FAST AND FURIOUS: SHOCK HEATED GAS AS THE ORIGIN OF SPATIALLY RESOLVED HARD X-RAY EMISSION IN THE CENTRAL 5 kpc OF THE GALAXY MERGER NGC 6240

JUNFENG WANG1,7, EMANUELE NARDINI1,8, GIUSEPPIA FARBIANO1, MARGARITA KAROVSKA1, MARTIN ELVIS1, SILVIA PELLEGRINI2, CLAIRE MAX3, GUIDO RISALITI1,4, VIVIAN U5,9, AND ANDREAS ZEZAS1,6

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; jfwang@northwestern.edu
2 Dipartimento di Astronomia, Università di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
3 Center for Adaptive Optics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
4 INAF-Arcetri Observatory, Largo E. Fermi 5, I-50125 Firenze, Italy
5 Institute for Astronomy, University of Hawai’i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
6 Physics Department, University of Crete, P.O. Box 2208, GR-710 03, Heraklion, Crete, Greece

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ABSTRACT

We have obtained a deep, subarcsecond resolution X-ray image of the nuclear region of the luminous galaxy merger NGC 6240 with \textit{Chandra}, which resolves the X-ray emission from the pair of active nuclei and the diffuse hot gas in great detail. We detect extended hard X-ray emission from $kT \sim 6$ keV ($\sim 70$ MK) hot gas over a spatial scale of 5 kpc, indicating the presence of fast shocks with a velocity of $\sim 2200$ km s$^{-1}$. For the first time, we obtain the spatial distribution of this highly ionized gas emitting Fe XXV, which shows a remarkable correspondence to the large-scale morphology of H$_2$(1–0) S(1) line emission and H$_\alpha$ filaments. Propagation of fast shocks originating in the starburst-driven wind into the ambient dense gas can account for this morphological correspondence. With an observed $L_{0.5–8\text{ keV}} = 5.3 \times 10^{44} \text{ erg s}^{-1}$, the diffuse hard X-ray emission is $\sim 100$ times more luminous than that observed in the classic starburst galaxy M82. Assuming a filling factor of 1% for the 70 MK temperature gas, we estimate its total mass ($M_{\text{tot}} = 1.8 \times 10^8 M_\odot$) and thermal energy ($E_{\text{th}} = 6.5 \times 10^{57} \text{ erg}$). The total iron mass in the highly ionized plasma is $M_{\text{Fe}} = 4.6 \times 10^5 M_\odot$. Both the energetics and the iron mass in the hot gas are consistent with the expected injection from the supernova explosion during the starburst that is commensurate with its high star formation rate. No evidence for fluorescent Fe I emission is found in the CO filament connecting the two nuclei.

Key words: galaxies: individual (NGC 6240) – galaxies: interactions – galaxies: starburst – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

In the local universe, NGC 6240 ($z = 0.02448 \pm 0.00003$; Downes et al. 1993) is a unique galaxy, in the throes of a violent merging event and on its way to becoming an elliptical galaxy (Tacconi et al. 1999; Tecza et al. 2000; Bush et al. 2008; Engel et al. 2010; Medling et al. 2011). It is experiencing intense star formation (e.g., $61 \pm 30 M_\odot$ yr$^{-1}$ in Yun & Carilli 2002; $25 M_\odot$ yr$^{-1}$ in Engel et al. 2010). With $L_{\text{FIR}} \sim 10^{11} L_\odot$ just below $10^{12} L_\odot$, the luminosity threshold for the ultraluminous infrared galaxies (ULIRGs; Sanders & Mirabel 1996; Genzel et al. 1998), NGC 6240 is expected to become a ULIRG when the galaxies coalesce and a final starburst is triggered (Engel et al. 2010).

The \textit{Chandra} X-ray images (Lira et al. 2002; Komossa et al. 2003) of the central region of NGC 6240 revealed two gravitationally interacting active supermassive black holes separated by 1.5′ ($\sim 0.7$ kpc). These sources are characterized by the highly absorbed hard X-ray spectra typical of Compton thick active galactic nuclei (AGNs; Iwasawa & Comastri 1998; Matt et al. 2000). They each have an observed luminosity of $L_{2–8\text{ keV}} \sim 10^{42} \text{ erg s}^{-1}$ and show prominent neutral Fe Kα lines at 6.4 keV present in the spectra of both nuclei (Komossa et al. 2003).

Limited by the number of counts, marginal evidence of an H-like Fe line in the spectral fit and extended hard X-ray emission in the morphology was also suggested by Komossa et al. (2003). This line emission could be associated with a spatially resolved, multi-temperature hot gas outflow, powered by the starburst activity that dominates the 0.5–3 keV X-ray emission ($L_{0.5–2\text{ keV}} \sim 10^{43} \text{ erg s}^{-1}$; Schulz et al. 1998; Komossa et al. 2003; Ptak et al. 2003; Huo et al. 2004; Grimes et al. 2005). \textit{XMM-Newton} observations (Boller et al. 2003; Netzer et al. 2005) resolved the Fe K line complex into three narrow lines, the neutral Fe Kα, Fe XXV, and a blend of Fe XXVI with Fe Kβ. Using a three-zone model, Netzer et al. (2005) further identified that the emission lines of higher ionization ions (e.g., the Fe XXV line) originated from the inner 2.1 kpc region. These \textit{XMM-Newton} data, however, do not have the resolution to resolve spatially the line-emitting regions.

In this paper, we focus on the spatially resolved 5.5–8 keV X-ray emission of the innermost central $\sim 5$ kpc ($\sim 10''$) region in NGC 6240 based on new, and archival, \textit{Chandra} imaging. This choice of hard energy range allows us to investigate the origin of the high-temperature gas and the highly ionized iron emission. A detailed study of the extended soft X-ray halo has been presented in a companion paper (Nardini et al. 2013). A third paper (J. Wang et al. 2014, in preparation) will discuss the extended soft X-ray emission in the $r \sim 15''$ region. Taking advantage of the order of magnitude deeper imaging, along with subpixel resolution, we are able to firmly establish the presence and
the spatial distribution of the hard X-ray emission. Throughout this work, we adopt a luminosity distance of $D_L = 107$ Mpc to NGC 6240 ($1'' = 492$ pc), based on the concordance cosmological parameters ($H_0 = 70.5$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$; Komossa et al. 2011).

