

DETECTION OF A SUPER-STAR CLUSTER AS THE IONIZING SOURCE IN THE LOW-LUMINOSITY ACTIVE GALACTIC NUCLEUS NGC 4303¹

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ABSTRACT

Hubble Space Telescope (HST) ultraviolet Space Telescope Imaging Spectrograph (STIS) imaging and spectroscopy of the low-luminosity active galactic nucleus (LLAGN) NGC 4303 have identified the previously detected UV-bright nucleus of this galaxy as a compact, massive, and luminous stellar cluster. The cluster with a size (FWHM) of 3.1 pc and an ultraviolet luminosity $\log L_{1500 \text{ \AA}} (\text{ergs s}^{-1} \text{ \AA}^{-1}) = 38.33$ is identified as a nuclear super-star cluster (SSC) like those detected in the circumnuclear regions of spirals and starburst galaxies. The UV spectrum showing the characteristic broad P Cygni lines produced by the winds of massive young stars is best fitted by the spectral energy distribution of a massive cluster of $10^5 M_{\odot}$ (for a Salpeter initial mass function law with lower mass cutoff of $1 M_{\odot}$) generated in an instantaneous burst 4 Myr ago. The ionizing energy produced by this cluster exceeds the flux needed to explain the nuclear H α luminosity. No evidence for an additional nonthermal ionizing source associated with an accreting black hole is detected in the ultraviolet. These new *HST*/STIS results unambiguously show the presence of a compact SSC in the nucleus of a low-luminosity AGN, which is also its dominant ionizing source. We hypothesize that at least some LLAGNs in spirals could be understood as the result of the combined ionizing radiation emitted by an evolving SSC (i.e., determined by the mass and age) and a black hole accreting with low radiative efficiency (i.e., radiating at low sub-Eddington luminosities) coexisting in the inner few parsecs region. Complementary multifrequency studies give the first hints of the very complex structure of the central 10 pc of NGC 4303, where a young SSC apparently coexists with a low-efficiency accreting black hole and with an intermediate/old compact star cluster and where, in addition, an evolved starburst could also be present. If structures such as those detected in NGC 4303 are common in the nuclei of spirals, the modeling of the different stellar components and their contribution to the dynamical mass has to be established accurately before deriving any firm conclusion about the mass of central black holes of few to several million solar masses.

Subject headings: galaxies: active — galaxies: individual (NGC 4303) — galaxies: nuclei — galaxies: star clusters — galaxies: starburst — ultraviolet: galaxies

On-line material: color figures

1. INTRODUCTION

Low-luminosity active galactic nuclei (LLAGNs) including low-luminosity Seyfert galaxies, classical LINERs, weak-[O I] LINERs, and LINER/H II transition-like objects are the most common types of galaxies showing nuclear activity. LINERs alone make up 50%–70% of AGNs and 20%–30% of all galaxies in surveys of nearby bright galaxies (Ho, Filippenko, & Sargent 1997). It is therefore of fundamental importance to unambiguously identify the nature of the energy source in LLAGNs and to quantify the contribution of stars and accreting black holes to their energy output.

Recent X-ray observations of LLAGNs confirm that some LINERs are the low-luminosity end of the luminous AGN phenomenon identified in Seyfert 1 galaxies and quasi-stellar objects (QSOs) in which accreting black holes are the dominant energy source (Ho et al. 2001; Eracleous et al. 2002), while in others the energy output seems to be dominated by powerful starbursts (Terashima et al. 2000; Eracleous et al. 2002). *Hubble Space Telescope (HST)* ultraviolet imaging and spectroscopy has shown the presence of young massive stars at various scales in AGNs. Seyfert 2 galaxies known to have bright kiloparsec size star-forming rings show that the AGN core is barely detected in the UV and that the massive stars dominate the observed circumnuclear UV emission (Colina et al. 1997a). The detection of stellar winds and photospheric absorption lines in the ultraviolet spectra of Seyfert 2 galaxies (Heckman et al. 1997; González Delgado et al. 1998) has unequivocally proved the presence of clusters of massive young stars in the circumnuclear regions of these galaxies. These nuclear starbursts are dusty star-forming regions of a few hundred parsecs in size and with an average age of 3–6 Myr (González Delgado et al. 1998). Optical and UV studies of Seyfert 2 galaxies have detected the presence of young massive starbursts within 300 pc of the nucleus in 30%–50% of the galaxies investigated (Cid Fernandes et al. 2001 and references therein). Finally, the compact ultraviolet sources detected in some UV-bright LINERs are nuclear star clusters with sizes of

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about 10–15 pc, as in NGC 4569 (Maoz et al. 1998; Barth et al. 1998).

In summary, recent evidence collected mainly with *HST* and *Chandra* indicates the presence of massive stellar clusters in the circumnuclear regions (few to several hundred parsecs) in a large fraction of LINERs and Seyfert 2 galaxies that substantially contribute to their energy output. However, the fundamental question of whether massive stellar clusters exist in the central few pc region, i.e., nucleus, of LLAGNs contributing substantially to, or even dominating, the energy output, requires detailed investigations in selected nearby galaxies such as NGC 4303.

NGC 4303 (M61) is a barred spiral classified as SAB(rs)bc (de Vaucouleurs et al. 1991) and is located in the Virgo cluster (adopted distance of 16.1 Mpc hereafter; see also Colina et al. 1997b). Multiwavelength *HST* images of NGC 4303 have unveiled the presence of a nuclear stellar bar of 250 pc in size centered on a bright optical and near-IR nucleus,⁶ itself connected with a nuclear star-forming spiral of about 250 pc in radius (Colina et al. 1997b; Colina & Arribas 1999; Colina & Wada 2000). The UV luminosity of the spiral dominates the observed integrated UV output. The brightest knots delineating the spiral have observed UV luminosities $L(2200 \text{ \AA}) \sim 2 \times 10^{37} \text{ ergs s}^{-1} \text{ \AA}^{-1}$ similar to that of the R136 cluster in 30 Doradus (Vacca et al. 1995) and in the high-UV luminosity end of the distribution function of compact stellar clusters detected in star-forming rings (Maoz et al. 1996).

