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RADIO CONTINUUM OBSERVATIONS OF THE CANDIDATE SUPERMASSIVE BLACK HOLE IN THE DWARF ELLIPTICAL VCC 128

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ABSTRACT

The presence of black holes (BHs) at the centers of dwarf elliptical galaxies (dEs) has been argued both theoretically and observationally. Using archival *HST* WFPC2 data, we found the Virgo cluster dwarf elliptical galaxy VCC 128 to harbor a binary nucleus, a feature that is usually interpreted as the observable signature of a stellar disk orbiting a central massive black hole. Debattista et al. estimated its mass as $M_\bullet \sim 6 \times 10^6$–$5 \times 10^7\ M_\odot$. One of the most robust means of verifying the existence of a BH is radio continuum and/or X-ray emission; however, because of the deficiency of gas in dEs, radio continuum emission is the best option here. We have tried to detect the X-band radio emission coming from the putative black hole in VCC 128 when it accretes gas from the surrounding ISM. While we made a positive 4 σ detection of a point source 4.63″ southwest of the binary nucleus, no statistically significant evidence for emission associated with the nuclei themselves was detected. This implies either that VCC 128 has no massive central black hole, which makes the nature of the binary nucleus hard to explain, or, if it has a central black hole, that the physical conditions of the ISM (predominantly its density and temperature) and/or of the surrounding accretion disk do not allow for efficient gas accretion onto the black hole, making the quiescent black hole very difficult to detect at radio wavelengths.

Subject headings: galaxies: dwarf — galaxies: individual (VCC 128) — galaxies: nuclei — radio continuum: galaxies

1. INTRODUCTION

The masses of the massive central black holes observed in many galaxies exhibit a variety of scaling relations, such as the $M_\bullet$-σ relation between black hole mass, $M_\bullet$, and central velocity dispersion, σ (Gebhardt et al. 2000; Ferrarese & Merritt 2000) and the $v_{\rm circ}$-σ relation between circular velocity, $v_{\rm circ}$, and central velocity dispersion (Ferrarese 2002; Baes et al. 2003; Pizzella et al. 2005; Buyle et al. 2006). The latter can be interpreted, via the $M_\bullet$-σ relation, as a relation between the mass of the central black hole and the total mass of the host galaxy. These correlations suggest a strong coupling between the formation of massive central black holes and the formation of galaxies.

The literature abounds with scenarios for producing massive central black holes. Models designed to explain the properties of QSOs in massive galaxies typically produce central seed black holes with a minimum mass of $M_\bullet \gtrsim 10^6\ M_\odot$, e.g., through the collapse of a massive central gaseous disk or a supermassive stellar object (Loeb & Rasio 1994; Haehnelt et al. 1998; Silk & Rees 1998). This seed can grow even more massive by feeding from a surrounding gas disk. These models are motivated by the necessity of producing supermassive black holes very rapidly after the big bang, and therefore may be biased to large seed masses. The gravitational collapse of a relativistic star cluster, supposedly born during a starburst, might produce black hole seeds with masses up to $10^4\ M_\odot$ (Shapiro 2004). Scenarios for growing less massive black holes, aptly called intermediate-mass black holes, also exist in the literature (Madau & Rees 2001; Miller & Hamilton 2002; Portegies Zwart & McMilan 2002). Their applicability seems to be restricted to very dense systems, such as, for instance, globular clusters or galactic nuclear star clusters, because they rely on dynamical friction to sink stellar-mass seed black holes, possibly originating from Population III objects, as suggested by Madau & Rees (2001), to the center of the system on short enough timescales.

The picture becomes even more complicated if the fact that galaxies grow via a process of hierarchical merging is taken into account. Recently, the impact of the co-evolution of central black holes and their host galaxies has been incorporated into semianalytical models (SAMs) of galaxy evolution. Kauffmann & Haehnelt (2000), Malbon et al. (2007), and Kazantzidis et al. (2005), for example, allow massive central black holes to grow by two processes: (1) the influx of gas into the galaxy center due to the starburst and the strongly nonaxisymmetric forces that accompany a galaxy-galaxy merger, and (2) merging of the black holes after the host galaxies have merged. These SAMs can reproduce the aforementioned scaling relations between the black hole mass and the properties of the host galaxy. Using a high-resolution small-volume cosmological *N*-body/SPH simulation, Micic et al. (2007) show they can grow $M_\bullet \sim 10^6\ M_\odot$ central black holes in Milky Way size halos by a redshift of $z \sim 6$ by allowing central black holes to merge if their host galaxies merge and by gas accretion during mergers.

