A VERY LARGE ARRAY RADIO SURVEY OF EARLY-TYPE GALAXIES IN THE VIRGO CLUSTER

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ABSTRACT

We present the results of an 8.4 GHz Very Large Array radio survey of early-type galaxies extracted from the sample selected by Côté and collaborators for the Advanced Camera for Surveys Virgo Cluster Survey. The aim of this survey is to investigate the origin of radio emission in early-type galaxies and its link with the host properties in an unexplored territory toward the lowest levels of both radio and optical luminosities. Radio images, available for all 63 galaxies with \( B_T < 14.4 \), show the presence of a compact radio source in 12 objects, with fluxes spanning from 0.13 mJy to 2700 mJy. The remaining 51 galaxies, undetected at a flux limit of \( \sim 0.1 \) mJy, have radio luminosities \( L \lesssim 4 \times 10^{18} \text{ W Hz}^{-1} \). The fraction of radio-detected galaxies are a strong function of stellar mass, in agreement with previous results: none of the 30 galaxies with \( \log M_{\star} \leq 7.9 \) is detected, while 8 of the 11 most massive galaxies have radio cores. There appears to be no simple relation between the presence of a stellar nucleus and radio emission. In fact, we find radio sources associated with two nucleated galaxies, while the majority of nucleated objects are not a radio emitter above our detection threshold. A multiwavelength analysis of the active galactic nucleus (AGN) emission, combining radio and X-ray data, confirms the link between optical surface brightness profile and radio loudness in the sense that the bright core galaxies are associated with radio-loud AGNs, while non-core galaxies host radio-quiet AGNs. Not all radio-detected galaxies have an X-ray nuclear counterpart (and vice versa). A complete census of AGNs (and supermassive black holes, SMBHs) thus requires observations, at least, in both bands. Nonetheless, there are massive galaxies in the sample, expected to host a large SMBH \((M_{\text{BH}} \sim 10^8 \text{ M}_{\odot})\), whose nuclear emission eludes detection despite their proximity and the depth and the spatial resolution of the available observations. Most likely this is due to an extremely low level of accretion onto the central SMBH.

Key words: galaxies: active – galaxies: clusters: individual (Virgo) – galaxies: dwarf – galaxies: elliptical and lenticular, cD – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

Nuclear radio emission is almost invariably associated with the presence of an active galactic nucleus (AGN) and this is an indication that the process of accretion onto a supermassive black hole (SMBH) naturally produces a signature in the form of radiation in the radio domain. The separation between radio-loud (RL) and radio-quiet (RQ) AGNs is in fact only a measure of the relative flux in the radio band with respect to the optical or X-ray nucleus (Kellermann et al. 1994; Terashima & Wilson 2003); but also RQ AGNs, when studied at sufficient depth, usually show the presence of at least a nuclear radio component (Ulvestad & Wilson 1989; Nagar et al. 2005). For RL AGNs the radio core results from synchrotron emission produced by the unresolved base of their jets; for RQ AGNs the situation is more controversial and it has been recently proposed, besides the possibility of a jet origin, that their radio nuclei are the manifestation of the presence of a thermal outflow or of an active disk corona (Blundell & Kuncic 2007; Laor & Behar 2008).

When combined to the very limited effects that absorption has on radio waves, the study of radio emission provides, in principle, a very powerful tool to detect accretion onto SMBH and, consequently, to establish when an SMBH is present in a given galaxy. However, to take full advantage of this approach, we must reach a much deeper understanding of what determines the radio luminosity of a given galaxy and how this is related to its level of accretion.

A large effort has been dedicated to explore the connection between the host properties (mostly from an optical point of view) and its radio emission. Already from the pioneering study by Auriemma et al. (1977) it was clear that more massive galaxies have on average a higher radio luminosity than smaller galaxies, while apparently there are no distinctions between cluster and non-cluster members (Ledlow & Owen 1996). The radio luminosity functions (RLFs) of galaxies of different optical magnitudes are similar but they differ strongly in their scaling. More recent studies confirm the early results, indicating that the normalization of the RLF scales with the host luminosity as \( L_r \sim L_{r,5} \) (e.g., Best et al. 2005; Mauch & Sadler 2007). However, galaxies of given optical magnitude show a very large range of radio power, more than 5 orders of magnitude, and the relation between the radio and optical luminosity can only be described in terms of a probability distribution.