2. OBSERVATIONS AND DATA REDUCTION

NGC 6240 was observed on 2011 May 31 with the Chandra Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) for 146 ks (ObsID 12713, PI: Fabbiano). The binary nucleus of NGC 6240 was placed near the nominal aimpoint of the backside-illuminated, low energy-sensitive S3 chip. The ACIS data were reprocessed with the of the backside-illuminated, low energy-sensitive S3 chip. The nucleus of NGC 6240 was placed near the nominal aimpoint for 146 ks (ObsID 12713, PI: Fabbiano). The binary

| ObsID   | Date          | Exposure (ks) | Instrument       | Data Mode | Roll Angle (°) |
|---------|---------------|---------------|------------------|-----------|----------------|
| 1590    | 2002 Feb 22   | 37            | ACIS-S           | Faint     | 246.2          |
| 6909    | 2006 May 11   | 143           | HETG/ACIS-S      | VFaint    | 129.9          |
| 6908    | 2006 May 16   | 159           | HETG/ACIS-S      | VFaint    | 138.1          |
| 12713   | 2011 May 31   | 146           | ACIS-S           | Faint     | 167.2          |

Total Effective Exposure (ks) 363

Note. The effective exposure time for the Chandra HETG zeroth-order image refers to the equivalent exposure needed if the data were taken with direct Chandra ACIS imaging, calculated by comparing its effective area to that of the ACIS imaging without the grating.

3. IMAGING SPECTROSCOPIC ANALYSIS OF THE NGC 6240 CENTRAL REGION

Figure 1 shows the Chandra ACIS image of the inner 25'' × 25'' (~12 kpc across) region of NGC 6240 in the 5.5–8 keV band extracted from the merged data, together with an archival Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS)/Wide Field Camera F814W image (Cycle 14 program 10592, PI: A. Evans), highlighting the highly disturbed optical morphology of NGC 6240. The two nuclei are resolved as the brightest X-ray point sources in the center, with peak emission separated by 1.492 (710 pc), matching the nuclear compact radio source positions (e.g., N1 and N2 in the 8.4 GHz map of Colbert et al. 1994, N1 and S in the 1.4 and 5 GHz maps of Beswick et al. 2001, and North and South black hole positions in Max et al. 2007).

Diffuse emission is clearly present (Figure 1(b)), extending to $r = 10''$ (~5 kpc). Hereafter, we refer this region as the central region of NGC 6240. The X-ray morphology resembles a “heart” with loop-like features in the south, the northeast, and the northwest directions (Figure 1(b)). A comparison between the observed surface brightness profile and that of a point source further confirms the presence of significant hard X-ray emission reaching $r \sim 10''$ radial distance. Figure 2 shows the excess of hard X-rays over the scattered emission in the wings of the point-spread function (PSF). The radial profile flattens past 10'', where background emission dominates. The Chandra PSF shown in Figure 2 was created simulating a point source at the same position on the detector as the center of NGC 6240 in the single observation of the longest exposure (ObsID 12713) using the Chandra Ray Tracer (ChaRT) and the MARX simulator. This PSF was then rescaled to match the combined 5.5–8 keV

$\Omega_{\Lambda} = \frac{\Delta \lambda}{E_0 - 0.01 \text{ keV}} \approx 0.012 \text{ Å}, 11 \text{ FWHM}$ and the systematic uncertainty in the HETG wavelength calibration is $\sim 0.01$ keV ($\sim 430$ km s$^{-1}$) at 6.4 keV. Table 1 summarizes the Chandra ACIS and HETG observations used in our work.

**Table 1**

| ObsID   | Date          | Exposure (ks) | Instrument       | Data Mode | Roll Angle (°) |
|---------|---------------|---------------|------------------|-----------|----------------|
| 1590    | 2002 Feb 22   | 37            | ACIS-S           | Faint     | 246.2          |
| 6909    | 2006 May 11   | 143           | HETG/ACIS-S      | VFaint    | 129.9          |
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Total Effective Exposure (ks) 363

Note. The effective exposure time for the Chandra HETG zeroth-order image refers to the equivalent exposure needed if the data were taken with direct Chandra ACIS imaging, calculated by comparing its effective area to that of the ACIS imaging without the grating.

$^{10}$ http://cxc.harvard.edu/ciao/threads/createL2/
$^{11}$ http://cxc.harvard.edu/proposer/POG/html/HETG.html
$^{12}$ http://space.mit.edu/CXC/calib/hetgcal.html
$^{13}$ http://cxc.harvard.edu/chart/
$^{14}$ Version 4.4.0; http://space.mit.edu/cxc/marx/.
counts from the two nuclei. Since the nuclei are separated by 1.5" and we are interested in demonstrating the presence of extended emission several arcseconds from the nuclei, this is an adequate procedure. For the investigation of extended emission close to the nuclei (e.g., between the nuclei), we have performed a more complex two-dimensional (2D) image fitting with two PSF components, described in the next section.

3.1. Spectral Analysis: Neutral, He-like, and H-like Fe K Lines

Previous work by Boller et al. (2003) identified ionized Fe K emission lines from the presence of a collisionally ionized plasma with a temperature $kT = 5.5 \pm 1.5$ keV, producing the Fe XXV (at 6.7 keV) and Fe XXVI (at 6.93 keV) Kα recombination lines. Boller et al. also inserted in their fit the neutral or low-ionization Fe Kα line (expected at 6.4 keV) and Kβ line (at 7.058 keV), each modeled with a Gaussian line. Such fluorescent lines of large (up to few keV) equivalent widths (EWs) arise from large column density gas that strongly attenuates directly viewed X-rays from the AGNs.

To shed light on the spectral properties of the spatially resolved central region, we extracted the spectra of both nuclei and all the emission in the 10" radius circle. Figure 3(a) compares the ACIS spectra of the central region of NGC 6240 (circle in Figure 1; all emission within $r = 10"$, ~5 kpc from the nuclei) and the innermost region containing the two nuclei (ellipse in Figure 1, where the full lengths of the axes are 4" × 2").

The complex Fe K line structure detected in XMM-Newton spectra (Boller et al. 2003; Netzer et al. 2005) is clearly
present in the *Chandra* ACIS spectra (Figure 3) and contributes most counts, in contrast to the low continuum in the same region. Approximately 80% of this continuum comes from the innermost region enclosing the nuclei. There are notable differences between the two spectra, which are further illustrated in Figure 3 showing the residual spectrum excluding the nuclei. Following Boller et al. (2003), we added four narrow Gaussian emission lines (representing neutral Fe Kα, Fe XXV, Fe XXVI, and Fe Kβ) to a highly absorbed power-law continuum to fit the spatially resolved spectra (the northern nucleus, the southern nucleus, and the extended emission within $r = 10''$, i.e., nuclear+diffuse). This phenomenological approach is adopted to identify the spatial distribution of the line emission and a more physically meaningful model will be used in the later section. To prevent oversubtraction of diffuse emission from the hot gas in the nuclear region, we did not exclude the innermost region when evaluating the hot gas content in the $r \leq 10''$ emission; instead, we included nuclear components to represent the contribution from the AGNs.

