

## The X-ray nature of the nucleus in Seyfert 2 galaxy NGC 7590 \*

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Received 2011 November 5; accepted 2012 March 12

**Abstract** We present the results of the *Chandra* high-resolution observation of the Seyfert 2 galaxy NGC 7590. This object was reported to show no X-ray absorption in the low-spatial resolution *ASCA* data. The *XMM-Newton* observations show that the X-ray emission of NGC 7590 is dominated by an off-nuclear ultra-luminous X-ray source (ULX) and extended emissions from the host galaxy, and the nucleus is rather weak, likely hosting a Compton-thick AGN. Our recent *Chandra* observation of NGC 7590 enables us to effectively remove the X-ray contamination from the ULX and the extended component. The nuclear source remains undetected at the flux level of  $\sim 4 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>. Although not detected, the *Chandra* data give a 2–10 keV flux upper limit of  $\sim 6.1 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup> (at a  $3\sigma$  level), a factor of three less than the *XMM-Newton* value, strongly supporting the Compton-thick nature of the nucleus. In addition, we detected five off-nuclear X-ray point sources within the galaxy's  $D_{25}$  ellipse, all with 2–10 keV luminosity above  $2 \times 10^{38}$  erg s<sup>-1</sup> (assuming the distance of NGC 7590). In particular, the ULX previously identified by *ROSAT* data is resolved by *Chandra* into two distinct X-ray sources. Our analysis highlights the importance of high spatial resolution images in discovering and studying ULXs.

**Key words:** galaxies: active — galaxies: individual (NGC 7590) — galaxies: nuclei — X-rays: galaxies

### 1 INTRODUCTION

According to the current unification model for active galactic nuclei (AGNs), Seyfert 1 (Sy1) and Seyfert 2 (Sy2) galaxies are intrinsically the same type of object, and their observational differences are caused by orientation effects (Antonucci 1993). In an Sy2 nucleus, the broad line region (BLR) is blocked by an optically thick torus along the line of sight, so that no optical broad emission lines (BELs) are directly visible. The discovery of hidden BELs in many Sy2s from both near-IR spectroscopic and optical spectropolarimetric observations has given much support to this picture (Veilleux et al. 1997; Moran et al. 2000; Tran 2001; Shu et al. 2007, 2008). Further support for the unification model comes from the X-ray observations, showing that the column densities in Sy2s are typically above  $10^{23}$  cm<sup>-2</sup> (see e.g. Risaliti et al. 1999), much higher than those of Sy1s.

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\* Supported by the National Natural Science Foundation of China.

However, recent observations have also questioned the applicability of the unification model to all AGN populations, finding that there exists a subset of “unobscured” Sy2s that show little to no X-ray absorption ( $N_{\text{H}} < 10^{22} \text{ cm}^{-2}$ , Pappa et al. 2001; Panessa & Bassani 2002; Barcons et al. 2003; Wolter et al. 2005; Gliozzi et al. 2007). The peculiar X-ray spectra of these “unobscured” Sy2s could be explained by the absence of a BLR, where their appearance as Sy2s is intrinsic and not a result of the X-ray absorption (Nicastro et al. 2003; Georgantopoulos & Zezas 2003; Bianchi et al. 2008; Panessa et al. 2009; Tran et al. 2011). Alternatively, the appearance of the X-ray spectra of these “unobscured” Sy2s could be due to an extremely high dust-to-gas ratio compared to the Galactic value (see Huang et al. 2011).

However, one has to be cautious in identifying the candidates of the “unobscured” Sy2s, since their type 2 classification may be uncertain due to the insufficient quality of optical spectroscopy (e.g. Panessa et al. 2009; Gliozzi et al. 2010). On the other hand, some of the Sy2s that appear to lack the X-ray absorption may indeed be Compton-thick. In such sources where the intrinsic absorption is so high ( $N_{\text{H}} > 10^{24} \text{ cm}^{-2}$ ) that the direct component below 10 keV is completely absorbed, the *unabsorbed* scattered component or the extended emission from the host galaxy would dominate the observed spectrum in the 2–10 keV band (see e.g., Pappa et al. 2001). Brightman & Nandra (2008) presented a detailed spectral analysis of six unabsorbed Sy2 candidates, and found that four of them are in fact heavily obscured. Furthermore, Shi et al. (2010) presented a multi-wavelength study of a sample of “unobscured” Sy2 galaxies, and found that most of them are actually intermediate-type AGNs with weak BELs or Compton-thick sources.