These studies focused mostly on massive galaxies and had a relatively high threshold for the radio detection. The analyses reached the lowest level of luminosity (in both bands) were performed by Sadler et al. (1989) and Wrobel & Heeschen (1991), with limits at \( L_r \sim 2.5 \times 10^{19} \text{ W Hz}^{-1} \) and \( M_r \sim -18.5 \). Consequently, the information on the radio properties of galaxies of lower mass is sparse and incomplete. Similarly, there is still a dominant fraction of massive galaxies (\( \sim 70\% \)) undetected in radio surveys, for which only an upper limit to their radio luminosity can be derived.

Clearly, a survey reaching lower radio and optical luminosities can provide new insights on the origin and properties of the
radio emission of early-type galaxies. The Virgo cluster represents a unique laboratory for such studies. In fact, it includes hundreds of early-type galaxies, spanning a wide range of stellar masses, for which a vast suite of data is available in the literature. In particular, the recent *Hubble Space Telescope* (HST) survey performed by Côté et al. (2004) provides us with a detailed analysis of their optical brightness profiles whose properties, including the presence of a stellar nucleus, can be included in the study of their radio emission. Given its proximity, its members can be observed at high spatial resolution (1'' at a distance of 17 Mpc corresponds to ~80 pc) and their nuclear emission can be studied down to extremely low luminosity level. For this reason, we performed a radio survey of 63 early-type galaxies in Virgo with the Very Large Array (VLA). Since the aim of these observations is to explore their nuclear properties, the data were taken at high resolution (with the telescope in the A array configuration) and at relatively high frequency (8.4 GHz).

The paper is organized as follows. In Section 2, we describe the sample and the VLA observations; in Section 3, we discuss the link between the radio properties of the galaxies considered with their stellar mass, with their optical brightness profile and with the presence of a stellar nucleus; we then perform an analysis of the multiwavelength properties of their nuclear emission, taking advantage of X-ray data taken from the literature. Summary and conclusions are given in Section 4.

2. SAMPLE SELECTION AND VLA OBSERVATIONS

We considered initially the same sample selected by Côté et al. (2004) for their *HST* survey of early-type galaxies in the Virgo cluster. More specifically, they selected early-type galaxies from the VCC catalog (Binggeli et al. 1987) that consists of 2096 galaxies within this ~140 deg² region. A total of 1277 VCC galaxies were considered by Binggeli et al. (1987) to be members of Virgo, and radial velocities are available for 403 cluster members. A faint-end cutoff at $B_T < 16$ yields 352 galaxies, 163 of which are early-type galaxies according to the VCC morphological classifications of Binggeli et al. (1985). A subset of 100 early-type galaxies was then selected for observations with the Advanced Camera for Surveys (ACS) on *HST*, excluding objects with uncertain morphologies, lacking a clearly visible bulge component, with the presence of strong dust lanes, or signs of strong tidal interactions.

Of the 100 galaxies in the ACS Virgo cluster survey, high-quality radio data already exist for seven sources, all of them within the top third in terms of optical luminosity. We observed an additional 56 galaxies with the VLA, in order of decreasing $B_T$-band magnitude, for a total of 63 objects reaching $B_T = 14.4$.

2.1. VLA Observations and Data Reduction

The galaxies were observed at 8.4 GHz with the VLA in the A-array configuration on 2006 April 17. The source scans, which were each ~30 minutes long, were interspersed with ~2 minutes scans of the nearby phase calibrator, 1239+075, 3C286 was used as the flux density calibrator for the experiment. The data were reduced using the standard calibration and reduction procedures in the Astronomical Image Processing System (AIPS). The amplitude and phase calibration using the calibrators, the sources were split from the main data set and imaged using the task IMAGR. The detected radio sources were weak and were therefore not self-calibrated.

The resolution of the radio images is typically around 0''3 × 0''2, corresponding to a linear size of ~20 pc at the distance of Virgo. The typical resulting rms in the radio images is 30 $\mu$Jy beam$^{-1}$. Five objects were detected with a peak to rms ratio larger than 5, and radio fluxes of these galaxies are reported in Table 1, together with the radio core measurements of the seven radio galaxies found in the literature.

Radio images of these five sources are reproduced in Figure 1. The radio structures are typically unresolved and core-like; the exception is VCC1030, which appears elongated over ~0''2 approximately along the direction of its large-scale dusty disk. The position of the radio source is always within less than 0''8 from the galaxy’s center as measured in the *HST* images, and consistent with being coincident with it considering the uncertainties in the relative astrometry.