Figure 3 also shows a hint of two peaks in the Fe XXV line, which resembles double-peaked emission line profiles seen in the optical spectra of AGNs with biconical outflows (e.g., Mrk 78; Whittle & Wilson 2004). However, it is statistically insignificant: the probability that the model with one more Gaussian component improves over the current fit is only 80% based on a likelihood ratio test (10,000 simulations) performed using XSPEC. In fact, the energy resolution of the ACIS S3 detector is 0.2 keV FWHM (6.4 keV, whereas the apparent double peaks are separated by 0.05 keV. Therefore, we suggest that it is not a real resolved feature. The Fe XXVI and Kβ lines are blended together at the spectral resolution of the ACIS CCD, therefore we fixed the Kβ line center energy at 7.058 keV (rest frame) and scaled the line intensity according to the theoretical ratio (1/8.8; e.g., Palmeri et al. 2003) relative to the Kα line. The best-fit centroid energies, EWs, line fluxes, and associated 1σ errors are summarized in Table 2.

Although the first-order *Chandra* HETG spectrum is faint, we attempted to spectroscopically resolve the various Fe features. The grating spectrum was rebinned for a minimum signal-to-noise ratio of three and was fit with the similar model consisting of an absorbed power-law continuum plus Gaussian lines using XSPEC. Again, we caution that the best-fit value of $\Gamma$ for the simplistic power-law continuum model is not physically meaningful but simply parameterization. We recovered a FWHM = 2860 ± 550 km s$^{-1}$ for the Fe Kα 6.4 keV line, consistent with the FWHM $\sim$ 2810 km s$^{-1}$ reported in Shu et al. (2011). Interestingly, the Fe XXV line at 6.7 keV is marginally resolved at 2.4σ significance with the measured FWHM $\sim$ 5550 km s$^{-1}$, implying a large velocity range in the hot gas kinematics. Furthermore, the HETG spectrum does not resolve this line into two peaks, although it shows the line is broad (FWHM $\sim$ 5550 km s$^{-1}$). More counts would have allowed finer binning to attempt resolving the broad line into two or more kinematic components.

The line fluxes further confirm that the Fe XXV emission is spatially extended while the neutral Fe Kα emission is concentrated at the nuclei. The neutral or weakly ionized Fe Kα line emission at 6.4 keV (centered at 6.25 keV in the observer frame) is also mostly associated with the nuclei, with $\sim$15% of the total Fe Kα emission in the extended region (Figure 3). At the 6.4 keV energy, the PSF scattering of nuclear emission to the larger radii cannot be neglected, which is $\sim$10%. Taking this into account, the spatially extended Fe Kα emission is 5% of the total. The Fe XXVI emission is fully accounted for by the innermost nuclear emission, indicating that the mostly ionized H-like iron is confined in this region. In contrast, $\sim$30% of Fe XXV line emission appears to originate in the extended region outside of the nuclear region (taking into account of the PSF contribution). In the following, we will investigate the morphology of this emission. Given that the XMMspectra (Netzer et al. 2005) come from a larger region, the similarity of the fluxes with our *Chandra* measurements excludes significant Fe emission beyond $r = 10''$.

### 3.2. Narrowband Hard X-Ray Images

The analysis above shows that the AGNs alone in NGC 6240 cannot account for the observed Fe K complex, except for the Fe Kα and Kβ emission (the latter fainter and blended

### Table 2

*Chandra* ACIS Measurements of the Complex Fe K Lines in NGC 6240

| Region  | Counts (5.5–8 keV) | Energy (keV) | Flux | EW (eV) | Fe i   | Fe xxv   | Fe xxvi   |
|---------|-------------------|--------------|------|--------|--------|----------|----------|
| Nuc-N   | 908               | 6.26 ± 0.01  | 10.7 ± 0.8 | 645 ± 600 | 6.54 ± 0.03 | 6.86 ± 0.04 |
| Nuc-S   | 2096              | 6.23 ± 0.01  | 13.5 ± 0.9 | 342 ± 30 | 6.46 ± 0.01 | 6.66 ± 0.03 |
| r ≤ 10''| 4856              | 6.25 ± 0.01  | 28.4 ± 1.3 | 359 ± 22 | 6.51 ± 0.02 | 6.74 ± 0.02 |
| r ≤ 70''|                   | 6.26 ± 0.02  | 26 ± 8     | 300 ± 100| 6.52 ± 0.02 | 6.84 ± 0.04 |

Notes:

- a Observed energies of the line centers.
- b Photon flux in the unit of 10$^{−6}$ photons s$^{−1}$ cm$^{−2}$.
- c XMM-Newton EPIC measured Fe K line complex from Boller et al. (2003). Because of the lower angular resolution of XMM-Newton, the spectrum is extracted using a circular region with a radius of 70''.

15 http://cxc.harvard.edu/proposer/POG/html/cha6.html
with Fe\textsuperscript{xxvi}, which is due to the fluorescence of neutral or low-ionization material near the AGNs. Guided by the spectra (Figures 3 and 4), we extracted \textit{Chandra} narrowband line images to investigate the morphology of the emission line gas.

Figure 5 shows images in the 5.5–6 keV continuum band that is free from any significant line emission, the Fe Kα line (6–6.4 keV), and the Fe\textsuperscript{xxv} line (6.4–6.7 keV). The blended Fe\textsuperscript{xxvi} and Fe\textit{i} Kβ emission was examined but not shown here, since it does not show any evidence for emission beyond the nuclear region. Although the line emission dominates in these narrow bands, the contribution of the continuum has been removed from the images regardless, assuming a single power law with a photon index (\(\Gamma = 0.8\)) from the spectral fit of the continuum in the central region. The contribution from the continuum in the emission line bands is calculated using the photon index and the counts over 5.5–6.0 keV, taking into account the difference in the effective areas. Given that the starburst likely dominates the extended emission (e.g., Netzer et al. 2005), we further confirmed that the following results do not change adopting a thermal bremsstrahlung spectrum (\(kT \sim 6\) keV for the hot gas) to approximate the flat continuum.

The continuum-subtracted line emission images clearly show that the 6.4 keV Fe\textit{i} Kα line peaks at the dual nuclei, with weak emission extending to \(r = 3''\) from the nuclei and contributing \(~10\%\) of the total \(~900\) Fe Kα counts. The Fe\textsuperscript{xxv} emission is also centrally peaked at the nuclear region with a dominating southern nucleus, but it appears more extended to the southwest and to the east; the \(r = 10''\) region outside of the nuclei contains \(~40\%\) of the \(~500\) total Fe\textsuperscript{xxv} counts. These values are in good agreement with the results from the spectral analysis above.