The two-dimensional velocity field of the warm ionized gas and cold molecular gas shows that the nucleus is also the dynamical center of a disk of 300 pc in radius and in which the star-forming spiral is embedded (Colina & Arribas 1999; Schinnerer et al. 2002). Ground-based spectroscopy reveals that the optical emission lines emitted by the nuclear region (~ 100 pc size) have ratios in the borderline of Seyfert 2 galaxies and LINER nuclei (Colina & Arribas 1999). These observations confirm that the bright nucleus of NGC 4303 is a low-luminosity AGN and is indeed located at the true center of the galaxy.

2. OBSERVATIONS

Ultraviolet imaging and spectroscopy of NGC 4303 was obtained using STIS on board *HST*. The ultraviolet image was taken on 2000 July 7 through filter F25QTZ ($\lambda_p = 2364.8 \text{ \AA}$) for a total integration time of 2080 s. Spectroscopy was done on 2001 February 12 with the $52''0 \times 0''2$ long-slit and G140L grating covering the 1100–1700 Å spectral range with a dispersion of $0.6 \text{ \AA pixel}^{-1}$. The roll angle of the telescope during the observations was such that the slit was oriented along position angle (P.A.) 220° , i.e., along the line connecting the UV-bright nucleus of NGC 4303 with the brightest circumnuclear stellar cluster as identified in the previous *HST*/WFPC2 ultraviolet image (cluster G; Colina et al. 1997b). Total integration time for the spectroscopy was 13,442 s divided in five individual exposures taken during five contiguous orbits and therefore using the same guide stars. The individual imaging and spectroscopic exposures were dithered, and therefore they were calibrated inde-

pendently with the standard STIS calibration pipeline using the most updated calibration files. The individual images and spectra were combined afterward to generate the final image and long-slit spectrum.

A high signal-to-noise ratio long-slit optical spectrum was obtained with the Intermediate dispersion Spectrograph and Imaging System (ISIS) double spectrograph attached at the William Herschel Telescope (WHT) during an observatory service observing run on 2001 May 29. The $1''0$ wide slit was oriented along P.A. 220° on the sky to cover the nucleus and circumnuclear clusters. The total integration time was 3600 s, split in three equal exposures of 1200 s each. The seeing conditions were stable, and values of $1''.5\text{--}2''.0$ were measured. The final spectra were obtained combining two independent blue (3600–6280 Å) and red (6205–6990 Å) spectral ranges taken simultaneously with the two-arm spectrograph. The spectral dispersion was 0.8 and $0.9 \text{ \AA pixel}^{-1}$ for the red and blue ranges of the spectrum, respectively. Calibration was done following standard long-slit spectroscopic procedures. These data are used here only to measure the H α nuclear flux and to obtain a new determination of the optical emission-line ratios (see Table 1). Although the air mass was in the 1.3–1.55 range during the observations, atmospheric differential refraction has no effect on the emission-line ratios since the slit was positioned close to the parallactic angle (off by up to 10°).

3. RESULTS

The high-resolution ($0''.025 \text{ pixel}^{-1}$) deep STIS ultraviolet image (Fig. 1) shows in much more detail the structure already detected in a previous lower resolution ($0''.1 \text{ pixel}^{-1}$) WFPC2 image (Colina et al. 1997b). Each of the previously unresolved star-forming knots located in the circumnuclear spiral structure breaks now into several smaller, fainter knots separated by distances of less than $0''.2$ (i.e., ≤ 15 pc; see our Fig. 1 and WFPC2 UV image in Colina 1997b for a comparison). However, the UV-bright nucleus, unresolved in our previous WFPC2 image, remains as a compact source. Although a full analysis of the STIS image is beyond the scope of this paper and the results will be published elsewhere (L. Colina et al., in preparation), it is relevant for the purpose of this paper to establish the size of the compact UV-bright nucleus. The STIS PSF for the filter F25QTZ was modeled using Tiny Tim version 6.0 (Krist & Hook 2001) and assuming a flat spectrum ($F_\lambda = \text{constant}$) source. Encircled energy measurements and two-dimensional Gaussian fits to the core of the Tiny Tim PSF light profile were performed and subsequently compared with the results obtained for the observed light distribution of the UV-bright nucleus. The results of this analysis allow one to conclude that the nucleus of NGC 4303 is resolved and has a size (FWHM) of $0''.040(\pm 0''.005)$ in the UV, equivalent to 3.1 pc at the assumed distance of NGC 4303. In addition, simulations of extended sources of various sizes convolved with the modeled Tiny Tim PSF were also performed. For these simulations, the modeled PSF was computed considering a subsampling factor of 5, i.e., $0''.005 \text{ pixel}^{-1}$. Extended sources were simulated as regions of constant surface brightness with diameters ranging from $0''.015$ to $0''.055$. The extended sources were convolved with the subsampled PSF, and the resulting images were rebinned by a factor of 5 to generate the final simulated images with a pixel size of $0''.025$, i.e., the pixel scale of STIS detectors in the ultraviolet.

⁶ Throughout the paper, we distinguish between nucleus, nuclear, and circumnuclear regions, each indicating different physical sizes of about 0.01, 0.1, and 1 kpc, respectively.

TABLE 1
ULTRAVIOLET AND OPTICAL PROPERTIES OF THE NUCLEUS AND CIRCUMNUCLEAR CLUSTERS

Region	$F_{UV}(1500 \text{ \AA})^a$ ($10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$)	$E(B-V)^b$	$\log L_{UV}(1500 \text{ \AA})^c$ ($\text{ergs s}^{-1} \text{ \AA}^{-1}$)	$\log([\text{O III}]/\text{H}\beta)^d$	$\log([\text{O I}]/\text{H}\alpha)^d$	$\log([\text{N II}]/\text{H}\alpha)^d$	$\log([\text{S II}]/\text{H}\alpha)^d$
Nucleus.....	3.40	0.07 (0.10)	38.33	0.28	-1.35	0.06	-0.32
	...	0.0	...	0.50	-0.96	0.01	-0.31
Cluster G	0.84	0.10 (0.15)	37.85	-0.37	...	-0.27	-0.54
	...	0.1	...	-0.72	...	-0.35	-0.64
Cluster L.....	0.25	0.10 (0.15)	37.33

^a Observed ultraviolet flux, not corrected for extinction.

