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DISCOVERY OF A BINARY ACTIVE GALACTIC NUCLEUS IN THE ULTRALUMINOUS INFRARED GALAXY NGC 6240 USING *CHANDRA*

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ABSTRACT

Ultraluminous infrared galaxies (ULIRGs) are outstanding due to their huge luminosity output in the infrared, which is predominantly powered by superstarbursts and/or hidden active galactic nuclei (AGNs). NGC 6240 is one of the nearest ULIRGs and is considered a key representative of its class. Here we report the first high-resolution imaging spectroscopy of NGC 6240 in X-rays. The observation, performed with the ACIS-S detector aboard the *Chandra X-Ray Observatory*, led to the discovery of two hard nuclei, coincident with the optical-IR nuclei of NGC 6240. The AGN character of *both* nuclei is revealed by the detection of absorbed, hard, luminous X-ray emission and two strong neutral Fe Kα lines. In addition, extended X-ray emission components are present, changing their rich structure in dependence of energy. The close correlation of the extended emission with the optical Hα emission of NGC 6240, in combination with the softness of its spectrum, clearly indicates its relation to starburst-driven superwind activity.

Subject headings: quasars: individual (NGC 6240) — X-rays: galaxies

1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs) are characterized by their huge luminosity output in the infrared, which is predominantly powered by superstarbursts and/or hidden active galactic nuclei (AGNs; e.g., Genzel et al. 1998; Sanders 1999). Many distant SCUBA sources—massive and dusty galaxies—are believed to be ULIRG equivalents at high redshift (e.g., Barger et al. 1998; Lawrence 2001). Local ULIRGs, of which NGC 6240 is regarded as a key representative, are therefore important laboratories to study the physics of superwinds driven by the nuclear starbursts and the processes of intergalactic medium enrichment, to search for the presence of hidden AGNs, and to study the physics of galaxy formation (many ULIRGs are interacting galaxies that are believed to be on the verge of forming elliptical galaxies).

NGC 6240 is one of the nearest members of the class of ULIRGs and has been intensely studied at virtually all wavelengths. The galaxy shows conspicuous loops and tails and two optical nuclei separated by $\sim1\farcs8$ (Fried & Schulz 1983) that are also detected in the IR and radio band. Recent observations suggest that NGC 6240 is in a relatively early merger state (Tacconi et al. 1999; Tecza et al. 2000; Gerssen et al. 2001). It is expected to finally form an elliptical galaxy. Ground-based optical spectroscopy of NGC 6240 shows LINER-like emission-line ratios.

Given the importance of the questions as to whether an AGN is present and as to whether it is the ultimate power source of the ULIRG NGC 6240, efforts to search for such an AGN were undertaken at all wavelengths (see § 1 of Komossa, Schulz, & Greiner 1998 for a review). Recent observations include the detection of flaring water vapor maser emission from NGC 6240 (Nakai, Sato, & Yamauchi, 2002), the presence of a high-excitation [O IV] infrared emission line (Genzel et al. 1998), and the compactness of the radio cores (Beswick et al. 2001). In X-rays, NGC 6240 exhibits exceptionally luminous extended emission (Schulz et al. 1998; Komossa et al. 1998; Kolaczyk & Dixon 2000) that is likely powered by superwinds and an iron line that is superposed on hard X-ray emission (Mitsuda 1995; Schulz et al. 1998; Iwasawa & Comastri 1998) extending beyond 10 keV (Vignati et al. 1999; Ikebe et al. 2000) and interpreted as arising from an absorbed active nucleus. It is the hard X-ray observations that give the best evidence for the presence of an AGN in NGC 6240. It remained basically an open question as to which of the two nuclei of NGC 6240 was the active one (or whether even both of them were); *Hubble Space Telescope* (*HST*) observations (Rafanelli et al. 1997) suggested that the southern nucleus harbors an AGN or a heavily obscured LINER.

