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THE NATURE OF ULTRALUMINOUS X-RAY SOURCES IN NGC 4565

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ABSTRACT

We report the optical identifications of two X-ray–luminous point sources in the spiral galaxy NGC 4565 based on archive data of *Chandra* and the *Hubble Space Telescope*. The central X-ray point source, RX J1236.3+2559, is found to be the nucleus of NGC 4565 with an X-ray luminosity of $L_X \approx 4.3 \times 10^{39}$ ergs s^{-1}. We show that its multiband properties are consistent with its being a low-luminosity active galactic nucleus. A faint optical counterpart with $B \approx 25.1$ and $I \approx 24.0$ was identified for the off-nucleus X-ray point source, RX J1236.2+2558. Its extinction-corrected B magnitude is estimated to be 24.5. The X-ray–to–optical flux ratio (f_X/f_B) is about 540. From the optical and X-ray properties, we argue that RX J1236.2+2558 is an ultraluminous X-ray compact source with $L_X \approx 6.5 \times 10^{39}$ ergs s^{-1}. The source is probably located in a faint globular cluster at the outer edge of NGC 4565's bulge.

Subject headings: galaxies: individual (NGC 4565) — galaxies: nuclei — X-rays: galaxies

1. INTRODUCTION

Recent observations present new evidence for the existence of off-nuclear X-ray–luminous point sources in nearby spiral galaxies, starburst galaxies, and elliptical galaxies. X-ray luminosities of these sources are 10^{39}–10^{40} ergs s^{-1} in the 0.5–10 keV band, which are significantly larger than the Eddington luminosity of a 1 $M_\odot$ object and are intermediate between classic X-ray binaries (with $L_X \approx 10^{36}$–10^{38} ergs s^{-1}) and active galactic nuclei (AGNs) (with $L_X \gtrsim 10^{41}$ ergs s^{-1}). These X-ray–luminous, non-AGN, nonsupernova remnant compact objects have been called ultraluminous compact X-ray sources (ULXs) (Fabbiano 1989; Matsumoto et al. 2001; Makishima et al. 2000; Roberts et al. 2002; Sarazin, Irwin, & Bregman 2001 and references therein). The nature of ULXs is far from clear. Current models include intermediate-mass (≥ 50 $M_\odot$) black holes (Madau & Rees 2001) and significantly beamed binary systems (e.g., Körding, Falcke, & Markoff 2002; King et al. 2001 and references therein; for more, see § 4).

To understand the nature and origin of ULXs, it is important to explore their multiband properties and their environments. Given the superior spatial resolution of *Chandra*, it is possible to identify the optical counterparts of ULXs in nearby galaxies. Such studies are underway. The ULX in the nearby starburst galaxy M82 (J095550.2+694047) was proposed to be an intermediate-mass black hole (BH) (100–1000 $M_\odot$) in an intense starburst region, from *Chandra* and millimeter observations (Matsumoto et al. 2001; Matsushita et al. 2001). Recently, Roberts et al. (2001, 2002) found that two ULXs in NGC 5204 are located in cavities of emission-line gas nebulae, while six ULXs in the interacting pair galaxies NGC 4485 and NGC 4490 are located in star-forming regions. Wang (2002) also found that the ULX X-9 in M81 is related to a shell-like optical nebula in the tidal arm of M81. In another study, Liu, Bregman, & Seitzer (2001) found several optical counterparts of ULXs in M81, M51, and NGC 2403; these optical counterparts are all quite blue, with properties consistent with O stars. Most recently, Pakull & Mirioni (2002) reported their optical survey results for ULXs in 11 nearby galaxies. At the position of several ULXs, they found emission-line nebulae of a few hundred parsecs in diameter, which often show both low- and high-ionization emission lines. On the other hand, ULXs have also been found in globular clusters of giant elliptical galaxy NGC 1399 (Angelini, Loewenstein, & Mushotzky 2001). It is not yet clear whether ULXs located in globular clusters have different properties from those in star formation regions.

NGC 4565 is a nearby edge-on spiral galaxy of type Sb. It is at a distance of 10 Mpc based on surface brightness fluctuations and planetary nebulae (Jacoby, Ciardullo, & Harris 1996 and references therein). Its surface brightness profile has been extensively studied (Wu et al. 2002 and references therein). Using *ROSAT* and *ASCA* data, Mizuno et al. (1999) found two bright pointlike X-ray sources in the field of NGC 4565. The fainter one is positionally coincident with the nucleus of NGC 4565 and would normally be considered as a low-luminosity AGN. However, Mizuno et al. argued that it is a ULX instead because the neutral hydrogen column density determined from X-ray spectral fitting is too low for a central AGN. On the other hand, the brighter source is off-center and about 2 kpc above the galaxy disk if it is associated with NGC 4565. Spectral fittings of *ASCA* data show that a multicolor disk (MCD; see, e.g., Mitsuda et al. 1984) model provides the best fit for both sources, and their 0.5–10 keV luminosities are higher than 10^{39} ergs s^{-1}. Therefore, Mizuno et al. (1999) concluded that both sources are ULXs. However, because of its low spatial resolution, *ASCA* cannot separate these two X-ray–bright sources well, so their conclusion needs to be carefully verified.