None of the observed galaxies is detected in the FIRST survey (with a limiting point source flux density of ~1 mJy) with the exceptions of VCC 1535, VCC 1154, VCC 1030, that are also seen in our images. For the undetected sources we provide the corresponding upper limits in Table 2.
Figure 1. VLA 8.4 GHz radio maps of the five detected sources. The beam size is reported in the bottom left inset. All sources are consistent with being unresolved, with the exception of VCC1030, which appears elongated.

Table 2
The Radio Undetected Galaxies

| Name     | $B_t$ | $F_{conv}$ | Name     | $B_t$ | $F_{conv}$ | Name     | $B_t$ | $F_{conv}$ | Name     | $B_t$ | $F_{conv}$ |
|----------|-------|------------|----------|-------|------------|----------|-------|------------|----------|-------|------------|
| VCC0798  | 10.09 | 0.11       | VCC1938  | 12.11 | 0.10       | VCC1146  | 12.93 | 0.08       | VCC1871  | 13.86 | 0.09       |
| VCC0731  | 10.51 | 0.10       | VCC1279  | 12.15 | 0.15       | VCC1025  | 13.06 | 0.09       | VCC0009  | 13.93 | 0.08       |
| VCC1903  | 10.76 | 0.10       | VCC1720  | 12.29 | 0.11       | VCC1303  | 13.10 | 0.09       | VCC0575  | 14.14 | 0.08       |
| VCC1231  | 11.10 | 0.13       | VCC0355  | 12.41 | 0.10       | VCC1913  | 13.22 | 0.09       | VCC1910  | 14.17 | 0.12       |
| VCC1062  | 11.40 | 0.08       | VCC1883  | 12.57 | 0.10       | VCC1327  | 13.26 | 0.17       | VCC1049  | 14.20 | 0.17       |
| VCC2092  | 11.51 | 0.08       | VCC1242  | 12.60 | 0.09       | VCC1125  | 13.30 | 0.10       | VCC0856  | 14.25 | 0.10       |
| VCC0369  | 11.80 | 0.08       | VCC0784  | 12.67 | 0.08       | VCC1475  | 13.36 | 0.26       | VCC0140  | 14.30 | 0.08       |
| VCC0759  | 11.80 | 0.07       | VCC1537  | 12.70 | 0.08       | VCC1178  | 13.37 | 0.14       | VCC1355  | 14.31 | 0.08       |
| VCC1692  | 11.82 | 0.07       | VCC0778  | 12.72 | 0.08       | VCC1283  | 13.45 | 0.13       | VCC1087  | 14.31 | 0.08       |
| VCC0685  | 11.99 | 0.09       | VCC1321  | 12.84 | 0.08       | VCC1261  | 13.56 | 0.12       | VCC1297  | 14.33 | 0.15       |
| VCC1664  | 12.02 | 0.09       | VCC0828  | 12.84 | 0.08       | VCC0698  | 13.60 | 0.11       | VCC1861  | 14.37 | 0.10       |
| VCC0654  | 12.03 | 0.11       | VCC1250  | 12.91 | 0.08       | VCC1422  | 13.64 | 0.10       | VCC0543  | 14.39 | 0.10       |
| VCC0944  | 12.08 | 0.10       | VCC1630  | 12.91 | 0.08       | VCC2048  | 13.81 | 0.09       |

Note. a 3σ upper limits in mJy.

3. RESULTS

3.1. Radio Emission and Host Stellar Mass

In Figure 2, left panel, we show the 3.6 cm radio luminosity of the VCC sources against their stellar masses, estimated using the recipe of Bell et al. (2007)

$$\log(M_*/L_{gas}) = 0.698(g_0 - z_0) - 0.367,$$

where $g_0$ and $z_0$ are the extinction corrected Sloan Digital Sky Survey (SDSS) total magnitudes. We adopted the distances estimated by Mei et al. (2007) from the analysis of the surface brightness fluctuations (see Table 1) and set the radio upper limits at 3 times the rms noise in the images. The typical radio flux limit of $\sim 1$ mJy corresponds to a radio luminosity of $L \sim 4 \times 10^{18}$ W Hz$^{-1}$.

