AMUSE-VIRGO. I. SUPERMASSIVE BLACK HOLES IN LOW-MASS SPHEROIDS

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ABSTRACT

We present the first results from the AGN Multiwavelength Survey of Early-Type Galaxies in the Virgo Cluster (AMUSE-Virgo). This large program targets 100 early-type galaxies with the Advanced CCD Imaging Spectrometer on board the Chandra X-Ray Observatory and the Multiband Imaging Photometer on board the Spitzer Space Telescope, with the aim of providing an unbiased census of low-level supermassive black hole activity in the local universe. Here we report on the Chandra observations of the first 16 targets, and combine them with results from archival data of another, typically more massive, 16 targets. Pointlike X-ray emission from a position coincident with the optical nucleus is detected in 50% of the galaxies (down to our completeness limit of \( \sim 4 \times 10^{38} \) ergs s\(^{-1}\)). Two of the X-ray nuclei are hosted by galaxies (VCC 1178 [N4464] and VCC 1297 [N4468B]) with absolute B magnitudes fainter than –18, where nuclear star clusters are known to become increasingly common. After carefully accounting for possible contamination from low-mass X-ray binaries, we argue that the detected nuclear X-ray sources are most likely powered by low-level accretion on to a supermassive black hole, with a \( \leq 11\% \) chance contamination in VCC 1178, where a star cluster is barely resolvable in archival Hubble Space Telescope images. Based on black hole mass estimates from the global properties of the host galaxies, all the detected nuclei are highly sub-Eddington, with luminosities in the range \(-8.4 < \log(L_{0.3-10\,\text{keV}}/L_{\text{Edd}}) < -5.9\). The incidence of nuclear X-ray activity increases with the stellar mass \( M_* \) of the host galaxy: only between 3% and 44% of the galaxies with \( M_* < 10^{10} \) M\(_\odot\), harbor an X-ray active supermassive black hole. The fraction rises to between 49% and 87% in galaxies with stellar mass above \( 10^{10} \) M\(_\odot\) (at the 95% confidence level).

Subject headings: black hole physics — galaxies: clusters: individual (Virgo) — galaxies: nuclei

Online material: color figures

1. INTRODUCTION

One of the main recent developments in the study of galaxy formation and evolution has been the realization of the key role played by nuclear activity due to accretion onto supermassive black holes (SMBHs). Low-level accretion-powered activity has been suggested to be relevant for a variety of phenomena, including regulating star formation at galaxy scales via energy feedback to solve the "downsizing" problem and providing extra energy to solve the "cooling flow" problem (Cowie et al. 1996; Dalla Vecchia et al. 2004; Springel et al. 2004; Treu et al. 2005a, 2005b; Bundy et al. 2005, 2007; Juneau et al. 2005; De Lucia et al. 2006, Abraham et al. 2007, Sijacki et al. 2007, McNamara & Nulsen 2007). The most compelling pieces of evidence supporting a strong connection between galaxy formation and nuclear activity are the tight empirical scaling relations connecting the mass of the central SMBH with global properties of the host galaxy, such as bulge luminosity and mass (Kormendy & Richstone 1995; McLure & Dunlop 2002; Marconi & Hunt 2003; Haring & Rix 2004), galaxy-light concentration (Graham et al. 2001; Erwin 2004), and stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000). An issue of fundamental importance in understanding the galaxy—black hole connection is the "duty cycle" of nuclear activity, and its dependence on, e.g., black hole mass. If SMBHs are indeed ubiquitous in galactic bulges, little is known about the frequency and intensity of nuclear activity, the more so at the low-mass end (see Greene & Ho 2007a). Even though a minimum level of accretion should be present, fueled by mass loss during stellar evolution (e.g., Ciotti et al. 1991; Ciotti & Ostriker 2007), the inferred accretion-powered luminosities are often lower than what expected from standard Bondi-Hoyle accretion (as found e.g., for the Galactic center SMBH Sgr A*; Baganoff et al. 2003).

From an empirical point of view, optical studies are mostly limited to samples of known active nuclei (e.g., Woo & Urry 2002; Heckman et al. 2004; Kollmeier et al. 2006; Greene & Ho 2007b) with limited coverage of the black hole mass-Eddington luminosity (\( \text{MBH-}\text{LEdd} \)) plane. Prior to the launch of the Chandra X-Ray Observatory, searches for low-level accretion powered X-ray emission from apparently inactive galaxies were effectively limited to X-ray luminosities \( \geq 10^{38} \) ergs s\(^{-1}\) (e.g., Fabbiano & J uda 1997; Allen et al. 2000; Sulkanen & Bregman 2001). The greatly improved Chandra sensitivity, together with its fine spatial resolution, has made it possible to investigate nuclear emission associated with SMBH activity down to 3 orders of magnitude deeper, effectively bridging the gap between active galactic nuclei (AGNs) and inactive galaxies. Perhaps surprisingly, only very low levels of nuclear X-ray luminosity (\( L_X/L_{\text{Edd}} < 10^{-6} \), 2–10 keV) have been observed in nearby massive ellipticals (Di Matteo et al. 2000; Ho et al. 2001; Loewenstein et al. 2001; Pellegrini 2005; Soria et al. 2006a, 2006b; Santra et al. 2007), despite their containing vast fuel reservoirs in the form of hot X-ray-emitting interstellar gas. While these results rule out radiatively efficient solutions for the accretion flow, the detected X-ray-emitting luminosities can vary by orders of magnitude when plotted against the Bondi accretion rate (Pellegrini 2005), with a large fraction of systems being even fainter than predicted by advection-dominated accretion flow models (Narayan & Yi 1994).
These observations are closely related to the role of SMBH feedback in inhibiting star formation at a galaxy scale level. Semi-analytical models applied to state of the art cold dark matter simulations have recently highlighted the importance of highly sub-Eddington SMBH activity. In the formulation by Croton et al. (2006), a low level of prolonged activity (the so-called radio mode) is essential to prevent the reservoir of gas surrounding the most massive galaxies from cooling and producing young stars, and thus reproduce their red colors. In this scenario, low-level SMBH feedback halts the gas supply to the disk from the surrounding hot halo, truncating star formation and allowing the existing stellar population to redden.

So far, however, these studies have been sparse and necessarily focused on the small number of galaxies at the high-mass end of the local population. At the same time, while the paucity of AGNs in the local universe is a known phenomenon, recent studies point toward an actual decline in the spatial density of local active black holes with mass below \(10^{6.5} - 10^7 \, M_\odot\) (Greene & Ho 2007b), possibly due to low black hole occupation fraction and/or low bulge fraction in dwarf galaxies. In turn, this can place constraints on the very mechanism by which SMBHs formed in the early universe, since different models for the formation of black hole seeds predict different black hole occupation fractions at redshift zero. This effect becomes more prominent down the mass function. In particular, models where the black hole seeds are formed in the nuclei of gravitationally unstable pregalactic disks that form through the collapse of halos at redshift \(\sim 10\) (e.g., Madau & Rees 2001; Begelman et al. 2006; Lodato & Natarajan 2006) predict the existence of a population of faint low-mass galaxies with no black hole at their center (Volonteri et al. 2008a, 2008b).

