

DISCOVERY OF A TRANSIENT X-RAY SOURCE IN THE COMPACT STELLAR NUCLEUS OF NGC 2403

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ABSTRACT

We report the discovery of an X-ray source coincident with the nuclear star cluster at the dynamical center of the nearby late-type spiral galaxy NGC 2403. The X-ray luminosity of this source varies from below detection levels, $\sim 10^{35}$ erg s⁻¹ in the 0.5 – 8.0 keV band, to 7×10^{38} erg s⁻¹ on timescales between observations of <2 months. The X-ray spectrum is well-fit by an accretion disk model consisting of multiple blackbody components and corresponding physically to a compact object mass of $\gtrsim 5 M_{\odot}$. No pulsations nor aperiodic behavior is evident in its X-ray light curve on the short timescales of the individual observations. The X-ray properties of the source are more similar to those of the nuclear source X-8 in M33, believed to be a low-mass X-ray binary, than to those of the low-luminosity active galactic nucleus in NGC 4395. The brightness of the nuclear star cluster, $M_I \sim -11.8$ mag, is typical of clusters in late-type spirals but its effective radius, $r_e \sim 12$ pc, is several times larger than average indicating a relatively relaxed cluster and a low probability of a central massive object. The cluster has a mass $\gtrsim 10^{6.5} M_{\odot}$ and an age of ~ 1.4 Gyr estimating from its observed colors and brightness.

Subject headings: galaxies: individual (NGC 2403) — galaxies: nuclei — galaxies: star clusters — galaxies: evolution — X-rays: galaxies — X-rays: binaries

1. INTRODUCTION

Tight correlations have been measured between the masses of central supermassive black holes in early-type galaxies and their bulge mass (Magorrian et al. 1998; Häring & Rix 2004), luminosity (Kormendy & Richstone 1995), central velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002), and central light concentration (Graham et al. 2001). It is unclear if these correlations extend to less massive galaxies and to galaxies of later morphological type. If so, do the scaling properties still hold? That is, do disk-dominated late-type spirals with small bulges host intermediate-mass black holes or is there a minimum galaxy mass below which black holes fail to form and/or to grow?

High-resolution *Hubble* images (Carollo et al. 1998; Böker et al. 2002, 2004) show that the majority, $\sim 75\%$, of late-type spirals have distinct compact stellar nuclei or nuclear star clusters (NSCs). These are not, however, a smooth extension from the massive bulges of early-type galaxies. They are much more dense and more compact (Walcher et al. 2005); hence, while typical NSC masses can be comparable to those of dwarf spheroidal galaxies, they are 4 orders of magnitude denser. In this sense, NSCs are more like Milky Way globular clusters with scaled-up masses and densities. In addition, they are much more luminous than the old globular clusters (Böker et al. 2004) due in large part to the comparatively young age, 100 Myr, of their most luminous stellar component (Rossa et al. 2006). Still, their dynamical masses suggest a hidden older population is present as well (Walcher et al. 2005; Rossa et al. 2006) so that they may grow through occasional bursts of star formation and may be forming stars in the current epoch

at low levels.

While the NSCs are, by definition, at or very near the dynamical centers of their host galaxies (e.g. Böker et al. 2002), it is not certain if they originated there nor whether or not they are presently accreting gas and forming stars. It has been suggested that some of the most massive globular clusters may be relic dE nuclei tidally stripped and absorbed into larger galaxies (e.g. Freeman 1993; Layden & Sarajedini 2000). If they commonly host (intermediate-mass) black holes, then they may be potential candidates for ultraluminous X-ray sources (King & Dehnen 2005) and, if they migrate to the cores of the larger host galaxies, may be the seed (intermediate-mass) black holes that evolve into supermassive black holes.

The SAB(s)cd galaxy NGC 2403 is a member of the M81 group of galaxies at a distance $D = 3.2$ Mpc ($1' = 1$ kpc; Madore & Freedman 1991). NGC 2403 lacks a central bulge but does host a luminous compact NSC (Davidge & Courteau 2002). We derive physical properties for this cluster from recent *Hubble* Advanced Camera for Surveys observations and other archival data in § 2. We have discovered a bright transient X-ray source within the NGC 2403 NSC in archival *Chandra* and *XMM/Newton* observations. The nuclear transient is easily resolved from nearby X-ray sources including the well-known ultraluminous X-ray source located about $2.6'$ to the west of the nucleus (e.g., Swartz et al. 2004). We present the X-ray spectra and light curve of the nuclear source in § 3. The optical properties of the NSC and the X-ray properties of the transient source are compared to other nearby compact nuclei in § 4. We find the NSC is older and less compact than typical for late-type galaxies. The properties of the

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X-ray source are consistent with an X-ray binary containing an $\sim 5 M_{\odot}$ compact object or larger accreting from a low-mass companion. Further discussion is given in § 5

2. THE NUCLEAR STAR CLUSTER IN NGC 2403

The contrast between the nucleus of NGC 2403 and the underlying galaxy disk is clearly visible in optical and near-IR images where it appears extended at high resolution (Figure 1). We used the method described in Böker et al. (2004) to analyze the morphology of the cluster.