^b Internal extinction. First row gives the value as derived from the UV spectra considering an LMC extinction curve. Values in parenthesis were derived using Calzetti's law (Calzetti et al. 2000). Second row presents the value derived from the $\text{H}\alpha/\text{H}\beta$ ratios.

^c Extinction-corrected luminosity using the listed $E(B-V)$ values.

^d Extinction-corrected emission-line ratios. In addition to the hydrogen Balmer lines, the collisionally excited lines used are $[\text{O III}]$ 5007 \AA , $[\text{O I}]$ 6300 \AA , $[\text{N II}]$ 6584 \AA , and the $[\text{S II}]$ doublet 6717, 6731 \AA . First row of values is derived from the long-slit WHT/ISIS spectrum using an aperture of $1'' \times 1''$. Second row are the values derived from previous integral field spectroscopy (Colina & Arribas 1999). The spectrum for cluster L, at a distance of $0''.6$ from cluster G, cannot be obtained from our ground-based spectroscopic observations because of spatial resolution limitations.

let. As before, encircled energy measurements and two-dimensional Gaussian fits were performed on the rebinned images. The size of the nucleus obtained in this way is consistent with the value derived from the previous analysis and corresponds to that of an extended region of $0''.045$ in diameter.

The STIS UV long-slit spectrum along P.A. 220° shows three independent spectra associated with the nucleus, the brightest circumnuclear cluster (cluster G after Colina et al. 1997b), and a fainter cluster (cluster L, not previously identified). The one-dimensional spectra from the nucleus, cluster G, and cluster L were extracted from the long-slit

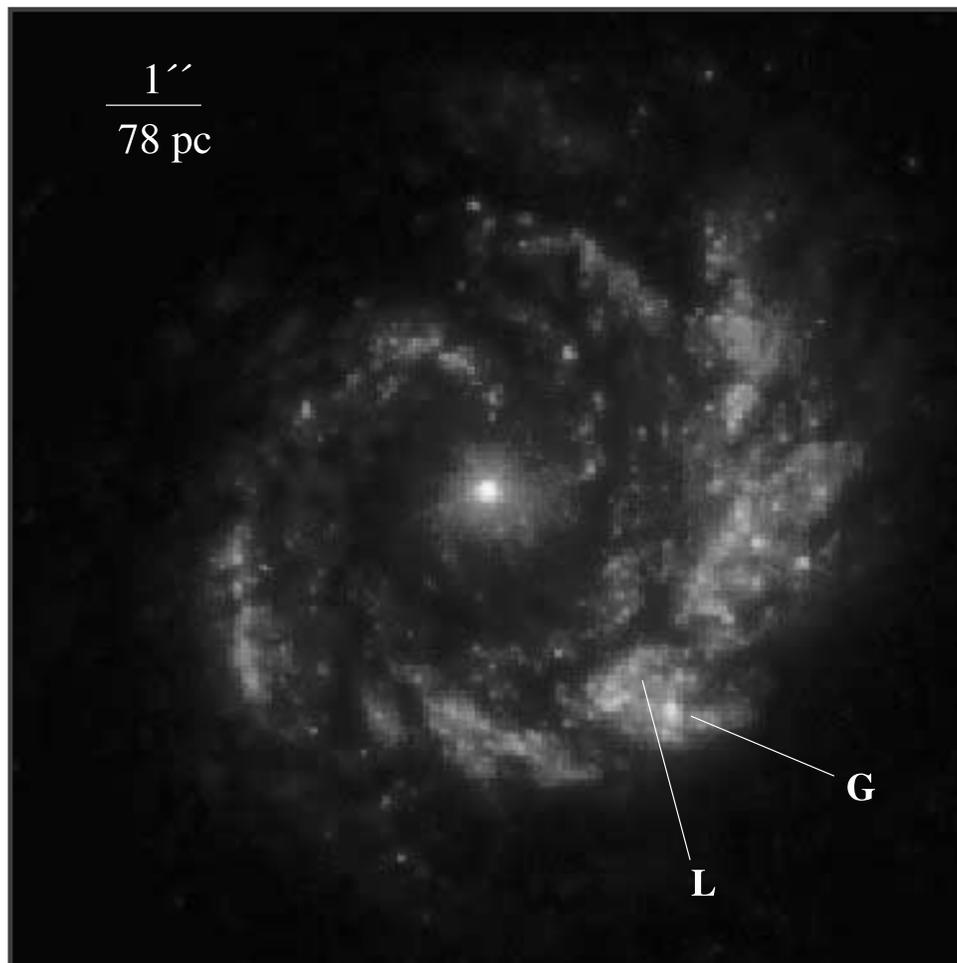


FIG. 1.—STIS F25QZ ultraviolet image of NGC 4303 nucleus and the surrounding star-forming spiral structure, already detected in a previous WFPC2 image (Colina et al. 1997b). The positions of clusters G and L detected in our long-slit STIS spectrum are indicated for reference. North is up, and east is to the left. [See the electronic edition of the Journal for a color version of this figure.]