In this paper, we present the optical identifications for these two X-ray point sources in NGC 4565 using the archive data from a *Chandra* snapshot survey and from the *Hubble Space Telescope* (*HST*) observations. The outline of the paper is as follows: In § 2, we briefly describe the obser-

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vational data we used and the data reduction; in § 3, we discuss the optical identification of the two X-ray–bright sources in NGC 4565 and their properties; in § 4, we summarize our results and further discuss the nature of these two point sources.

2. OBSERVATIONS AND DATA REDUCTION

The X-ray data for NGC 4565 are retrieved from the *Chandra* archive.[5] The data are from a *Chandra* snapshot survey for a volume-limited sample of 25 low-luminosity AGN candidates.[6] The survey was taken using the ACIS-S instrument on board the *Chandra X-Ray Observatory*. The observations of NGC 4565 were performed on 2000 June 30, with a total exposure time of about 2 ks. The data reduction was carried out using the *Chandra* software package, CIAO2.1, with the latest calibration database, CALDB2.8. Both X-ray–bright sources in NGC 4565 are clearly detected by *Chandra* ACIS-S3. The photon counts are 121 and 269 for the central (RX J1236.3+2559) and the off-center (RX J1236.2+2558) sources in a circular region of radius 2$''$.5 and 3$''$, respectively. Even under the subarcsecond resolution of *Chandra* ACIS-S, these two X-ray sources in NGC 4565 remain unresolved.

HST WFPC2 images in two bands (F450W and F814W) were retrieved using NED.[7] The total integration times of the F450W and F814W images are 600 and 480 s, respectively. More detailed information can be found in Kissler-Patig et al. (1999). To augment the *HST* observations, we also performed narrowband Hα imaging for NGC 4565 using the 2.16 m telescope and the 60/90 cm Schmidt telescope at the Xinglong Station of the National Astronomical Observations of the Chinese Academy of Sciences (NAOC) on 2001 May 18 and April 13, respectively. The central source (RX J1236.3+2559) was clearly detected in Hα. All the optical data reductions are performed using the IRAF package through standard procedures.

3. RESULTS

3.1. *Optical Identifications of Two Bright X-Ray Point Sources*

Figure 1 shows the *HST* WFPC2 F814W image of the bulge of NGC 4565. An image of the whole galaxy is shown in the bottom right inset. The bottom left and top right insets show the optical counterparts of the two *Chandra* X-ray–bright point sources. The pluses in the insets show the *Chandra* X-ray source positions. It is clear from Figure 1 that the optical nucleus and the off-center faint source are located within a 0$''$.5 error circle of the two *Chandra* bright point sources. To confirm the existence of the faint optical counterpart of RX J1236.2+2558, we carefully checked the six precombined *HST* images (three F450W and three F814W images) individually. The faint optical counterpart appears in all of the six images. Radio continuum observations at 6 and 20 cm by the Very Large Array (VLA)[8] for NGC 4565 detected the nuclear source (Ho & Ulvestad 2001). The positional accuracy of the radio observations is about 0$''$.1. The cross in the bottom left inset of Figure 1 shows the radio position of the nuclear source. Table 1 lists the positions of RX J1236.3+2559 and RX J1236.2+2558 determined by *HST*, *Chandra*, and VLA.

Notice that, in Table 1 the optical positions for both RX J1236.3+2559 and RX J1236.2+2558 are about 0$''$.3 north from the corresponding *Chandra* positions. Such a shift can arise because of the uncertainty in the absolute astrometry in both *HST* and *Chandra* coordinate systems. After correcting this shift, the *HST* and *Chandra* positions agree very well, with a relative positional error of about 0$''$.1.

3.2. *RX J1236.3+2559: A Low-Luminosity Active Galactic Nucleus in NGC 4565*

The high-resolution observations for NGC 4565 by *Chandra*, *HST*, and VLA accurately determine the positions of the nuclear source to about 0$''$.1 (corresponding to a physical scale of about 5 pc). These observations allow us to investigate the properties of RX J1236.3+2559 and to establish its physical nature.