Calibrated *Hubble* images acquired with the Advanced Camera for Surveys (ACS) operated in WFC mode were obtained from the Multimission Archive at STScI⁵. These images were already cleaned of cosmic rays and bad pixels and were corrected for geometric distortion; we performed no further processing of the data. The data were taken 2004-08-17 and include images through the F475W, F606W, F658N, and F814W filters (dataset identifiers J90ZX1010 through 1040).



FIG. 1.— 3-color combined *Hubble*/ACS image of the $20'' \times 20''$ region centered on the nuclear star cluster in NGC 2403. Colors blue, green, and red correspond to the filters F475W, F606W and F814W, respectively. The image has been rotated for display purposes such that north is up and east is to the left.

The $200'' \times 200''$ *Hubble*/ACS field contained both SN 2004dj (the target of the original investigation) and the nucleus of NGC 2403. Although the location of SN 2004dj is known to high precision (Beswick et al. 2005) and the ACS resolution is $\sim 0.''1$ (with $0.''05 \text{ pixel}^{-1}$ sampling), the supernova is saturated in these images and this is the dominant contribution to the uncertainty in the position of the nucleus: Our best estimated position for the nucleus is R.A. = $7^{\text{h}}36^{\text{m}}50.^{\text{s}}070$, Decl. = $+65^{\circ}36'3.''54$ (J2000.0) with an uncertainty of $\sim 0.''1$ radius based on a circular Gaussian model fit to the location of the supernova in the F606W filter image. The position of the nucleus is consistent with the kinematic center of the galaxy determined

⁵<http://archive.stsci.edu/>

⁶ISHAPE documentation is available from <http://www.astro.uu.nl/~larsen/baolab/>

by Fraternali et al. (2002) from the HI rotation curve.

A model point spread function (PSF) of the *Hubble*/ASC detector at the location of the source was constructed using TinyTim (Krist & Hook 1997) assuming a spectral energy distribution equivalent to that of an A5V star (following Böker et al. 2004). We then fit analytic models to the surface brightness distribution using the program ISHAPE (Larsen 1999) which convolves the model PSF with these analytic profiles. ISHAPE⁶ allows for circular or elliptical models but cannot reproduce the azimuthal asymmetries clearly seen in the *Hubble* images of NGC 2403. Therefore, we restricted our selection to circular Moffat and King model profiles. The standard power indices and concentration parameters for these models (see Larsen 1999) provided poor fits to the data. A trial King model applied to the azimuthally-averaged radial profile suggested a Moffat model with power index of 1.35 would improve the model fit. This did give the best fit of all our trials. Figure 2 displays this model, the data, and the fit residuals. Following Böker et al. (2004), we derive an effective radius of $r_e = 11.7 \pm 0.1 \text{ pc}$ from the ISHAPE fitting. This is larger than the average, $\sim 3.5 \text{ pc}$, found by Böker et al. (2004) for a sample of 39 NSCs in late-type galaxies.

We estimate the intrinsic, background-subtracted, *I*-band luminosity to be $1.1 \times 10^{39} \text{ erg s}^{-1}$ in a $2\pi r_e^2$ region centered on the NSC after correcting for an extinction of $E(B - V) = 0.2 \text{ mag}$ (see below). The average surface brightness, $I_e = 323 L_{\odot} \text{ erg s}^{-1} \text{ pc}^{-2}$, is near the low luminosity range of the NSCs in Sd galaxies in the Böker et al. (2004) sample and near the high luminosity end of Milky Way globular clusters (cf. their Fig. 5). The observed absolute blue magnitude is $M_B = -9.3 \text{ mag}$ (giving an extinction-corrected $M_B^0 = -10.2 \text{ mag}$, see below).