However, when the members of a binary black hole system merge, there can be a considerable beaming of the gravitational radiation emitted during the final stages of the plunge. This results in a recoil of the newly formed black hole. Fully relativistic calculations of black hole binary mergers have shown that this

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recoil velocity can be as high as a few hundred km s^{-1}, depending on the holes' spin, orientation, and orbital eccentricity (Pollney et al. 2007). This could potentially hamper the retention of black holes in merging low-mass protogalaxies and by extension the build-up of supermassive black holes.

Clearly, the search for massive central black holes in low-mass galaxies is of considerable interest for the study of the symbiosis of host galaxies and their central black holes and for constraining the minimum mass of seed black holes. Nuclear activity in dwarf galaxies has turned up a number of central black holes with estimated masses in the range $M_\bullet \sim 10^4$–$10^6\ M_\odot$ (Filippenko & Ho 2003; Barth et al. 2004; Greene & Ho 2004). Dynamical modeling of ground-based stellar kinematics of dwarf elliptical galaxies ruled out the presence of central black holes with masses $M_\bullet \gtrsim 10^7\ M_\odot$ (Geha et al. 2002).

Obtaining and modeling high-quality stellar kinematics of faint dwarf galaxies is, unfortunately, a very time-consuming way of searching for inactive central black holes. This prompted us to look for a more efficient, photometry-based method. Using archival *Hubble Space Telescope* (*HST*) images, we found the Virgo Cluster dwarf elliptical galaxy (or dE) VCC 128 to harbor a binary nucleus (Debattista et al. 2006). At the time, only two other galaxies with binary nuclei were known: M31 and NGC 4486B (Lauer et al. 1993, 1996, 2005). In both cases, the binary nucleus was interpreted as the observable signature of a stellar disk orbiting a central massive black hole (Tremaine 1995; Lauer et al. 1996). This suggested that the binary nucleus in VCC 128 might also be the hallmark of a central massive black hole.

However, the presence of a central massive black hole in VCC 128 still needs to be established by independent means. An observationally rather undemanding method for detecting massive central black holes is through the radio emission they produce when they accrete gas. In § 2, we give a short discussion of this method, followed by an account of our radio continuum observations of VCC 128 with the Very Large Array (VLA) in § 3. We end by presenting our results and conclusions in § 4.

2. RADIO FLUX DENSITY PREDICTION FOR AN ACCRETING BLACK HOLE

In order to predict the expected radio continuum flux density of an actively accreting BH, we need an estimate of the BH's mass. In the case of VCC 128 we can make use of the optical photometry from *HST* of the double nuclei. By comparing the observed SED of the nuclei with population synthesis models, we estimated the combined nuclear stellar mass to be $\sim 10^6\ M_\odot$. Assuming that the disk to black hole mass ratios of M31 ($M_{\rm disk}/M_\bullet = 0.16$) and NGC 4486B ($M_{\rm disk}/M_\bullet = 0.019$) are typical, Debattista et al. (2006) estimated the mass of the putative black hole in VCC 128 as $M_\bullet \sim 6 \times 10^6$–$5 \times 10^7\ M_\odot$. As a verification, they used the Faber-Jackson relation of dEs in order to estimate the galaxy's central velocity dispersion, σ, at $\sigma \sim 35$–65 km s^{-1}. This result is in good agreement with the empirical scaling $M_\bullet$-σ relation (Merritt & Ferrarese 2001; Wyithe 2006).

Merloni et al. (2003) observationally derived a fundamental plane relation between 5 GHz radio luminosities $L_{\rm cont}$, X-ray luminosities $L_{\rm X}$, and BH masses $M_\bullet$ of Galactic and extragalactic BHs. Unfortunately, an X-ray luminosity does not exist for VCC 128. Still, the fundamental plane relation and its projections provide us with a useful tool to estimate the radio continuum flux density produced by VCC 128 if an actively accreting BH were present (see Bash et al. 2008 for a similar approach). From Figure 2 in Merloni et al. (2003), for $M_\bullet \gtrsim 6 \times 10^6\ M_\odot$ one would expect a 5 GHz radio luminosity well above $L_{\rm cont} \sim 10^{35}$ erg s^{-1}.