The radio detections are concentrated at the high end of the mass distribution, with no detections for the 30 galaxies with $M_* < 1.7 \times 10^{10} M_\odot$ (or $M_B > -18.6$). The fraction of detected galaxies increases with increasing stellar mass (Figure 2, right panel), reaching $\sim 70\%$. This is qualitative agreement with previous results on the bivariate radio-optical
luminosity function of early-type galaxies that show that the fraction \( f \) of galaxies brighter than a given radio luminosity \( L \) is a strong function of the host mass, i.e., \( f \propto M_*^{2.0-2.5} \) (e.g., Best et al. 2005; Mauch & Sadler 2007).

More quantitatively, we estimated the number of objects of our sample expected to be detected, assuming that the Best et al. (2005) probability law, derived from SDSS selected galaxies, can be extended to our regime of lower masses and radio-luminosities. We computed the probability of a radio detection for each source and derived the number of expected detections up to a given host mass. At the low mass end this predicts the detection of 0.06 sources up to \( M_* < 1.7 \times 10^{10} M_\odot \), in agreement with the lack of radio detections in the 30 fainter galaxies of the sample. Considering now the high end mass, the probability law saturates to 100% at \( M_* \sim 10^{11} M_\odot \), implying that all galaxies above this level are expected to be seen at the depth of our radio images. This is not the case since we have three radio undetected, optically bright, galaxies. Previous studies, characterized by far higher radio luminosity thresholds concur that a saturation of the detection rate at a \( \sim 30\% \) level occurs at the high mass end (e.g., Mauch & Sadler 2007). Not surprisingly, expanding the radio luminosity coverage downward by 4 orders of magnitude we reach a higher detection rate, \( \sim 70\% \). Nonetheless, we still have three bright galaxies without a radio source associated with them. These objects are \( \gtrsim 30,000 \) times fainter than the radio core of M 87 (the brightest VCC galaxy) and at least \( \gtrsim 200,000 \) times fainter in terms of total radio power, despite the similar stellar mass. This result emphasizes the probabilistic nature of the radio-optical bivariate law and that the optical luminosity of a given galaxy is not a good predictor of its level of radio emission.

3.2. Nucleation and Radio Emission

From the analysis of the data set of HST images, Côté et al. (2006) found that a large fraction of VCC early-type galaxies is nucleated, with a frequency of 66%-82%. Core galaxies do not follow this general rule, since they lack resolved stellar nuclei but, conversely, they often show unresolved optical nuclear sources (defined as nucleation class II). The origin of the nuclei in this class of galaxies, many of them associated with bright radio-sources, must be ascribed to the active nucleus and most likely they represent the synchrotron emission from the basis of their radio jets (Chaberge et al. 1999; Balmaverde & Capetti 2006; Capetti et al. 2007).

We examine the possible presence of a link between nucleation and radio emission. Leaving aside the core galaxies, we are left with only five galaxies with a radio detection and a Sérsic profile. There are two clear nuclei (classes Ia and Ib), two uncertain nuclei (classes Ic and Id), and a dusty galaxy (VCC1030) that cannot be classified from the point of view of nucleation (class 0). In the whole sample of 100 VCC the breakdown in terms of nucleation is 62:15:12:6 in the classes Ia–b:Ic–d:II:0 respectively.4

The stronger connection between nucleation and radio proper- ties is therefore the high incidence of radio nuclei in the core galaxies of the sample, lacking stellar nuclei. Leaving aside the core galaxies, the statistics is clearly very poor, but apparently there is no simple relation between nucleation and the detection of a radio source. In fact, we find radio sources associated with two certainly nucleated galaxies, but the majority of nucleated objects are not radio emitters above our detection threshold. Furthermore, the two nucleated galaxies for which we have a radio detection are among the brightest sources of our sample.

These results are consistent with the study by Seth et al. (2008) on the coincidence of nuclear star clusters and activity. They found that nucleated galaxies can host an AGN (thus a star cluster and an AGN are not mutually exclusive) and the fraction of nucleated active increases strongly with increasing galaxy mass. However, since this result applies also to the general population of galaxies, regardless of their nucleation, they concluded that the presence of a stellar nucleus is not linked to nuclear activity.

4 With an additional five sources of class Ie, reserved for compact sources offset from the galaxy center.
VCC 1049 < VCC 9 < VCC 1178 38 VCC 1913 < VCC 1720 < VCC 1664 39 VCC 685 39 VCC 1154 < VCC 1535 < VCC 1632 39 VCC 1231 38 VCC 763 39 VCC 1978 39 VCC 1316 41

luminosities are given in Table 3. They conclude that these images are seriously contaminated by the presence of a large-scale dusty disk that prevent the study of the SBP.