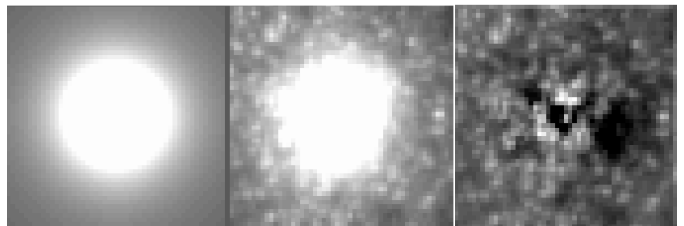


FIG. 2.— ISHAPE (Larsen 1999) model fit to the *I*-band surface brightness distribution of the nuclear star cluster in NGC 2403. From left to right: Model, data, and fit residuals. Grayscale of model and data cover the same range. The model is a Moffat profile with a power index of 1.35 (see text).

Lacking an optical spectrum of the NGC 2403 nucleus we cannot accurately constrain the mass and age of the cluster. However, we can obtain estimates of the cluster age from the observed colors and the cluster mass from M_B^0 using the stellar synthesis models of, e.g., Leitherer et al. (1999). The observed colors are (using the conversions from *Hubble*/ACS to Johnson-Cousins given by Sirianni et al. 2005) $B - V = 1.0 \text{ mag}$, $V - I = 1.2 \text{ mag}$, and $J - K = 0.6 \text{ mag}$ (the latter from Davidge & Courteau 2002). These colors can be self-consistently reproduced by a single starburst episode aged $\sim 1.4 \text{ Gyr}$ viewed through an extinction of $E(B - V) = 0.2 \text{ mag}$. They cannot be

reproduced by models with continuous star formation nor can the metallicity of the cluster be radically different from the solar value. The implied intrinsic colors are consistent with those of G2V to K0V stars. As shown in § 3.2, the extinction estimate is consistent with the hydrogen column density towards the NSC X-ray source according to the best-fitting X-ray spectral model.

Rossa et al. (2006) show there is a strong correlation between the observed $B - V$ color of NSCs and their luminosity-weighted cluster age, τ_L . Using their linear correlation coefficients gives $\tau_L = 10^{9.8 \pm 0.4}$ yr. The age-mass correlation (Rossa et al. 2006) then gives $\log M = 10^{8.3 \pm 1.8} M_\odot$ for the total mass of the NSC. These values are much higher than expected for a late-type spiral galaxy like NGC 2403 based on the (weaker) correlations Rossa et al. (2006) find between cluster mass or cluster age and galaxy morphological type.

There is no correction for extinction in the work of Rossa et al. (2006). One possibility is that the NSC in NGC 2403 is more reddened than typical. Figure 1 shows the cluster is, in fact, at the edge of a dark region however our best-fitting extinction is only $E(B - V) = 0.2$ mag. Using the implied intrinsic $B - V = 0.8$ mag color reduces the estimated age to $\tau_L = 10^{9.3 \pm 0.3}$ yr and the cluster mass to $M = 10^{7.6 \pm 1.7} M_\odot$. This age is consistent with the age estimated above from the colors using the starburst models of Leitherer et al. (1999). A mass estimate can also be deduced from the age and intrinsic blue magnitude using these starburst models. The mass estimated in this way is $M \sim 10^{6.4} M_\odot$ depending weakly on starburst metallicity and IMF.

The age estimated here is much older than the ~ 100 Myr age deduced by Davidge & Courteau (2002) for individual AGB stars in the vicinity of the nucleus. (Many of these stars are visible as blue sources in the composite *Hubble* image of Figure 1.) Davidge & Courteau (2002) point out that the $J - K$ color of the cluster is somewhat bluer than these surroundings suggesting an age gradient. According to Leitherer et al. (1999), the $J - K$ color for a starburst becomes bluer with age (after an early reddening phase) implying that the NSC in NGC 2403 is older than its surroundings. This is consistent with our calculations.

Although the bulk of the star formation in the cluster appears to have occurred some ~ 1.4 Gyr ago, there may be a low level of current star formation present (and, likely, an underlying older population of stars as well). For star-forming clusters, the current star formation rate can be estimated from the $H\alpha$ luminosity. We have constructed a continuum-subtracted $H\alpha$ image from the *Hubble*/ACS images and find no net $H\alpha$ emission; the 2σ upper limit to the $H\alpha$ luminosity within a $1.''5$ radius circle about the NSC is $3 \times 10^{35} \text{ erg s}^{-1}$. Thus there is no evidence for current star formation in the NSC.

3. THE TRANSIENT X-RAY SOURCE IN THE NUCLEUS OF NGC 2403

The nuclear region of NGC 2403 was observed with *Chandra* ACIS-S four times over a 3.7 year interval and three times with *XMM/Newton* within this same time interval. Table 1 provides a log of these observations. Earlier

observations with the *Einstein*, *ASCA*, and *ROSAT* Observatories show no evidence for a nuclear X-ray source although the quality of the data is poor compared to the recent *Chandra* and *XMM/Newton* observations.