An alternative method to obtain the radio flux $F_{\rm cont}$ without knowing $L_{\rm X}$ is proposed by Maccarone (2004), assuming a flat radio spectrum and the fundamental-plane relationship between radio luminosity, X-ray luminosity, and black hole mass (Merloni et al. 2003; Falcke et al. 2004; De Rijcke et al. 2006). For a given gas accretion rate onto the black hole, expressed as a fraction of the Bondi accretion rate which depends on the gas density and temperature, the X-ray luminosity can be calculated, assuming that 10% of the rest mass energy of the infalling matter is converted into radiation. Unfortunately, no Hα imaging or 21 cm radio line emission data are available for VCC 128, leaving us without direct constraints on the gas density and temperature or even an indication that gas is at all present in this dwarf galaxy.

Thus, it is in principle possible to detect massive central black holes and to estimate their masses (or place broad upper limits thereon), allowing for a large uncertainty due to the combination of several empirical scaling relations and the unknown properties of the accreting gas, using straightforward and relatively short radio observations. We wish to stress that the detection of a radio continuum signal from the center of VCC 128 would provide strong evidence for the presence of a central black hole, independent of the reliability and accuracy of the methods with which we can estimate its mass.

3. OBSERVATIONS AND DATA REDUCTION

We observed VCC 128 with the Very Large Array (VLA) in New Mexico (USA) around midnight of 2007 June 28 (project number AB1248). The VLA is being replaced gradually by the Expanded VLA (EVLA), and therefore at the time of our observations consisted of 16 antennas. The radio continuum emission in a region around the center of the galaxy was mapped in the X-band (8.6 GHz), which is at the VLA's maximum sensitivity. The VLA was in its A configuration at that time, yielding a spatial resolution of 0.24″, corresponding to 19 pc at the distance of VCC 128 (16.5 Mpc). The total project time was 3 hr. At startup, the flux calibrator 1331+305 was observed for 7 minutes, followed by alternating observations of the phase calibrator 1222+042 (with an angular separation of 5.5° from VCC 128) with a 2 minute exposure time, and the galaxy VCC 128 with a 15 minute exposure time. This gives a total on-source integration time of 129 minutes. Standard flagging and calibration of the *u*-*v* data was performed with the Astronomical Image Processing Software (AIPS). We preferred to use MIRIAD (Sault et al. 1995) to derive a natural weighted map. This map was cleaned (1000 iterations) and yields a final image beam size of 0.19″ × 0.18″.

4. RESULTS AND CONCLUSIONS

We created a radio continuum map of the central 12″ × 12″ region of VCC 128 with an rms noise of 30 μJy beam^{-1}. This map is presented in Figure 1, overplotted on a *V*-band image of VCC 128 obtained with FORS1 mounted on the VLT (ESO program 079.B-0632(B)). The data reduction and analysis of the optical imaging of VCC 128 will be reported in detail elsewhere. A 4 σ detection of a point source was made at R.A. $12^{\rm h}14^{\rm m}59.66^{\rm s}$, decl. $+9°33'50.94''$ (J2000). This is 4.63″ southwest of the binary nucleus. The source has a flux density of 1.66 ± 0.05 mJy. Unfortunately, no emission was found at the optical position of the nucleus.

Since we do not detect any radio emission coming from the center of VCC 128, we can only place a $S_\nu \approx 90\ \mu$Jy 3 σ upper limit on the radio continuum emission of the putative central black hole. Assuming a flat radio spectrum, this corresponds to a 3 σ upper limit on the 5 GHz radio luminosity of $L_{\rm cont} = \nu L_\nu \approx 1.5 \times 10^{35}$ erg s^{-1}.