To extract more morphological information from the data, we performed image restoration using the Expectation through Markov Chain Monte Carlo (EMC2) algorithm (Esch et al. 2004; Karovska et al. 2005). The effectiveness of this method with \textit{Chandra} images was demonstrated with a number of astronomical imaging studies (Karovska et al. 2005, 2007; Wang et al. 2009, 2012). The EMC2 deconvolution is more effective for preserving diffuse features compared with other PSF-deconvolution algorithms (e.g., Lucy 1974). Only the single deep imaging observation (ObsID 12713) and the associated PSF were used to minimize the PSF variations across multiple observations. The PSF-deconvolved images, shown in Figure 6, provide the highest resolution view of the central region. In particular, the faint diffuse Fe\textsuperscript{xxv} emission is more obvious in Figure 6(c).

3.3. Sub-kiloparsec-scale Extended Emission Between the Nuclei

Close examination of the images suggests the possibility of some extended hard X-ray emission in the region between the two nuclei, especially in the Fe\textsuperscript{xxv} band (and perhaps in the Fe Kα band; see Figures 5 and 6). However, evaluating the significance of this emission is very difficult because of the close separation (1:5) of the nuclei. The PSF wings of the two X-ray point sources overlap in this region and enhance the emission here, which needs to be taken into account. Simulating two point sources convolved with the PSF, we performed 2D image fitting to subtract the PSF\textsuperscript{16} on the 5.5–8 keV image, as well as individual narrowband images, using \textit{Sherpa}\textsuperscript{17}. The results are shown in Figure 7. For the 5.5–8 keV image that has most counts, besides the clear extension to the southwest and the northeast (already noted above as the extended central region), the residual image further indicates that there is extended emission in the region between the two nuclei, immediately to the north of the southern nucleus, at \(~10\sigma\) significance level when evaluated using a 1" × 1" box region. For the narrowband images, the statistics are poorer; nevertheless, this extended feature is seen in all three residual images. Its significance

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Top to bottom: ACIS spectra and fits for the extended central emission, the northern nucleus, and the southern nucleus. Both ACIS data (black) and HETG (red) zeroth-order data were used. The model components are also shown as dashed lines (see Table 2). (A color version of this figure is available in the online journal.)}
\end{figure}
Figure 5. Narrowband ACIS images: (a) the 5.5–6 keV continuum band, (b) Fe Kα line (6–6.4 keV), and (c) Fe xxv line (6.4–6.7 keV). The latter two images were continuum subtracted (see the text).

(A color version of this figure is available in the online journal.)

Figure 6. Narrowband ACIS images, with EMC2 PSF deconvolution applied: (a) the continuum band (5.5–6 keV), (b) line image for the neutral Fe Kα line (6–6.4 keV), and (c) the Fe xxv (6.4–6.7 keV).

(A color version of this figure is available in the online journal.)

ranges from \( \sim 6\sigma \) in the Fe xxv line emission to \( \sim 3\sigma \) in the Fe Kα line emission.

We further checked for possible contamination from the PSF artifact\(^{18}\) found in ACIS data. Using the CIAO tool `make_psf_asymmetry_region`, this artifact should lie in position angle \( 0°–50° \) in our data. Given that this PSF asymmetry feature may contain only 5% of the flux\(^{19}\), it would have in any case minimal impact on our results.

3.4. Comparison with Multiwavelength Images

In this section, we compare the hard X-ray morphology of the center of NGC 6240 with a number of high spatial resolution images available in other wavelength ranges, aiming to find clues for the physical origin of the extended X-ray emitting gas. The absolute astrometry of our Chandra ACIS image is excellent, indicated by the agreement between the coordinates of the X-ray and the radio nuclei (\( \sim 0'0.2 \) accuracy; see Max et al. 2007 for a further astrometry discussion).

We first compare the 5.5–8 keV emission with the optical Hα emission morphology from the HST/WFPC2 F673N image (Lira et al. 2002), as shown in Figure 8(a). The 5.5–8 keV image was adaptively smoothed with CIAO tool `dmimgadapt` using a Gaussian kernel with smoothing scales of 1 pixel to 20 pixels, to better visualize structures in the diffuse emission. As a separate approach, the same 5.5–8 keV image with the PSF deconvolution applied is also shown in Figure 8(b). The optical peaks are not aligned with the X-ray nuclei due to obscuration. Lira et al. (2002) and Komossa et al. (2003) have previously shown that on a 10′ (4.9 kpc) scale, the Hα emission and the soft X-ray emission share a similar morphology consisting of filaments and loops. The overall morphology of the soft X-ray emission in our deep image (J. Wang et al. 2014, in preparation) is similar to that shown in Komossa et al. (2003) but with finer structure details, closely following the optical Hα emission. Such morphological correspondence is seen but less obvious in the hard X-ray emission, except for the bright Hα filament to

\(^{18}\) http://cxc.harvard.edu/ciao4.4/caveats/psf_artifact.html

\(^{19}\) See the document written by Vinay Kashyap (CXC) available at http://cxc.harvard.edu/cal/Hrc/PSF/acis_psf_2010oct.html.
Figure 7. 2D image fitting of the innermost nuclear region in (a) 5.5–8 keV, (b) 5.5–6 keV (continuum), (c) 6.0–6.4 keV (Fe\textsc{i}), and (d) 6.4–6.7 keV (Fe\textsc{xxv}). For each band, the observed image, simulated pair of point sources representing the double nuclei, and the residual emission are shown. The two circles mark the compact radio nuclear sources (Colbert et al. 1994).

(A color version of this figure is available in the online journal.)
the east and the loop to the northwest of the nuclei. Figures 8(c) and (d) further compare the Hα morphology with images in the 5.5–6 keV continuum band and the Fe XXV band. A close morphological correspondence between the Hα and the hard X-rays can be found at the base of an incomplete loop to the west of the nuclei (Figures 8(c) and (d), and at the filament to the south and east of the southern nucleus (Figure 8(d)).

Next, we compare the 5.5–8 keV image with the [Fe ii] 1.644 μm line emission (van der Werf et al. 1993) in Figure 9. The [Fe ii] emission in NGC 6240 could be produced by shocks in supernova remnants (SNRs; see van der Werf et al. 1993 for detailed discussion on possible excitation mechanisms) and is brightest at the locations of the two nuclei, consistent with the presence of nuclear starbursts (Engel et al. 2010). The two [Fe ii] emission peaks fall close to the X-ray nuclei, with a slight offset (0′′.2) to the north relative to the X-ray northern nucleus.