The background-subtracted X-ray spectrum of RX J1236.3+2559 was extracted with an aperture of a radius of 2$''$.5, where we have determined the background using a local source-free annulus between radius 5$''$ and 15$''$. At the present flux level, the pileup fraction of the count rate for both X-ray sources is expected to be much less than 10%, so we ignored the pileup effect in our spectrum extraction. Not surprisingly, the small number of detected photons from the *Chandra* snapshot survey observation prevents us from discriminating different models for the X-ray spectra of RX J1236.3+2559. Indeed, both an absorbed power-law model and an absorbed multicolor disk blackbody (MCD) model provide an acceptable fit for the spectrum. The fitting parameters (including the χ^2 per degree of freedom) for both models are listed in Table 2; the top panel of Figure 2 shows the best absorbed power-law fit.

For the absorbed power-law model, the photon index is $\Gamma = 1.6$, with a neutral hydrogen column density of $N_{\rm H} = 1.1 \times 10^{21}$ cm^{-2}, which is consistent with the result of Mizuno et al. (1999), who obtained $N_{\rm H} \leq 2.0 \times 10^{21}$ from *ASCA* observations. As pointed out by Vogler, Pietsch, & Kahabka (1996), this value is below the H I column density of about 5×10^{21} cm^{-2} derived from an H I map of NGC 4565 at a resolution of 40$''$ (Rupen 1991). As NGC 4565 is an edge-on spiral galaxy, Mizuno et al. argued that the column density along the galaxy disk to the nucleus of NGC 4565 should be at least 1×10^{22} cm^{-2}. Based on this, they rejected the possibility of RX J1236.3+2559 being a low-luminosity AGN. Instead, they suggested that it is a ULX located at the near side of this disk galaxy.

However, this conclusion is uncertain because the interstellar medium is known to be clumpy, so the H I column density toward a particular line of sight can be lower or higher than the average value. So we carefully investigated the extinction in the nuclear region of NGC 4565 using the

[5] The *Chandra* Data Archive (CDA) is part of the *Chandra X-Ray Observatory* Science Center (CXC), which is operated for NASA by the Smithsonian Astrophysical Observatory.

[6] PI: Garmire, *Chandra* OBSID 404.