As a matter of fact, “light” SMBHs, presumably harbored by faint dwarf galaxies, remain elusive: the strong limits placed by dynamical studies on the masses of the nuclear objects in M33 (Gebhardt et al. 2001; Merritt et al. 2001) and NGC 205 (Valluri et al. 2005) suggest that neither galaxy hosts a SMBH of the mass expected from extrapolation of the known scaling relations in massive bright galaxies. Ferrarese et al. (2006a) suggest that, while SMBHs are common in bright (absolute \(B\) magnitude \(M_B < -20\)) massive galaxies, they would be progressively replaced by compact stellar nuclei moving down the mass function, and may disappear entirely at the faint end. On the other hand, compelling evidence exists for a \(3.7 \times 10^6 \, M_\odot\) black hole at the center of our own Milky Way (Ghez et al. 2005), providing us with the best example of highly radiatively inefficient black hole accretion (the measured X-ray luminosity between 2 and 10 keV can be as low as \(10^{33.3} \, \text{ergs s}^{-1}\); Baganoff et al. 2003). Although no direct dynamical black hole mass determination exists below \(10^6 \, M_\odot\), indirect evidence points toward the existence of such objects in active galaxies (Filippenko & Ho 2003; Peterson et al. 2005; Barth et al. 2004; Greene & Ho 2004, 2007a), globular clusters (Gebhardt et al. 2002, Gerssen et al. 2002) and (some) ultraluminous X-ray sources (Miller 2005).

In this paper we present the first results from an extensive multiwavelength survey of 100 spheroids—elliptical, lenticular and dwarf spheroidal galaxies—in the Virgo Cluster, conducted with the Chandra X-Ray Observatory and the Spitzer Space Telescope: AMUSE-Virgo (AGN Multiwavelength Survey of Early Type Galaxies in Virgo). As described in § 2, the survey is designed to provide the first unbiased census of low levels of nuclear activity in the local universe as a function of host galaxy mass for early-type galaxies. Section 3 describes our analysis of the new and archival Chandra data obtained so far (32/100 galaxies), as well as of archival Hubble Space Telescope (HST) images used to connect the X-ray detections with their optical counterparts and with the host galaxy properties. In § 4 we use the known correlations with host galaxy properties (stellar velocity dispersion \(\sigma\) and spheroid luminosity \(L_B\)) to estimate masses for the central black holes. Section 5 presents our main results, which are summarized in § 6.

2. AMUSE-VIRGO: PROGRAM DESCRIPTION

This Chandra Large Program (ID 08900784, Cycle 8, 454 ks; PI: Treu) targets the 100 early-type galaxies of the ACS/WFC Virgo Cluster Survey (ACSVCS; Côté et al. 2004), with the aim of providing an unbiased census of SMBH luminosity in the local universe. Mid-infrared observations with the Multiband Imaging Photometer on board Spitzer (MIPS; total exposure 9.5 hr) complete the X-ray survey, allowing us to probe obscured accretion-powered emission through 24 \(\mu\)m observations.

The Chandra survey has been designed to be sensitive (at 3\(\sigma\)) to a 3 \(M_\odot\) object accreting at the Eddington limit. As described in detail in § 5, this is the optimal depth for an extensive survey: the threshold is deep enough to be interesting, yet bright enough to ensure negligible contamination by stellar mass black holes (or background sources) within the Chandra point-spread function (PSF). The desired sensitivity is accomplished by means of snapshot (5.4 ks) observations of 84 targets. The new data are combined with deeper archival Chandra observations of the remaining (on average more massive) 16 targets.

Based on the comparison with the spectral energy distribution (SED) of LINERs (low-ionization nuclear emitting regions; see, e.g., Maoz et al. 1998) and unobscured AGNs (both radio-loud and radio-quiet), the mid-IR band flux is expected to exceed the Chandra flux by at least a factor 3. Hence, the Spitzer —which will acquire new data for 57 objects, to be combined with archival data for the remaining 43—has been designed to probe down to \(\sim 3 \times 10^{-14} \, \text{ergs s}^{-1}\text{cm}^{-2}\) (3 times higher than the Chandra threshold).

Based on empirical scaling relations between the black hole mass and the host properties, the ACSVCS sample covers over 5 orders of magnitude in black hole mass as estimated from the mass-velocity dispersion relation (see § 3 for a critical assessment), large enough that it can be divided in SMBH mass bins to test whether the nuclear activity duty cycle is mass dependent; given our sensitivity, we will probe X-ray Eddington ratios in the range \(10^{-9}\) to \(10^{-5}\).

3. DATA ANALYSIS

In this section we report on the analysis of Chandra data for the 16 targets observed in Cycle 8 at the time of submission of this paper (§ 3.1), and on the analysis of the nuclear X-ray emission of the 16 galaxies of the survey that have archival Chandra data (§ 3.2). Section 3.3 describes the analysis of archival HST data used to compare the location of X-ray detections to the optical center of the host galaxies (and nuclei when present), and to estimate their stellar mass. The target list and observation log are given in Table 1.

3.1. Chandra Cycle 8 Data

We observed each galaxy with the Advanced CCD Imaging Spectrometer (ACIS) detector on board Chandra for 5.4 ks of

\[5\] See http://tartufo.physics.ucsb.edu/\~amuse.

\[6\] Advanced Camera for Surveys, onboard the Hubble Space Telescope.
The table provides data for X-ray nuclei and optical nuclei, with several columns for identification, VCC source name, other name, observation starting date, exposure time, X-ray counts, and additional parameters such as right ascension and declination. The notes at the bottom of the page explain the units, the nominal exposure time in faint mode, and other details.

Further analysis was restricted to energies between 0.3 and 7.0 keV in order to avoid calibration uncertainties at low energies and to limit background contaminations at high energies. We applied a wavelet detection algorithm over each activated chip, using CIAO wavdetect with sensitivity threshold corresponding to a \(10^{-6}\) chance of detecting one spurious source per PSF element if the local background is uniformly distributed. We used the default wavelet parameters, with scales increasing by a factor of \(\sqrt{2}\) between 1 and 4 pixels on a full resolution circular region of 512 pixel radius centered on the nominal position of the target. However, we only considered the X-ray properties of the nuclei.

The table also notes that the data was analyzed using the Chandra Interactive Analysis Observation (CIAO) software version 3.3.0.1 and the calibration database version 3.3.0.1. Standard level 2 event lists, processed for cosmic-ray rejection and good time filtering, were employed. As Chandra is known to encounter periods of high background which especially affect the S1 and S3 chips, we first checked for background flares and removed time intervals with background rate greater than 3 \(\sigma\) above the mean level.