We find a close correlation of the spatially extended Fe XXV emission with the near-infrared H2(1–0) 2.12 μm emission obtained with Keck II (Max et al. 2005). Previous work (van der Werf et al. 1993; Max et al. 2005) noted that the H2(1–0) emission in NGC 6240 does not follow the stellar light but peaks between the two nuclei; this emission is thought to be excited by shocks (Moorwood & Oliva 1988; van der Werf et al. 1993). To compare H2 and our X-ray images, the astrometry of the H2 image was first registered using an infrared-bright star (2MASS J16530119+0224138, K = 10.4 mag) in the field. Figure 10 shows a remarkably good correspondence between the observed (top panel) and especially the deconvolved (lower panel) Fe XXV line emission and the H2(1–0) 2.12 μm emission.

Finally, we compare the Fe i Kα emission with the cold molecular gas distribution in the nuclear region, traced by the CO(3–2) emission obtained with the Submillimeter Array from U et al. (2011; see also Iono et al. 2007). Figures 11(a) and (b) show that the CO emission resembles a “bridge” or filament between the two nuclei, with the bright peak offset to the north of the southern Fe i Kα peak. The evidence for fluorescent Fe i emission from this cold gas is marginal at most, with Fe Kα emission extending to the north of the southern nucleus at a 3σ significance level.

### 3.5. Spectral Fit with the Thermal Plasma Model

To extract the physical parameters of the highly ionized gas responsible for the Fe XXV and Fe XXVI emission, we fit the 5.5–9 keV spectra of the r < 10′′ region. The contribution from the lower temperature gas (e.g., kT = 0.7 keV and kT = 1.4 keV components; Boller et al. 2003) found in previous studies is negligible in this energy range. We adopted an absorbed single temperature thermal plasma model (APEC; Smith et al. 2001) for the collisionally ionized gas producing the highly ionized Fe XXV and Fe XXVI emission lines, plus zero-width Gaussian lines centered at 6.400 keV and 7.058 keV (rest frame) as the neutral Fe Kα and Kβ lines, respectively. A photoionized origin for the Fe XXV was not considered as this was previously ruled out by the detailed photoionization calculation given by Netzer et al. (2005). The continuum
contribution from the two nuclei is accounted for by including an absorbed power-law component, representing the reflected nuclear emission. The Gaussian line components were also subject to this absorption column. The absorption column ($N_H = 4 \times 10^{23} \text{ cm}^{-2}$), the photon index ($\Gamma = 0.9$), and the normalization ($A = 1.5 \times 10^{-4}$) are fixed to be the best-fit values combining the two nuclei. The abundance $Z$ is fixed at solar values (Grevesse & Sauval 1998).

The spectrum with the best-fit model is plotted in Figure 12, which is well represented with a $\chi^2$/dof = 300/246, where dof refers to degrees of freedom. The temperature of the hot plasma is $6.15 \pm 0.33 \text{ keV}$ with an absorption column of $N_H = 5.5 \pm 1.7 \times 10^{21} \text{ cm}^{-2}$. The observed $0.5$–$8 \text{ keV}$ luminosity is $5.3 \pm 1.0 \times 10^{41} \text{ erg s}^{-1}$ and $L_{0.5–8 \text{ keV}} = 5.5 \pm 1.4 \times 10^{42} \text{ erg s}^{-1}$ after correction for absorption. The normalization is $2.5 \pm 0.5 \times 10^{-3}$, in units of $(10^{-14}/(4\pi D_A(1+z)^2) \int n_e n_H dV)$, where $D_A$ is the angular size distance to NGC 6240 (cm), $n_e$ is the electron density (cm$^{-3}$), and $n_H$ the hydrogen density (cm$^{-3}$). We obtain an emission measure ($\equiv \int n_e n_H dV$) of $3.1 \times 10^{65} \eta \text{ cm}^{-3}$, where $\eta$ is a volume filling factor.

It is unlikely that all the hot plasma emission is affected by a high column, given the clumpy morphology and the spatial extent. Fortunately, because we are working in the hard X-ray range, the absorption-corrected luminosity is less vulnerable to the uncertainty in the absorption column. Previous studies (Boller et al. 2003) and the broadband fit indicate that an absorption column of $N_H = 4.1 \times 10^{22} \text{ cm}^{-2}$ is reasonable outside of the nuclear region. This implies that our

\[ \text{(a) Fe K}\alpha (6-6.4 \text{ keV}) \quad 1 \text{ arcsec} \]
\[ \text{(b) Fe XXV (6.4-6.7 keV)} \quad 1 \text{ arcsec} \]
\[ \text{(c) Fe K}\alpha (6-6.4 \text{ keV}) \quad 1 \text{ arcsec} \]
\[ \text{(d) Fe XXV (6.4-6.7 keV)} \quad 1 \text{ arcsec} \]
absorption-corrected luminosity could be overestimated by a factor of two (or 0.3 dex in log $L_x$). To investigate the impact of the soft X-ray thermal components that are clearly present (Ko- mossa et al. 2003; Netzer et al. 2005), we modeled the broadband spectrum of the extended emission (the same $r \lesssim 10''$ region). Figure 13 shows the 0.3–8 keV band ACIS spectrum (grating zeroth-order spectra were not combined because of the low effective area in the soft X-ray band; see the discussion in Nardini et al. 2013). The best-fit model components are overplotted including two more thermal components with lower temperature ($kT_1 = 1.03$ keV, $kT_2 = 1.56$ keV), each subjected to an absorption column ($N_{H,1} = 3.3 \times 10^{21}$ cm$^{-2}$, $N_{H,2} = 5.3 \times 10^{22}$ cm$^{-2}$).

The high-temperature component has a similar $kT_3 = 6.0$ keV that is consistent with the previous fitted value. Fixing their abundances at solar values gives statistically unacceptable fits ($\chi^2 > 3$) and allowing for variation relative to solar abundance improves the fit to $\chi^2 = 1.32$. The remaining residuals are a few peaks higher than the model-predicted line emission at line energies corresponding to Mg xii (rest frame 1.47 keV), Si xiv (2.01 keV), and S xvi (2.62 keV), indicating likely anomalous abundances for these elements. Indeed, Netzer et al. (2005) suggested these elements have $\sim 2$ times higher abundance. A
word of caution is that the soft X-ray emission over a large spatial scale suffers from blending of thermal plasma of inhomogeneous absorption, temperature, and abundance, therefore spatially resolved studies in small regions are preferred. For our purpose of evaluating the contamination from these components to the hard energy range, we only add in Gaussian lines to improve the fit ($\chi^2 = 1.18$), which are shown in Figure 13. We evaluated that the declining hard tails of the $\AA$ soft X-ray spectral components only contaminate the 5.5–8 keV spectral range at 8% level, which has a minimal impact on the derived $N_{\text{H}}$ (4.0 ± 0.3 × 10$^{23}$ cm$^{-2}$ when the hard tails from the softer X-ray components are accounted for).