[7] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

[8] The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

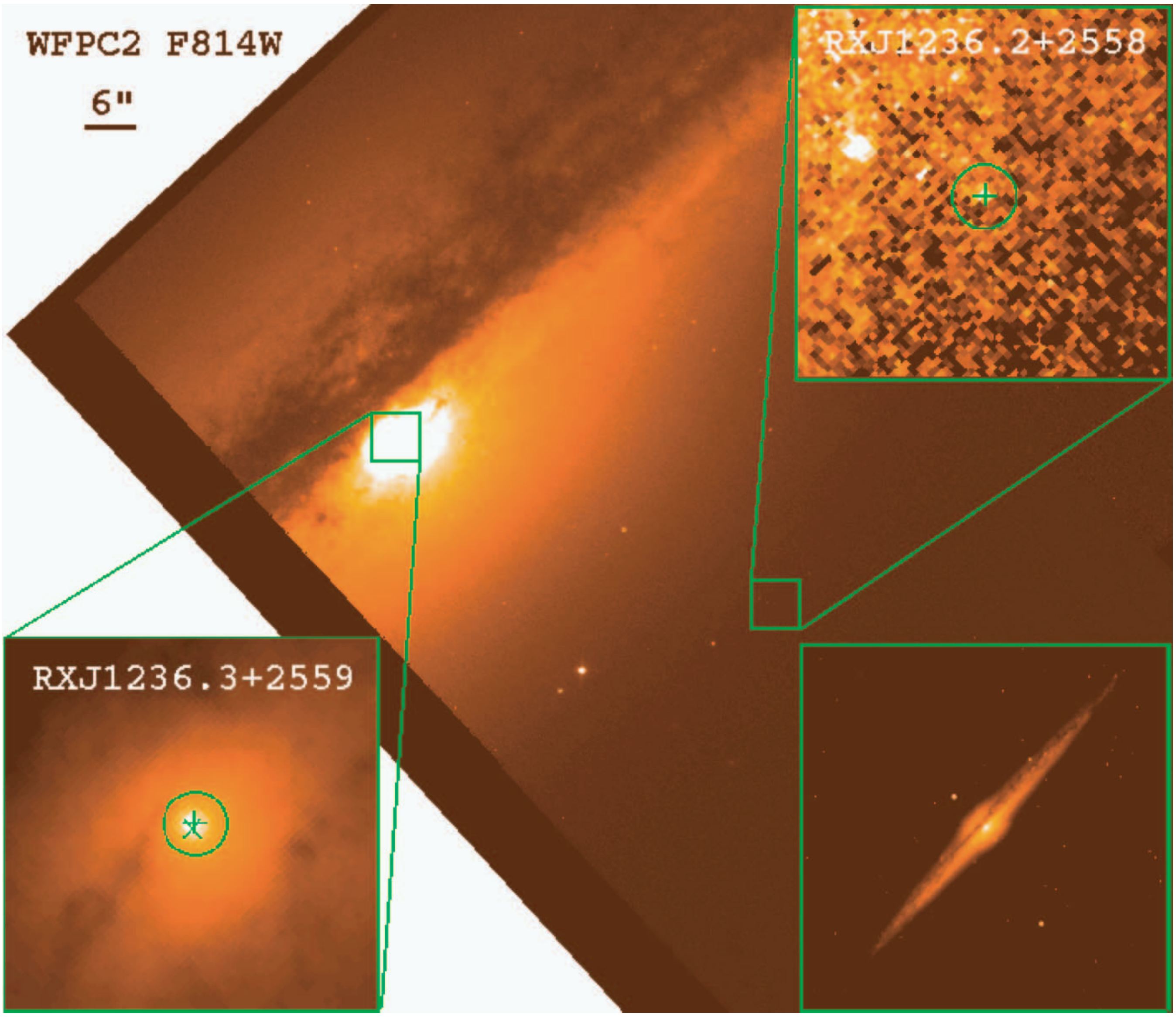

FIG. 1.—*HST* WFPC2 image of the bulge of NGC 4565 in the F814W filter. The positions of X-ray sources RX J1236.3+2559 and RX J1236.2+2558 are indicated by two boxes. The bottom left and top right insets present zoomed views of the nuclear X-ray source RX J1236.3+2559 and the off-center X-ray source RX J1236.2+2558; both are shown as a plus with an error circle of 0."5. The cross symbol is the 6 and 20 cm radio position from Ho & Ulvestad (2001). The coordinate system of the WFPC2 F814W image was shifted to match that of *Chandra*. From the zoomed images, we find that both X-ray sources have optical counterparts and that the position agreement between optical and X-ray sources is better than 0."1, within the absolute astrometric error of *Chandra* and *HST*. The bottom right inset shows the whole image of NGC 4565 from the 60/90 cm Schmidt telescope of NAOC.

TABLE 1

POSITIONS (IN J2000.0) FOR THE CENTRAL AND OFF-CENTER X-RAY POINT SOURCES FROM X-RAY (*Chandra*), OPTICAL (*HST*), AND RADIO (VLA) AT 6 AND 20 cm

	RX J1236.3+2559		RX J1236.2+2558	
POINT SOURCE	R.A.	Decl.	R.A.	Decl.
X-ray	12 36 20.779	25 59 15.74	12 36 17.402	25 58 55.44
Optical	12 36 20.785	25 59 16.04	12 36 17.404	25 58 55.80
Radio	12 36 20.781	25 59 15.64	...	...

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

color determined from the *HST* F814W and F450W images.

We find that the nucleus is located in a low-reddening area just outside the dust lane. Therefore, it seems plausible that the H I column density in the nucleus is lower than the value estimated from the low-resolution H I map. This leads us to postulate that the X-ray emission of RX J1236.3+2559 is from a low-luminosity AGN.

To further prove the low-luminosity AGN hypothesis for RX J1236.3+2559, we collected all the available multiband information for this source from the literature. The optical photometry is obtained from Kissler-Patig et al. (1999). The measured *I*- and *B*-band nuclear magnitudes with an aperture size of 0."5 are 17.2 and 19.5, respectively. The near-

TABLE 2

BEST-FIT SPECTRAL PARAMETERS FOR THE X-RAY SPECTRA OF THE CENTRAL AND OFF-CENTER SOURCES IN NGC 4565

Source (1)	Model (2)	Absorption (3)	T_{in} or Γ (4)	f(0.1–2.4 keV) (5)	f(0.5–10 keV) (6)	χ^2/dof (7)
Center	MCD	<1.6	$1.2^{+0.8}_{-0.4}$	$1.2^{+2.4}_{-0.2}$	$2.1^{+4.1}_{-0.5}$	15.4/18
	Power law	$1.1^{+1.0}_{-0.9}$	$1.6^{+0.4}_{-0.4}$	$2.1^{+0.4}_{-0.4}$	$3.6^{+0.6}_{-0.6}$	16.3/18
Off-center	MCD	<0.8	$1.1^{+0.4}_{-0.2}$	$2.9^{+4.3}_{-1.8}$	$5.4^{+7.3}_{-3.4}$	21.8/22
	Power law	$1.5^{+0.5}_{-0.3}$	$1.8^{+0.2}_{-0.2}$	$7.1^{+0.7}_{-0.7}$	$7.5^{+0.8}_{-0.8}$	20.2/22