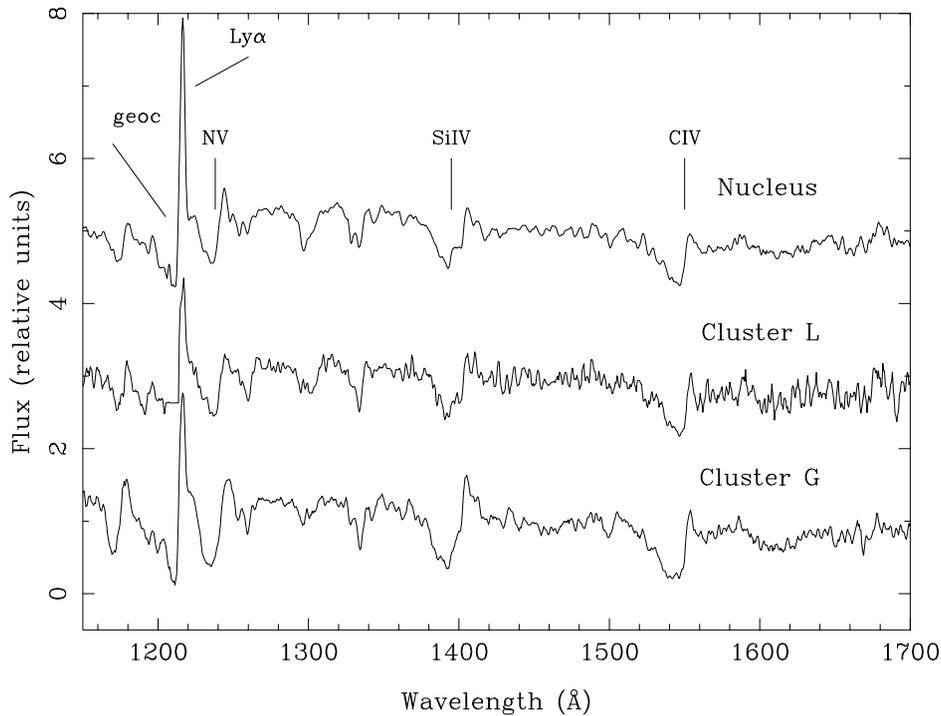


FIG. 2.—Rest-frame STIS UV spectra of the nucleus and circumnuclear clusters G and L. The three spectra show the characteristic broad P Cygni lines (N v 1240 Å, Si iv 1400 Å, and C iv 1550 Å) produced by the winds of massive young stars. In addition, the three spectra show a narrow Ly α line in emission but no trace of other emission lines such as Si iv 1400 Å and C iv 1550 Å, typical of luminous Seyfert galaxies.

spectrum using apertures of 0".9, 0".8, and 0".5, respectively. The three spectra are almost indistinguishable (see Fig. 2), all of them showing very prominently the characteristic broad P Cygni lines (N v 1240 Å, Si iv 1400 Å, and C iv 1550 Å) produced by the winds of massive young stars. In addition, the three spectra show a narrow Ly α line in emission but no trace of other strong emission lines like Si iv 1400 Å, C iv 1550 Å, and He ii 1640 Å typical of luminous Seyfert 2 galaxies such as NGC 1068 (Crenshaw & Kraemer 2000) or gas heated by fast shocks (Allen, Dopita, & Tsvetnov 1998).

In order to establish the age and mass of the stellar clusters, as well as the internal absorption toward them, a detailed comparison of the observed and synthetic ultraviolet spectra has been performed assuming a given extinction law. Differences between Calzetti's law, derived from ultraviolet observations of starburst galaxies (Calzetti et al. 2000), and LMC extinction law cannot be appreciated because of the small wavelength range covered by the STIS spectra. However, extinction in star-forming regions seems to follow an LMC- or SMC-like law, i.e., with a rather weak bump at 2200 Å, independent of the metallicity of the region (Mas-Hesse & Kunth 1999). These authors concluded that the high ionizing flux produced by the young massive stars would destroy the graphite grains, which are responsible for the shape of the Galactic extinction law, leaving mostly silicates, whose extinction properties are closer to the shape of the LMC-SMC laws. Therefore, a LMC extinction law is used throughout the following analysis. The extinction values using Calzetti's law are also given in Table 1 for completeness. The ages of the clusters have been obtained by comparing the observed profile of the P Cygni lines with the model predictions for solar metallicity stars. Synthetic spectra with metallicities lower than solar (obtained using a mix

of LMC and SMC stellar libraries) do not reproduce the intense P Cygni lines detected in NGC 4303. Moreover, instantaneous bursts are preferred over continuous star formation because the Si iv 1400 Å profile is better fitted by instantaneous bursts of a given age. Finally, once the age of the clusters and stellar upper mass of the initial mass function (IMF) are fixed, the mass and internal extinction of the clusters are derived by comparing the slopes of the observed and synthetic (stellar plus extinction) continua over the entire ultraviolet spectral range available to us.

Following the methodology outlined above, the UV spectrum of the nucleus with its prominent broad P Cygni lines is best fitted with the synthetic spectrum of an unobscured [$E(B-V) = 0.07$ for an LMC extinction law], massive $1 \times 10^5 M_{\odot}$, 4 Myr old instantaneous starburst, with a Salpeter IMF in the 1–100 M_{\odot} stellar mass range (see Fig. 3 and Table 2). The circumnuclear clusters are similarly best fitted by unobscured, less massive ($\sim 10^4 M_{\odot}$), younger (3–3.5 Myr) clusters (see Table 2 for detailed parameters). The best fit for cluster G requires an IMF characterized by a slope of 1.5, i.e., flatter than Salpeter, indicating the need for a large fraction of very massive stars to explain the UV spectral features. The need for a flat IMF does not necessarily imply an IMF different than Salpeter but could be understood if cluster G were extended and therefore due to mass segregation within the cluster, we could be biased toward the more massive stars since the width of the slit is only of 0".2 (i.e., 15.6 pc) and its orientation was selected along the line connecting the UV-bright nucleus and the UV-peak emission of cluster G.

Although the UV spectra of the nucleus and circumnuclear stellar clusters are almost indistinguishable, the optical emission-line ratios derived from the WHT narrow long-slit spectrum show that the excitation conditions in the nucleus