Recently, with three *XMM-Newton* observations we carried out a preliminary X-ray study of NGC 7590, an Sy2 previously identified to be unabsorbed in the X-ray (Shu et al. 2010, hereafter Paper I). We found that the X-ray emission of NGC 7590 is dominated by an off-nuclear ultra-luminous X-ray source (ULX) and extended emissions from the host galaxy. The small ratio of the 2–10 keV to the [O III] fluxes suggests that this galaxy is likely Compton-thick rather than X-ray “unobscured” as previously believed. However, due to the contamination from the ULX and the extended component, we are unable to isolate the nuclear X-ray emission from NGC 7590. In this paper, we investigate the X-ray nature of the nucleus in NGC 7590, using data from higher spatial resolution *Chandra* observations. The new *Chandra* data have enabled a clear view of the true nuclear emission. Although not detected, the upper limit of the derived flux in the range 2–10 keV is a factor of three less than that measured by the *XMM-Newton*, confirming the Compton-thick nature of the NGC 7590 nucleus.

## 2 OBSERVATIONS

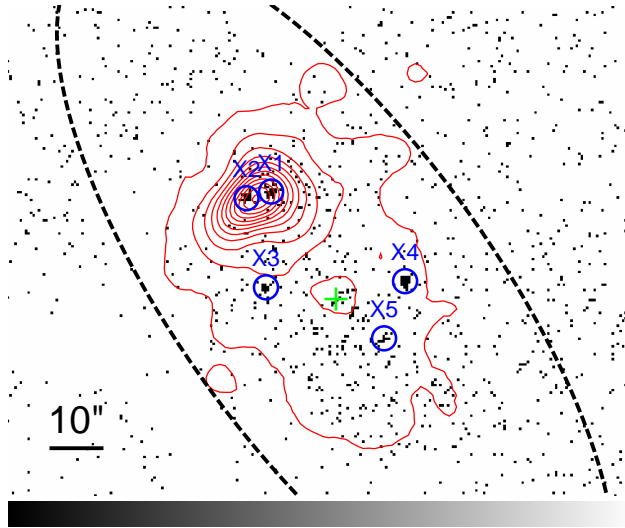
NGC 7590 was observed by *Chandra* on 2010 August 22 (observation ID 12240, PI: Shu) for an exposure of 30 ks, using the front-illuminated chips of the Advanced CCD Imaging Spectrometer (ACIS-I). The galaxy was placed at the aimpoint of the I3 chip, which provides a spatial resolution of  $0.492''$ . The field of view in this mode covers the whole galaxy (encompassing the full  $D_{25}$ <sup>1</sup> area of the galaxy). The data were processed with CIAO (version 4.3) and CALDB (version 4.4.1), following standard criteria. Level 2 event lists were reprocessed with observation-specific bad pixel files. The CIAO task *wavedetect* was run to determine the detections of the X-ray source candidates and the resulting source positions were used for the following spectral extraction.

## 3 DATA ANALYSIS

### 3.1 Imaging

There are five sources in total detected by *Chandra* inside the galaxy’s  $D_{25}$  ellipse. The detected sources, together with the *XMM-Newton* X-ray contours, are shown in Figure 1. The dashed line

<sup>1</sup>  $D_{25}$  is the apparent major isophotal diameter measured at the surface brightness level of  $\mu_B=25.0 \text{ mag arcsec}^{-2}$ .



**Fig. 1** *Chandra* image of NGC 7590 with the *XMM-Newton* X-ray contours (*red*) overlaid. The plus marks the optical nucleus of the galaxy. The blue circles correspond to five X-ray sources detected by *Chandra* inside the galaxy's  $D_{25}$  ellipse (*the black dashed line*). Thanks to its sub-arcsecond spatial resolution, *Chandra* clearly reveals two closely-spaced X-ray sources (X1 and X2), which were not resolved with the *XMM-Newton* images.

represents the  $D_{25}$  ellipse of NGC 7590, while the plus represents the position of the galaxy's optical nucleus. As can be seen from Figure 1, the nuclear source is not detected by *Chandra* which has a  $3\sigma$  upper limit for counts of 20.6, calculated following Gehrels (1986) for Poisson statistics. It is interesting to note that the brightest point source, which was detected by *XMM-Newton* about  $25''$  away from the galaxy's nucleus (also originally identified in the *ROSAT* All-Sky Survey as a ULX, see Colbert & Ptak 2002), was resolved into two sources, X1 and X2, with the high resolution *Chandra* image.