We obtained level 1 event lists from the *Chandra* data archive⁷ and reprocessed them using the Chandra Interactive Analysis of Observations (CIAO) version 3.3.0.1 tool `acis_process_events` and the calibration database (CALDB) version 3.2.1. Reprocessing removed pixel randomization and applied CTI and time-dependent-gain corrections. We then filtered the data of events with non-*ASCA* grades and bad status bits as well as hot pixels and columns.

The European Photon Imaging Camera (EPIC) event lists from the *XMM/Newton* observations were obtained from the HEASARC data archive⁸. We processed the event lists using the current calibration files with the routines in SAS 6.5.0.

We checked for periods of high background that could affect our spectra and timing analysis; excluding some short intervals from the *XMM/Newton* datasets. The final Good Time Intervals for data used in our analysis are listed in Table 1.

3.1. X-ray Light Curve

A bright, point-like X-ray source was detected in several of the observations at the location of the nuclear star cluster. We used the common source, SN 2004dj, to match the location of the X-ray source and the NSC. The X-ray source is well within the $>1''$ optical extent of the cluster. Figure 3 shows the 0.5 – 8.0 keV light curve of the source, designated CXOU J073650.0+653603, constructed from the average flux during each individual observation based on spectral fits (§ 3.2). For observations in which the source was not detected, a 2σ flux upper limit was calculated by scaling from the fitted measurements by the background-subtracted count rate in an appropriate source region. The corresponding observed X-ray luminosities, assuming a distance of 3.2 Mpc, are tabulated in Table 1. The X-ray source was undetected in five observations and orders of magnitude above (*Chandra*) detection thresholds in three observations which qualifies it as a transient source (e.g. van Paradijs & McClintock 1995). The shortest measured interval between a detection and a non-detection is 21 days (observations number 5 and 6 of Table 1) but the *XMM/Newton* upper limit is not particularly compelling. The time between the *Chandra* non-detection observation number 4 and the detection observation 6 is 41 days.

We also inspected the light curve from observations in which the source was detected for variability during the observation. These X-ray light curves, binned into 1 ks intervals, displayed no conspicuous variability and were formally consistent with a constant flux model. Searches for short-term aperiodic variability using a power-spectrum analysis found no excess power above the Poisson noise. Searches for coherent pulsations, using the Z_n^2 statistics (Buccheri et al. 1983), detected nothing significant.

⁷<http://cxc.harvard.edu/cda/>

⁸<http://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl>

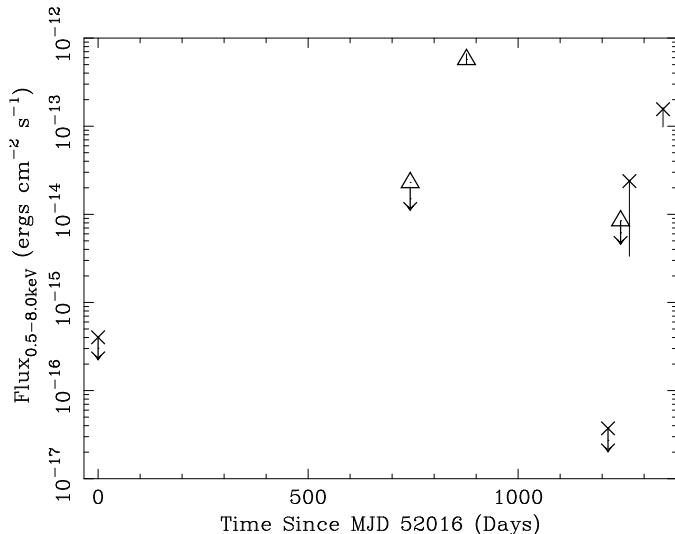


FIG. 3.— Lightcurve of the X-ray source in the nucleus of NGC 2403. Time is measured since the first *Chandra* observation on 2001-04-17. Upper limits for non-detections are represented with arrows. Crosses denote *Chandra* observations. Triangles denote *XMM/Newton* observations. Error bars denote two-sided errors. Table 1 provides the numerical values shown here.