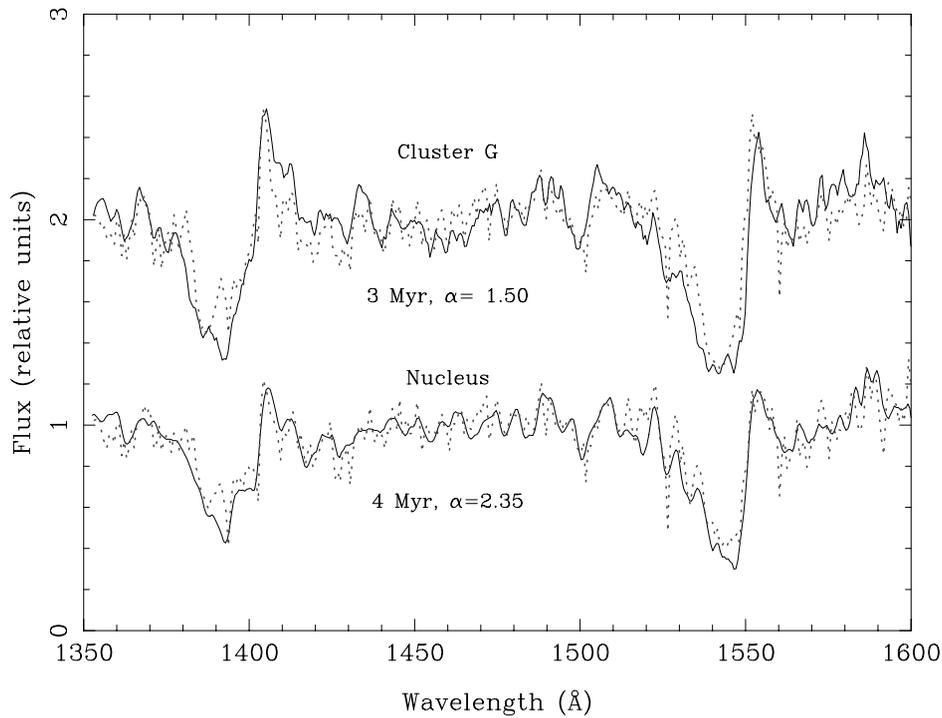


FIG. 3.—Rest-frame STIS UV spectra of the nucleus and cluster G, centered on the Si iv 1400 Å and C iv 1550 Å lines, are shown (*thin solid line*). The best-fitted instantaneous starburst model for the observed spectra are superposed (*dotted lines*). The age and slope of the IMF for each of the modeled clusters are also indicated. [See the electronic edition of the *Journal* for a color version of this figure.]

are clearly different from those present in the circumnuclear stellar clusters (see Fig. 4 and Table 1). While the circumnuclear clusters show the typical emission-line ratios of compact H II regions, the spectrum of the nucleus ($1''.0 \times 1''.0$) is classified as a LINER or, due to the weakness of the [O I] 6300 Å line, as a weak-[O I] LINER (Fig. 4). However, our previous two-dimensional integral field spectra identified the nucleus as a low-luminosity Seyfert 2/LINER borderline AGN (Colina & Arribas 1999). Discrepancies between these two classifications illustrate the difficulties in classifying LLAGNs, mostly because of the intrinsic uncertainties in ground-based measurements in general, i.e., positioning of a narrow slit ($1''.0$), corrections in the Balmer emission lines due to stellar absorptions, structure, and size of extended ionized gas, measurement of weak emission lines against the bright continuum emitted by the bulge population, etc. For NGC 4303, the structure of the ionized gas and the contribution of the H β line in absorption could be relevant factors working in opposite directions when computing the O III/H β ratio. The surface brightness of the H β

and [O III] 5007 Å lines along P.A. 220° indicates that the high-excitation [O III]-emitting gas is more centrally concentrated than the low-excitation H β -emitting gas, as traced by the steep gradient in the [O III] light distribution with the available $0''.3$ pixel resolution. This could have an important effect in decreasing the [O III]/H β ratio when obtaining the integrated spectrum for a region of $1''.0$ – $1''.5$ across. Therefore, this suggests that the [O III]/H β ratio would increase if a spectrum sampling the central $0''.1$ were available. On the other hand, the nuclear optical continuum of NGC 4303 redward of 4800 Å can be fitted reasonably well with a 1 Gyr stellar population. The core of the corresponding stellar H β absorption line with an equivalent width of 1.8 Å will decrease the flux of the H β nebular line by a factor of about 2. If this correction were applied to the observed [O III]/H β ratio, its value would drop by a factor of 2 with respect to the value given in Table 1. Therefore, although the most recent ground-based spectra favors the classification of the LLAGN nucleus of NGC 4303 as a [O I]-weak LINER, the final classification will not be obtained until the new sched-

TABLE 2
MODELED PROPERTIES OF THE NUCLEAR AND CIRCUMNUCLEAR STELLAR CLUSTERS

Region	IMF Index	Age (Myr)	Mass ($10^4 M_{\odot}$)	$\log Q_{\text{model}}^{\text{a}}$ (photons s^{-1})	$\log Q_{\text{H}\alpha}^{\text{b}}$ (photons s^{-1})
Nucleus.....	2.35	4.0	10.0	51.10	50.9
Cluster G	1.50	3.0	0.7	51.04	50.4
Cluster L	2.35	3.5	0.8	50.22	...

^a Q_{model} is derived integrating the synthetic spectral energy distribution of the modeled clusters for photons with energies above 13.6 eV.

^b Derived from the WHT/ISIS H α flux after correction for stellar absorption and aperture effects and assuming $Q_{\text{H}\alpha}$ is given as $7.5 \times 10^{11} \times L(\text{H}\alpha)$ photons s^{-1} .