Notes:—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Columns are as follows: (1) ACS VCS target number; (2) VCC source name; (3) other name; (4) Chandra observation identity; (5) observation starting date; (6) net exposure (after flares’ removal); (7) nuclear X-ray source net counts extracted—or extrapolated to—between 0.3 and 7 keV, with net errors in parenthesis; (8) X-ray nucleus right ascension, with the positional uncertainty on the centroid position given in parenthesis, in arcsec; (9) X-ray nucleus declination, with the positional uncertainty on the centroid position given in parenthesis, in arcsec; (10) optical nucleus right ascension; (11) optical nucleus declination.

a Very faint mode.
b In order to avoid contamination from the diffuse gas emission, the nuclear counts were extracted between \(E_1\) and 7 keV (see \(\S\) 3.2), where typically \(E_1 \simeq 2\) keV, and then extrapolated to between 0.3 and 7 keV in webPimms adopting an absorbed power law model with Galactic absorption and photon index \(\Gamma = 2\).
Individual source locations are subject to statistical uncertainties affecting the centroiding algorithm and to the dispersion of photons due to the PSF. For ACIS-S, Garmire et al. (2000) estimate 90% confidences of ±0.5″ for sources with ~10 counts, ±0.2″ for 20–50 count sources, and negligible for >100 count sources. In addition, the statistical uncertainties depend on the off-axis angle from the aim point: we calculated the 95% confidence error radii, \( r_x \), as a function of net counts and off-axis angle according to the empirical formula based on the results of Hong et al. (2005). The statistical uncertainties affecting the centroid errors in the positions of the X-ray sources, combined with the ±0.1″ positional error of SDSS, results in a final astrometric frame that is accurate to between 0.2″ (fields with ≥20 counts sources) and 0.5″ (fields with faint sources).

After registering the Chandra images to SDSS, we ran again wavdetect to refine the positions, and searched for pointlike X-ray emission centered at the galaxy optical center, derived from archival HST ACS images registered to the SDSS world coordinate system as described in the next subsection. We searched for X-ray counterparts to the ACS nuclei within an error circle which is the quadratic sum of the positional uncertainty for the X-ray source, the uncertainty in the optical astrometry, and the uncertainty in the X-ray bore-sight correction, multiplied by the chosen confidence level scale factor (3σ):

\[
R_{\text{err}} = \sqrt{r_x^2 + r_{\text{opt}}^2 + r_{\text{bore}}^2}.
\]

The coordinates of the detected X-ray nuclei, with their statistical uncertainty, are listed in Table 1. More details about the optical astrometry are provided in §3.3.

For the X-ray aperture photometry, we adopted a circular region with a 2″ radius centered on X-ray centroid position. For all the observations considered here, the aim points were specified with inner and outer radii \( P \). The statistical uncertainties affecting the centroiding algorithm and to the dispersion of photons due to the PSF at 1.5 keV for ACIS. We inspected the morphology of the detected nuclei by constructing the Chandra PSF at 1.5 keV and normalized it to the actual number of detected counts; all the detected X-ray nuclei in the Cycle 8 observations are consistent with being pointlike.

We adopted an annulus with inner radius 20″ and outer radius 30″ for background subtraction (off-nuclear X-ray sources, if present, were masked out). We estimated the corresponding fluxes using webPimms\(^7\), and assuming an absorbed power law model with photon index \( \Gamma = 2 \) and hydrogen equivalent column \( N_H = 2.5 \times 10^{20} \) cm\(^{-2}\), i.e., the nominal Galactic value determined from the \( \mathrm{H} \) studies of Dickey & Lockman (1990). Since none of galaxies under exam shows evidence for prominent dusty lanes in the \( \mathrm{HST} \) images (Ferrarese et al. 2006b), it is reasonable to assume that the Galactic value provides a correct estimate for the actual absorbing column. Under this assumption, 10\(^{-3}\) count s\(^{-1}\) in the 0.3–7 keV energy band correspond to an intrinsic flux of 7.19 \times 10\(^{-15}\) ergs cm\(^{-2}\) s\(^{-1}\) between 0.3 and 10 keV (ACIS-S).

In case of no significant detection we applied Poisson statistics to derive upper limits on the nuclear luminosity at the 95% confidence level (Gehrels 1986), listed in Table 2. To obtain a more stringent limit on the average flux, we stacked the images of the nondetections centered on the optical centers, resulting in 62.3 ks of effective total exposure. We extracted the counts from a 2″ radius circular aperture, and background from an annulus with inner and outer radii \( R_{\text{in}} = 2″ \) and \( R_{\text{out}} = 9″ \), centered on the stacked nucleus position (see Fig. 1). We found 5 counts within the 2″ radius aperture, while 3.1 are expected from the background. The Poisson probability of obtaining 5 counts or more when 3.1 are expected is 0.2, indicating no significant detection. This corresponds to an exposure weighted, average count rate < 1.6 \times 10\(^{-4}\) count s\(^{-1}\) for the undetected sources (95% confidence level), or \( \langle L_X \rangle < 3.8 \times 10^{37} \) ergs s\(^{-1}\) (0.3–10 keV) at the average distance of 16.5 Mpc (Mei et al. 2007).

3.2. Chandra Archival Data

We followed the same procedure as outlined above for the 16 galaxies which have Chandra archival data (marked by footnote a in Table 2). For these targets, event 1 lists were first filtered (and cleaned, in the case of Vary Faint telemetry) following the standard CIAO threads. As the archival sample is mainly made of massive, X-ray-bright galaxies, we had to model/account for the diffuse gas contribution in order to constrain any possible accretion-powered, nuclear X-ray emission. This was achieved by first determining for each galaxy the energy \( E_i \) above which hot gas contribution is negligible. The threshold energy \( E_i \) was derived as follows. As a first step, we extracted the spectrum of the total diffuse emission over a circular aperture of 150″ centered on the galaxy nucleus and excluding all the resolved point sources detected by wavdetect. The background for this spectrum was extracted on the S3 chip as far away as possible from the galaxy, using an annulus of inner and outer radius 250″ and 300″ , respectively (masking out the resolved X-ray sources). We analyzed the extracted spectra with XSPEC version 11.2.0 (Arnaud 1996), using a combination of optically thin thermal emission for the diffuse gas plus a nonthermal component (power-law model) to represent the emission from the unresolved point sources, under the assumption that the hard spectral component seen in the diffuse emission is mainly due to the contribution of unresolved low-mass X-ray binaries (LMXBs). We fixed the power-law photon index \( \Gamma \) of the hard component due to unresolved LMXBs to the value measured for the cumulative spectrum of all the resolved X-ray sources (\( \Gamma = 1.6 \pm 1.9 \)). As a model for the diffuse thermal emission, we employed the Astrophysical Plasma Emission Code (APEC) thermal-emission model (Smith et al. 2001) in its most recent version (vapec), which includes a wealth of accurate atomic data. The abundances of neon, magnesium, silicon, and iron were left free to vary. The two spectral components are subjected to a common absorption (\( N_H = 2.5 \times 10^{20} \) cm\(^{-2}\)). As a consistency check, we also rerun the fits by letting both the \( N_H \) column and the power-law photon index vary, and recovered the same parameters, within errors.