The questions regarding the onset of starburst and AGN activity and their evolution in mergers are of fundamental importance for our understanding of AGN/black hole formation and evolution in general. Given the complex nature of the X-ray emission of NGC 6240, with contributions from many components suggested from previous X-ray observations (Schulz et al. 1998; Komossa et al. 1998; Iwasawa & Comastri 1998; Netzer, Turner, & George 1998; Vignati et al. 1999; Ikebe et al. 2000), spatially resolved spectroscopy is crucial in order for us to disentangle all contributing components, determine their nature, and derive their physical properties. In this Letter, we report the *Chandra* discovery that *both* nuclei of NGC 6240 are active, and we show first results on the remarkably structure-rich extended X-ray emission.

Luminosities were calculated using a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}. At a distance of NGC 6240 of 144 Mpc, $1''$ corresponds to 700 pc in the galaxy.

2. X-RAY OBSERVATIONS AND DATA ANALYSIS

NGC 6240 was observed as part of the guaranteed time observer program with the Advanced CCD Imaging Spectrometer (ACIS-S) instrument on board the *Chandra X-Ray Observatory*. The observation was carried out on 2001 July 29 with an effective exposure time of 37 ks. The pointing of the telescope was such that the X-ray photons of the target source were registered on the back-illuminated S3 chip of ACIS. The data analysis was prepared using the CIAO2.2 software tool.

Spectra were grouped to have at least 25 photons bin^{-1}. Since few photons were detected below 0.5 keV and since the in-

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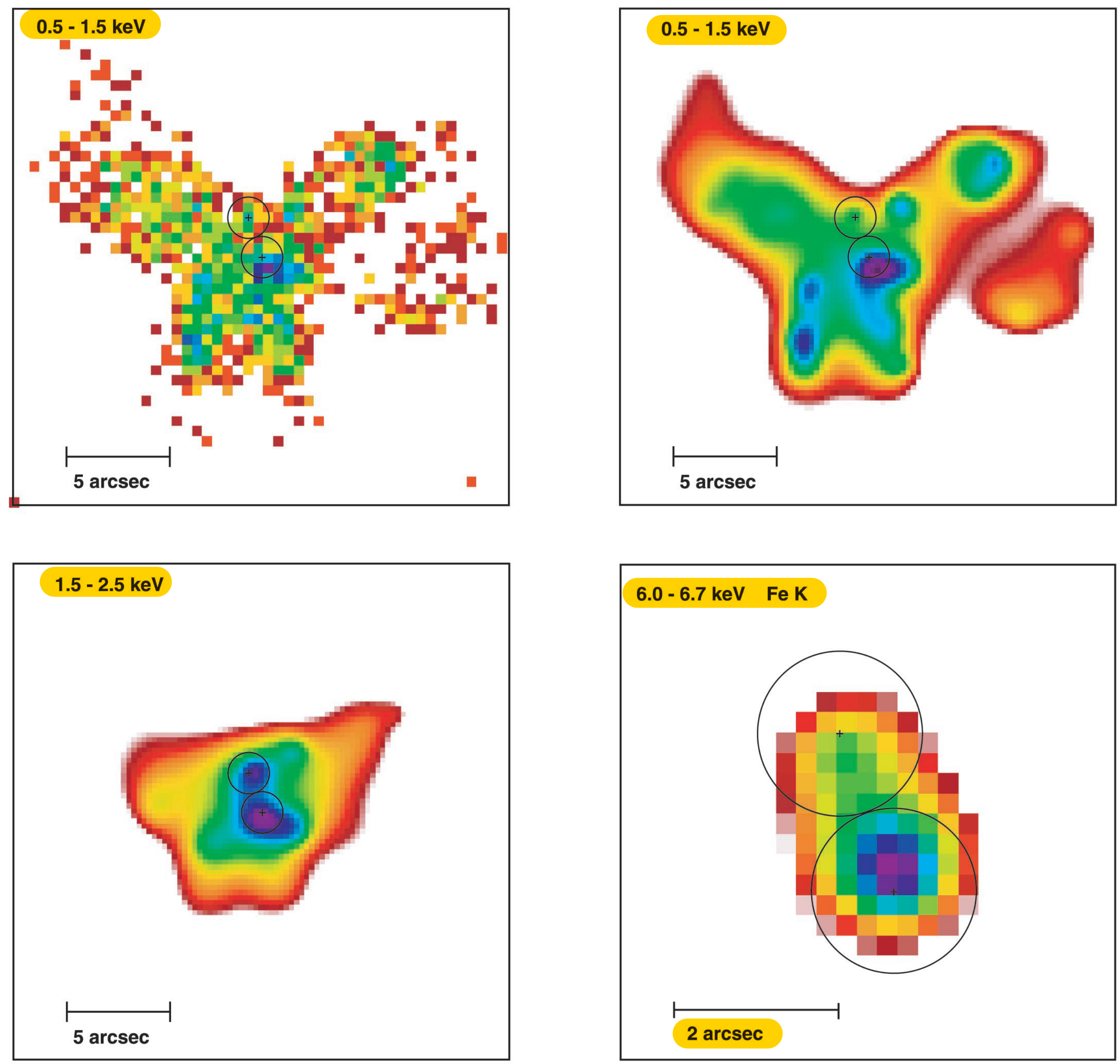