Using the Fe xxv line emission as a tracer for the extent of the hottest thermal component, which is confined within the central $r = 10''$, we can obtain the volume of the thermal gas-emitting hard X-rays, $V = 1.5 \times 10^6 \eta_4^{-1/2}$ cm$^3$, assuming a spherical geometry. This implies $n_e = 0.15 \eta_4^{-1/2}$ cm$^{-3}$. Following the calculations done in Richings et al. (2010), the 70 MK gas contains a total mass of $M_{\text{hot}} = 1.8 \times 10^9 \eta_4^{1/2}$ $M_\odot$ and a thermal energy of $E_{\text{th}} = 6.5 \times 10^{58} \eta_4^{1/2}$ erg. Since we assumed solar abundance, this implies the total iron mass in the highly ionized plasma is $4.6 \times 10^9 \eta_4^{1/2}$ $M_\odot$. Note that we also explored fitting with the abundance left free and the best-fit model gives $Z = 0.5^{+0.3}_{-0.2} Z_\odot$ with a lower $kT = 4.9 \pm 1.1$ keV, which has minor impact on the above estimated values. In addition, there is a degeneracy between the flat power-law component (which is most effectively constrained by the very hard end of the spectrum) and the hot thermal component (most effectively constrained by the Fe xxv line assuming fixed solar abundance). We find that a 0.05 dex increase in the normalization for the power-law component corresponds to a 0.09 dex decrease in the thermal component. When non-solar abundance is allowed, it leads to a 0.19 dex decrease in the normalization for the thermal component. This has negligible impact on our discussion later on the energetics of the hot gas.

The filling factor of the hot gas is poorly constrained observationally. Nevertheless, hydrodynamic simulations by Strickland & Stevens (2000) suggest that $n$ ranges between 0.1% and 10% for X-ray bright galactic winds. In the starburst region, $\eta$ is considered to be higher than the large-scale wind, close to 100% (Strickland & Heckman 2007). To facilitate our discussion, we assume $n / 0.9$ and caution the large uncertainty on this value. We consider that this is a reasonable average value for the large volume spanned by the hot gas; the true filling factor is most probably close to unity in the innermost X-ray brightest region and $\ll 1$% in the outer sphere. However, we also note that the dependence on $n$ is relatively weak for the hot gas mass and thermal energy ($n^{1/2}$).

4. DISCUSSION: ORIGIN OF THE DIFFUSE HARD X-RAYS

We have unambiguously detected diffuse hard (5.5–8 keV) X-ray emission in the central region of the merging galaxy NGC 6240. The Fe Kα and Kβ fluorescent lines in NGC 6240 have been firmly associated with the photoionized gas of high column density and low ionization close to the AGNs (e.g., Komossa et al. 2003; Netzer et al. 2005). Most of the observed Fe I line flux is explained by the emission from the NGC 6240 nuclei and the spatial concentration at the nuclear positions is consistent with this interpretation. Even with the long exposure, we do not find strong evidence that the dense molecular clouds in the nuclear region are producing fluorescent Fe lines. The excess of Fe I Kα counts in the CO bridge between the nuclei (Figure 11) is marginal (3σ significance) when the scattered counts from both AGNs are excluded.

What is the origin of the highly ionized gas emitting the Fe xxv line that extends over 5 kpc in NGC 6240? Given the LIRG nature of NGC 6240 characterized by a high star formation rate (SFR, 25 $M_\odot$ yr$^{-1}$; Engel et al. 2010), we first estimate the contribution to hard X-ray emission by the ensemble of X-ray binary (XRB) systems in the starburst. Using the correlation between the galaxy-wide 2–10 keV luminosity and the SFR provided by the Chandra survey of LIRGs (Lehmer et al. 2010, Table 4), the expected $L_{\text{HX}}^{\text{gal}}$ from the XRB population is $3.3 \times 10^{39}$ erg s$^{-1}$ in the 2–10 keV band, adopting a SFR $\sim 25 M_\odot$ yr$^{-1}$ (Engel et al. 2010). This is only 5% of the observed 2–10 keV luminosity of the extended hard X-ray emission, strongly indicating that the diffuse emission is dominated by hot gas. Such hard X-ray emission is most likely associated with the thermal gas from merged supernova (SN) ejecta and stellar winds present during a starburst. The He-like Fe xxv line emission is also observed in other well-known starburst galaxies like NGC 253 and M82 (e.g., Pietsch et al. 2001; Mushiake et al. 2011), the ULIRG Arp 220 (Iwasawa et al. 2005), and the integrated spectrum of a number of LIRG/ULIRG systems (Iwasawa et al. 2009), suggesting the existence of similar high-temperature plasma. It is worth noting that the observed diffuse hard X-ray emission in NGC 6240 here is almost 100 times more luminous than that observed in the classic superwind system M82 ($L_{\text{2–6 keV}} = 4 \times 10^{39}$ erg s$^{-1}$; Strickland & Heckman 2007).

Using optical imaging and spectroscopy to identify outflows in the warm ionized medium, Heckman et al. (1990) have shown NGC 6240 to host a superwind. Superwinds are believed to be driven by the thermal and ram pressure of an initially very hot ($T \sim 10^8$ K), high-pressure ($P/k \sim 10^7$ K cm$^{-3}$), and low-density wind. According to the starburst-driven superwind model, a hot gas bubble of internally shocked wind material with a temperature of several keV forms in the region of intense star formation (Chevalier & Clegg 1985, Suchkov et al. 1994, Strickland & Heckman 2007); this hot gas eventually flows outward at a high-speed (few 1000 km s$^{-1}$) wind. Here, we detected and spatially constrained for the first time thermal X-ray emission from such hot ($T \sim 70$ MK) gas in NGC 6240, likely the thermalized SN ejecta within the vicinity of the starburst region.

To further investigate whether the thermal energy content of the hot gas could be powered by thermalization of SNe shocks, we need to estimate the kinetic energy input from the SNe during the starburst. The resulting heating by SNe shocks should at least be comparable to $E_{\text{th}}$, considering that there are lower temperature phases and the gas has also bulk kinetic energy. The most often quoted SN rate for NGC 6240 is $\sim 2$ yr$^{-1}$ (e.g., van der Werf et al. 1993; Beswick et al. 2001; Pollock et al. 2007), which will be used next, although we note there is a small range of estimates. Engel et al. (2010) calculated a lower SN rate of 0.3 yr$^{-1}$ assuming 20 Myr of continuous star formation at 25 $M_\odot$ yr$^{-1}$, based on the measured K-band luminosity. Using the correlation between [Fe II] 1.257 μm and the SN rate recently found by Rosenberg et al. (2012) from a sample of nearby starburst galaxies (Equation (2) and Figure 9 therein), we find a higher but comparable SN rate ($\sim 3$ yr$^{-1}$). Assuming a fraction ($\alpha = 0.1$; Chevalier & Clegg 1985; Thornton et al. 1998) of the kinetic energy input (10$^{51}$ erg per SN) is converted into thermal energy of the hot gas, the total energy deposited during the past $\Delta t_{\text{SB}} \sim 20$ Myr of the most recent starburst...
Figure 12. X-ray spectra of the NGC 6240 $r = 10''$ central emission (black: ACIS data; red: HETG zeroth-order data) and the fit using thermal plasma model for the hot gas (see the text in Section 3.5).