The fits yielded the temperature of the hot thermally emitting gas, \( kT_y \), for each galaxy, and allowed us to estimate the energy \( E_i \) above which the optically thin thermal emission contributes to less than 5% to the measured flux. As an example, the 0.3–7 keV spectrum of the diffuse emission of VCC 1978 (N4649) is best-fit by a two-component model with total flux of 2.99 \times 10\(^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\). The absorbed thermal component accounts for 69% of this flux, but contributes to less than 5% above \( E_i = 1.92 \) keV (see Fig. 2). In this case, the fitted gas temperature is \( kT_y = 0.78^{+0.04}_{-0.02} \) keV.

As in the analysis of the new data described in §3.1, we converted the measured count rates (\( E_i - 7 \) keV) extracted from a 2″ circular region centered at the optical nucleus into 0.3–10 keV unabsorbed luminosity within webPimms, by assuming an absorbed power law model with photon index \( \Gamma = 2 \). We extracted and fitted the actual source spectrum when dealing with more than 50 hard (\( E_i \) photons (i.e., for VCC 1613 [M87], VCC 1632 [N4552], obtaining \( \Gamma = 2.21 \pm 0.04, \Gamma = 1.7^{+0.8}_{-0.5} \), respectively).
3.3. Hubble Space Telescope Imaging

Images from the ACS Virgo Cluster Survey (Côté et al. 2004) were downloaded from the HST archive. The observations of each galaxy consist of two 375 s exposures in the F475W filter (nearly equivalent to SDSS g-band, effective wavelength $\lambda_{\text{eff}} = 4825 \, \text{Å}$; Fukugita et al. 1996), two 560 s exposures in the F850LP filter (nearly equivalent to SDSS z'-band, $\lambda_{\text{eff}} = 9097 \, \text{Å}$; Fukugita et al. 1996), and a single 90 s exposure in the F850LP filter, all in the wide field channel. In order to facilitate the best possible matching between X-ray and optical sources, the astrometry of HST images has been referenced to the that of SDSS-DR5 according to the following procedure. First, individual exposures in each band are combined using the PYRAF task multidrizzle, which includes cosmic-ray rejection and correction of geometric distortion. Detection images are built by producing a surface brightness profile of the galaxy using either the PYRAF tasks eclipse and bmodel or GALFIT (Penč et al. 2002), as appropriate. The X-ray source appears slightly elongated; $L_{\text{X,nuc}}$ is estimated within the Chandra PSF at 1.5 keV.

![Table 2](http://cas.sdss.org/dr5/en/tools/search/radial.asp)
first, objects in each catalog are uniquely matched to their nearest neighbor in the opposite catalog and the offset between each pair of objects is calculated; any remaining unmatched objects are discarded. Next, statistics on the offsets in right ascension and declination are gathered by an initial pass through all object pairs. Finally, successive rounds of sigma clipping are performed to discard outliers and spurious detections, leaving a minimum of 10 pairs of matched objects from which the overall right ascension and declination offsets are calculated. Observed offsets range from 0.01" to 1.2", with errors of 0.01"–0.07". Offset values are confirmed by manually comparing coordinates of stars and/or galactic nuclei in the ACS images to the SDSS database. No rotation of the world coordinate system is required, as the residual r.m.s. scatter is much smaller than the uncertainty on the position of the X-ray sources, which is dominated by the 

Chandra PSF and the small number of counts for faint nuclear sources.

Published measurements by the ACSVCS group (Ferrarese et al. 2006b) were used to estimate the $B$-band luminosity and stellar mass of the host galaxies. Synthetic Vega $B$-band magnitudes (hereafter $B$) were obtained from the total (i.e., as obtained from model fitting), extinction-corrected $g_0$ and $z_0$ band AB magnitudes, using a broad range of stellar population models (Bruzual & Charlot 2003) to compute the transformation to first order in the color term. We find the transformation to be

$$B = g_0 + 0.193 + 0.026(g_0 - z_0).$$

Since the $B$ band is close in wavelength to the $g_0$ band, the transformation introduces only a minimal uncertainty of order 0.01–0.02 mag. The resulting $B$ magnitudes listed in Table 2 typically supercede the photographic $B_T$ magnitudes (see Côté et al. 2004 and references therein) and, unless otherwise indicated, will be used throughout this series (although for VCC 1030 and VCC 1535, the $B_T$ magnitudes are retained since HST photometry was not available). For all the objects with HST photometry, stellar masses were estimated from the $g_0$ and $z_0$
band AB model magnitudes using the recipe of Bell et al. (2003):

$$\log(M^*/L_{gb}) \equiv 0.698(g_0 - z_0) - 0.367.$$

This recipe—and its use of the HST photometry—was found to be more robust than similar ones that use the 2MASS K-band data listed in Ferrarese et al. (2006b), perhaps due to the difficulty of measuring fluxes of the lowest mass galaxies, or with matching the measurement apertures between different types of observation. For the two objects with no HST photometry, we use $B_T$- and K-band magnitudes and the coefficients provided in Bell & de Jong (2001) to compute

$$\log(M^*/L_B) = 0.591(B_T - K) - 1.743,$$

which in these cases gives stellar masses that sit well with objects of comparable luminosity and measured with HST. As noted by Bell et al., the mass-to-light ratios calculated with these recipes have systematic uncertainties of some 0.2 dex arising from the assumed initial mass function (a Salpeter function was used in the derivation of the coefficients used here).

4. BLACK HOLE MASSES

In order to construct the distribution of Eddington ratios for our sample, we first need to estimate the masses of the (putative) SMBHs; throughout this section, we shall assume that a SMBH exists at the center of every galaxy in the sample; this working hypothesis will be tested and discussed in $\S$ 5.

Although bulge stellar velocity dispersion is arguably the best estimator of $M_{\text{BH}}$ (e.g., Bernardi et al. 2007), there is considerable interest in comparing $\sigma$-based estimates with other estimates. For the most luminous galaxies, such as brightest cluster galaxies, $\sigma$ and optical luminosity ($L_B$) predict different $M_{\text{BH}}$ (Lauer et al. 2007a) pointing toward a break down of at least one of the two scaling relations or to a departure from a simple power law. Under the assumption that a SMBH exists at the center of each targeted galaxy, in the following we compare the $M_{\text{BH}}$ values obtained by employing different empirical scaling relations, specifically the mass-bulge luminosity ($M_{\text{BH}} - L_B$) or the mass-dispersion velocity ($M_{\text{BH}} - \sigma$) relation. Unless otherwise indicated, we will employ the scalings given by Ferrarese & Ford (2005, hereafter FF05).

Velocity dispersions are available in the literature for 74 out of the 100 targets belonging to the ACSVCS, from a variety of sources. In this work we make use of a compilation kindly provided by Lauren MacArthur (MacArthur et al. 2007). However, as black hole mass is a steep function of stellar velocity dispersion, imprecise or inaccurate spectroscopic measurements could introduce significant uncertainty in $\sigma$ and bias to the black hole mass estimates. After considering different velocity dispersion values from 12 different sources in literature, and investigating the instrumental resolutions and S/N ratios of the original measurements, a subset of high-quality velocity dispersions was identified, yielding a "secure" subsample of 54 galaxies (see MacArthur et al. 2007 for details).