FIG. 1.—X-ray images of NGC 6240 in selected energy intervals. The first image (*upper left corner*) shows the raw ACIS-S image in the energy range of 0.5–1.5 keV. The circles mark the optical positions of the two nuclei of NGC 6240. Further images are shown in selected energy intervals, as marked in the figures. The images were adaptively smoothed using the fast Fourier transform algorithm in the CSMOOTH routine available in CIAO 2.2.

strument response is still somewhat uncertain at low energies, we restricted our modeling to photon energies above 0.5 keV.

The ACIS-S background is very low. It was determined in a circular, source-free region north of the central X-ray emission and was subtracted. In order to carry out the spectral analysis of each nucleus separately, source photons from the northern and southern nuclei were extracted in circular regions of radii 0″.8 and 0″.9, respectively, centered at the X-ray positions of the nuclei. Given the widening of the point-spread function at hard X-ray energies, these radii ensure an encircled energy of 85% (at ~6 keV). Further details on photon extraction areas for other regions of NGC 6240 are given below.

3. X-RAY MORPHOLOGY

The *Chandra* image of NGC 6240 reveals a wealth of structure, changing in dependence of energy (Fig. 1). A large part of the X-ray emission of NGC 6240 is extended, confirming previous results from *ROSAT* (Komossa et al. 1998; Schulz et al. 1998) and from a short *Chandra* HRC-I observation (Lira et al. 2002). The previous observations, however, did not provide any energy information.

Several X-ray "loops" and knots are visible that correlate well with the Hα emission (Keel 1990; Gerssen et al. 2001) of NGC 6240. Apart from the complex central emission, only

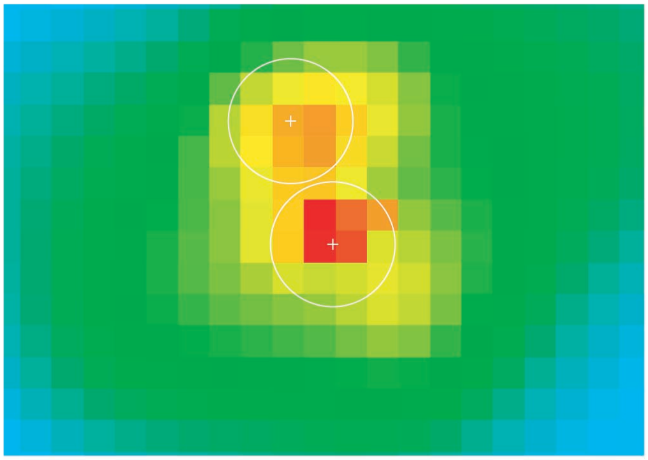

FIG. 2.—X-ray image of NGC 6240 in the energy range of 2.5–8 keV, zoomed on the two nulcei. The circles mark the optical positions of the nuclei.

one X-ray source is detected within the optical confines of NGC 6240. Its spectrum is rather hard. The source could be a background AGN. In particular, the following features stand out in energy images of NGC 6240:

The 0.1–3.0 keV *band*.—Below 0.5 keV, barely any X-ray photons are detected. This can be traced back to the high absorption toward NGC 6240. Above 0.5 keV, extended looplike emission and several knots appear. They are prominent below 2.5 keV. Of special interest is the "blob" southwest of the southern nucleus, which appears above 1 keV (see Figs. 1 and 2). It is the strongest feature between 1.0 and 1.5 keV and is spatially extended. Inspecting *HST* images of Gerssen et al. (2001), we find that it correlates with a region of increased Hα emission and may correspond to a more recent superwind outflow than the more widely extended structures. Above 1.5 keV, X-ray emission from the direction of the northern nucleus of NGC 6240 starts to emerge.