NOTE.—Two models are presented: an absorbed multicolor disk model (MCD) and an absorbed power-law model. The absorption column density (col. [3]) is in units of 10^{21} cm^{-2}. Col. (4) indicates either the inner disk temperature (T_{in}) for the MCD model or the photon index for the power-law model. The absorption-corrected fluxes in the 0.1–2.4 keV and 0.5–10 keV bands are both in units of 10^{-13} ergs cm^{-2} s^{-1}. The error bars in the table are 90% confidence limits.

infrared *J*-, *H*-, and *K*-band photometry is from Rice et al. (1996). A 5″ aperture size was used for photometry in these three bands, and the measurements were transformed into flux densities. The 1.4–15 GHz radio data are from VLA observations by Nagar, Wilson, & Falcke (2001) and Ho & Ulvestad (2001) within an aperture size of about 0″.5. The ultraviolet data are from the *HST* Faint Object Camera (Maoz et al. 1996), which gives the integrated 2300 Å flux with an aperture of 22″ × 22″; this can only be considered as an upper limit of the nucleus flux because of the contribution from other stars in the bulge.

All these data are presented in Table 3, and the spectral energy distribution for the nucleus of NGC 4565 is shown in Figure 3. As a comparison, we also plotted the spectral energy distribution for the low-luminosity active galactic nucleus in M81 (*dotted line*) and NGC 4579 (*solid line*) from Ho (1999). As one can see, the spectral energy distribution of NGC 4565 from radio, to optical, to X-ray is quite similar to those of M81 and NGC 4579, although differences in the near-infrared bands exist. As mentioned above, because of the larger aperture adopted for the photometry of *J*, *H*, and *K* bands, their values can only be regarded as upper limits. As suggested by Ho (1999), the contamination from starlight in the near-infrared greatly exceeds those in other bands. The resemblance of the spectral energy distribution for the nucleus of NGC 4565 with those of low-luminosity AGNs is another piece of evidence that it is a low-luminosity AGN.

Furthermore, we studied the relation of Hα and X-ray emissions. The Hα flux for RX J1236.3+2559 is 2.4×10^{-14} ergs s^{-1} cm^{-2} within an aperture of radius 5″, which corresponds to an Hα luminosity of 2.8×10^{38} ergs s^{-1}. As the X-ray luminosity of nuclear source of NGC 4565 is 4.3×10^{39}

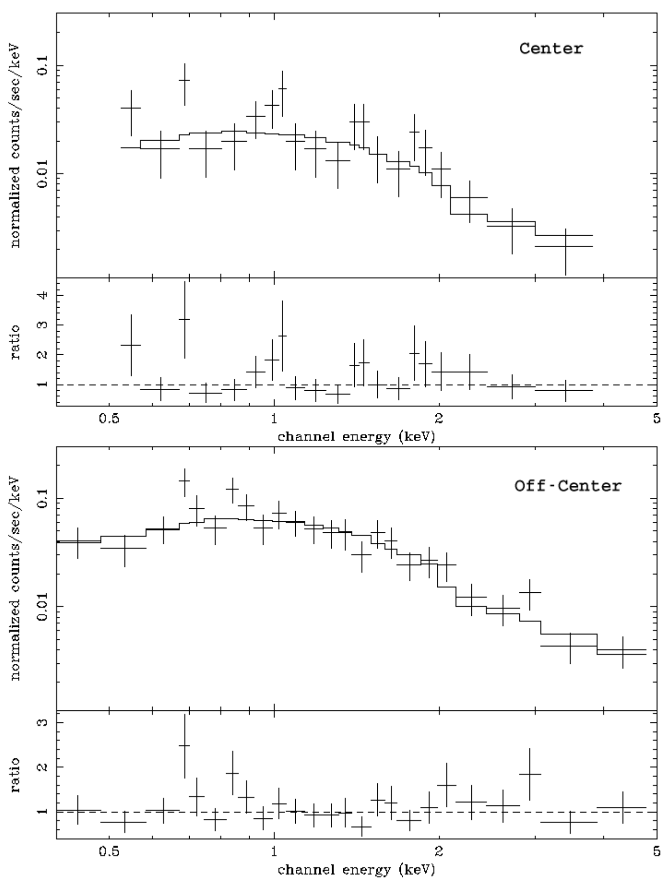

FIG. 2.—X-ray spectra for the nuclear source RX J1236.3+2559 (*top panel*) and the off-center source RX J1236.2+2558 (*bottom panel*) in NGC 4565. The spectrum of the nuclear source is fitted by an absorbed power law, and the off-nucleus source is fitted by an absorbed multicolor disk model. The fitting parameters are listed in Table 2.