3.2. X-ray Spectrum

Models were fit to observed spectra of the source. Table 2 lists the models attempted, the resulting best-fit model parameters with 90% confidence extremes for a single interesting parameter, and the fit statistic for each of the three observations in which the source was detected. CXOU J073650.0+653603 was most luminous during the *XMM/Newton* observation of 2003 September. The spectrum from this observation is shown in Figure 4. Following the procedures outlined in Page et al. (2003), the average *XMM/Newton* spectrum from the three detectors was modeled in XSPEC using the χ^2 fit statistic. Absorbed `diskbb` and `powerlaw` models were applied. Adding additional model components did not significantly improve the fit statistics according to the F-test. We used an unbinned spectrum with C-statistic in XSPEC in fitting the low-count *Chandra* observations. Only single-component models were applied to the *Chandra* spectra. It was necessary to fix the multiplicative absorption model component at the Galactic value $n_H = 4 \times 10^{20} \text{ cm}^{-2}$ in fits to some of the *Chandra* data to prevent convergence to an unphysically low value.

The best-fitting model in all cases is the `diskbb` model (Makishima et al. 1986, 2000) representing a spectrum dominated by a geometrically-thin accretion disk which extends to the innermost stable orbit often referred to as a high/soft state (Remillard & McClintock 2006). The model fit parameters are proportional to the inner disk temperature and radius or, alternatively, can be expressed in terms of the mass of the central object. These parameters are listed in Table 2. They suggest a compact object mass, $M \sim 2.3/T_o^2(L_{\text{disk,bol}}/10^{38})^{1/2}$ where $T_o \sim T_{\text{in}}$ is the disk color temperature, of about $5 M_\odot$ and that the peak observed luminosity is therefore about the Eddington value. The mass could be up to about a factor-of-two larger depending on viewing angle, black hole spin, and hardening factor.

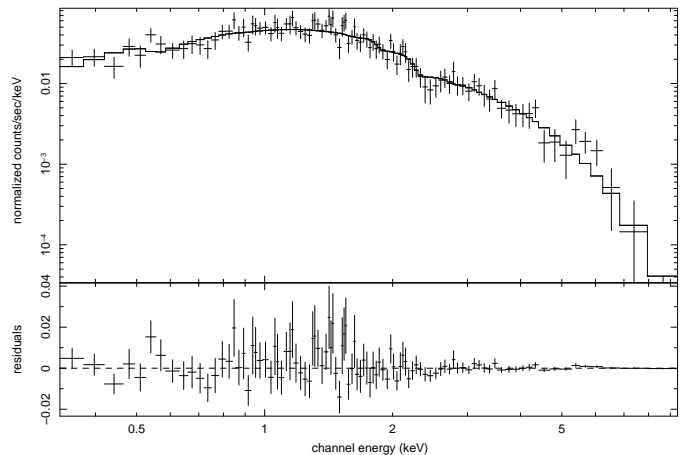


FIG. 4.— *XMM/Newton* spectrum of CXOU J073650.0+653603 with the best fit disk-blackbody model (upper panel) and fit residuals.

4. COMPARISON TO OTHER NUCLEAR STAR CLUSTERS

As mentioned in the Introduction, some 75% of late-type spirals host NSCs. In this section we briefly compare NGC 2403 to two well-studied objects with very different interpretations for their X-ray emission mechanisms: NGC 598 (M33), another Scd galaxy with a NSC and a bright point-like nuclear X-ray source, is thought to contain a luminous X-ray binary; and NGC 4395, the optically least-luminous broad-line AGN known, is thought to contain a “proper” nuclear black hole at the low end of their mass distribution ($M \sim 10^5 M_\odot$).

4.1. M33 X8

NGC 598 is a disk-dominated late type spiral galaxy as is NGC 2403. Its NSC is as luminous ($M_B = -10.2$, Kormendy & McClure 1993) as that of NGC 2403 but much more compact (FWHM < 1 pc, Gordon et al. 1999). Analysis of the cluster optical spectrum shows it formed from two major starburst episodes; one ~ 1 Gyr ago and the other occurring only 40–70 Myr in the past (O’Connell 1983; Gordon et al. 1999; Long et al. 2002). The best estimated upper limit for the mass of any central compact object in the cluster is $M_{\text{BH}} \sim 1500 M_\odot$ based on modeling the narrow-slit *Hubble* spectrum (Gebhardt et al. 2001).

The nucleus contains a bright unresolved X-ray source, designated X-8 (Trinchieri et al. 1988), with a luminosity as high as $\sim 2 \times 10^{39} \text{ erg s}^{-1}$ in the 0.5–10 keV band (Foschini et al. 2004). It has long been debated whether this source could be a weak AGN. The optical spectrum shows no evidence of AGN activity although a strong component would be expected if the measured X-ray flux is extrapolated using the known X-ray to optical flux relationship for AGNs (Long et al. 2002). The current consensus is that X-8 is a luminous X-ray binary in the NSC of NGC 598 rather than a weak AGN (e.g., La Parola et al. 2003). The mass of the compact object must be $\sim 10 M_\odot$ or more unless it is radiating above the Eddington limit in the X-ray band.