6 In the Appendix we derive a classification of two galaxies of our sub-sample (VCC 1030 and VCC 1535) from new infrared images. Their optical images are seriously contaminated by the presence of a large-scale dusty disk that prevent the study of the SBP.

3.3. Host Brightness Profile and Nuclear Multiwavelength Properties

The ACS/HST Virgo survey images were used by Ferrarese et al. (2006) to explore the properties of the surface brightness profiles (SBP) of the VCC galaxies. They found that while the SBP are in general well described by a Sérsic (1968) model, in most of the brightest galaxies the inner profiles are lower than expected based on an extrapolation of the outer Sérsic law. These galaxies are better described by a core-Sérsic profile as defined by Trujillo et al. (2004). Table 1 reports the complete list of optical classifications.

Gallo et al. (2008) presented preliminary results of a program of Chandra observations of the VCC sample. They report the analysis of X-ray images for 32 objects, 25 in common with our sub-sample, and found X-ray nuclei in 16 galaxies, whose luminosities are given in Table 3. They conclude that these nuclear sources are most likely the manifestation of the presence of a low luminosity active nucleus. This opens the possibility of exploring the link between host brightness profile and AGN multiwavelength properties.

Chandra observations revealed an X-ray nucleus in five core galaxies, and all of them are consistent with the correlation linking radio and X-ray emission for RL AGNs derived by Balmaverde & Capetti (2006, see Figure 3). Moving to the Sérsic galaxies, two have nuclei detected both in radio and X-ray, while 10 are only detected in the X-ray images. The location of these sources in the L<sub>r</sub> versus L<sub>x</sub> plane indicates that they are low luminosity RQ AGNs. These results confirm the relation between optical surface brightness profile and radio loudness (Capetti & Balmaverde 2006, 2007) in the sense that core galaxies are associated with RL AGNs, while non-core galaxies host RQ AGNs.

A consequence of these findings is that, not surprisingly, it is easier to detect the AGN emission in the radio band for a RL source and in the X-ray band for a RQ AGN. This has an important consequence when we seek for a complete census of AGNs and consequently of SMBHs in a sample of galaxies, since only by combining radio and X-ray data it is possible to cover all AGN manifestations. For example, the presence of an AGN in VCC 1226, the brightest cluster member, is not visible in X-ray images, while it is clearly shown by its radio images.

4. SUMMARY AND CONCLUSIONS

We presented the results of a radio survey of early-type galaxies in the Virgo cluster, extracted from the sample selected by Côté et al. (2004) for their ACS Virgo Cluster Survey. We observed 56 galaxies at 8.4 GHz with the VLA that, combined with data from the literature, provide radio images for all 63 galaxies brighter than B<sub>T</sub> = 14.4. The aim of this survey is to investigate the origin of radio emission in early-type galaxies and its link with the host properties in an unexplored territory toward the lowest levels of both radio and optical luminosities.

Compact radio sources are found in 12 objects, with fluxes from 0.13 to 2700 mJy. The remaining 51 galaxies are un-detected at a flux limit of ~0.1 mJy, corresponding to radio luminosities L<sub>r</sub> ≲ 4 × 10<sup>18</sup> W Hz<sup>-1</sup>. The fraction of radio-detected galaxies is a strong function of stellar mass, in agreement with previous results on the bivariate radio/optical luminosity function of early-type galaxies: while none of the 30 galaxies with