TABLE 3

DATA FOR THE NUCLEUS OF NGC 4565

ν (Hz)	νf_ν (ergs s^{-1} cm^{-2})	Aperture (arcsec)	Reference
1.42×10^9	3.27×10^{-17}	0.5	1
4.86×10^9	1.31×10^{-16}	0.5	1
5.0×10^9	1.25×10^{-16}	0.5	2
8.4×10^9	2.10×10^{-16}	0.5	2
1.5×10^{10}	4.65×10^{-16}	0.5	2
2.97×10^{13}	$<2.55 \times 10^{-11}$	6.0	3
1.36×10^{14}	8.43×10^{-11}	5.0	4
1.82×10^{14}	1.93×10^{-10}	5.0	4
2.40×10^{14}	1.18×10^{-10}	5.0	4
3.75×10^{14}	2.50×10^{-12}	0.5	5
6.58×10^{14}	6.93×10^{-13}	0.5	5
1.30×10^{15}	$<3.00 \times 10^{-12}$	22	6
2.42×10^{17}	8.1×10^{-14}	2.5	7

REFERENCES.—(1) Ho & Ulvestad 2001; (2) Nagar et al. 2001; (3) Rieke & Lebofsy 1978; (4) measured from *J*, *H*, and *K* images (Rice et al. 1996); (5) measured from *HST* archive images (Kissler-Patig et al. 1999); (6) Maoz et al. 1996; (7) this paper.

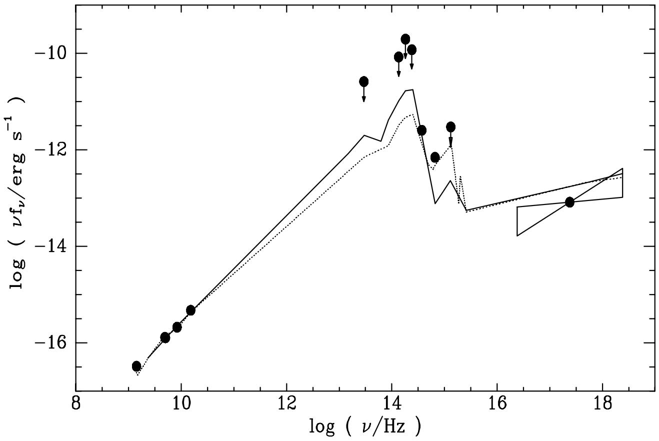

FIG. 3.—Spectral energy distribution for the nucleus of NGC 4565 (see Table 3). The solid and dotted lines are the spectral energy distributions for the nuclei of NGC 4579 and M81 from Ho (1999), respectively. For the purpose of comparison, the curves have been shifted downward by -1.0 and -1.5, respectively. Upper limits are indicated by points with arrows (see § 3.3.3).

ergs s^{-1}, the ratio of the X-ray luminosity to the Hα luminosity for NGC 4565 is 15.3, which is just the median ratio (15) for low-luminosity AGNs (Ho et al. 2001). Therefore, we conclude that RX J1236.3+2559 is a low-luminosity AGN.

3.3. *RX J1236.2+2558: A ULX in a Stellar Cluster*

3.3.1. *The Optical and X-Ray Properties of RX J1236.2+2558*

As shown in Figure 1, the bright X-ray point source RX J1236.2+2558 lies at the outskirts of the bulge of NGC 4565. Photometry measurement reveals that the optical counterpart of RX J1236.2+2558 is quite faint, with $B = 25.1 \pm 0.4$ and $I = 24.0 \pm 0.3$ within an aperture of 0''.5.

The X-ray spectrum was extracted with an aperture size of 3'' and with the local source-free background in an annulus subtracted. Both an absorbed power-law model and an absorbed MCD model can fit the spectrum. The bottom panel of Figure 2 shows the best MCD model spectrum of RX J1236.2+2558. All the fitting parameters are listed in Table 2. Based on the MCD model, and assuming RX J1236.2+2558 is in NGC 4565, the absorption-corrected soft X-ray (0.1–2.4 keV) luminosity of RX J1236.2+2558 is $\approx 3.5 \times 10^{39}$ ergs s^{-1}. It coincides with 3.2×10^{39} ergs s^{-1} from the *ROSAT* Position Sensitive Proportional Counter observation (Vogler et al. 1996). The absorption-corrected X-ray luminosity in the 0.5–10 keV band is $\approx 6.5 \times 10^{39}$ ergs s^{-1}, which is about one-third of the value 2.3×10^{40} ergs s^{-1} obtained using the *ASCA* data (Mizuno et al. 1999). In comparison, the luminosity for the central source in the *ASCA* data is about twice of that in the *Chandra* data. So there is some evidence that both the nucleus and the off-center source are variable, although the variability needs to be established more carefully, as the spatial resolution of *ASCA* is insufficient to resolve these two sources.