The source X-ray flux has remained at about its current level since discovery although it does vary by about a factor of two on short timescales. This is in contrast with many low-mass XRBs which are soft X-ray transients that

vary by factors of 100 or more on timescales of weeks or months (as does the nuclear source in NGC 2403). It has been suggested that M33 X-8 is similar to GRS 1915+105 (e.g., Long et al. 2002; Dubus & Rutledge 2002) in that both are steady sources with comparable X-ray luminosities and spectral states. Both are also radio sources (Dubus & Rutledge 2002). GRS 1915+105 is a low-mass X-ray binary with a $14 \pm 4 M_{\odot}$ compact object accreting from a low mass, evolved (K or M giant) companion (Greiner, Cuby, & McCaughrean 2001).

4.2. NGC 4395

NGC 4395 is the optically least-luminous AGN known. It is a SA(s)m dwarf galaxy with a distinct though weak type 1 Seyfert spectrum (Filippenko & Sargent 1989). The nuclear brightness is only $M_B \sim -11$ mag which makes it only twice as bright as the NSC in NGC 2403. Filippenko & Ho (2003) estimate the mass of its compact object to be less than $\sim 10^5 M_{\odot}$. Its X-ray spectrum is a moderately absorbed, $N_H = (1.2 - 2.3) \times 10^{22} \text{ cm}^{-2}$, hard power law ($\Gamma \lesssim 1.5$, Shih et al. 2003; $\Gamma \sim 0.6$, Moran et al. 2005). The absorption-corrected 2–10 keV luminosity is nearly $10^{40} \text{ erg s}^{-1}$ (Iwasawa et al. 2000; Moran et al. 2005). It is highly variable in X-rays (Moran et al. 1999, 2005; Shih et al. 2003) exhibiting factor of 10 changes in X-ray flux in less than 2 ks.

The low power law index, moderate absorption, and rapid flux variability of the AGN in NGC 4395 is unlike the behavior of the nuclear source in NGC 2403 in all respects.

5. DISCUSSION

We have presented a new study of the NSC in NGC 2403. We discovered that it contains a transient X-ray source; its X-ray luminosity varies from $\sim 7 \times 10^{38}$ to $\lesssim 5 \times 10^{34} \text{ erg s}^{-1}$ over a few months. The question is whether this accreting source is the galaxy’s nuclear black hole or, instead, a lower-mass black hole formed in the star cluster from stellar processes.

Its luminosity is consistent both with a stellar-mass black hole (BH) and with a supermassive black hole (SMBH) emitting a few orders of magnitude below its Eddington limit (as are the large majority of SMBHs in the Local Universe). Its X-ray variability pattern, over at least 4 orders of magnitude over a few months to years, is more consistent with typical X-ray binaries. Its X-ray spectrum when the source is bright is exactly what we expect from a BH of mass $\sim 5 - 10 M_{\odot}$ in the thermal dominant state ($L_X \sim 8 \times 10^{38} \text{ erg s}^{-1} \sim L_{\text{Edd}}$, $T_{\text{in}} \sim 1 \text{ keV}$, $R_{\text{in}}(\cos \theta)^{1/2} \sim 50 \text{ km}$). SMBHs may have comparable X-ray luminosities but tend to have power-law spectra in the X-ray band, because their characteristic disk temperatures are $\lesssim 0.1 \text{ keV}$. We conclude that the X-ray source in the NSC of NGC 2403 is more likely to be an ordinary X-ray binary, similar to the nuclear source in the NSC of M33.

X-ray studies of nuclear sources associated with NSCs provide an additional tool to understand and quantify the relation between the formation of galactic bulges and the presence and properties of a central “compact massive object” (CMO). Ideally, one should look for correlations that extend unbroken from large ellipticals to small late-type disk galaxies. One such fundamental correlation seems to hold between the bulge mass and the CMO mass (Ferrarese

et al. 2006; Wehner & Harris 2006), where the CMO is a supermassive BH in ellipticals and early-type spirals and a NSC in late-type spirals. The CMO mass is $\sim 1/500$ of the spheroidal mass (bulge mass in spirals). Qualitatively, this suggests that the initial galaxy assembly processes led to the rapid collapse of a nuclear gas component into a BH in the more massive galaxies, while a star cluster was formed in galaxies with a shallower gravitational potential, where the central accumulation of gas occurred more slowly.