Figure 3 illustrates the $M_{\text{BH}}$ distribution of the entire ACSVCS sample as obtained using the two different mass tracers: $L_B$-based masses (blue histogram) tend to be higher than $\sigma$-based masses (green shaded histogram), particularly at the low-luminosity and low-mass end. While this is a known fact (e.g., Bernardi et al. 2007), in this specific case it can be due to a combination of underestimated $\sigma$, overestimated bulge luminosity $L_B$ (because of low bulge fraction), as well as different slopes of the $M_{\text{BH}} - L_B$ and $M_{\text{BH}} - \sigma$ relations. Irrespective of the chosen tracer, however, the distribution of the ACSVCS sample peaks below $10^7 M_\odot$, where very few direct $M_{\text{BH}}$ measurements are available.

Studies of active galaxies indicate that the $M_{\text{BH}} - \sigma$ relation extends down to the masses probed by our sample (Barth et al. 2005), supporting our working hypothesis that $\sigma$ provides the best estimate of $M_{\text{BH}}$. Therefore, the results presented in the rest of the paper will be based on this "secure" sample of stellar velocity dispersions (for 54/100 targets), and on $L_B$ for the remaining targets. This fiducial $M_{\text{BH}}$ distribution adopted in this paper is shown in Figure 3 as a shaded histogram; making use of $\sigma$ values introduces a minor correction at the low-mass end. Black hole masses based on this secure sample are further compared to $L_B$-based $M_{\text{BH}}$ for different morphological types in the right panel of Figure 4. While a full discussion on the comparison between different $M_{\text{BH}}$ tracers is beyond the scope of this paper, the plots show that—although the mismatch is reduced when considering only high-quality $\sigma$—it is present even for pure ellipticals and thus cannot be explained entirely with varying bulge fraction, pointing instead toward a genuine break-down of at least one of the two scaling relations at the low-mass end.

The conclusions of this paper are not significantly affected if different scalings/black hole mass indicators are employed (such as Tremaine et al. [2002] or Marconi & Hunt [2003], for $M_{\text{BH}} - \sigma$ and $M_{\text{BH}} - L_B$, respectively).

5. RESULTS

Table 2 lists the nuclear X-ray properties for the 32 targets under analysis. We detect pointlike X-ray emission from a position consistent with the optical nucleus in 16 targets, four of which (VCC 2092, VCC 1692; VCC 1883, and VCC 1178) belong to the list of new snapshot (5.4 ks) Chandra observations. A montage of the ACIS-S images of the detected nuclei is shown in Figure 5. For the 16 targets with archival data, we were able to compare our results on the nuclear X-ray sources (or lack
Fig. 5.—Chandra ACIS-S images of the 16 detected X-ray nuclei, smoothed with a Gaussian of $\sigma = 3''$. The circle represent the count extraction region, centered on the wavdetect centroid. Four of the detected targets belong to the large program survey and were observed during Cycle 8 (VCC 2092, VCC 1883, and VCC 1178); three targets have archival observations but no literature reference for the nuclear source (VCC 1903, VCC 1231, and VCC 2095). The faintest detection, both in terms of nuclear X-ray luminosity and host galaxy magnitude ($M_B = -16.85$), is VCC 1297, and was previously reported by Soria et al. (2006b). [See the electronic edition of the Journal for a color version of this figure.]
thereof) with the literature in 11 cases, finding good agreement with the published values: after rescaling to the same distances, we obtain an average luminosity difference of 0.03 dex, with a scatter of 0.17 dex. No fluxes/upper limits had been published for the nuclear emission for the remaining five targets. We briefly comment on them below. VCC 1903: the Chandra data for this galaxy have been analyzed and discussed in a number of publications, focusing either on the diffuse X-ray emission properties or the X-ray binary population. VCC 881 and VCC 1535: The data for these galaxies have been discussed in the context of X-ray binary population studies, excluding the central regions (e.g., Sivakoff et al. 2007). VCC 1231 and VCC 2095: No publication has been found regarding these Chandra data sets.

A fundamental point to be addressed is the nature of the detected nuclear X-ray emission. In principle, hard X-rays provide us with some clear-cut diagnostics for accretion-powered emission, as a result of nonthermal processes such as Comptonization. In particular, here we ask the question whether accretion-powered emission from a SMBH is at the origin of the detected nuclear sources. In the following, we shall carefully address the issue of contamination from background X-ray sources as well as low-mass X-ray binaries (§ 5.1), which are the major source of concern. This is closely related to the issue of whether SMBHs exist and/or they are detectable at the center of faint spheroids which may host compact stellar clusters (§ 5.2). The Eddington distribution of the detected nuclei is presented in § 5.3, and discussed in the context of the various model for inefficient accretion and mechanical feedback from SMBHs.

5.1. Origin of the Detected X-Ray Emission

We argue that the detection of pointlike X-ray emission from a position coincident with the optical nucleus is unlikely to be due to any process other than accretion onto a nuclear SMBH. Based on the results by Rosati et al. (2002), we estimate that the chance of detecting a background X-ray source within the Chandra PSF at 1.5 keV (convolved with the positional uncertainty) is lower than 10^{-6}. Hence, the most likely contamination arises from LMXBs. In a broad stellar mass range, and in the absence of a nuclear star cluster (see § 5.2), the total number of LMXBs and their cumulative X-ray luminosity are proportional to the stellar mass of the host galaxy, M_\star (Gilfanov 2004; Kim & Fabbiano 2004; Humphrey & Buote 2006). The number n_X of expected sources per unit stellar mass above a certain luminosity threshold can be estimated from the X-ray luminosity function for LMXBs (e.g., Gilfanov 2004). In turn, the number of expected sources within the Chandra PSF (convolved with the positional uncertainty) is given by n_X times M_\star,PSF: the stellar mass within the central aperture. We estimated M_\star,PSF for each galaxy from the archival ACS images, adopting the same procedure as described in § 4. The number of expected LMXBs above the X-ray luminosity of the detected nuclei turns out to be typically lower than a few 10^{-2} for the most massive galaxies (which do not harbor prominent stellar clusters at the center; Ferrarese et al. 2006b). High-mass X-ray binaries are not expected to contribute in early-type galaxies, where star formation is nearly absent. As an example, the number of expected LMXB with L_X > L_X,nucl = 4.7 \times 10^{38} \text{ ergs s}^{-1} (VCC 1178) is about 6 per 10^{11} M_\odot (this is obtained employing the functional shape obtained by Gilfanov [2004] specifically for early-type galaxies). This means that fewer than 0.06 sources as bright/brighter than the detected nucleus are expected within the central aperture, home to ~9 \times 10^{9} M_\odot. Given the shape of the LMXB luminosity function at high luminosities (above a few 10^{38} \text{ ergs s}^{-1}), we can also confidently rule out that the central X-ray source is due to a collection of fainter LMXBs, as the integral \int n_X \times L_X dL_X is dominated by the luminosity term. The same conclusion is reached by Sivakoff et al. (2007) in an extensive study of the X-ray luminosity function of globular clusters in early-type galaxies (see § 5.2). As an example, in the case of VCC 1178, the number of expected nuclear LMXBs brighter then 1/10 of the detected nucleus is less than 0.6. However, massive star clusters have been shown to become more and more common at the center of spheroids moving down the mass function (Ferrarese et al. 2006a), and may well increase the chance of harboring bright X-ray binaries. This is further explored in the next section.