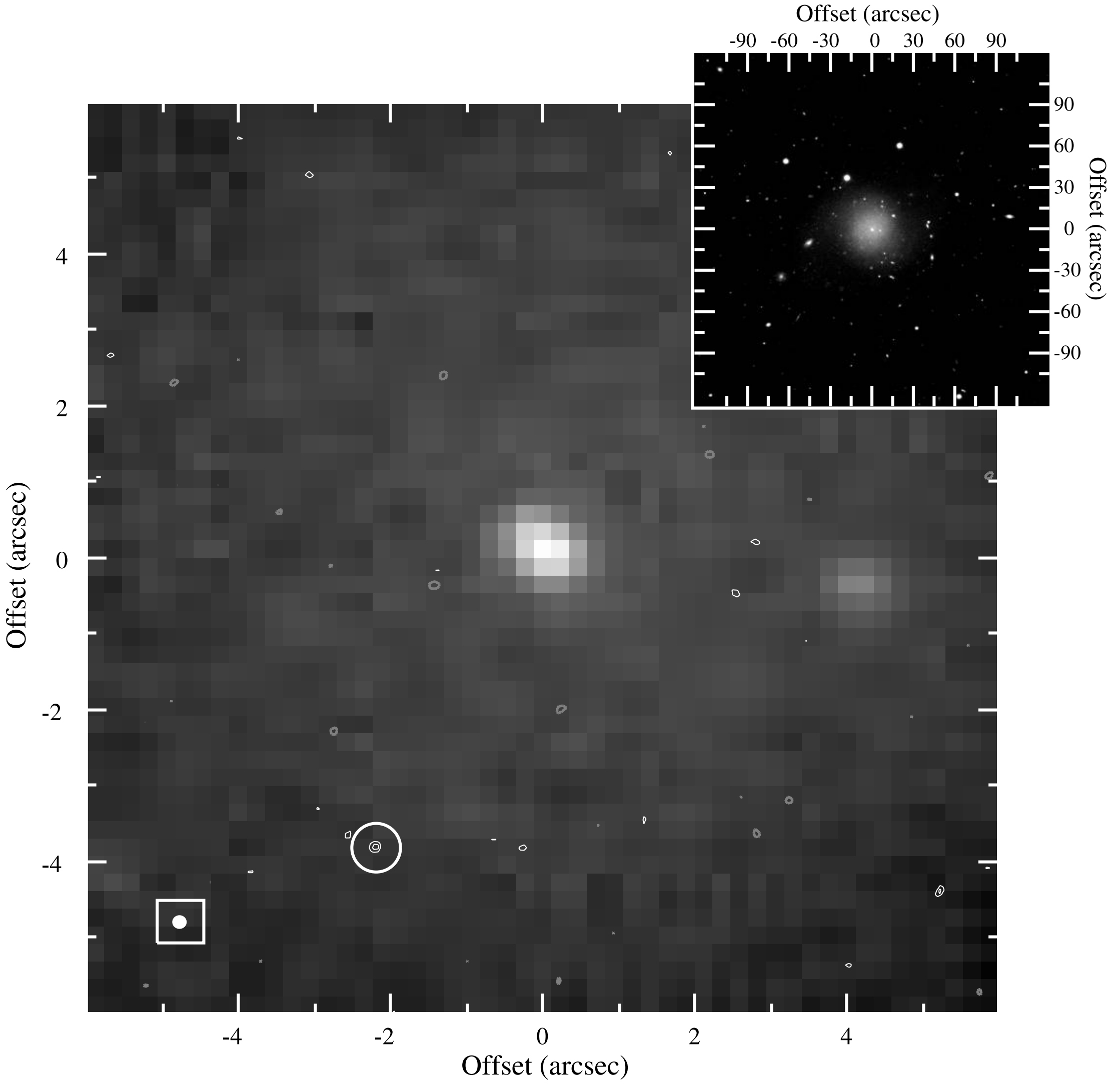

FIG. 1.—Contour plot of the VLA radio observations on top of a *V*-band image of the center of VCC 128. The figure shows the $12'' \times 12''$ region centered on the binary nucleus, which is just resolved in this image. The white contours correspond in increasing order to the contour levels $3\ \sigma$, $4\ \sigma$, $5\ \sigma$, . . . , with $1\ \sigma = 30\ \mu$Jy, while the gray contours correspond to $-3\ \sigma$. The detected source, at $4\ \sigma$ significance, can be seen SW of the center (*circled*). The synthesized beam is shown in the bottom left corner. A *V*-band image of entire VCC 128 is shown in the top right corner.

This is lower than the expected radio luminosity of an actively accreting BH with a mass $M_\bullet \gtrsim 10^6\ M_\odot$.

We conclude that either (1) VCC 128 does not contain a central massive black hole or, alternatively, (2) VCC 128 might contain a central massive black hole with a mass of the order of a few $10^6\ M_\odot$, but the gas near the galaxy center is either too hot or too rarefied, or conditions near the black hole are unsuitable for efficient accretion. In the former case, one needs to rethink the nature of the binary nucleus. As detailed in Debattista et al. (2006), all other explanations for the binary nucleus other than it being the observational signature of a stellar disk rely on rather contrived chance configurations.

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