(A color version of this figure is available in the online journal.)

Figure 13. Broadband (0.3–8 keV) ACIS spectrum of the NGC 6240 $r = 10''$ central emission (black line: the total model emission). The best-fit model components are overplotted including three thermal components for the hot gas, two with lower temperature ($kT_1 = 1.03$ keV component; cyan dash-dotted line; $kT_2 = 1.56$ keV), and one with a high temperature ($kT_3 = 6.0$ keV) emitting the Fe XXV line (green solid line). The absorbed power-law component (blue dashed line) represents the scattered nuclear continuum and the four narrow Gaussian lines correspond to the Mg XII, Si XIV, S XVI, and Fe Kα lines (see the text in Section 3.5).

(A color version of this figure is available in the online journal.)

(Tecza et al. 2000) is $E = 4 \times 10^{57}$ erg, which is comparable to $E_{th} = 6.5 \times 10^{57}$ erg. Adopting a 10% filling factor for the hot gas results in a larger $E_{th}$ and a larger deficiency ($E < E_{th}$ for $\alpha = 0.1$), but it does not impair our conclusion, considering that the thermalization efficiency can be higher than the adopted value of 0.1 in an environment where many SNe are exploding (Strickland & Heckman 2009), which will yield a larger $E$ that is still consistent with $E_{th}$. These estimates demonstrate that the observed diffuse thermal gas traced by the highly ionized iron line emission in NGC 6240 is consistent with being heated by SNe shocks in the starburst. The cooling time of this thermal gas is $\tau_{cool} = E_{th}/L_x \sim 40$ Myr, slightly larger than the starburst duration, which implies that such X-ray bright phases will be short lived once the starburst ceases.

Following Mitsuishi et al. (2011), another useful check is the comparison between the ejected iron mass from SNe and the observed iron mass. Adopting $M = 8.4 \times 10^{-2} M_\odot$ as the ejected iron mass per Type II SN (Iwamoto et al. 1999) and an average SN rate of $\sim 2$ yr$^{-1}$, the expected iron mass for the 20 Myr starburst is $M_{Fe,SB} = 3.4 \times 10^6 M_\odot$, which can easily account for the observed $M_{Fe,X-ray} = 4.6 \times 10^5 M_\odot$ considering that not all of the iron ejecta are currently X-ray.
emitting. Therefore, this comparison also supports the above scenario that starbursts are the origin for the 70 MK gas.

However, the morphological comparison showed some interesting correspondences and differences: (1) in the nuclear region, while Fe xxv and [Fe ii] both peak (Figure 9) at the radio nuclei, bright H₂ emission is observed between the nuclei (Figure 10), (2) H₂ and the X-ray Fe xxv emission share similar morphology at the “arms” extending southeast and southwest of the southern nucleus (Figure 10), which is not seen with the [Fe ii] emission. Why do the near-infrared H₂ and the X-ray Fe xxv emission share similar extended morphology, but not [Fe ii]? We suggest that these differences can be attributed to two aspects. First, there are presence of shocks in different velocity ranges. Second, the physical scales of SNRs are much more localized compared with starburst-driven winds.

van der Werf et al. (1993) suggested that the [Fe ii] emission in NGC 6240 may originate in shocks associated with SNRs during the starburst in the nuclei, based on the high [Fe ii]/Brγ ratio. When dust grains are destroyed by fast shocks, the Fe abundance in the gas phase is enhanced. Thus, it is straightforward to expect that the [Fe ii] and the highly ionized Fe emission peak at the nuclei of NGC 6240, where the intense star formation activities are and young SNR are produced (Teeza et al. 2000; Pollack et al. 2007; see also spatially resolved [Fe ii] emission in NGC 5135, Colina et al. 2012). Note that Fe xxv in the southern nucleus is ~3 times brighter than the northern one (see Figure 10 and Table 2), in agreement with a ratio of ~2 found in [Fe ii] and implying a higher SN rate in the southern nucleus.

From the X-ray perspective, the gas is heated to the high temperature, producing the observed hard X-ray emission by the thermalization of the kinetic energy from an ensemble of SNe and winds from massive stars inside the starburst region and by internal shocks in the supernovae at larger radii (Tomisaka & Ikeuchi 1988, Norman & Ikeuchi 1989, Heckman et al. 1990). Fe xxv emission also peaks at the radio nuclei and the peaks of [Fe ii] emission (Figure 9). We can assume that we observe the shocked wind matter, whose temperature then gives us a measure of the shock velocity. For non-radiative, strong shocks in a fully ionized, monoatomic gas, the post-shock temperature is \( T_{sh} = 3\mu k T / 16k \), where \( \mu \) is the mean mass per particle and \( k \) is Boltzmann’s constant (McKee & Hollenbach 1980).

For the observed hot gas (\( kT = 6.15 \text{ keV} \) or ~9 x 10⁵ \( K \)), we obtain a shock velocity \( v_{sh} = 2200 \text{ km s}^{-1} \). Other than shocks driven by the starburst, such high-velocity shocks are unlikely to be induced by the merger process in NGC 6240: even in direct collision systems like the Taffy Galaxy (UGC 12914/5), the progenitors collided at ~600 km s⁻¹ (Braine et al. 2003). The merging galaxies in NGC 6240 have well passed their first encounter, without showing a morphology like the ring galaxies exemplifying such a strong direct collision and the estimated collision velocity from the CO line width is only between 150 and 300 km s⁻¹ (Wang et al. 1991; Teeza et al. 2000).