5.2. SMBHs in Low-Mass Spheroids

Possibly the most noteworthy result of this study is the detection of nuclear hard X-ray emission from faint early-type galaxies: in particular, two of the detected nuclei are hosted in galaxies with absolute B magnitudes lower than -18: VCC 1178 (N4464) and VCC 1297 (N4486B) have M_B = -17.68 and M_B = -16.91, respectively.

From an observational standpoint, the very existence of SMBHs (of the same sort that define the known scalings in massive galaxies) in faint inactive galaxies remains questionable. Ferrarese et al. (2006a) suggest that the creation of a “central massive object,” SMBH or compact stellar nucleus, would be the natural byproduct of galaxy evolution, with the former being more common in massive bright galaxies (M_B brighter than -20), and the latter dominating—possibly taking over—at magnitudes fainter than -18.

This finds support in semianalytical models which follow the formation and evolution of black holes seeds formed at high redshift in the context of hierarchical cosmologies. On one side, SMBH formation mechanisms seem to be more efficient in halos of high mass; on the other, low-mass objects are more likely to eject their nuclear SMBH following a major merger as a result of gravitational recoil. The combination of these two effects may lead to a lower black hole occupation fraction in low-mass galaxies at redshift zero (Volonteri et al. 2008a, 2008b; it should be stressed, however, that in this scenario nuclear SMBHs and compact star clusters are not necessarily mutually exclusive). Observationally, the fraction of X-ray detectable SMBHs (assuming that they can indeed be distinguished from bright LMXBs) would naturally place a lower limit on the black hole occupation fraction in low-mass spheroids. We investigate this below.

As shown in Figure 6, VCC 1178 and VCC 1297 do not have a particularly prominent nuclear star cluster, consistent with the findings of Ferrarese et al. (2006b). However, the case for a SMBH is quite strong in VCC 1297 (N4486B): based on data from the Wide Field Planetary Camera 2 (WFPC2), Lauer et al. (1996) showed evidence for a central double nucleus in this galaxy; subsequently, based on stellar kinematics studies, Kormendy et al. (1997) derived a nuclear “dark mass” of 6 \times 10^6 M_\odot, both arguing in favor of a nuclear SMBH. A small excess with respect to the model fit in the inner region of the profile is just noticeable in VCC 1178. We note however that this conclusion is highly dependent on the assumed form of the profile of the underlying faint galaxy, which has no fundamental reason to follow exactly a Sersic law. In fact, Lauer et al. (2007b) performed deconvolved HST ACS surface photometry study of a sample of early-type galaxies, including VCC 1178 (N4464), and found evidence for a nuclear source in this system by modeling the profile with a Nuker law. Assuming that the excess flux is due to a nuclear star cluster in this galaxy, we estimate its luminosity to be approximately 2.8 \pm 0.3 \times 10^7 L_\odot, where the error bar is the semidifference of the results obtained from two different methods that should bracket the
true answer: (1) fitting a point-spread function + Sersic model; (2) aperture photometry on the residuals of the Sersic fit within a 0.5\,000\,radius aperture. This corresponds to a stellar mass in the range $(3.7\,−\,4.6) \times 10^7$ M$_\odot$, where we have adopted a mass-to-light ratio $Y_z = 1.45$, to ensure a proper comparison with the work by Sivakoff et al. (2007), which provides an expression for the expected number of bright LMXBs specifically in globular clusters (rather than averaged over the entire galaxy).

It is known that, while hosting a small percentage of the galaxy stellar mass, globular clusters are home to about 50% of the observed LMXBs. In this environment, the number of expected LMXB sources scales nonlinearly with the cluster mass (Sivakoff et al. 2007); this also leads to the prediction that high X-ray luminosity clusters (with super-Eddington luminosities for $3 M_\odot$) contain a single LMXB. Sivakoff et al. (2007) derive an expression for the expected number $n_X$ of LMXBs brighter than $3.2 \times 10^{38}$ ergs s$^{-1}$ (the luminosity limit is set by the sample completeness) in a star cluster of stellar mass $M$, half-mass radius $r_{h,\text{corr}}$, and color $(g-z)$:

$$n_X = 8 \times 10^{-2} (M/10^6 M_\odot)^{1.237} 10^{0.9(g-z)} (r_{h,\text{corr}}/1 \text{ pc})^{-2.22}$$  

where $r_{h,\text{corr}} = r_h \times 10^{0.17(g-z)-1.2}$. An estimate of the half mass radius of the star cluster in VCC 1178 is obtained by measuring the light in the residuals as a function of photometric aperture, and varies between 25 and 30 pc. Together with the fitted luminosities, this implies $n_X = 0.06 \sim 0.12$ (obtained by adopting the fitted parameters with methods 1 and 2, respectively). The expected number of LMXBs in a globular cluster can be converted to a probability $P_X$ that there is at least one LMXB brighter than the adopted X-ray luminosity threshold assuming a Poisson distribution: $P_X \lesssim 0.11$ (95% confidence).
We note that this value represents a conservative estimate of the actual probability contamination, in that it is estimated for a LMXB X-ray luminosity threshold lower than any of the detected nuclei in our sample. In addition, LMXBs are found more often in globular clusters with smaller half-mass radii: since there is no correlation between the half-mass radius and the mass in globular clusters (e.g., Jordán et al. 2005), this simply implies that LMXBs are found more often in denser environments, with higher encounter rates (Sivakoff et al. 2007). The inferred half-mass radius of the (possible) nuclear star cluster in VCC 1178 (20–30 pc) is much higher than the typical radius estimated for standard globular clusters (a few pc, with a median value of 2.2 pc in the work by Sivakoff et al.). From this, we conclude that a bright LMXB is unlikely to be at the origin of the observed nuclear emission in VCC 1178, with a maximum chance contamination of 11%.