| Name | L<sub>r</sub> (0.3–10 keV) | vL<sub>x</sub> | Profile |
|------|----------------|-----------|---------|
| VCC 1226 | < 38.49 | 36.81 | cS |
| VCC 1316 | 41.20 | 39.68 | cS |
| VCC 1978 | 39.05 | 37.52 | cS |
| VCC 763 | 39.73 | 38.57 | cS |
| VCC 1632 | 39.58 | 37.94 | cS |
| VCC 2095 | 38.71 | 36.33 | S |
| VCC 0881 | < 38.64 | 35.85 | cS |
| VCC 1535 | < 38.21 | 36.95 | cS |
| VCC 1154 | 39.03 | 36.17 | S |
| VCC 798 | < 38.43 | < 35.55 | cS |
| VCC 731 | 39.00<sup>a</sup> | < 35.54 | cS |
| VCC 1903 | 39.11 | < 35.34 | S |
| VCC 1231 | 38.60 | < 35.48 | S |
| VCC 2092 | 38.59 | < 35.32 | S |
| VCC 1692 | 38.45 | < 35.34 | S |
| VCC 665 | 39.14 | < 35.38 | S |
| VCC 1664 | 39.95 | < 35.34 | S |
| VCC 1720 | < 38.54 | < 35.48 | S |
| VCC 1883 | 38.35 | < 35.47 | S |
| VCC 1913 | < 38.46 | < 35.46 | S |
| VCC 1178 | 38.67 | < 35.54 | S |
| VCC 2048 | < 38.12 | < 35.38 | S |
| VCC 9 | < 38.15 | < 35.38 | S |
| VCC 1049 | < 38.08 | < 35.65 | S |
| VCC 1297 | 38.42 | < 35.61 | S |

| Name | L<sub>x</sub> (0.3–10 keV) | vL<sub>r</sub> | Profile |
|------|----------------|-----------|---------|
| VCC 1226 | < 38.49 | 36.81 | cS |
| VCC 1316 | 41.20 | 39.68 | cS |
| VCC 1978 | 39.05 | 37.52 | cS |
| VCC 763 | 39.73 | 38.57 | cS |
| VCC 1632 | 39.58 | 37.94 | cS |
| VCC 2095 | 38.71 | 36.33 | S |
| VCC 0881 | < 38.64 | 35.85 | cS |
| VCC 1535 | < 38.21 | 36.95 | cS |
| VCC 1154 | 39.03 | 36.17 | S |
| VCC 798 | < 38.43 | < 35.55 | cS |
| VCC 731 | 39.00<sup>a</sup> | < 35.54 | cS |
| VCC 1903 | 39.11 | < 35.34 | S |
| VCC 1231 | 38.60 | < 35.48 | S |
| VCC 2092 | 38.59 | < 35.32 | S |
| VCC 1692 | 38.45 | < 35.34 | S |
| VCC 665 | 39.14 | < 35.38 | S |
| VCC 1664 | 39.95 | < 35.34 | S |
| VCC 1720 | < 38.54 | < 35.48 | S |
| VCC 1883 | 38.35 | < 35.47 | S |
| VCC 1913 | < 38.46 | < 35.46 | S |
| VCC 1178 | 38.67 | < 35.54 | S |
| VCC 2048 | < 38.12 | < 35.38 | S |
| VCC 9 | < 38.15 | < 35.38 | S |
| VCC 1049 | < 38.08 | < 35.65 | S |
| VCC 1297 | 38.42 | < 35.61 | S |

Note. The identification of the brightest X-ray source with the AGN is uncertain (Sivakoff et al. 2003).
\( M_* < 1.7 \times 10^{10} \, M_\odot \) is detected, 8 of the 11 most massive galaxies have radio cores. However, the galaxy mass is not a good predictor of its level of radio emission. This is clearly seen from a comparison of the radio properties of the brightest galaxies of the VCC. While they span only a factor of 10 in stellar mass, they cover a range of \( \gtrsim 4.5 \) orders of magnitude in radio-core power, and three of them are not detected in our radio images.

We note that VCC early-type galaxies with strong dust lanes or of signs of interactions were excluded by the original definition of the sample for the ACS Virgo cluster survey. Considering the links between mergers, dust content, and nuclear activity suggested by previous studies of early-type galaxies (e.g., Tran et al. 2001; de Ruiter et al. 2002; Lauer et al. 2005) the sub-sample considered might be biased against active galaxies with respect to the overall population. This effect, however, does not affect the bright luminosity end, since the sample is complete down to \( B_T = 12 \).

We examined the possibility of a link between nucleation and radio emission. Core galaxies lack stellar nuclei and show a high incidence of radio nuclei. In the rest of the sample, only two nucleated galaxies show the presence of a radio source. Thus nuclear activity can coexist with a stellar nucleus, but the fraction of active galaxies is not related to nucleation.

We considered the properties of the surface brightness profiles, separating galaxies reproduced by a Sérsic law from those better described by a core-Sérsic profile. Furthermore, we relied on the results of X-ray Chandra observations by Gallo et al.