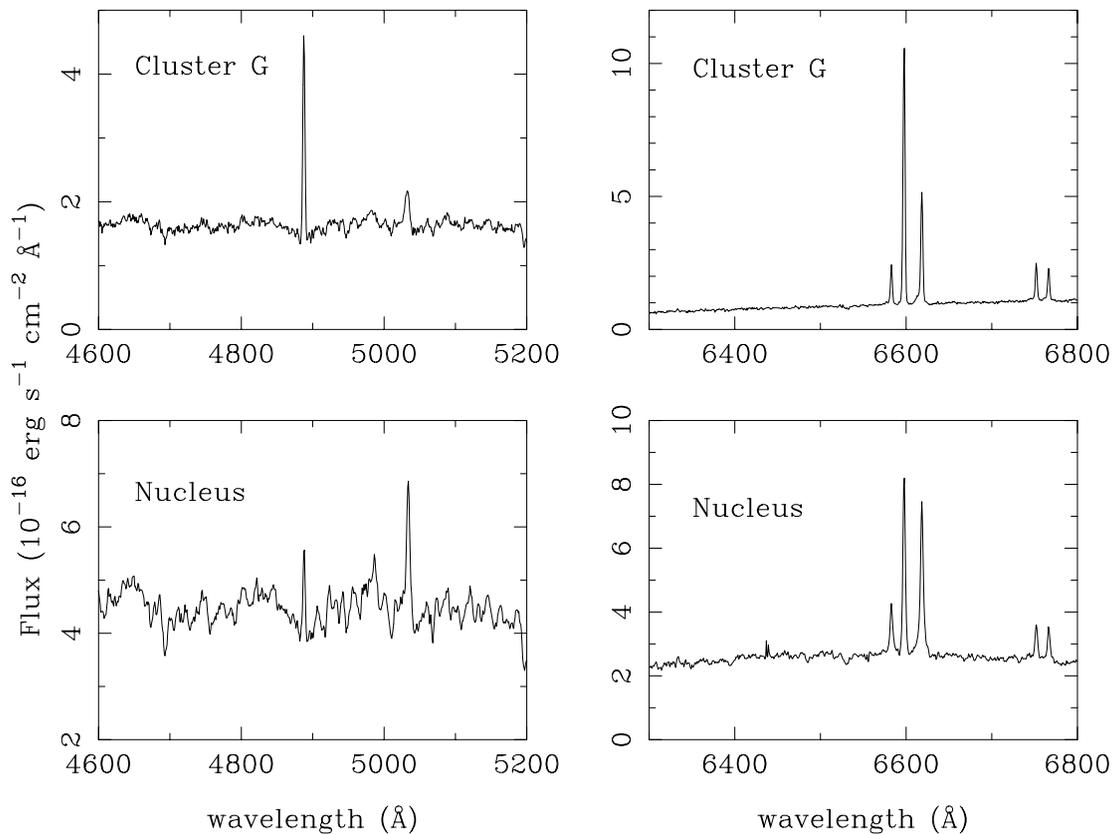


FIG. 4.—WHT optical observed spectra of the nucleus and cluster G illustrating the different excitation conditions in these regions as traced by the changes in the observed ratios of the optical emission lines. The left side plots show the H β and [O] III 4959, 5007 Å part of the spectra, while the right side plots present the H α , [N] II 6548, 6584 Å and the [S] II 6717, 6731 Å lines. The wavelength axis indicates the observed wavelength, not redshift-corrected.

uled *HST*/STIS spectroscopic data, isolating the emission from the nucleus with a slit width of 0".2 and covering the entire 1200–9000 Å range, are taken.

Finally, the internal extinction toward the nucleus and circumnuclear stellar clusters is very low, with $E(B-V)$ values of less than or equal to 0.1, as derived from the UV shape of the spectrum (see Table 1 for specific values). These values agree with those derived from the H α /H β line ratios after the fluxes of the nebular Balmer lines are corrected by a stellar absorption of 1.8 Å (see above).

4. DISCUSSION

4.1. NGC 4303 Nucleus: A LLAGN Powered by Super-Star Cluster

The nuclear cluster characterized by its size of 3.1 pc, its mass of $10^5 M_{\odot}$, and its ultraviolet luminosity $\log L_{1500 \text{ \AA}} (\text{ergs s}^{-1} \text{ \AA}^{-1}) = 38.33$ or $\log L_{1500 \text{ \AA}} (\text{ergs s}^{-1}) = 41.51$, assuming $\nu \times f_{\nu} \times 4\pi D^2$ as the monochromatic luminosity, belongs to the class of luminous super-star clusters (SSCs) found at the heart of spirals (Carollo et al. 1997) and in nuclear starburst galaxies (Meurer et al. 1995). At the derived age of 4 Myr, the SSC in the nucleus of NGC 4303 is extremely luminous, with a bolometric luminosity of about $10^8 L_{\odot}$ and an ionizing flux capable of producing an H α luminosity of up to about $1.7 \times 10^{39} \text{ ergs s}^{-1}$, if all ionizing photons are absorbed by the surrounding interstellar medium.

The H α flux in the 1"0 \times 1"0 nuclear region along P.A. 220° corresponds to a luminosity of $1.2 \times 10^{39} \text{ ergs s}^{-1}$, after correcting for a stellar absorption of 1.8 Å (equivalent width) and after slit/seeing aperture correction effects have been taken into account. The ratio of the predicted H α flux emitted by the SSC to the measured nuclear H α flux is 1.4. Therefore, no additional ionizing source other than the SSC itself is required to explain the ionized gas luminosity.

4.2. NGC 4303 Nucleus: Coexisting Star Clusters and AGN

As mentioned above, no evidence for a second energy source is present in the ultraviolet spectrum of the nucleus. However, its absolute optical magnitude $M_{F606W} = -14.2$ and very red nuclear colors $m_{F606W} - m_{F160W} = +3.5$ obtained from *HST* 0".2 radius aperture measurements with filters WFPC2/F606W and NIC2/F160W⁷ (see also Colina & Wada 2000) cannot be explained by the emission due to the unobscured UV-bright SSC. According to the STARBURST99 models (Leitherer et al. 1999), the 4 Myr, $10^5 M_{\odot}$ UV-bright cluster should have an absolute visual magnitude of about -13 , i.e., 3 times fainter than measured, and an optical–near-infrared color $V-H \sim +0.2$, i.e., much bluer than measured. Optical emission lines could affect the measured F606W magnitude, and therefore the observed $V-H$

⁷ Although filters F606W and F160W have a broadband profile different from the standard ground-based V and H filters, their effective wavelengths are very similar, and consequently we adopt here the same names for simplicity.

color could not represent the intrinsic continuum value, which would be even redder than observed. The WFPC2/F606W filter is an extreme broadband filter with a bandpass of almost 1600 Å that includes all the optical emission lines in the 4800–7000 Å spectral range. The predicted equivalent widths of the Balmer lines produced by a 4 Myr cluster are about 100 and 400 Å for H β and H α , respectively (Leitherer et al. 1999). However, the ionized region centered on the nucleus is extended over about 1''.5, as traced by the angular size of the Ly α emission-line region in our STIS long-slit spectrum. Moreover, the combined equivalent width of the nuclear [N II]+H α line complex, as measured in our WHT spectrum of the nuclear region, corresponds to about 20 Å, indicating dilution by the bulge starlight contribution, which dominates the optical continuum in our ground-based spectrum. In summary, the contribution of the optical emission lines to the measured nuclear F606W flux is not expected to be more than a few percent.