In contrast, the bright H₂ emission observed between the nuclei of NGC 6240 has been interpreted to originate in global dissipative shocks resulting from the collisions of the interstellar medium (ISM) of the merging disk galaxies (Herbst et al. 1990; van der Werf et al. 1993; Max et al. 2005). The shock velocity was constrained to be at most 40 km s⁻¹ (van der Werf et al. 1993). However, the fainter large scale “arms” of H₂ emission extending southeast and southwest of the southern nucleus need a different explanation, as they closely follow the X-ray emission. As fast outflows (several thousand km s⁻¹) driven by the starburst are expected (e.g., Heckman et al. 1990, Fabbiano et al. 1990; see Veilleux et al. 2005 for a review), this large-scale H₂ emission can be interpreted as originated from molecular material entrained and shocked by the superwind. The thermal velocity of this 6 keV gas, estimated as the adiabatic sound speed \( v_{th} = (5kT/3\mu m_H)^{1/2} \sim 1260 \text{ km s}^{-1} \) (assuming solar abundance), is much higher than the escape velocity \( v_{esc} = \sqrt{2GM/r} \), which is ~210 km s⁻¹ at r ~ 1 kpc using the dynamical mass \( M_{dyn} = 6 \times 10^9 M_\odot \) in Tacconi et al. (1999). Therefore, the expanding hot bubble can “blow out” to larger radial distance such as the 5 kpc extent seen here. Following a simple model of a shock propagating in an inhomogeneous ISM in van der Werf et al. (1993), the high-velocity shock (\( v_1 = 2200 \text{ km s}^{-1} \); see above) in the low-density wind responsible for the Fe xxv emission will slow down significantly when it encounters a layer of cold molecular gas. The decreased shock speed \( v_2 \) can be estimated using the density contrast between the X-ray gas (\( \rho_1 \sim 0.1\eta^{1/2} \text{ cm}^{-3} \)) and the molecular cloud (\( \rho_2 \sim 10^4 \text{ cm}^{-3} \)), following \( v_2/v_1 = \sqrt{\rho_1/\rho_2} \) (Spitzer 1978, Equations (12)-(39); note this is different from the shock jump condition). The expected \( v_2 \sim 7–20 \text{ km s}^{-1} \) agrees well with the velocity constraint from shock excitation for the observed H₂ emission (e.g., van der Werf et al. 1993). We have also shown that the hard X-ray emission shares similar characteristics with the optical Hα emission (Figure 8), with a few filaments and loops that are more apparent in the soft X-rays (Komossa et al. 2003; J. Wang et al. 2014, in preparation). The overall picture is that previous models, consisting of multi-temperature, multi-zone thermal plasma powered by a starburst, can explain the observed emission properties given that the outflows (and consequently, the shocks) have a large velocity range: the hard X-rays are associated with fast shocks driven by SN explosions and the soft X-rays/Hα are related to slower shocks associated with mass-loaded starburst winds.

More evidence supporting this scenario also comes from the presence of high-velocity H₂ and Hα emission in the “arms” region, based on prominent wings in the H₂ 1–0 S(1) line (with full width at zero intensity of ~1600 km s⁻¹; van der Werf et al. 1993; Engel et al. 2010) and Hα line profile (Heckman et al. 1990), tracing the ambient gas entrained and shocked by the superwind. In a very recent CO(1–0) interferometry observation of NGC 6240, Feruglio et al. (2013) further identified evidence for a shock wave that propagates eastward from the nuclei. One of the resolved structures of blueshifted CO emission is spatially coincident with the southeast H₂ filament (Max et al. 2005), which is also associated with Hα and soft X-ray emission. The derived kinetic power of the outflowing CO gas is \( 6 \times 10^{42} \text{ erg s}^{-1} \), with an estimated age > 2 x 10⁷ yr. This implies a total kinetic energy of \( E_{kin} = 3.8 \times 10^{57} \text{ erg} \). Recall that the available kinetic input from the multiple SN explosions during the starburst is \( 4 \times 10^{58} \text{ erg} \) per SN x 2 yr⁻¹ x 2 x 10⁷ yr; there seems no deficit in the energy budget. However, we cannot yet draw conclusion that no additional energy injection is required until a full tally of the bulk kinetic energy and thermal energy of the outflowing gas in other phases is available for NGC 6240. Under the assumption that the 70 MK gas is volume filling (\( \eta = 100\% \)); Strickland & Stevens 2000), its \( E_B \) would exceed the available kinetic energy provided by the recent starburst by 2.5 x 10⁵⁸ erg, implying additional kinetic power input such as from an AGN outflow or multiple star-forming episodes. In fact, the thermal energy content in the large-scale (~100 kpc) soft X-ray halo (\( kT = 0.65 \text{ keV} \)) in NGC 6240 identified by Nardini et al. (2013) is estimated to
be $4.9 \times 10^{58}$ erg, which hints at additional energy input from widespread, enhanced star formation proceeding at steady rate over $\sim 200$ Myr (Nardini et al. 2013) besides the most recent nuclear starburst.

Lastly, we note that a good spatial correlation is also expected if the $H_2$ emission is excited by localized X-ray irradiation of molecular clouds (Draine & Woods 1990). However, this was concluded to be unlikely (van der Werf et al. 1993), since the required SN rate of 7 yr$^{-1}$ (Draine & Woods 1991) is much higher than the inferred rate from radio, infrared, and our X-ray measurement. Thus, we conclude that propagation of fast shocks originated in the starburst-driven wind into the ambient dense gas can account for the large-scale X-ray and $H_2$ morphological correspondence.

5. CONCLUSIONS

Combining new and archival Chandra observations of NGC 6240, we have obtained the deepest X-ray image of the central $r = 5$ kpc ($10''$) of the merging ULIRG NGC 6240 with subarcsecond resolution. Studying the hard X-ray emission centered at Fe K complex and comparing with images in other wavebands, we clearly resolved, for the first time, hard extended emission with subarcsecond resolution. Studying the hard X-ray emission around the active nuclei. No evidence for fluorescent Fe ii emission is found in the CO filament connecting the two nuclei.

Although the above superwind scenario accounts for the extended hard X-ray emission and observational evidence in other wavebands, we cannot yet rule out additional energy injection in the central region of NGC 6240 (e.g., heating by an AGN outflow). Given the poorly constrained volume filling factor of the X-ray emitting gas, the thermal energy of the hot gas may exceed the available kinetic energy provided by the SN explosions during the most recent starburst ($E_{\text{th}} - E_{\text{SB}} = 2.5 \times 10^{58}$ erg for $\eta = 100\%$), implying additional energy input such as from an AGN outflow or more complex star formation activities besides the recent nuclear starburst (see the discussion in Nardini et al. 2013). A full tally of the bulk kinetic energy and thermal energy of the outflowing gas in other phases is crucial for the evaluation of the energy budget in the NGC 6240 system. We will further characterize the soft X-ray emission within the central 15 kpc in this merging galaxy in a forthcoming paper (J. Wang et al. 2014, in preparation).

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Facility: CXO (ACIS)

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Combining new and archival Chandra observations of NGC 6240, we have obtained the deepest X-ray image of the central $r = 5$ kpc ($10''$) of the merging ULIRG NGC 6240 with subarcsecond resolution. Studying the hard X-ray emission centered at Fe K complex and comparing with images in other wavebands, we clearly resolved, for the first time, hard extended emission with subarcsecond resolution. Studying the hard X-ray emission around the active nuclei. No evidence for fluorescent Fe ii emission is found in the CO filament connecting the two nuclei.

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