Taking into account the extinction correction of A_B as 0.6 (see § 3.3.2), the B magnitude of RX J1236.2+2558 is 24.5, which implies an X-ray–to–optical flux ratio (f_X/f_B) of about 540. This value is similar to that of the brightest ULX in M82 (Stocke, Wurtz, & Kühr 1991).

3.3.2. *Is RX J1236.2+2558 a Foreground or Background Object?*

If we assume the optical counterpart of RX J1236.2+2558 is a foreground star in Milky Way, it would be an F-type star according to its color. Then, its optical luminosity implies a distance of 100 kpc, which is at the edge of the halo of our Galaxy. More importantly, the high X-ray–to–optical flux ratio of RX J1236.2+2558 is outside the observed range (10^{-4} to 10^{-1}) for normal B- to M-type stars, where the X-ray emission arises from a hot corona (Maccacaro al. 1988). The value is also outside the range (0.1–10) for cataclysmic variables (Bradt & McClintock 1983). Only low-mass X-ray binary systems (LMXBs) could reach such a high ratio. From Bradt & McClintock (1983), most LMXBs with high X-ray–to–optical flux ratios are distributed close to the Galactic disk. The high Galactic latitude location (86°.44) of the source disfavors this association. Furthermore, as Mizuno et al. (1999) pointed out, the *ASCA* spectrum of RX J1236.2+2558 is softer than those of LMXBs, and hence the possibility that RX J1236.2+2558 is a LMXB can be ruled out. Therefore, the optical counterpart of RX J1236.2+2558 is unlikely to be an object in the Milky Way.

On the other hand, if RX J1236.2+2558 is a background extragalactic source, then the object can only be a BL Lac object from its very high X-ray–to–optical flux ratio. However, the ratio for BL Lac objects is still about 1 order of magnitude lower than that of the off-center source (Maccacaro et al. 1988). We emphasize that the observed f_X/f_B cannot be made compatible with those of BL Lac objects through extinction, as it requires $A_B \approx 3$ mag. Such a high extinction is inconsistent with $A_B \approx 0.6$ mag, estimated using $N_H/E(B-V) = 5.8 \times 10^{21}$ cm^{-2} (Bohlin, Savage, & Drake 1978) and $A_B = 4E(B-V)$ for $N_H \approx 0.8 \times 10^{21}$ cm^{-2} (appropriate for the MCD model, Table 2). In addition, no radio emission has been detected at the position of RX J1236.2+2558 by VLA (Ho & Ulvested 2001). Therefore, RX J1236.2+2558 is unlikely to be a background BL Lac object. Combining all the evidence, we conclude that RX J1236.2+2558 is probably not a background extragalactic object.

3.3.3. *A ULX in NGC 4565*

Given that RX J1236.2+2558 is neither a foreground star nor a background AGN, we are left with only one possibility, i.e., this source is an X-ray–luminous point source in NGC 4565. The X-ray luminosity in the 0.5–10 keV band is 6.5×10^{39} ergs s^{-1}, placing it in the category of ULXs in a nearby normal spiral galaxy.

At a distance of 10 Mpc, the faint optical counterpart of RX J1236.2+2558 has $M_B = -4.9$ and a color index of $B-I \approx 1.1 \pm 0.5$; both numbers have not been corrected for reddening. Candidates for pointlike objects with $B \approx -5.0$ are only O stars (with type later than O7) or globular clusters. However, the optical counterpart of RX J1236.2+2558 is very unlikely to be an O star as such stars have much bluer colors ($B-I \approx -0.8$ instead of $B-I \approx 1.1$, as observed); the conclusion is unchanged even if we allow reddening ($A_B \approx 0.6$). Moreover, we do not expect an O star in the outer region of the bulge. Similarly, the object is unlikely to be a very compact star formation region, as these are usually found close to galactic disks. Another possibility is that the optical counterpart is associated with a dwarf galaxy. Its color is consistent with that of some dwarf galaxies in the local group; however, its luminosity and size are both too small, compared with those of dwarf galaxies (e.g., Table 4 in Mateo 1998). One speculative scenario may be that the optical counterpart is the core of a tidally stripped dwarf galaxy with the AGN activity triggered by the tidal interaction.