The incidence of X-ray "active" (hereafter defined as detected in the X-ray band down to our luminosity threshold of \( \sim 4 \times 10^{38} \) ergs s\(^{-1} \)) SMBHs as a function of the host galaxy stellar mass, \( M_\ast \), is illustrated in the top panel of Figure 7. Splitting the sample in two mass bins, above and below a stellar mass threshold of \( 10^{10} \, M_\odot \), and by making use of binomial statistics applied to small number of observed events (Gehrels 1986) we are able to conclude that the incidence of nuclear X-ray supermassive black hole activity—down to our completeness limit of \( \sim 4 \times 10^{38} \) ergs s\(^{-1} \)—increases with the stellar mass of the host (see Fig. 7, bottom panel). Specifically: between 3% and 44% of the galaxies with stellar masses \( < 10^{10} \, M_\odot \) are found to host an active SMBH (2 of 12). The incidence of nuclear activity increases to between 49% and 87% in galaxies with stellar masses above \( 10^{10} \, M_\odot \) (14 out of 20 are active; percentages are given at the 95% confidence level). For comparison, in a recent comprehensive optical spectroscopic census of nuclear activity associated with late-type galaxies in Virgo, Decarli et al. (2007) find no AGNs in galaxies with dynamical mass lower than \( 10^{10} \, M_\odot \) (in that work, line ratios are adopted in order to classify/distinguish AGN from transition objects and/or H \( \alpha \) regions, specifically: \( N_\alpha /H_\alpha > 0.6 \) unambiguously identifies AGNs).

5.3. Eddington-Ratio Distribution and Nuclear SMBH Feedback

Having shown that pointlike nuclear X-ray emission is likely due to accretion onto a SMBH—and under the assumption that the sample galaxies all host a SMBH whose mass obeys the known scaling relations defined by SMBHs in massive bright galaxies—we can construct the \( L_X / L_{\text{edd}} \) distribution of our sample, shown in Figure 8 by adopting the fiducial black hole mass distribution described in \( \S \) 4.

For any plausible value of the bolometric correction \( f_{\text{bol}} = L_{\text{bol}} / L_X \) (which may vary between \( \sim 8 \) and \( \sim 60 \); Marconi et al. 2004), the detected nuclei are highly sub-Eddington. Under the conservative assumption that only as little as 2% of accretion-driven emission is emitted in the X-ray band, the inferred \( L_{\text{bol}} / L_{\text{edd}} \) ratios do not exceed \( 10^{-4.7} \) for this subsample (inferred for VCC 1883, the highest \( L_X / L_{\text{edd}} \) nucleus among our 16 snapshot observations). Similarly, the upper limit to the average X-ray luminosity in the stacked image of the 12 undetected nuclei with snapshot observations (Fig. 2, left panel) amounts to \( 3 \times 10^{37} \) ergs s\(^{-1} \), or \( (L_X / L_{\text{edd}}) \lesssim 3 \times 10^{-8} \), over 0.3–10 keV) for an average black hole mass of \( 9 \times 10^6 \, M_\odot \).

Similar results are obtained by Santra et al. (2007) for a sample of 13 early-type galaxies in the core of the Perseus cluster with a deep Chandra exposure, as well as from Soria et al. (2006a) and Pellegrini (2005). Following their approach (see eqs. [4] and [5] in Soria et al. 2006a), we can compare the measured X-ray luminosities to the bolometric accretion power \( L_{\text{acc}} \) is expected from Bondi accretion of the interstellar medium: \( L_{\text{acc}} = \eta \dot{M}_B c^2 \), where the radiative efficiency \( \eta \) is a fraction \( f \) of the total accretion efficiency \( f \), and \( \dot{M}_B \)—the Bondi accretion rate—can be expressed as

\[
\dot{M}_B = 1.6 \times 10^{-5} \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right)^2 \left( \frac{0.5 \text{ keV}}{kT} \right)^{3/2} \left( \frac{n_0}{0.01 \text{ cm}^{-3}} \right) M_\odot \text{ yr}^{-1},
\]

being \( T \) and \( n_0 \) the temperature and density of the hot interstellar gas \( (k \) is the Boltzmann constant). Adopting conservative values of \( 0.01 \text{ cm}^{-3} \) for \( n_0 \) (in order to minimize \( L_{\text{acc}} \)) and for the range of temperatures which we infer for the hot gas (\( \S \) 3.2), we obtain

\[
\frac{L_X}{0.1 \dot{M}_B c^2} = f_X f_x \left( \frac{\eta}{0.1} \right) \left( \frac{\dot{m}}{\dot{m}_B} \right) \sim 2 \times 10^{-5} \sim 0.6,
\]

where \( f_X = 1 / f_{\text{bol}} \) (0.02 \( \leq f_X \leq 0.12 \), Marconi et al. 2004), \( \dot{m} \) and \( \dot{m}_B \) are Eddington-scaled \( \dot{m} \) and \( \dot{m}_B \), respectively, and \( c \) is the speed of light. All the detected nuclei in the AMUSE-Virgo subsample presented here are underluminous with respect to Bondi accretion from the interstellar medium.

The accretion mode responsible for powering low-luminosity black holes is still a matter of debate. Observations of highly sub-Eddington black holes, most notably the Galactic center Sag A*, paved the way to radiatively inefficient accretion flow models (RIAFs). Advection-dominated accretion flows (ADAFs; Ichimaru 1977; Narayan & Yi 1994) are popular analytical models for the dynamics of RIAFs at low accretion rates. However, they face a number of difficulties. In particular, Blandford & Begelman (1999, 2004) argued that the accreting gas in an ADAF is generally unbound and free to escape to infinity, and elaborated an alternative model, named the adiabatic inflow outflow solution (ADIOS). Here the key notion is that the excess energy and angular momentum is lost to a wind at all radii; the final accretion rate into the hole may be only a tiny fraction of the mass supply at large radii. This is a generalization of and an alternative to an advective inflow. Deep Chandra observations of nearby massive ellipticals (Allen et al. 2006), have shown that a tight, almost linear, correlation exists between the Bondi accretion rate and the jet kinetic power (measured from the \( p \times dV \) work exerted on X-ray cavities). The correlation implies that a substantial fraction of the energy associated with gas entering the Bondi radius must be dissipated mechanically, via jets/outflows.

This is closely related to the role of SMBH feedback in galaxy evolution (see e.g., McNamara & Nulsen 2007). Semianalytical models applied to dark matter simulations for the growth and evolution of cosmic structures have recently emphasized the role of mechanical, rather than radiated, SMBH feedback. A prolonged phase of low-level accretion, resulting in sub-Eddington luminosities, proves to be effective at quenching star formation. It is worth stressing although, that in this formulation SMBH feedback plays a role in the most massive bright galaxies only: once star formation has halted, these massive red galaxies continue to grow through merging. This allows the brightest cluster galaxies to gain a factor of 2 or 3 in mass without significant star formation. However, it is not clear whether such a mechanism might switch off at or be still important at low masses.
Merloni & Heinz (2007) have addressed this issue of mechanical SMBH feedback by comparing a sample of 15 sub-Eddington nuclei for which information on the Bondi rate, kinetic power, and radiative power is available. For these objects, they find that the Eddington-scaled black hole kinetic power, $L_{\text{kin}}$ (which is a proxy for $L_{\text{BH}}$—the SMBH power feedback—in the formalism of Croton et al. 2006) scales with the nuclear X-ray luminosity (2–10 keV) according to the following relation:

$$\log (L_{\text{kin}}/L_{\text{Edd}}) = 0.49 \log \lambda_X - 0.78,$$

where $\lambda_X = 5 \times L_{\text{2-10 keV}}/L_{\text{Edd}}$ (with a scatter of 0.39 dex).
Applying the Merloni & Heinz scaling to our sample (where with are arbitrarily assuming that the same correlation applies to lower mass, lower luminosity objects spheroids9), the measured X-ray luminosities translate into Eddington-scaled kinetic luminosity in the range ~10^{-3} (VCC 1664) to ~10^{-5} (VCC 1978), which suggest that energy feedback might be effective even in low-mass spheroids.