The details of all the sources above are given in Table 1. In addition to the source name and the equatorial coordinates (J2000.0), we give the counts, absorbed flux, and luminosity (all in the 2–10 keV band) in columns (3), (4) and (5), respectively. For X1, X2 and X4, source counts were extracted from a circular aperture centered on the detected source position, with a radius of 4.67 pixels (or  $2.3''$ , 1.3 times the on-axis 95% encircled energy radius at 1.5 keV on ACIS-I). Background counts were taken from an annulus with an inner radius of twice (or 3 times for X1 and X2), and

**Table 1** The Nucleus of NGC 7590 and the Detected X-ray Sources

Name	Equatorial Coordinates (J2000)	Net Counts	$F_{2-10\text{keV}}$ ( $10^{-14}$ erg cm $^{-2}$ s $^{-1}$ )	$L_{2-10\text{keV}}$ ( $10^{39}$ erg s $^{-1}$ )
Nucleus	23 18 54.8, -42 14 21	< 20.6	< 0.61	< 0.37
X1	23 18 55.9, -42 14 00	$77.5 \pm 8.9$	$2.8^{+1.3}_{-0.8}$	$1.7^{+0.8}_{-0.5}$
X2	23 18 56.5, -42 14 01	$32.4 \pm 5.8$	$0.86^{+0.78}_{-0.20}$	$0.53^{+0.41}_{-0.13}$
X3	23 18 56.0, -42 14 18	$17.2 \pm 4.4$	$0.47^{\dagger}$	$0.28^{\dagger}$
X4	23 18 53.6, -42 14 17	$61.0 \pm 7.9$	$1.11^{+0.63}_{-0.47}$	$0.68^{+0.35}_{-0.31}$
X5	23 18 54.0, -42 14 28	$16.3 \pm 4.5$	$0.44^{\dagger}$	$0.27^{\dagger}$

$\dagger$ : The flux and luminosity are estimated by assuming a power-law spectrum with  $\Gamma = 1.9$  (see Sect. 3.1 for details).

an outer radius of 3.5 times (or 5.5 times for X1 and X2) the source circle radius, avoiding the nearby point sources that could fall within the annulus. For the remaining two off-nuclear sources, X3 and X5, which did not have enough counts (less than 20 counts) for a meaningful spectral fitting, we performed a conversion from count rate to flux assuming a power-law spectrum of  $\Gamma = 1.9$ , consistent with the spectrum of low-mass X-ray binaries in nearby galaxies (see e.g. Prestwich et al. 2003).

### 3.2 Spectroscopy

Using the extraction radius mentioned above, we obtained spectra for the three brightest sources (X1, X2 and X4) for which it is possible to perform spectral analysis. The spectra were then grouped to have at least one count per bin, and the method of  $C$ -statistics (Cash 1979) was adopted for minimization. Spectral fitting was performed in the 0.3–7 keV range using XSPEC (version 11.3.2). All statistical errors stated hereafter correspond to 90% confidence for one interesting parameter ( $\Delta\chi^2 = 2.706$ ), unless stated otherwise. In all of the model fittings, the Galactic column density was fixed at  $N_{\text{H}} = 1.96 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman 1990). All model parameters will be referred to in the source frame. In Table 2, we present the results of spectral fits for the above three sources.