**Figure 4.** HST/NICMOS image of VCC 1030 and (on the right panel) the derived surface brightness profile. The solid line reproduces the best-fit Sérsic law. The vertical dashed line marks the value of the effective radius, \( r_e = 3.9'. \) The vertical axis gives the logarithm of the surface brightness in unit of \( (\text{erg s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1} \, \text{arcsec}^{-2}) \).

In the bottom inset we show the residuals of the fit.

(A color version of this figure is available in the online journal.)

**Figure 5.** Same as Figure 4 for VCC 1535. The vertical dashed line marks the value of the core radius, \( r_c = 0'.15. \) The dot-dashed line is the best-fit Sérsic law to the external regions \( (r > 1') \) of the galaxy, that overpredicts the central surface brightness.

(A color version of this figure is available in the online journal.)
radio loudness (Capetti & Balmaverde 2006) is found also in the VCC sample, since RL AGNs are associated with core galaxies, while non-core galaxies only host RQ AGNs.

Not all radio-detected galaxies have an X-ray nuclear counter part, and vice versa. Not surprisingly, it is easier to detect the AGN emission in the radio band for a RL source and in the X-ray band for a RQ AGN. This has an important consequence when we seek for a complete census of AGNs and consequently of SMBHs for which a combination of (at least) radio and X-ray data is required.

Nonetheless, nuclear emission is not detected in a significant fraction of VCC galaxies in either observing band. Clearly, there is the possibility that the VCC sample crosses the minimum galaxy mass at which a SMBH is present (if such a threshold indeed exists). However, there are no signs for the presence of an AGN in relatively massive VCC galaxies (e.g., VCC 798 and VCC 1720) despite the fact that they are expected to host a large SMBH ($M_{\text{BH}} \sim 10^8 M_\odot$), based on a typical ratio of 0.002 between SMBH and galaxy’s mass (Marconi & Hunt 2003). This is particularly worrisome for a general use of AGNs as black-hole tracers, considering the proximity of the Virgo cluster, the depth, and the spatial resolution of the available observations.

In general, for the quiescent galaxies we cannot distinguish between a scenario (1) of a transition toward galaxies lacking an SMBH due to a low mass threshold, (2) the possibility that the SMBH has been ejected due to the recoil caused by the coalescence between two black holes following a galaxy merger (e.g., Campanelli et al. 2007), and (3) of extremely low accretion rate.

In fact, a crucial role in our ability to detect an active nucleus, and in setting its level of activity, is certainly played by the level of accretion onto the central SMBH. At least for low-power RL AGNs, it has shown that a suggestive linear correlation exists between the accretion rate of hot gas (estimated in a spherical approximation) and the jet power, over several orders of magnitude (Allen et al. 2006; Balmaverde et al. 2008). Therefore, to take full advantage of active nuclei as black hole tracers, it is necessary to combine a multiwavelength approach with estimates of the accretion rate. It is certainly of great interest to explore, for example, whether the connection between the level of accretion and activity can be extended to the lowest level of radio emission seen in the RL VCC galaxies, and how this compares with similar estimates for RQ AGNs.

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APPENDIX

The optical images of two galaxies of the sample (namely VCC 1030 and VCC 1535) both detected in the VLA images show the presence of large-scale dusty disks (Côté et al. 2004) that prevent the study and classification of their surface brightness profiles. We then retrieved their infrared images where the impact of dust absorption is less severe from the HST archive. The images were taken with NICMOS/HST through the filter F160W (H band) and were processed by the standard HST pipeline. The camera NIC1 was used, with a pixel size of 0′.043, for a field of view of ≈11′ × 11′.

Elliptical isophotes were fit to both images using the IRAF task “ellipse” (Jedrzejewski 1987). Although these images are still affected by dust absorption (see Figures 4 and 5), there are sufficient dust-free regions to derive the SBP after proper masking. Since the image of VCC 1535 fills completely the field of view, we extended the radial coverage of the SBP using the H-band image from the Two Micron All Sky Survey (2MASS).

The SBP were fit using a Sérsic law (Sérsic 1968) convolved with the appropriate point-spread function before comparison with the data. The SBP of VCC 1030 are reproduced very closely by a Sérsic model with an effective radius of $r_e = 3.9$ and a Sérsic index $n = 1.7$. This is not the case of VCC 1535 that shows a strong light deficit in the innermost regions with respect to the Sérsic that describes the external regions and requires the presence of a flat central core. We therefore fit its SBP with a core-Sérsic model (Trujillo et al. 2004); the parameters of the best fit are an effective radius $r_e = 106''$, an index $n = 5.2$, a core radius $r_c = 0.15$, and a inner slope $\gamma = 0.06$. This analysis leads to a classification based on the SBP properties of VCC 1030 as a Sérsic galaxy and of VCC 1535 as a core-Sérsic galaxy.