The nuclear $m_{F606W} - m_{F160W}$ color is also redder than the average bulge's color in face-on spirals ($V-H = 2.71 \pm 0.33$; de Jong & van der Kruit 1994), and therefore the presence of an additional red and luminous source has to be invoked. This additional source could either be an intermediate/old stellar population associated with the bulge, an evolved starburst dominated by red supergiants (about 10 Myr), or an accreting black hole. These alternatives are discussed below.

The first possibility would be that the bright near-infrared source traces the presence of an intermediate/old nuclear star cluster. Optical *HST* imaging has shown that many nearby spirals harbor nuclear star clusters, with a small fraction (about 5%) being unresolved (Carollo et al. 1997). Our long-slit optical continuum integrated over 1''0 \times 1''0 seems indeed to be dominated by an evolved stellar population around 1–5 Gyr old, with a total initial mass around $10^8 M_{\odot}$ (Salpeter IMF normalized between 1 and $100 M_{\odot}$). Even allowing for some reddening [$E(B-V)$ of 0.4 and 0.1 for both ages, respectively], the $V-H$ color of this population would not be redder than around 2.5, not being able to explain completely the observed infrared luminosity.

The excess H -band luminosity could also originate, at least partially, from a population of red supergiant stars formed in a previous starburst episode around 10 Myr ago (Cerviño & Mas-Hesse 1994; Leitherer et al. 1999), so that a two-stage starburst consisting of 4 and 10 Myr old stars within a few pc could coexist in the nucleus of NGC 4303. This scenario of a two-stage starburst is reminiscent of the star formation observed in the central 0.5 pc of the Milky Way and in NGC 1569, where a recent 4–8 Myr starburst, fully accounting for the ionizing and bolometric luminosities, coexists with an older cluster (Krabbe et al. 1995; Gonzalez Delgado et al. 1997). If a 10 Myr cluster were the dominating source of the luminous H -band point source ($M_{F160W} = -17.7$) in NGC 4303, it would have had a mass of about $2 \times 10^6 M_{\odot}$. If we include the H -band luminosity associated with the very intermediate/old (>1 Gyr) stellar population, a starburst of about $5 \times 10^5 M_{\odot}$ would be required. In either case, such a massive, unobscured cluster would produce an ultraviolet flux in excess of what is observed and would produce a much bluer optical continuum than observed. Therefore, if the 10 Myr old starburst were present, it should be very significantly obscured both in the optical and ultraviolet ranges, with its associated light emerging only in the infrared, if at all.

Finally, the nuclear luminous near-infrared source could alternatively indicate the presence of an AGN. The radiation emitted by the accreting black hole would dominate the energy output in the near and mid-infrared, as in most Seyfert 2 galaxies (Alonso-Herrero et al. 2001). Recent near-infrared imaging with *HST* has shown that all surveyed Seyfert 1 and 50% of the Seyfert 2 galaxies contain a luminous unresolved continuum source at 1.6 μm (Quillen et al. 2001). The H -band luminosity of the NGC 4303 nucleus ($M_{F160W} = -17.7$) agrees with the average value obtained by Quillen et al. (2001) for the subsample of Seyfert 2 galaxies with unresolved nuclear sources. There are additional independent indications that an accreting black hole exists in the nucleus of NGC 4303. The ground-based optical spectrum of the nuclear region (~ 100 pc) have line ratios anywhere between weak-[O I] LINERs and Seyfert 2 galaxies (see Table 1). However, the strongest evidence for an accreting black hole might come from recent *Chandra* images (E. Jiménez-Bailón et al. 2002, in preparation) that reveal the presence of an unresolved hard X-ray (2–10 keV) power-law source astrometrically coincident with the UV-bright nucleus and similar in luminosity to other LLAGNs recently studied with *Chandra* (Ho et al. 2001). Following recent determinations of the black hole mass to velocity dispersion relationship (Ferrarese & Merritt 2000; Tremaine et al. 2002), the central velocity dispersion of 74 km s $^{-1}$ (Héraudeau & Simien 1998) implies a mass of $1.2\text{--}2.5 \times 10^6 M_{\odot}$ for the central black hole in NGC 4303. Given this mass, the X-ray-accreting black hole would radiate very inefficiently, at extremely low sub-Eddington luminosities, as in other LLAGNs (Terashima et al. 2000).

In summary, the high spatial resolution multifrequency studies done so far give the first hints of the very complex structure of the central 10 pc of NGC 4303, where a young, luminous SSC apparently coexists with a low efficiency accreting black hole and with an intermediate/old star cluster. The young SSC is the dominant ionizing source, the accreting black hole is a minor contributor to the overall ionization, and the old cluster contributes substantially to the optical and near-infrared flux. Some additional red supergiant stars associated with an evolved starburst could also contribute to the near-infrared continuum.

4.3. Implications for LLAGNs: The SSC-AGN Connection

Low-luminosity AGNs such as the one identified in the nucleus of NGC 4303 make up the vast majority of the AGN population (Ho et al. 1997). The empirical evidence obtained so far indicates that a powerful SSC seems to coexist with an accreting black hole within the central 3 pc of NGC 4303. SSCs like the one detected in NGC 4303 are a common phenomenon in the nuclear regions of early- and late-type spirals (Carollo et al. 1997, 2002; Carollo, Stiavelli, & Mack 1998; Boeker et al. 2002) and in galaxies with nuclear starbursts and circumnuclear star-forming rings (Meurer et al. 1995; Maoz et al. 1996). Therefore, SSCs are a natural consequence of the star formation processes in the nuclear regions of spirals. On the other hand, the tightness of the black hole mass and stellar velocity dispersion relation (Ferrarese & Merritt 2000 and references therein; Tremaine et al. 2002) implies a link between massive black holes (MBH) and bulge formation in galaxies, and therefore nuclear MBHs should also be a natural consequence of the physical processes that formed present-day galaxies. Thus,

it is reasonable to hypothesize that, as detected in the LLAGN NGC 4303, powerful SSCs could coexist with MBHs in the nucleus, i.e., inner few parsecs, of a large fraction of spirals. Under this hypothesis, at least some types of LLAGNs could be understood primarily as a consequence of, on one hand, the age and mass of the SSC and, on the other hand, the accretion rate and mass of the BH. Massive SSCs with masses of 10^5 – $10^6 M_\odot$ would have peak bolometric luminosities of 0.2 – $2 \times 10^9 L_\odot$ at an age of 3 Myr. The associated, unobscured $H\alpha$ luminosities produced in the ionized interstellar medium surrounding the SSC would be in the 0.14 – 1.4×10^{40} ergs s^{-1} range. On the other hand, low-mass black holes such as the one in NGC 4303 (see § 4.2) surrounded by accretion disks radiating at extremely low sub-Eddington luminosities ($\sim 10^{-4}$ to $10^{-5} L_E$; Terashima et al. 2000) would emit bolometric luminosities of 10^6 – $10^7 L_\odot$, i.e., a factor of 100 less than a young SSC.