The 5.0–8.0 keV *band*.—The hard X-ray image is dominated by emission from two compact sources (see Figs. 2 and 3) that are spatially coincident within the errors with the IR position of the two nuclei of NGC 6240. With a distance of $1\farcs4$, the X-ray nuclei are slightly closer together than the optical nuclei (Fig. 2), consistent with the previous interpretation that extinction causes a wavelength-dependent shift in the flux centroids of the nuclei (Schulz et al. 1993). Both nuclei show emission from the neutral iron line. The southern nucleus is more prominent in this line than the northern nucleus. Running a standard source detection routine, both nuclei are detected as sources in the energy interval 5–8 keV with signal-to-noise ratios of 9.9 (southern nucleus) and 3.5 (northern nucleus).

We do not detect any X-ray emission from the location of the steep off-nuclear velocity gradient (Bland-Hawthorn, Wilson, & Tully 1991; Gerssen et al. 2001), which was recently suggested to be possibly due to a kinematic gradient in a starburst wind. No correlation of X-ray emission with the radio arm west of the nuclei, described by Colbert, Wilson, & Bland-Hawthorn (1994) and suggested to be linked to superwind activity, was found. Finally, no X-ray point source was detected from the direction of the supernova SN 2000bg.

4. X-RAY SPECTROSCOPY

4.1. *Extended Emission*

Representative of the extended emission, we report here results of spectral fits to the northeastern loop extended emission (Fig. 1). Source photons were extracted from an elliptical region centered at R.A. = $16^{h}52^{m}59\fs3$, decl. = $02°24'08\farcs1$ (ellipse radii: $8\farcs9$ and $10\farcs6$, angle = 45°). We find that the X-ray spectrum is well described by a MEKAL model (Mewe, Kaastra, & Liedahl 1995) with $kT = 0.81 \pm 0.05$ keV and absorption with column density $N_H = (3.1 \pm 0.4) \times 10^{21}$ cm^{-2}