**Table 2** Results of the X-ray Spectral Fitting

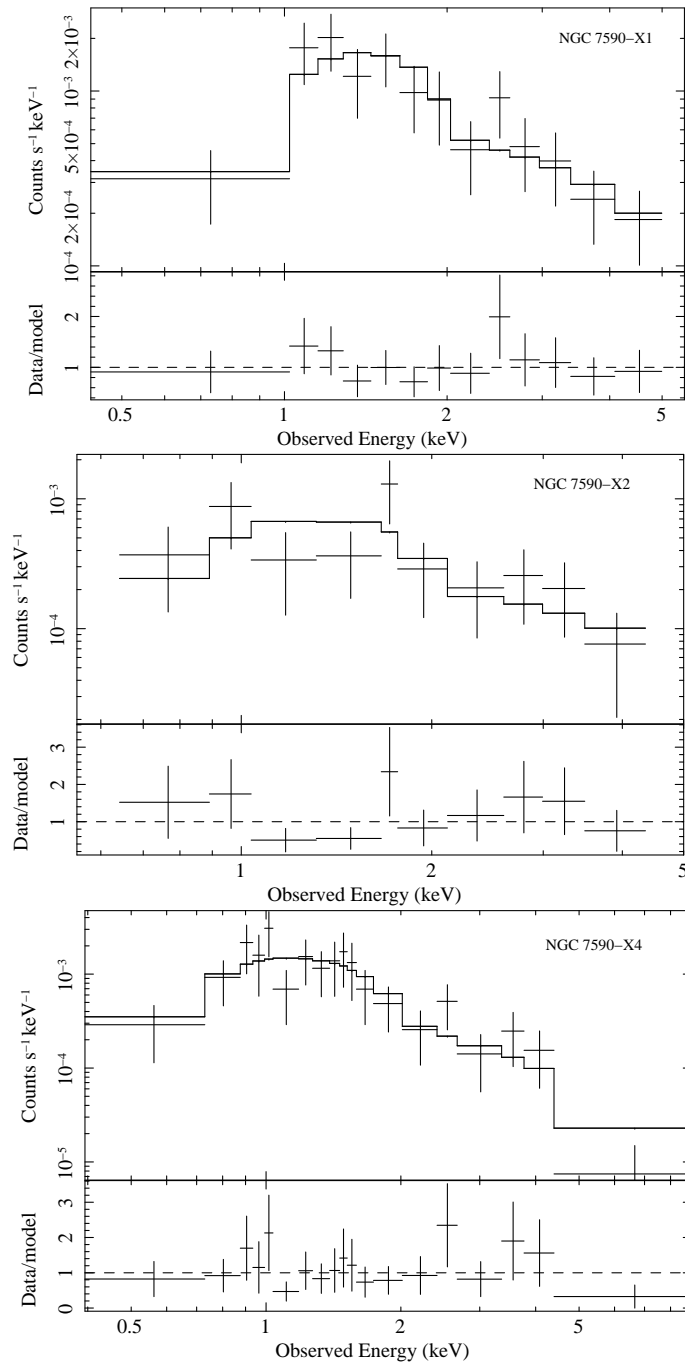
Target	$N_{\text{H}}$ ( $10^{22} \text{ cm}^{-2}$ )	$\Gamma$	$C/\text{dof}$
X1	$0.5^{+0.5}_{-0.4}$	$1.96^{+0.85}_{-0.69}$	46.1/63
X2	< 0.8	$1.91^{+1.03}_{-0.78}$	25.3/27
X4	< 0.4	$2.23^{+0.74}_{-0.60}$	31.8/53

All three sources are reasonably well fitted with a simple absorbed power-law model. Although there are substantial uncertainties due to the limited photon statistics, the photon index ( $\Gamma \simeq 2.0^{+0.8}_{-0.7}$ ) for the brightest source X1 is consistent with the value measured by *XMM-Newton* data. Note that due to the lower spatial resolution of *XMM-Newton* the resulting spectra in fact consist of the summed emission from both X1 and X2. The spectra and residuals of X1 and X2 are shown in Figure 2.

