The nature of ultra-luminous 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, RXJ1236.3+2559, is found to be the nucleus of NGC 4565 with an X-ray luminosity of $L_x \approx 4.3 \times 10^{39}$ erg s$^{-1}$. We show that its multi-waveband properties are consistent with it 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, RXJ1236.2+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 RXJ1236.2+2558 is an ultra-luminous X-ray compact source with $L_x \approx 6.5 \times 10^{39}$ erg 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 (NGC4565) – 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 of $10^{39} - 10^{40}$ erg s$^{-1}$ in the 0.5-10 keV band, which are significantly larger than the Eddington luminosity of a $1M_\odot$ object and are intermediate between classic X-ray binaries (with $L_x \approx 10^{36} - 10^{38}$ erg s$^{-1}$) and active galactic nuclei (with $L_x \approx 10^{41}$ erg s$^{-1}$). These X-ray luminous, non-AGN, non-supernova remnant compact objects have been called ultra-luminous 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

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include intermediate-mass ($\geq 50 M_\odot$) black holes (Madau & Rees 2001) and significantly beamed binary systems (King et al. 2001 and references therein; for more, see the discussion).

To understand the nature and origin of ULXs, it is important to explore their multi-wavelength 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 (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 NGC4485/4490 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 NGC2403; 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 et al. 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 point-like 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 active galactic nucleus (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 multi-color disk (MCD) model provides the best fit for both sources and their 0.5-10 keV luminosities are higher than $10^{39}$ erg s$^{-1}$. Therefore, Mizuno et al. (1999) concluded that both sources are ULXs. However, due to 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 following. In §2, we briefly describe the observational 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 active galactic nuclei 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 June 30, 2000 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 (RXJ1236.3+2559) and the off-center (RXJ1236.2+2558) sources in a circular region of radius 2.5" and 3", respectively. Even under the sub-arcsecond 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 600s and 480s, respectively. More detailed information can be found in Kissler-Patig et al. (1999). To augment the HST observations, we also performed narrow band H\(\alpha\) imaging for NGC 4565 using the 2.16m telescope and the 60/90cm Schmidt telescopes at the Xinglong Station of NAOC on May 18, 2001 and April 13, 2001, respectively. The Central source (RXJ1236.3+2559) was clearly detected in H\(\alpha\). 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

Fig. 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 Fig. 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 RXJ1236.2+2558, we carefully checked the six pre-combined HST images (three F450W and three F814W images) individually. The faint optical counterpart appears in all of the six images. Radio continuum observations at 6cm and 20cm by the Very Large Array (VLA) for NGC 4565 detected the nuclear source (Ho & Ulvestad 2001). The positional accuracy

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\(^5\)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

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\(^7\)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
of the radio observations is about 0.1″. The cross in the bottom-left inset of Fig. 1 shows the radio position of the nuclear source. Table 1 lists the positions of RXJ1236.3+2559 and RXJ1236.2+2558 determined by HST, Chandra and VLA.

Notice that, in Table 1 the optical positions for both RXJ1236.3+2559 and RXJ1236.2+2558 are about 0.3″ north from the corresponding Chandra positions. Such a shift can arise due to 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. RXJ1236.3+2559: a low-luminosity active galactic nucleus in NGC 4565

The high resolution observations for NGC 4565 by Chandra, HST and VLA determine accurately 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 RXJ1236.3+2559 and establish its physical nature.

The background-subtracted X-ray spectrum of RXJ1236.3+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″. 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 RXJ1236.3+2559. Indeed, both an absorbed power-law model and an absorbed multi-color disk blackbody (MCD) model provide an acceptable fit for the spectrum. The fitting parameters (including the $\chi^2$ 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 $N_H = 1.1 \times 10^{21}$ cm$^{-2}$, which is consistent with the result of Mizuno et al. (1999) who obtained $N_H \leq 2.0 \times 10^{21}$ from ASCA observations. As pointed out by Vogler, Pietsch, & Kahabka (1996), this value is below the HI column density of about $5 \times 10^{21}$ cm$^{-2}$ derived from an HI 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 $1 \times 10^{22}$ cm$^{-2}$. Based on this, they rejected the possibility of RXJ1236.3+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 HI 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 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 HI column density in the nucleus is lower than the value estimated
from the low resolution HI map. This leads us to postulate that the X-ray emission of RXJ1236.3+2559 is from a low-luminosity AGN.

To further prove the low-luminosity AGN hypothesis for RXJ1236.3+2559, we collected all the available multi-waveband 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-infrared J, H and K bands photometry are from Rice et al. (1996). A 5″ aperture size were used for photometry in these three bands and the measurements were transformed into flux densities. The 1.4GHz–15GHz 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 2300Å flux with an aperture of 22″ × 22″; this can only be considered as an upper limit of the nucleus flux due to 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 Fig. 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, optical to X-ray is quite similar to those of M81 and NGC 4579, though differences in the near infrared bands exist. As mentioned above, due to 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 active galactic nucleus.

Furthermore, we studied the relation of Hα and X-ray emissions. The Hα flux for RXJ1236.3+2559 is $2.4 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ within an aperture of radius 5″ which corresponds to an Hα luminosity of $2.8 \times 10^{38}$ erg s$^{-1}$. As the X-ray luminosity of nuclear source of NGC 4565 is $4.3 \times 10^{39}$ erg 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 RXJ1236.3+2559 is a low-luminosity AGN.