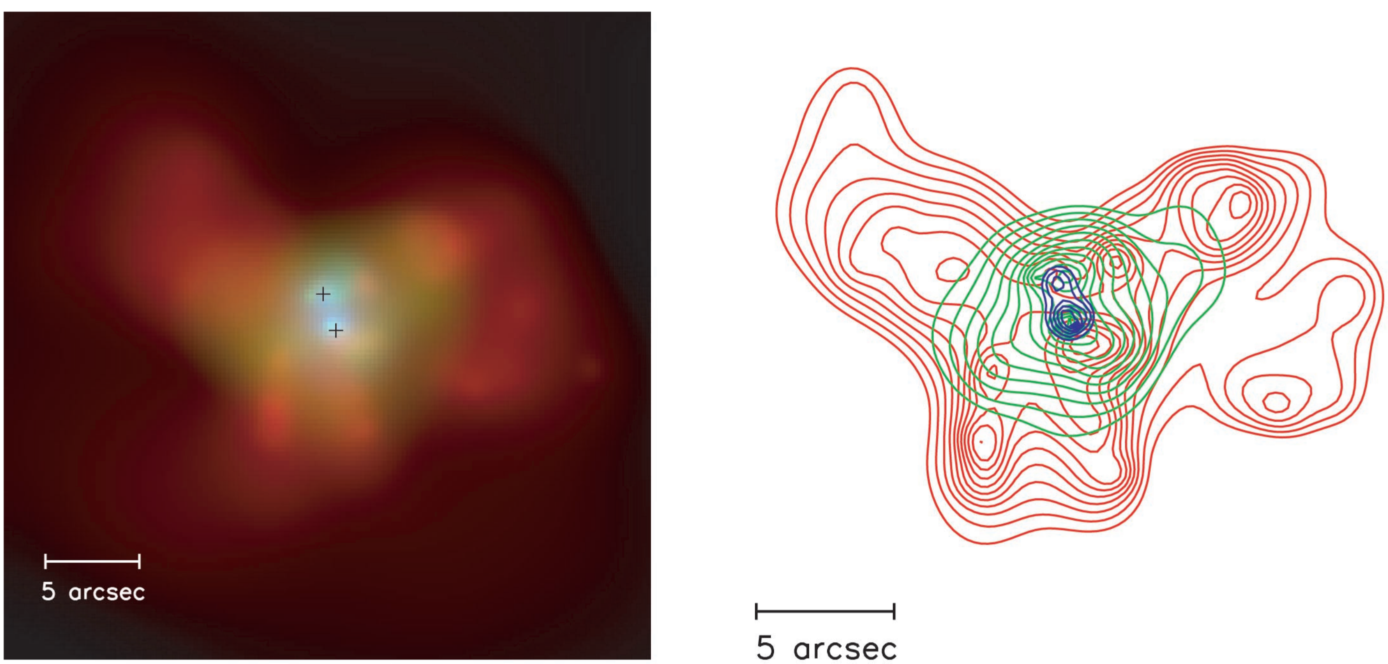

FIG. 3.—Multicolor image of NGC 6240. Red = soft (0.5–1.5 keV), green = medium (1.5–5 keV), and blue = hard (5–8 keV) X-ray band. The right image shows contour plots using the same color coding.

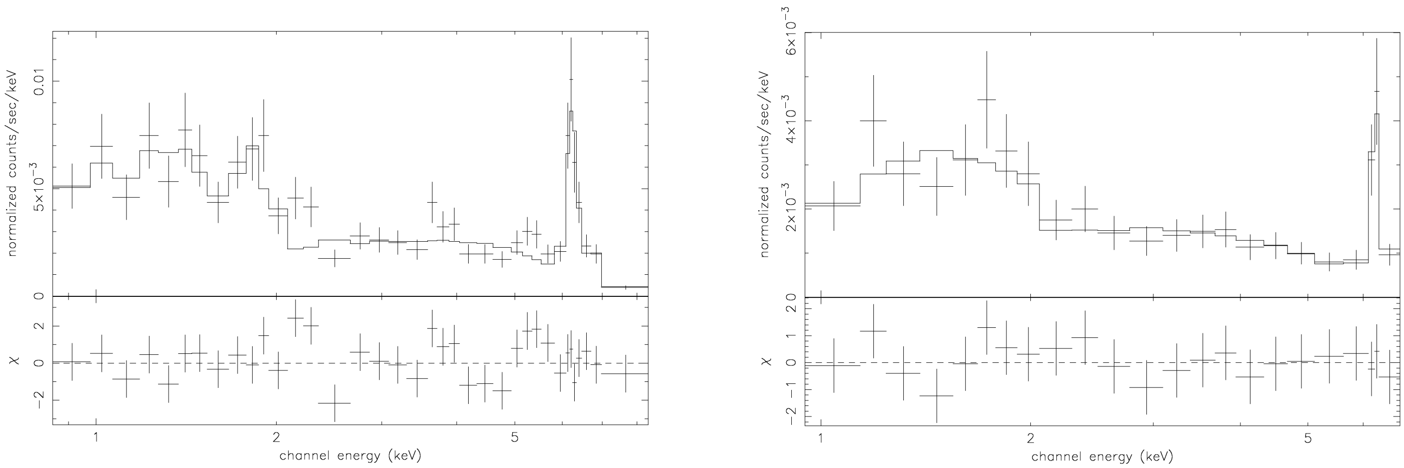

FIG. 4.—X-ray spectrum of southern nucleus (*left*) and the northern nucleus (*right*) of NGC 6240. A model consisting of thermal emission plus an absorbed power law and two Gaussian emission lines was fitted to the data. The lower panel of each figure shows the residuals.

($\chi^2_{\rm red} = 1.2$), which exceeds the Galactic value in the direction of NGC 6240, $N_{\rm Gal} = 5.49 \times 10^{20}$ cm^{-2}, and is consistent with optical estimates of the extinction toward the extended optical emission of $A_v \approx 1$ mag (Thronson et al. 1990). Metal abundances approach 0.1 times solar.