Overall, we favor the interpretation that the optical counterpart of ULX RX J1236.2+2558 is probably a globular cluster. It is interesting to compare the color and absolute magnitude of this counterpart with those of globular clusters. Most globular clusters have colors redder than $B-I = 1.4$ (see Fig. 3 in Kissler-Patig et al. 1999). The color of the object is $B-I = 1.1$, which is quite blue. However, with the large error bar ($\approx$0.5 mag) caused by its faintness, its color is still consistent with being at the blue tail of the color distribution for globular clusters. The *B*-band absolute magnitude of globular clusters is known to follow a roughly (universal) Gaussian distribution with a mean of $M_B = -7.1$ and a standard deviation of 1.1 mag. The extinction-corrected absolute magnitude with $M_B = -5.5 \pm 0.4$ of the optical counterpart for RX J1236.2+2558 is consistent with being at the faint end of the luminosity function (see Fig. 5 in Della Valle et al. 1998 and references therein). We conclude that the off-center X-ray source is hosted by a globular cluster. We discuss the implication of this association in more detail in § 4.

4. SUMMARY AND DISCUSSION

In this paper, we have shown that, from multiband observations in the optical, radio, and X-ray, the central X-ray source in NGC 4565 is entirely consistent with it being a low-luminosity AGN. We also argued that the off-center X-ray point source is a ULX and its optical counterpart is a globular cluster, as inferred from its color and absolute magnitude.

Typical globular clusters in our galaxy have X-ray luminosities ranging up to 5×10^{37} ergs s^{-1} (Ghosh et al. 2001). There are no globular clusters with X-ray luminosities above 10^{38} ergs s^{-1} in M31 (Supper et al. 1997). NGC 4565 is an Sb galaxy similar to our galaxy, but it seems to host a globular cluster that is about 2 orders of magnitude more luminous in the X-ray than those found in the Galaxy and M31. It is not clear what determines the upper cutoff in the X-ray luminosity function of globular clusters in disk galaxies. In this regard, the upper cutoff in NGC 4565 is similar to those seen in two elliptical galaxies, NGC 4697 and NGC 1399 (Sarazin et al. 2001; Angelini et al. 2001). For example, Angelini et al. (2001) found two of the three brightest point sources in NGC 1399 (with $L_X \approx 5 \times 10^{39}$ ergs s^{-1}) are hosted by globular clusters. At present, it is not known whether the extreme X-ray luminosity is a sum of many LMXBs or it is produced by an intermediate-mass black hole. Angelini et al. (2001) argued that the spectra of the two most luminous X-ray globular clusters are consistent with those seen in either high- or low-state black holes in our Galaxy.

The formation and evolution of ULXs is still an unsolved problem. Models proposed so far can be classified into two categories, i.e., unbeamed models and beamed models. The beamed models suggest that ULXs represent a short-lived phase in their evolution and are associated with young stellar populations, as observed for many ULXs (see Introduction). However, for RX J1236.2+2558, this model does not work, as it is apparently in a globular cluster. The unbeamed models, on the other hand, require an intermediate-mass BH ($\geq$100 $M_\odot$) in a binary with an evolved donor star (King et al. 2001). However, the formation of such systems is uncertain. An intermediate- and high-mass BH could be formed either through the merger of lower mass BHs in dense clusters or from early generation of zero-metallicity stars (so-called Population III stars; Madau & Rees 2001). It is also possible that $\geq$50 $M_\odot$ Population III BHs could form during the formation of globular clusters; they will then sink to the center of the cluster quickly and grow to $\sim 10^3$ $M_\odot$ by accretion in the cluster's lifetime (Miller & Hamilton 2002). However, moderate-mass BHs may be difficult to retain in off-nuclear star clusters such as RX J1236.2+2558 because of the shallow potential well of globular clusters (see Miller & Hamilton 2002 and references therein).

No matter what the origin of ULXs, it is important to further study them in multiple bands. Extreme objects like RX J1236.2+2558 offer ideal targets for such studies. As the exposure times for *Chandra* (2 ks) and *HST* ($\sim$500 s) are both quite short for RX J1236.2+2558, it is important to obtain deeper images in both wave bands. Optical observations with *HST* (particularly with the Advanced Camera for Surveys) will be useful to establish the color and the spatial extent of the optical counterpart. On the other hand, deeper integrations of *Chandra* will be useful to firmly establish the spectral behavior of the off-center ULX and its variability. The X-ray observations may also be used to probe the X-ray corona seen in some edge-on galaxies (e.g., NGC 4631; Wang et al. 2001). These observations are important for further understanding the nature of ULXs, and the question of why some disk galaxies have ULXs while others (like the Milky Way and M31) have none.

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