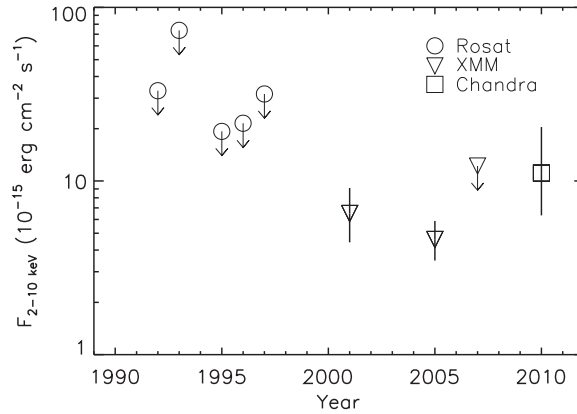
The third source, X4, has luminosity from *Chandra* spectral fits (assuming the distance of NGC 7590, see Table 1) exceeding the Eddington luminosity for stellar mass X-ray binaries of  $2 \times 10^{38} \text{ erg s}^{-1}$  (Makishima et al. 2000). This object was undetectable in previous *ROSAT* HRI observations (Liu & Bregman 2005), and recent *XMM-Newton* observations only show weak detections due to the contamination from the host galaxy. If this object could be associated with a ULX, it is interesting to investigate whether the *Chandra* detection corresponds to a recurrence or an outburst of the ULX (see e.g. Bauer & Pietsch 2005). We present the light curve of X4 in Figure 3, taken from *ROSAT* (circles), *XMM-Newton* (triangles), and *Chandra* (squares). Although there appears to be variability in long-term brightness, the upper limits of the flux prevent us from drawing any conclusive claims.

## 4 DISCUSSION

NGC 7590 was previously identified to be an “unobscured” Sy2 galaxy, based on the *ASCA* observation ( $\sim 1'$ ) which has poor spatial resolution in X-ray (Bassani et al. 1999). The higher spatial resolution ( $\sim 6''$  PSF FWHM) *XMM-Newton* observations show that the X-ray flux of the NGC 7590 nucleus is contaminated by a nearby bright ULX and an extended component from the host galaxy



**Fig. 2** *Chandra* spectra of three off-nuclear X-ray sources in NGC 7590, together with the best-fit model and residuals.



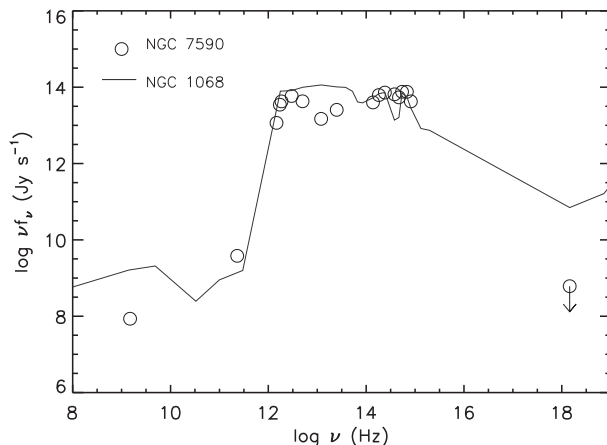
**Fig. 3** Light curve of NGC 7590–X4. Data are taken from *ROSAT* (circles), *XMM-Newton* (triangles), and *Chandra* (squares). The statistical errors for the flux shown correspond to 90% confidence. Arrows represent the corresponding  $3\sigma$  upper limit for fluxes.

(see Paper I). Because of the strong contamination, the *XMM-Newton* data can only give an upper limit for the nuclear X-ray emission with  $F_{2-10\text{keV}} = 1.6 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ . From the derived  $T$  ratio ( $F_{2-10\text{keV}}/F_{[\text{O III}]}$ )  $< 0.09$ , a value in the range of Compton-thick AGNs, see Guainazzi et al. 2005), we conclude that NGC 7590 likely hosts a heavily obscured nucleus (Paper I). Our new *Chandra* observation enables us to effectively remove the X-ray contaminations and provides the direct X-ray view of the NGC 7590 nucleus. The *Chandra* data show that the NGC 7590 nucleus is rather weak, with an upper limit for the 2–10 keV flux of  $0.6 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ . Although not detected, the corresponding upper limit of the  $T$  ratio ( $< 0.033$ ) suggests that the obscuration towards the nucleus is likely Compton-thick rather than “unobscured” as previously thought, supporting the results of the *XMM-Newton* observations.

Another insight into the X-ray nature of the NGC 7590 nucleus comes from the energy production mechanisms at different wavebands of the galaxy.