Second, the blob southwest of the southern nucleus was fitted after extracting its photons from a circular region centered at R.A. = $16^{\rm h}52^{\rm m}58^{\rm s}.8$, decl. = $02°24'1''.5$. Its spectrum is significantly harder and more heavily absorbed. Spectral fits consisting of a two-component MEKAL model were applied. Among these two components, one was assumed to be the extension of the widely extended soft X-ray emission of NGC 6240, part of which is projected onto the central region of NGC 6240. Explicitly, its parameters were all fixed to those determined for the northeastern loop extended X-ray emission (including abundances and the amount of absorption), apart from the normalization that was treated as a free parameter. The second, hotter MEKAL component was added to describe the X-ray emission from the southwestern blob itself. The spectrum of the southwestern blob is then well described by a MEKAL model with $kT = 2.8 \pm 0.8$ keV and $N_{\rm H} = (7 \pm 4) \times 10^{21}$ cm^{-2} ($\chi^2_{\rm red} = 0.95$). Abundances are not well constrained but are close to 0.8 times solar and were thus fixed to that value.

4.2. *Nuclear Emission*

Two circular regions centered at the southern and northern nuclei were selected for spectral analysis. The residual soft starburst emission projected onto the nuclei (Fig. 1) was fitted by a MEKAL model, and its normalization and temperature were left free to vary. The derived temperature ($kT = 0.9 \pm 0.2$ keV) is consistent within the errors with that of the northeastern loop emission. The extinction toward the nuclei estimated from IR observations, $A_v^S = 5.8$ mag and $A_v^N = 1.6$ mag (Tecza et al. 2000), corresponds to absorption column densities of $N_{\rm H}^S = 10^{22}$ cm^{-2} and $N_{\rm H}^N = 2.8 \times 10^{21}$ cm^{-2} and is expected to be the minimum amount of absorption along the line of sight toward the nuclei. MERLIN radio observations of neutral hydrogen toward the radio nuclei of NGC 6240 indicate column densities of order $N_{\rm H}^{S,N} \approx (1.5\text{–}2) \times 10^{22}$ cm^{-2} (Beswick et al. 2001).

Both nuclei show very hard X-ray spectra extending out to ~8–9 keV. If the spectra are fitted by a single power law, strong residuals around the location of the neutral 6.4 keV iron Kα line are visible (and further weaker ones around ~6.95 keV). The energy of the second line is close to H-like iron and Kβ of neutral iron. The southern nucleus is brighter in X-rays than the northern nucleus. Its spectrum is well fitted by a very flat power law of photon index (defined as in $F \propto E^{+\Gamma}$) $\Gamma_{\rm X} = -0.2 \pm 0.3$ and two narrow iron lines at energies corresponding to neutral and H-like iron (Fig. 4). The emission is dominated by the neutral iron line that is located at a (redshift-corrected) energy $E = 6.42 \pm 0.03$ keV, with 1.5×10^{-5} photons cm^{-2} s^{-1}. The amount of excess absorption is not well constrained. It is of order $N_{\rm H}^S \simeq 10^{22}$ cm^{-2} and is uncertain by at least a factor of 2. The spectrum of the northern nucleus is less hard and less absorbed. It is well described by a power law of photon index $\Gamma_{\rm X} = -0.9 \pm 0.2$, absorbed with $N_{\rm H}^N = (0.6 \pm 0.2) \times 10^{22}$ cm^{-2} in addition to the Galactic $N_{\rm Gal}$, and a narrow Fe Kα line of neutral iron (Fig. 4) that is about a factor of 3 weaker than in the southern nucleus. The absorption-corrected fluxes in the 0.2–10 keV band are $f_{{\rm X},S} = 7.6 \times 10^{-13}$ ergs cm^{-2} s^{-1} and $f_{{\rm X},N} = 2.7 \times 10^{-13}$ ergs cm^{-2} s^{-1} for the southern and the northern nucleus, respectively.