### 3.3. RXJ1236.2+2558: a ULX in a Stellar Cluster

#### 3.3.1. The Optical and X-ray Properties of RXJ1236.2+2558

As shown in Fig. 1, the bright X-ray point source RXJ1236.2+2558 lies at the outskirts of the bulge of NGC 4565. Photometry measurement reveals that the optical counterpart of RXJ1236.2+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 Fig. 2 shows the best MCD model spectrum of RXJ1236.2+2558. All the fitting parameters are listed in Table 2. Based on the MCD model and assuming RXJ1236.2+2558 is in NGC 4565, the absorption-corrected soft X-ray (0.1-2.4 keV) luminosity of RXJ1236.2+2558 is \( \approx 3.5 \times 10^{39} \) erg cm\(^{-2}\) s\(^{-1}\). It coincides with \( 3.2 \times 10^{39} \) erg cm\(^{-2}\) s\(^{-1}\) from the ROSAT PSPC observation (Vogler, Pietsch, & Kahabka 1996). The absorption-corrected X-ray luminosity in the 0.5-10 keV band is \( \approx 6.5 \times 10^{39} \) erg cm\(^{-2}\) s\(^{-1}\), which is about one third of the value \( 2.3 \times 10^{40} \) erg cm\(^{-2}\) 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 section 3.3.2), the B magnitude of RXJ1236.2+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 RXJ1236.2+2558 a Foreground or Background Object?

If we assume the optical counterpart of RXJ1236.2+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 RXJ1236.2+2558 is outside the observed range \( (10^{-4} - 10^{-1}) \) 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-latitude location of the source disfavors this association. Furthermore, as Mizuno et al. (1999) pointed out, the ASCA spectrum of RXJ1236.2+2558 is softer than those of LMXBs and hence the possibility that RXJ1236.2+2558 is a LMXB can be ruled out. Therefore, the optical counterpart of RXJ1236.2+2558 is unlikely to be an object in the Milky Way.

On the other hand, if RXJ1236.2+2558 is a background extra-galactic 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 one 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 Lacs 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 RXJ1236.2+2558 by VLA (Ho & Ulvested 2001). Therefore, RXJ1236.2+2558 is unlikely to be a background BL Lac object. Combining all the evidence, we conclude that RXJ1236.2+2558 is probably not a background extra-galactic object.

3.3.3. A ULX in NGC 4565

Given that RXJ1236.2+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 $6.5 \times 10^{39}$ erg 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 RXJ1236.2+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 point-like objects with $B \approx -5.0$ are only O stars (with type later than O7) or globular clusters. However, the optical counterpart of RXJ1236.2+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.

Therefore, the optical counterpart of ULX RXJ1236.2+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) due to 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 roughly a (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 RXJ1236.2+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 the next section.

4. Summary and Discussion

In this paper, we have shown that, from multi-waveband 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 $5 \times 10^{37} \text{erg s}^{-1}$ (Ghosh et al. 2001). There are no globular clusters with X-ray luminosities above $10^{38} \text{erg s}^{-1}$ in M 31 (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 two orders of magnitude more luminous in the X-ray that 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, Irwin & Bregman 2001; Angelini, Loewenstein & Mushotzky 2001). For example, Angelini et al. found two of the three brightest point sources in NGC 1399 (with $L_x \approx 5 \times 10^{39} \text{erg s}^{-1}$) 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. argued that the spectra of the two most luminous X-ray globular clusters are consistent with those seen in either high-state or low-state black holes.

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 the introduction). However, for RXJ1236.2+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 BHs 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 and 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 2001). However, moderate-mass BHs may be difficult to retain in off-nuclear star clusters such as RXJ1236.2+2558 due to the shallow potential well of globular clusters (Miller & Hamilton 2001 and references therein).

No matter what is the origin of ULXs, it is important to further study them in multi-wavebands. Extreme objects like RXJ1236.2+2558 offer ideal targets for such studies. As the exposure times for Chandra (2 ks) and HST ($\sim 500$) are both quite short for RXJ1236.2+2558, it is important to obtain deeper images in both wavebands. 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., NGC4631, Wang et al. 2001). These observations are important for further understanding the nature of ULXs, and the puzzle why some disk galaxies have ULXs while others (like the Milky Way and M31) have none.
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Table 1: Positions (in J2000) for the central and off-center X-ray point sources from X-ray (Chandra), optical (HST) and radio (VLA) at 6cm and 20cm

<table>
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<th>RXJ1236.2+2558</th>
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<td></td>
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Table 2: Best-fit spectral parameters for the X-ray spectra of the central and off-center sources in NGC 4565. Two models are presented, an absorbed multi-color disk model (MCD) and an absorbed power-law model. The absorption column density (third column) is in units of $10^{21}$ cm$^{-2}$. The fourth column indicates either the inner-disk temperature ($T_{\text{in}}$) 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 $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

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<th>Source</th>
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<th>$T_{\text{in}}$ or $\Gamma$</th>
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<th>f(0.5-10 keV)</th>
<th>$\chi^2$/dof</th>
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<td>MCD</td>
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<td>$3.6^{+0.6}_{-0.6}$</td>
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Table 3: Data for the nucleus of NGC 4565

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<th>$\nu f_\nu$ (erg s$^{-1}$ cm$^{-2}$)</th>
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</tr>
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<tr>
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Fig. 1.— HST WFPC2 image of the bulge of NGC 4565 in the F814W filter. The positions of X-ray sources RXJ1236.3+2559 and RXJ1236.2+2558 are indicated by two boxes. The bottom-left and top-right insets present zoomed views of the nuclear X-ray source RXJ1236.3+2559 and the off-center X-ray source RXJ1236.2+2558; both are shown as a plus with an error circle of 0.5″. The cross symbol is the 6cm and 20cm 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 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 60/90cm Schmidt telescope of NAOC.
Fig. 2.— X-ray spectra for the nuclear source RXJ 1236.3+2559 (upper panel) and the off-center source RXJ 1236.2+2558 (lower 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 multi-color disk model. The fitting parameters are listed in Table 2.
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 the text in §3.3.3).