6. SUMMARY AND CONCLUSIONS

This paper presents the first Chandra results of AMUSE-Virgo, a multiband survey of early-type galaxies in the Virgo Cluster, aimed at investigating the incidence and activity of supermassive black holes in the nuclei of 100 local nearby spheroids. The ACSVCS sample (Côté et al. 2004) is selected based on the properties of the host galaxies, and therefore it is an unbiased census of nuclear activity as a function of host galaxy stellar mass (and hence presumably black hole mass). Since the stellar mass distribution of the galaxies peaks below 10^{10} M_\odot, AMUSE-Virgo will provide us the deepest census of low-level accretion-powered activity in early-type galaxies over an unprecedented range of masses. In this paper we combine Chandra results from the first 16 targets with the analysis of archival data of 16, typically more massive, targets. The absolute B magnitudes of this sample of 32 objects range from M_B = -22.5 to M_B = -15.0.

The main results of this study can be summarized as follows:

1. We detect point-like X-ray emission from a position consistent with the optical nucleus in 50% of the targets; 12 detections out of 16 belong to the archival observations, but only 9 of those 12 were previously reported in the literature. The remaining four detections (VCC 2092, VCC 1692, VCC 1833, and VCC 1178) were made using new snapshot observations of low-mass targets.

2. Two of the detected nuclei (VCC 1178 and VCC 1297, having L_\text{X} = 4.7 \times 10^{38} and 2.6 \times 10^{36} ergs s^{-1}, respectively) are hosted in galaxies with absolute B magnitude fainter than -18 (M_B = -17.68 and -16.91), or host galaxy stellar mass lower than 10^{10} M_\odot (M_* = 8.1 \times 10^{9} M_\odot and 5.1 \times 10^{9} M_\odot). At these luminosities, massive stellar clusters are known to become increasingly common, and have been suggested to possibly even replace SMBHs (of the kind that define empirical scaling relations at the bright end; Ferrarese et al. 2006a).

3. Analysis of archival HST ACS images reveals a slight excess in the surface brightness profile of VCC 1178, with respect to a Sersic model. We conservatively interpret this as due to a nuclear star cluster. The inferred stellar mass does not exceed a few 10^{7} M_\odot, implying a less than 11% probability that the nuclear X-ray source is a solar mass compact object based on results by Sivakoff et al. (2007).

4. After carefully addressing possible contamination from low-mass X-ray binaries in the remaining objects (based on the luminosity function by Gilfanov 2004), we conclude that the nuclear X-ray sources are most likely due to low-level accretion-powered activity from a supermassive black hole.

5. Between 3% and 44% (95% confidence level) of the galaxies with stellar masses lower than 10^{10} M_\odot harbor an X-ray active SMBH—down to our completeness limit of ~4 \times 10^{38} ergs s^{-1}. The fraction of galaxies hosting an active SMBH increases to between 49% and 87% for host masses above 10^{10}. Even with only a third of the sample (32/100 galaxies), this study shows that there is statistically significant increase in the incidence of nuclear activity toward the high-mass end, consistent with what found in late-type Virgo galaxies (Decarli et al. 2007). This should be folded with the actual black hole mass function in order to properly constrain the distribution of nuclear activity.

6. The upper limit to the average X-ray luminosity in the stacked image of the 12 undetected nuclei with snapshot (5.4 ks) Chandra observations amounts to 3.8 \times 10^{37} ergs s^{-1}, or (<L_\text{0.3-10 keV}>/L_{Edd}) < 3 \times 10^{-8} for an average black hole mass of 9.3 \times 10^{6} M_\odot.

7. Based on “fiducial” values for the central black hole mass (based on “secure” measurements of the dispersion velocity for 24 targets, and on B magnitude otherwise) the ratio <L_\text{0.3-10 keV}>/L_{Edd} varies between 10^{-8.4} and 10^{-5.5} for the detected nuclei. The detected nuclei are underluminous with respect to Bondi accretion from the interstellar gas. In agreement with earlier works (e.g., Pellegreni 2005; Soria et al. 2006a, 2006b; Santra et al. 2007), this argues for an inefficient accretion mechanism, albeit our results cannot break the degeneracy between intrinsically low radiative efficiency and/or drastically reduced mass accretion rate onto the black hole (owing to outflows/winds).

A crucial question still to be addressed is that of the amount of power released in the form of kinetic energy. According to a recent study by Merloni & Heinz (2007), a (nonlinear) correlation exists between the Eddington-scaled kinetic power and the bolometric luminosity. The nonlinearity implies that the relative amount of power dissipated by these nuclei in the form of mechanical power decreases toward low X-ray luminosities. If the same scaling is applied to our subsample of 16 detected X-ray nuclei, the inferred kinetic power are between ~10^{-3} and 10^{-2} L_{Edd}, indicating that low-level SMBH feedback can be effective in faint spheroids as well as in bright massive elliptical galaxies.
Most of the galaxies yet to be observed as part of AMUSE-Virgo have stellar masses around $10^{13} M_\odot$, a mass range that remains largely unexplored as far as low-level nuclear SMBH activity is concerned. Chandra observations of 68 additional faint galaxies are under way, and will further constrain the fraction of galaxies that harbor a nuclear X-ray source. As shown by Ferrarese et al. (2006a), massive nuclear star clusters become increasingly common down the galaxy mass function, thereby increasing the chance of bright LMXB contamination. Detection of a high brightness temperature compact radio counterpart to the detected X-ray nuclei would provide definitive evidence for an accreting SMBH, as no Galactic X-ray binary can be possibly detected in the radio band at the Virgo Cluster distance with current instrumentation. In fact, with the exception of the known radio sources VCC 1226 (M49), VCC 1316 (M87), VCC 1978 (M60), VCC 763 (M84), VCC 1535 (N4526), and VCC 1632 (M89), none of the sample galaxies have a detected radio core brighter than the limiting flux density of 1.8 mJy at 1.4 GHz. At the average distance of 16.5 Mpc, this corresponds to an upper limit to the radio luminosity of $L_{\text{1.4 GHz}} < 8.3 \times 10^{28}$ ergs s$^{-1}$. Deep radio observations of the targeted nuclei, with the Very Large Array, are in progress, and will put further constraints on the spectral energy distribution at low frequencies. At the same time, while LMXBs are known to emit the bulk of the dissipated accretion power in the X-ray band, SMBHs typically emit at longer wavelengths, yielding bolometric corrections as high as 80 (Marconi et al. 2004); upcoming mid-IR observations, with the Spitzer Space Telescope, will hopefully enable us to estimate the bolometric luminosity of the detected nuclei, and to uncover obscured SMBH activity.

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