5. DISCUSSION

5.1. *Starburst-related Emission*

Could the widely extended X-ray emission of NGC 6240 still be powered by photoionization of the active nuclei? *Chandra* recently found some cases in which photoionization seems to dominate the ionization of circumnuclear matter out to large distances (~2 kpc in case of NGC 1068; Young, Wilson, & Shopbell 2001). However, the correlation of X-ray and Hα emission in combination with the *soft*, thermal-plasma–like spectrum of the extended emission of NGC 6240 strongly favors starburst-driven superwinds (Heckman, Armus, & Miley 1987) as the origin for the bulk of the extended X-ray emission of NGC 6240. According to the superwind models of Schulz et al. (1998), a mechanical input power of $L_{\rm mech} = 3 \times 10^{43}$ ergs s^{-1} (derived from a supernova rate of 3 yr^{-1}) can, within 3×10^7 yr, drive a single shell to an extent of $R \sim 10$ kpc within a medium of 0.1 cm^{-3} particle density. This model reproduces the observed X-ray luminosity of the extended emission of ~10^{42} ergs s^{-1}. A distance of 10 kpc corresponds to the extent of the five-finger structure seen in Hα, coincident with the brightest extended X-ray emission, including a correction for a disk inclined by up to 40° from edge-on.

The ionized iron line observed in addition to the neutral iron line may originate in "Cas A–type" supernova remnants (e.g., Willingale et al. 2002) or in a near-nuclear "warm scatterer" that is ionized by the AGN (Komossa et al 1998). The extended soft X-ray component and its link with non–X-ray morphological structures will be further discussed in a follow-up paper (S. Komossa et al. 2002, in preparation). In the following, we concentrate on the core region of NGC 6240.

5.2. *Emission from the Binary AGN*

Using *Chandra* ACIS-S, we found that *both* nuclei of NGC 6240 are emitters of luminous hard X-ray emission, on which a strong neutral iron Kα line is superposed. These properties identify both nuclei of NGC 6240 as active. In particular, a strong neutral Fe Kα line is not produced in a starburst superwind but originates from fluorescence in cold material illuminated by a hard continuum spectrum. For the first time, we can disentangle the contribution to the hard X-ray luminosity from the southern and northern nuclei. The observed 0.1–10 keV, absorption-corrected fluxes convert to *observed* X-ray luminosities of the southern and northern nuclei, $L_{X,S} = 1.9 \times 10^{42}$ ergs s^{-1} and $L_{X,N} = 0.7 \times 10^{42}$ ergs s^{-1}, respectively.

The *intrinsic* luminosities are significantly larger because it has been repeatedly argued that the emission we are seeing in X-rays below 10 keV is scattered emission from the AGN (e.g., Mitsuda 1995; Schulz et al. 1998; Komossa et al. 1998). The intrinsic AGN emission of NGC 6240 only shows up above ~9–10 keV (Vignati et al. 1999; Ikebe et al. 2000). The strength of the neutral Fe Kα line in both nuclei suggests a scattering geometry for *both* AGNs. This is also indicated by the flatness of the hard power-law spectra (§ 4.2).

We find marginal evidence that part of the hard emission is extended by a few arcsesonds; 3″ correspond to ~2 kpc in NGC 6240. It is interesting to note that this scale is similar to the extent of the hard X-ray emission and iron line of NGC 1068 detected with *Chandra* (Young et al. 2001). Dense cold gas that could provide the scattering agent is abundant in the center region of NGC 6240. Deeper *Chandra* observations of NGC 6240, still employing the superb imaging spectroscopy capabilities of the ACIS-S detector, will be indispensable for studying the complex central region of NGC 6240 in greater detail (for instance, for obtaining a high-quality image in the Fe Kα line).

The presence of supermassive binary black holes, as in NGC 6240, are of importance for our understanding of the formation and evolution of AGNs and the formation of elliptical galaxies via mergers. Ultimately, the binary AGN of NGC 6240 will coalesce to form one nucleus. The final merging of the supermassive black holes is expected to produce a strong gravitational wave signal. In fact, such events are expected to generate the clearest signals detectable with the gravitational wave detector LISA (Laser Interferometer Space Antenna) that will be placed in Earth orbit in the near future (e.g., Danzmann 1996).

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