REFERENCES

Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, MNRAS, 372, 21
Auriemma, C., Perola, G. C., Ekers, R. D., Fantì, R., Lari, C., Jaffe, W. J., & Ulrich, M. H. 1977, A&A, 57, 41
Balmaverde, B., Baldi, R. D., & Capetti, A. 2008, A&A, 486, 119
Balmaverde, B., & Capetti, A. 2006, A&A, 447, 97
Bell, E. F., Zheng, X. Z., Papovich, C., Borch, A., Wolf, C., & Meisenheimer, K. 2007, ApJ, 663, 834
Best, P. N., Kauffmann, G., Heckman, T. M., Brinchmann, J., Charlot, S., Ivezić, Ž., & White, S. D. M. 2005, MNRAS, 362, 25
Binggeli, B., Sandage, A., & Tammann, G. A. 1985, AJ, 90, 1681
Binggeli, B., Tammann, G. A., & Sandage, A. 1987, AJ, 94, 251
Blundell, K. M., & Kuncic, Z. 2007, ApJ, 668, L103
Campanelli, M., Lousio, C., Zlochower, Y., & Merritt, D. 2007, ApJ, 659, L5
Capetti, A., Axon, D. J., Chiaberge, M., Sparks, W. B., Duccio Macchetto, F., Cracraft, M., & Celotti, A. 2007, A&A, 471, 137
Capetti, A., & Balmaverde, B. 2006, A&A, 453, 27
Capetti, A., & Balmaverde, B. 2007, A&A, 469, 75
Chiaberge, M., Capetti, A., & Celotti, A. 1999, A&A, 349, 77
Condon, J. J., Cotton, W. D., & Broderick, J. J. 2002, AJ, 124, 675
Condon, J. J., Helou, G., Sanders, D. B., & Soifer, B. T. 1990, AJ, 100, 1163
Côté, P., et al. 2004, ApJS, 153, 223
Côté, P., et al. 2006, ApJS, 165, 57
de Ruiter, H. R., Parma, P., Capetti, A., Fantì, R., & Morganti, R. 2002, A&A, 396, 857
Ferrarese, L., et al. 2006, ApJS, 164, 334
Gallo, E., Treu, T., Jacob, J., Woo, J.-H., Marshall, P. J., & Antonucci, R. 2008, ApJ, 680, 154
Jedrzejewski, R. I. 1987, MNRAS, 226, 747
Kellermann, K. I., Sramek, R. A., Schmidt, M., Green, R. F., & Shaffer, D. B. 1994, AJ, 108, 1163
Lauer, T., & Behar, E. 2008, MNRAS, 390, 847
Lauer, T. R., et al. 2005, AJ, 129, 2138
Ledlow, M. J., & Owen, F. N. 1996, AJ, 112, 9
Mauch, T., & Sadler, E. M. 2007, MNRAS, 375, 931
Mei, S., et al. 2007, ApJ, 655, 144
Nagar, N. M., Falcke, H., & Wilson, A. S. 2005, A&A, 435, 521
Sadler, E. M., Jenkins, C. R., & Kotanyi, C. G. 1989, MNRAS, 240, 591
Sérsic, J.-L. 1968, Atlas de Galaxias Australes (Córdoba: Obs. Astron.)
Seth, A., Agueros, M., Lee, D., & Basu-Zych, A. 2008, ApJ, 678, 116
Sivakoff, G. R., Sarazin, C. L., & Irwin, J. A. 2003, ApJ, 599, 218
Stanger, V. J., & Warwick, R. S. 1986, MNRAS, 220, 363
Terashima, Y., & Wilson, A. S. 2003, ApJ, 583, 145
Tran, H. D., Tsvetanov, Z., Ford, H. C., Davies, J., Jaffe, W., van den Bosch, F. C., & Rest, A. 2001, AJ, 121, 2928
Trujillo, I., Erwin, P., Asensio Ramos, A., & Graham, A. W. 2004, AJ, 127, 1917
Ulvestad, J. S., & Wilson, A. S. 1989, ApJ, 343, 659
Wrobel, J. M., & Heeschen, D. S. 1991, AJ, 101, 148