Therefore, some types of LLAGNs could be understood as the result of the combined ionizing radiation emitted by an evolving SSC (i.e., determined by the mass and age) and an accreting black hole (i.e., radiating at sub-Eddington luminosities) coexisting in the inner few parsecs region. The SSC would have an ionizing spectral energy distribution peaking in the soft X-rays/far-UV, while the accreting black hole would have a harder radiation field with substantial flux beyond 1 keV. The nucleus of NGC 4303, with a central young (3–4 Myr old) SSC dominating its ionizing output in the inner few parsecs region, could be a prototype of the class of weak-[O I] LINERs. The LINER/H II nucleus in NGC 4569 could be another example of an SSC-dominated LLAGN (Maoz et al. 1998; Barth & Shields 2000; Gabel & Bruhweiler 2002). On the other hand, LLAGNs like classical LINERs, or even low-luminosity Seyfert 2 nuclei, could still host an evolved, i.e., 10 Myr or older nuclear stellar cluster that will make a minor contribution to the ionizing luminosity, dominated therefore by an accreting black hole.

4.4. Implications for LLAGNs: Measuring the Low End of the Black Hole Mass Function

The complementary multifrequency study of the nucleus of NGC 4303 has shown that stellar clusters of different ages seem to coexist with a black hole in the central few parsecs region of this LLAGN. Even the best $0''.1$ spatial resolution available with *HST* STIS spectrograph represents a linear resolution of 10 pc at a distance of 20 Mpc, not enough to resolve the sphere of influence of nuclear black holes with masses of less than $10^7 M_\odot$. Therefore, the mass contribution of massive young SSCs such as the one detected in NGC 4303, and of massive, compact, intermediate/old nuclear stellar clusters in spirals with central low-mass black holes (masses of a few million solar masses as in the Milky Way, or as the estimated in NGC 4303, see § 4.2), could not be negligible and has to be taken into account. Black hole mass measurements are generally done under the assumption that the mass-to-light ratio of the stars is the same for all spirals and spatially constant over the region used for the measurement (Sarzi et al. 2001, 2002). This might not be a bad assumption for ellipticals, but spirals could have large differences, in M/L or even gradients within same galaxy if there are young nuclear clusters of different ages. NGC 4303 is a clear example of a spiral for which the assumption of constant M/L would not be valid. Therefore, kinematical studies based on the analysis of optical emission lines alone

cannot provide the mass contribution of nuclear clusters, and therefore additional detailed multifrequency modeling and spectroscopy with *HST* would be required before deriving any reliable mass for central black holes with masses of a few to several million solar masses.

5. SUMMARY

The main results presented in this paper can be summarized as follows:

1. New *HST* ultraviolet STIS spectrum of the nucleus of the galaxy NGC 4303, classified as a LLAGN in the optical, unambiguously shows the presence of broad and intense P Cygni lines characteristic of young, massive stars and do not show any evidence of the strong UV emission lines characteristic of classical AGNs like NGC 1068.

2. The ultraviolet properties of the nuclear cluster correspond to that of a compact (3.1 pc), young (4 Myr), massive ($10^5 M_\odot$), and luminous [$\log L_{1500 \text{ \AA}} (\text{ergs s}^{-1} \text{ \AA}^{-1}) = 38.33$] star cluster. These properties are characteristic of the so-called super-star clusters (SSCs) commonly detected in the (circum)nuclear regions of spirals and starburst galaxies.

3. The SSC is the dominant ionizing source in the nucleus of NGC 4303. The ionizing energy produced by this cluster exceeds the flux needed to explain the extinction-corrected nuclear $H\alpha$ luminosity, and therefore an additional non-thermal ionizing source is not required.

4. A new ground-based optical spectrum of the nuclear region (100×100 pc) favors the classification of the LLAGN as a weak-[O I] LINER, although previous classification identified it as a LINER/Seyfert 2 borderline LLAGN. Scheduled *HST* observations will establish the final classification.

5. Circumnuclear stellar clusters at distances of 170–230 pc from the nucleus have similar ultraviolet spectra showing the broad and intense P Cygni lines characteristic of young, massive stars. These clusters are however a bit younger (3–3.5 Myr) and less massive (7 – $8 \times 10^3 M_\odot$) than the SSC detected in the nucleus.

6. Additional multifrequency studies give the first hints of the very complex structure of the nucleus, i.e., region of a few pc in radius of NGC 4303, where the SSC apparently coexist with a low-efficiency accreting black hole and with an intermediate/old (>1 Gyr) compact star cluster and where, in addition, an evolved (~ 10 Myr) starburst could also be present.

If the structure detected in the nucleus of NGC 4303 is common in spirals, there are two important implications that deserve further investigation:

1. Some types of LLAGNs should be understood as the result of the combined ionizing radiation emitted by an evolving SSC (i.e., determined by the mass and age) and an accreting black hole (i.e., radiating at sub-Eddington luminosities), coexisting in the inner few parsecs region. Under this scheme, the ionization in LLAGNs classified as LINER/H II nuclei or weak-[O I] LINERs would be dominated by a young (3–4 Myr) SSC. Classical LINERs and low-luminosity Seyfert 2 galaxies could still host an older (≥ 10 Myr) cluster, but the ionizing continuum would be dominated by an accreting black hole.

2. For spirals containing low-mass (i.e., less than few to several $10^6 M_\odot$) nuclear black holes, the contribution of

massive nuclear clusters to the dynamical mass within the inner 10 pc region has to be established accurately before deriving any firm conclusion about the mass of the black hole.

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