $\pm 22.56 \pm 0.05$ ($M_V = -8.5$ in P1) and $\pm 22.72 \pm 0.06$ (P2) in the F555W filter and $V - I = 0.9 \pm 0.07$ (P1) and $1.15 \pm 0.07$ (P2). The $S/N = 4.3 - 5.0$ in V and $6.2 - 6.6$ in I for the two nuclei and of the nucleus are shown in Figure 2. At the nucleus, the V − I color map (Figure 1) shows that the double nucleus is not caused by patchy obscuration. Each nucleus is resolved, with FWHM (from a Gaussian fit) of 3.1 and 3.9 pixels in the I-band, whereas the filter point spread function FWHM is 1.3 pixels.

The surface brightness profile of VCC 128 is quite flat and ellipse fitting in IRAF is unstable. Using GALFIT (Peng et al. [2002]) we fitted the surface brightness by a Sérsic model, after masking out stars and the nuclei. We obtained a Sérsic index $n = 0.35$ and a half light radius $R_{eff} = 9''$ for F814W and $n = 0.55$ and $R_{eff} = 14''5$ for F555W. The circun-nuclear region (measured within 1'' of the nuclei) has a surface brightness $\mu_V = 21.37 \pm 0.07$ and color $\mu_V - \mu_I \approx 1.0 \pm 0.1$. The average surface brightness within $R_{eff}$ (averaged between V and I-bands) is $\mu_V = 23.95 \pm 0.02$ mag/arcsec$^2$ and $\mu_I = 22.94 \pm 0.02$ mag/arcsec$^2$. The midpoint between the centroids of the two nuclei (measured within an aperture of 2 pixels) is offset by ~ 0.8' (~ 60 pc) from the photocenter of the galaxy as fitted by GALFIT but with these shallow images we cannot determine whether the photocenter varies with radius as in other offset nuclei (De Rijcke & Debattista [2004]). Possibly because of this offset, Lotz et al. [2004] classified VCC 128 as non-nucleated.

3. SPECTRAL ENERGY DISTRIBUTION

3.1. Observations and Reductions

We obtained long-slit spectra through the nucleus of VCC 128 at the Apache Point Observatory (APO) 3.5-m telescope using the Double Imaging Spectrograph with 0.4 pixels. We used the low resolution blue grating with a resolution 2.4 A/pixel over the wavelength range 3600 ≤ $\lambda$ ≤ 5600 Å. The data were obtained during two runs. In the first run on March 8, 2005 we obtained a total of 5.3 hours of data using a 1''5 slit. Seeing conditions varied significantly over the night, ranging from 0.8'' to >2'' and we had difficulty pointing at the nucleus during some of the exposures. Unsurprisingly, the double nucleus can be detected only in 2 one-hour exposures from this run. Therefore we also obtained data during a second run on April 21, 2006 under sub-arcsecond seeing. During this run we used the 0''9 slit to obtain 2 one-hour spectra.

The spectra were reduced with IRAF using standard tasks. Flux calibration, using the standard stars BD182647 for the first run, and BD262606, Feige 98 and HR 4554 for the second run, achieved a 7% uncertainty at wavelengths bluer than 4000 Å, increasing to 10% at 5500 Å. Data from the two runs were combined by smoothing the 2006 data to match the FWHM of the 2005 run (6A, or 454 km s$^{-1}$ at the CaII lines). The spectrum of the nucleus (spatially unresolved from the ground) is typically 6 pixels wide along the cross-dispersed axis, and that of the galaxy 51 pixels. We extracted the spectrum of the nucleus from the 4 exposures, integrated over the 6 central pixels. The galaxy’s spectrum was extracted below and above the nucleus for a total extension of 45 pixels along the spatial direction. To remove the galaxy contamination in the spectrum of the nucleus, we subtracted the scaled galaxy spectrum from it. The individual spectra of the nucleus and the galaxy were then averaged to increase their S/N ratio, which turned out to be ~ 2 and ~ 8 per pixel respectively. The spectra of the galaxy and of the nucleus are shown in Figure 2. At the nucleus, ~ 12% of the light comes from the nuclei, the rest being due to the galaxy.

3.2. Spectral analysis

The absence of emission lines in the nuclear spectrum rules out, at high confidence, that either P1 or P2 is a background emission line object. A foreground star can be ruled out on several counts. The nuclei are both ruled out on several counts. The nuclei are both require $\chi^2 < 2$ require $v > 500$ km s$^{-1}$, which is improbable for stars in the Milky Way halo. Hence, neither source at the center of VCC 128 can be a foreground star but in good agreement with Virgo Cluster membership, leading us to conclude that this is the nucleus of VCC 128.
because of the short lifetime of such a configuration (globular clusters 32 pc apart in the last stages of merging). The nuclei are located at RA $12^h14^m59^s.71$ Dec $09^\circ 33'55''.57$ (P1) and RA $12^h14^m59^s.73$ Dec $09^\circ 33'55''.82$ (P2) in J2000.0 coordinates.