However, many questions remain open. Some relatively massive ellipticals do have NSCs (Rossa et al. 2006; although they have not been found in galaxies brighter than $M_B \sim -20$ mag; Ferrarese et al. 2006). The range in which NSCs and SMBHs overlap may span several orders of magnitude: a SMBH with $M_{\text{BH}} \sim 3 \times 10^6 M_{\odot}$ is the CMO in the center of the Milky Way, and a SMBH with a mass $\sim 10^5 M_{\odot}$ is present in NGC 4395, but NSCs as massive as a few $10^8 M_{\odot}$ have been found in some elliptical galaxies (Rossa et al. 2006). It is not known whether the same galaxy can harbor both an SMBH and a NSC, or if they are mutually exclusive. It is also not yet clear which of the two classes of objects defines the more fundamental correlation with the galactic bulge; it was suggested (Rossa et al. 2006) that NSCs in large galaxies may be a factor of 3 more massive than SMBHs, for a given bulge mass. Furthermore, it is not known whether a linear relation between bulge and CMO masses may extend all the way down to bulgeless Scd galaxies (implying the existence of CMOs with masses as low as $10^3 - 10^5 M_{\odot}$), or if the relation breaks down for CMO masses $\lesssim 10^6 M_{\odot}$.

From its optical brightness and colors, we estimate a stellar mass of $\sim 2 \times 10^6 M_{\odot}$ for the NSC in NGC 2403, comparable to the mass of the SMBH in the Milky Way, even though NGC 2403 is bulgeless. Although our X-ray study suggests that the nuclear X-ray source is not from a SMBH, this does not rule out the presence of a SMBH inside the NSC: it may simply be quiescent. In that case, it would be among the faintest SMBHs, with a luminosity $\lesssim 10^{-10} L_{\text{Edd}}$. In a work currently in preparation, we shall use an X-ray survey of galactic nuclei to determine whether galaxies with NSCs may also have signs of AGN activity.

Even if we accept that a late-type galaxy such as NGC 2403 formed a NSC but no SMBH, there is a strong possibility that the NSC contains stellar-mass BHs formed via ordinary stellar processes, or perhaps an intermediate-mass BH (IMBH) formed via runaway core collapse and stellar coalescence (if the NSC was sufficiently compact). Then, those BHs could have grown over a Hubble time, via accretion during large-scale gas inflows towards the galactic center, via coalescence of stellar mass BHs inside the NSC, or via orbital decay and coalescence of accreted satellite galaxies or primordial halo remnants. Processes involving BH mergers may lead to the displacement or escape of the merged BH due to gravitational radiation recoil, and to the formation of a lower-density stellar core (Merritt et al. 2004). It is possible that some late-type galaxies have a three-tier hierarchical relation between a bulge, a NSC, and an IMBH inside the NSC. Theoretical arguments have suggested that if an IMBH forms via core collapse in the core of a massive star cluster, its mass should be $\sim 0.2\%$ of the host cluster mass, coincidentally

similar to the mass ratio between the bulge and its CMO.

In principle, the effective radius of a NSC may provide clues on its dynamical processes. In NGC 2403, the NSC is older and less compact ($r_e = 11.7$ pc) than most other NSCs in late-type spirals (typical $r_e \sim 3.5$ pc). If the cluster was formed with such a large r_e , it would not have been compact enough to form an IMBH via core collapse (Portegies Zwart et al. 2004). Alternatively, one may speculate that the NSC was originally more compact and has evolved to such a large radius because of the presence of one or more BHs in its core (Ebisuzaki et al. 1991; Milosavljević et al. 2002; Graham 2004). Other physical processes not related to BH coalescence may also cause a star cluster to expand. For example, studies of clusters in the LMC show clusters are born compact and evolve to a range of r_e as they age (Elson et al. 1989; Mackey & Gilmore 2003). But studies also show this evolution is not due to differences in IMF (deGrijs et al. 2002), time-varying external tidal fields, nor differences in the number of hard primordial binaries present (Wilkinson et al. 2003). If no massive BH formed, the cluster could still evolve to large r_e . For the LMC clusters (none of which are thought to host a massive BH!), r_e evolution is likely due to differences in star formation efficiencies with lower efficiencies tending to expel gas before a dense stellar core (with a population of massive stars) can form and leading eventually to cluster expansion (Goodwin 1997; Vine & Bonnell 2003). If evolution is through this mechanism, then we would expect a smooth distribution of cluster r_e values that included the value $r_e = 11.7$ pc found here for NGC 2403. This does not appear to be the case (cf. Fig. 4 of Böker et al. 2004) although the Böker et al. sample is not large.