Figure 4 shows the spectral energy distribution (SED) of NGC 7590 (open circles), constructed using the data collected from the NASA/IPAC Extragalactic Database (NED). The SED for NGC 7590 is compared with that of NGC 1068 (solid line), an archetypal Compton-thick Sy2 galaxy (e.g. Pounds & Vaughan 2006). Given the scaling of the comparison SEDs (normalized to the optical  $i$ -band), the NGC 7590 SED multiwavelength data are in general agreement with an obscured AGN template. However, there is a disagreement with regard to emission in the radio and near-IR band, which could be due to more intense star-formation in NGC 1068. On the other hand, it is evident that NGC 7590 is relatively weak in X-ray, which could be explained by a combination of both a low accretion central black hole and strong absorption of the nuclear emission. If NGC 7590 hosts a Compton-thick AGN with an SED similar to that of NGC 1068, then a luminous X-ray source should be present at higher energies ( $\sim 20$ – $30$  keV), which could be detected by future hard X-ray imaging telescopes (i.e. NUSTAR and ASTRO-H). However, caution must be kept in mind in interpreting the SED, as the measurements have been taken at different epochs and different apertures were used, in which the contamination from the host galaxy could be important.

With the unprecedented sub-arcsecond spatial resolution of *Chandra*, it is possible to separate even very closely spaced point sources, and easily distinguish them from the surrounding diffuse emission. The *Chandra* image of NGC 7590 clearly shows two sources (labeled X1 and X2 in this paper), about 25 arcsec north-east from the position of the optical nucleus (see Fig. 1). The two



**Fig. 4** The NGC 7590 SED (*open circles*). The upper limit of the X-ray flux is given by *Chandra* observations, while the fluxes at other bands are taken from NED. For comparison we also show the SED of the archetypal Compton-thick Sy2 galaxy NGC 1068 (*solid line*). The NGC 7590 SED was normalized to match that of NGC 1068 in the optical *i*-band.

sources were not separated by lower resolution *ROSAT* HRI and *XMM-Newton* observations, and have previously been identified as a ULX with 2–10 keV luminosity of  $\sim 5.7 \times 10^{39} \text{ erg s}^{-1}$  (Colbert & Ptak 2002; Paper I). The *Chandra* spectra of both sources can be adequately fitted with a simple absorbed power law (see Table 2), though the parameters were loosely constrained due to the poor statistics. Note that the results of spectral analysis for both sources are consistent with each other, but with X1 showing a factor of three higher flux than X2. As shown in Table 1, by simply summing the flux from X1 and X2, we found a 2–10 keV luminosity of  $\simeq 3.7 \times 10^{39} \text{ erg s}^{-1}$ , a factor of  $\sim 2.5$  lower than what was reported by Paper I for the *XMM-Newton* observations. Given the possible contamination by the emission from the host galaxy and a larger extraction radius of the *XMM-Newton* data, we cannot tell whether there is any variability of the ULX flux in the *Chandra* spectrum.

Our analysis highlights the importance of utilizing the *Chandra* observatory to discover and study ULXs. The sub-arcsecond spatial resolution of *Chandra* is essential to confirm the point-like nature of ULX candidates, and perhaps resolve additional sources that observatories with modest angular resolution (i.e. *XMM-Newton*) could not. Such confusing problems should be taken into account when studying the statistical properties of the X-ray source populations, in particular in distant galaxies with limited spatial resolution of X-ray observations, where the ULX luminosity may be *overestimated*. Since the X-ray luminosity is a defining property of the ULXs, the question we could ask instead is whether ULXs represent the high-luminosity end of a continuous distribution of typical X-ray sources such as X-ray binaries (e.g. Grimm et al. 2003; Swartz et al. 2004; Liu et al. 2006), or if they include new classes of objects including intermediate-mass black holes (Colbert et al. 2004; Farrell et al. 2009; Swartz et al. 2011). With the *Chandra* high resolution observations, we may need to re-visit the correlation between ULXs and star formation (Swartz et al. 2004; Liu et al. 2006; Walton et al. 2011), and to search for further similarities and/or differences between ULXs and less-luminous sources in both spiral and elliptical galaxies to confirm or rule out their X-ray binary nature.

**Acknowledgements** X.W.S. thanks the support from the China postdoctoral foundation. This work has been supported by the National Science Foundation of China (Grant Nos. 10825312 and 11103017) and the Fundamental Research Funds for the Central Universities (Grant Nos. WK

2030220004 and WK 2030220005). Partial support for this work was provided by NASA through Chandra Award GO1-12134X. The authors are grateful to the *Chandra* instrument and operation teams for making the observation possible.

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