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To estimate the mass of the nucleus, we compared the SEDs of both the galaxy and the nucleus with the population synthesis models of Bruzual & Charlot (2003). We generated a 64 × 64 grid of τ-models, i.e. composite stellar populations according to an exponentially decaying star formation rate that are then modeled at the resolution and pixel sampling of the observations, and compared via a maximum likelihood analysis. The formation epoch was fixed at $z_F = 3$. The two parameters explored in the grid are the exponential star formation timescale ($-1 < \log(\tau / \text{Gyr}) < 1$) and the metallicity ($-2 < \log(Z/Z_{\odot}) < +0.3$). Figure 2 shows the 1, 2 and 3σ (thick lines) confidence levels for the analysis of the galaxy (left) and of the nucleus (right). The plots overlay contours of stellar mass corresponding to the observed apparent magnitude assuming a Chabrier (2003) initial mass function (IMF), and using the total apparent magnitude of the galaxy ($m_B = 15.6$ Binggeli et al. 1985) and for the double nucleus combined. Our results for the ages and metallicities are independent of the assumed IMF but the masses are more sensitive to this change. The nucleus is consistent with having a relatively metal rich stellar population older than 8 Gyr. With the assumed IMF, the best-fit combined nuclear stellar mass is $\sim 10^6 M_{\odot}$. The galaxy spectrum gives − within error bars − a similar value for the age and metallicity.

In order to assess the effect of dust on the SED analysis, we ran a few sets of grids for various values of $E(B − V)$. The best fits obtained for these realizations gave consistently higher values of $\chi^2$, so that a color excess above $E(B − V) > 0.1$ mag. is ruled out at the 3σ level.

4. DISCUSSION AND CONCLUSIONS

Since the nucleus is old, the present configuration could not have resulted from recent gas infall. It is unlikely, though not impossible, that the two nuclei are both globular clusters 32 pc apart in the last stages of merging because of the short lifetime of such a configuration ($\sim 5$ Myr using the standard Chandrasekhar (1943) formula with $\ln \Lambda = 4$ and $v_c = 20 \text{ km s}^{-1}$). Two well-separated globular clusters projected so close to each other, so close to the center of the galaxy, and so similar in their properties is even more unlikely. The double nucleus in VCC 128 is similar in many ways to that in NGC 4486B. As in NGC 4486B, a nuclear disk surrounding a SMBH provides the best explanation: this would be a stable, long-lived configuration, and would account for the similar colors and magnitudes of the two components and for their location near the center of the galaxy.

If the double nucleus is a disk orbiting a SMBH, we can estimate a lower limit to $M_*$ by assuming that it is...
larger than the nuclear disk mass, $M_d = 10^6 M_\odot$. Alternatively we can use the ratio of $M_d$ to $M_\star$ in M31 ($M_d/M_\star = 0.16$ [Tremaine 1995]) and in NGC 4486B ($M_d/M_\star = 0.019$ [Kormendy & Gebhardt 1997; Lauer et al. 1995]) to estimate $M_\star \sim 6 \times 10^6 - 5 \times 10^7 M_\odot$ in VCC 128. We estimate a velocity dispersion, $\sigma$, for VCC 128 from the Faber-Jackson relation of de’s (de Rijcke et al. 2005). We obtain $\sigma \sim 35 - 65$ km s$^{-1}$. Thus within large uncertainties the postulated SMBH in VCC 128 could satisfy the $M_\bullet - \sigma$ relation, as we show in Figure 3.

Ferrarese (2002) proposed that galaxies with a dark matter virial velocity $v_{vir} \lesssim 200$ km s$^{-1}$ would not be able to form SMBH’s. Using her scaling relations between $\sigma$ and $v_{vir}$, we find that $v_{vir} \lesssim 65$ km s$^{-1}$ assuming the $\sigma$ estimated above. It is unlikely that there is enough scatter in the scaling relations as to accommodate $v_{vir} \simeq 200$ km s$^{-1}$ in VCC 128. Thus its SMBH probably violates the proposed limit unless VCC 128 has been heavily stripped in the cluster environment. Curiously however, VCC 128 would still satisfy the relation between $M_{\text{CMO}}$ and $B$–band magnitude $M_B$ [Wehner & Ferrarese 2003].

We have shown that the nucleus of VCC 128 is double, with the two components of equal magnitude and color. We proposed that this can be explained by the presence of a disk surrounding a SMBH. Simple estimates of its mass all put it in the regime $M_\star \sim 10^6 M_\odot$ or larger. If VCC 128 is on the fundamental plane, then these estimates put the SMBH at, or above, the $M_\bullet - \sigma$ relation. However the halo virial velocity would be smaller than the proposed limit for galaxies to be able to form SMBHs. Amongst the dwarf elliptical/spheroidal population of galaxies, this is only the second example of a system with evidence for a SMBH (Maccarone et al. 2005). Given the very interesting nature of this object, we suggest that further high-resolution imaging and spectroscopy of VCC128 would be well worthwhile.

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