Another difference between NSCs with or without a rel-

atively massive BH is the role of feedback. More powerful feedback is expected from a nuclear IMBH or SMBH, leading to gas expulsions, perhaps large-scale outflows, and cyclic episodes of star formations. In this sense, the distribution of stellar populations in a NSC provides a fossil record of past galactic activity, and may be used to reconstruct episodes of galactic mergers or phases of nuclear activity. However, in the case of a relatively low-mass NSC such as the one in NGC 2403, we find that normal stellar winds and SNe can provide enough energy to expel cool interstellar gas from the cluster and quench star formation, without the need of AGN feedback.

Interestingly, NGC 2403 is one of those rare galaxies with gas column densities below the critical value needed to sustain activity but has a normal star formation rate (Martin & Kennicutt 2001). Perhaps a strong outflow from the central region has helped trigger star formation at larger radii. Outflow may also account for some of the anomalous HI discovered in the halo of NGC 2403 (Fraternali et al. (2002, 2004). These points will be addressed in a future paper (Yukita et al., in preparation).

The time interval since the last star formation episode is longer for the NSC in NGC 2403 than is typical for clusters in late-type spirals. Davidge & Courteau (2002) also noted the lack of star formation activity more recent than ~ 100 Myr in the inner disk of NGC 2403 and suggested it may be due to expulsion of potential star-forming material from the central regions. Indeed, active star formation is ongoing in several giant HII regions (Drissen et al. 1999; Yukita et al., in preparation) surrounding the nucleus of NGC 2403 but the NSC itself contains perhaps the oldest collection of stars in the region.

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TABLE 1
 X-RAY OBSERVATIONS OF NGC 2403 AND ITS NUCLEAR SOURCE LUMINOSITY

No.	Mission/Instrument	Date/Identifier	$L_X(0.5-8.0 \text{ keV})$ ($10^{37} \text{ erg s}^{-1}$)	t_{exp} (ks)
1	<i>Chandra</i> /ACIS-S	2001-04-17/2014	< 0.049	36.1
2	<i>XMM/Newton</i> /MOS+PN	2003-04-30/0150651101	< 2.8	8.0
3	<i>XMM/Newton</i> /MOS+PN	2003-09-11/0150651201	$69.8^{+11.3}_{-8.2}$	7.5
4	<i>Chandra</i> /ACIS-S	2004-08-23/4628	< 0.005	47.1
5	<i>XMM/Newton</i> /MOS+PN	2004-09-12/0164560901	< 1.0	60.0
6	<i>Chandra</i> /ACIS-S	2004-10-03/4629	$2.9^{+0.1}_{-2.5}$	45.1
7	<i>Chandra</i> /ACIS-S	2004-12-22/4630	$18.7^{+0.9}_{-7.0}$	50.6

TABLE 2
 X-RAY SPECTRAL FIT PARAMETERS

	Observation 3	Observation 6	Observation 7
Fitted energy range (keV)	0.3 - 10.0	0.5 - 2.0	0.5 - 3.5
Disk Blackbody Model			
n_H (10^{21} cm^{-2}) ^a	$0.9^{+0.2}_{-0.2}$	$0.4^{+1.0}_{-0.0}$	$0.4^{+0.7}_{-0.0}$
T_{in} (keV)	$1.11^{+0.09}_{-0.09}$	$0.46^{+0.06}_{-0.12}$	$0.81^{+0.10}_{-0.13}$
R_{in} (km) ^b	$47.0^{+7.9}_{-6.6}$	$60.1^{+75.5}_{-15.1}$	$45.7^{+20.4}_{-9.1}$
M/M_\odot	5.4	7.2	5.4
\dot{M} ($10^{-7} M_\odot \text{ yr}^{-1}$)	1.24	0.05	0.30
$L_{disk,bol}$ ($10^{37} \text{ erg s}^{-1}$)	85.4	4.52	23.7
χ^2/DOF^c	73.8/97	115.6/101	215.7/204
Power Law Model			
n_H (10^{21} cm^{-2})	$3.0^{+0.4}_{-0.4}$	$2.2^{+2.1}_{-1.8}$	$2.1^{+1.1}_{-1.0}$
Γ	$2.22^{+0.13}_{-0.13}$	$3.05^{+1.24}_{-1.15}$	$2.28^{+0.42}_{-0.40}$
χ^2/DOF^c	91.7/97	116.5/101	218.2/204

^aFixed at Galactic value for Observations 6 & 7

^bAssumes $\cos \theta \sim 1$

^cC-statistic/Number of data bins for Observations 6 & 7